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Master´s Thesis
Industrial Economics

"Assessment of Norway's potential for a new CCS industry"

Universitetet i Stavanger

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Magnus Brun

Stavanger, June 2019

Preface

This master thesis is written as a final thesis for the master's programme in Industrial Economics at the University of Stavanger. The thesis is written in cooperation with AS Norske Shell.

We want to thank all the people we have consulted and that have helped giving us insight to relevant challenges for the thesis. We want to thank our supervisor at UiS, Kristin Engh, for thorough and good guidance throughout the project's lifetime. We also want to thank Anna Thorarinsdottir for helping us getting an exciting thesis in cooperation with Shell, and at last a special thanks to Kim Bye Bruun who has been our supervisor in Shell and invited us to participate at a OGCI climate meeting in The Hague, which gave us valuable insight and contacts that we've used throughout the thesis.

The work with this thesis has given us a broad understanding of the CCS cycle, and it has been a privilege to work with such a relevant and giving topic. We really look forward to seeing how the CCS adventure continues.

Svein Hugo Bringsjord Granstrøm og Magnus Brun

Stavanger, June 2019

Summary

This thesis will investigate whether Norway has a potential for a carbon capture and storage (CCS) industry. Norway has committed to the Paris agreement, and to reduce their non-ETS emissions by 40% from 2005 levels by 2030. The Intergovernmental Panel on Climate Change revealed that if the climate goals in the Paris agreement shall be met, CCS will play an important role and represents a solution in three out of four possible pathways for reaching the desired target. Currently, CCS deployment is slow and only 18 CCS facilities are operating today worldwide. The Global CCS institute argues that we need to capture 3.75 Gtpa by year 2040 to achieve the climate targets in the Paris agreement.

Norway has shown great interest for CCS, where it has been used at offshore platforms for decades. With the CCS test centre at Mongstad and the planned full-scale CCS facility from Norcem Brevik and Fortum Oslo, Norway can take a pioneering role and encourage global CCS deployment. This thesis will investigate how well suited the external framework around CCS is in Norway, and if the technology can offer a new important industry in Norway. The research was divided into two parts; a PESTEL analysis to highlight drivers and barriers for CCS deployment, and a mapping of CO_2-emitting sources in Scandinavia to reveal if there is a market for CO_2 storage in terms of access to industrial CO_2 emissions and available storage capacity.

The findings show that Norway is well positioned for large scale CCS deployment, particularly due to well-assessed storage capacity, sub-surface knowledge and experience, and public and private interest in investing in development of CCS projects. The mapping of CO_2 sources indicates that there is a potential for a big market in Scandinavia, with large emitting sources accessible by ship. However, the research also revealed that there are many barriers. The EU Directive for CCS is currently creating financial and reliability barriers that discourage operators and investors from investing in CO_2 storage. The technology has proven very costly, resulting in deficient political backing and incentives. Based on the above, it is concluded that Norway has great potential for CCS to become a new industry, but certain aspects would need to be solved before Norway can offer an environment in which CCS can thrive.

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Abbreviations

CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CEF	Connecting Europe Facility
CO_2	Carbon Dioxide
EJ	Exajoule, 1.0E+18 joule
E-PRTR	European Pollutant Release and Transfer Register
ENGO	Environmental Non-Governmental Organization
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
FOAK	First of a Kind
GDP	Gross domestic product
GHG	Greenhouse gasses
Gtpa	Giga tonne per annum
H_2	Hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MEA	Mono-ethanol amine
MSR	Market Stability Reserve
Mtpa	Mega tonne per annum
NOAK	Nth of a kind
NPV	Net Present Value
OGCI	Oil and Gas Climate Initiative
O&G	Oil and Gas
PCI	Projects of Common Interest
PESTEL	Political, Economic, Social, Technological, Legal

1. Introduction

Human activities are estimated to have increased the global warming by 1.0°C above pre-industrial levels, and is expected to increase to 1.5°C somewhere between 2030 and 2052 at the current rate (IPCC, 2018). If global warming exceeds this to about 2°C, the planet will likely see irreversible climate impacts, including sea-rise and loss of ecosystems (IPCC, 2018).

To avoid these irreversible effects, the Paris agreement was reached in 2015 to help bring nations together and assist in the common cause of battling climate change. The main goal is to keep the global temperature rise this century well below 2°C above pre-industrial levels, and hopefully limit it to 1.5°C (United Nations, 2015). As stated by the United Nations themselves, reaching these goals requires *"appropriate financial flows, a new technology framework and an enhanced capacity building framework"* (UNFCCC, 2018). By committing to this agreement, the nations must develop a national plan for how to reduce greenhouse gases (GHG). Every five year from 2020, this plan will be replaced by an updated and more ambitious plan on how to reduce emissions. Rich countries are expected to contribute financially and help underdeveloped countries to reach their climate targets and to drive the technology towards more climate friendly solutions (United Nations Association of Norway, 2018). As of June 2019, the agreement was signed by 197 parties and ratified by 185, constituting a worldwide collaboration (UNFCCC, 2019)

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for investigating and researching climate change and the science behind it. In October 2018, IPCC released their "Special Report on Global Warming of 1.5°C (SR15)", which is used globally to highlight challenges regarding climate change and mitigation of these. In three out of four pathways used by IPCC to reach the 1.5°C target, carbon capture and storage (CCS) was used as a key technology needed to meet the target (IPCC, 2018). By committing to the Paris Agreement, Norway must contribute to the climate solutions - and according to IPCC, CCS is a big part of the climate solution.

1.1 Carbon Capture and Storage

CCS is a technology used to reduce large emissions of CO_2. It is a three phased process, consisting of capturing the CO_2, transport it and store it. The idea is to capture the CO_2 from emission sources before it enters the atmosphere. When the CO_2 is separated from the emissions, it is compressed and liquified for easier transport, and eventually transported away from the facility through pipelines, ships or trucks. The liquid CO_2 is then injected into a reservoir below the surface on land or offshore, within geological formations able to keep the CO_2 trapped. By doing this, less CO_2 will be emitted to the atmosphere and hence limit global warming (IPCC, 2005).

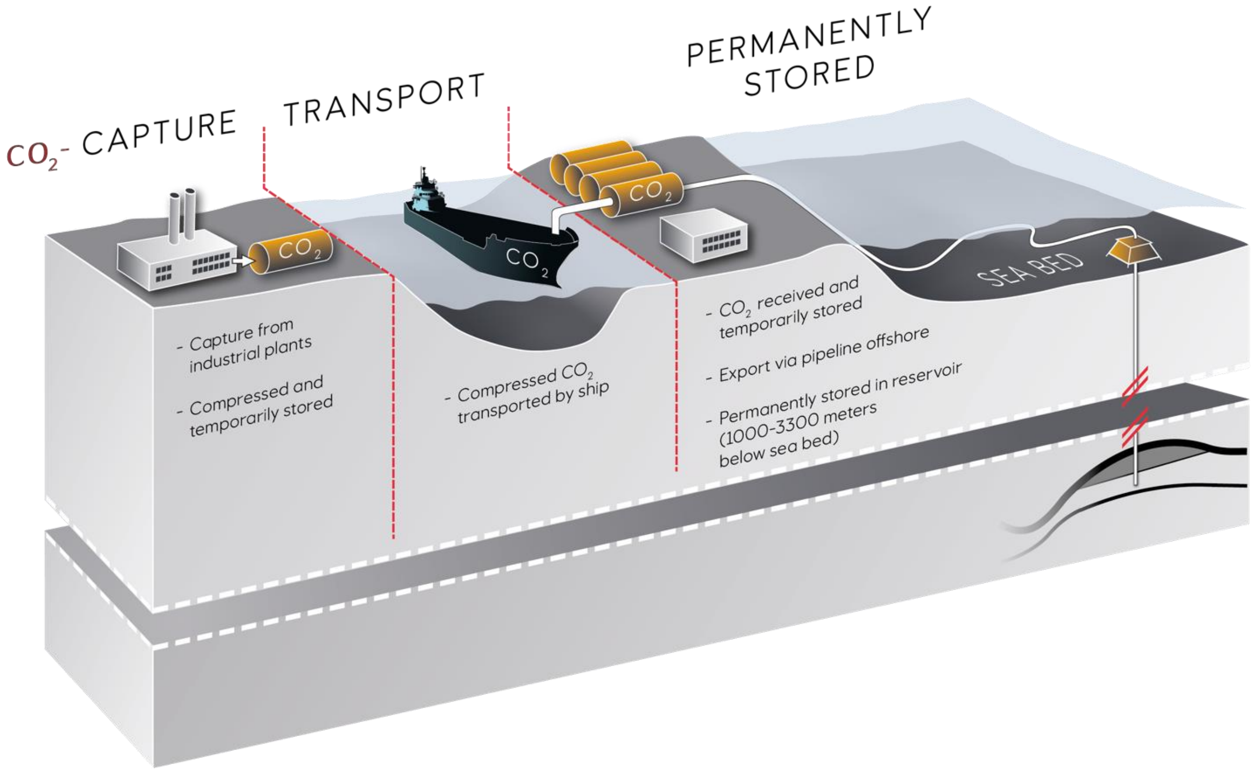

Figure 1 - Northern Lights project illustration (Equinor, 2018)

There are currently three main technologies available for CCS; pre-combustion, post-combustion and oxyfuel-combustion, all of which will be discussed in section 3.4 “Technology”. Large scale CCS facilities have been used since the 1970´s, and all three phases of capture, transportation and storage have been proven effective and safe for decades. In 2018, there were 18 large scale CCS facilities operating around the world (Global CCS Institute, 2018). Although CCS has received increased focus and acknowledgement in recent years, the world needs many more CCS facilities than the 18 currently in operation. It is estimated that by year 2040, we need 2 500 CCS facilities, each with a capacity of capturing 1.5 million tonnes CO_2 per annum (Mtpa) which equals a total of 3.75 Gtpa (gigatons per annum) (Global CCS Institute, 2018).

Through the Paris agreement, Norway are imposed to cut its non-ETS[1] emissions by 40% from 2005 levels by 2030, and both IEA and IPCC estimates that around 12-20% of these reductions need to come from CCS (Norwegian Ministry of Climate and Environment, 2019) (IPCC, 2018). Globally, a total of 2.5 Gtpa needs to be captured from CCS, or 7% of the total CO_2 emissions based on 2017 levels (Global Carbon Project, 2018). Today we capture around 40 Mtpa – equivalent to 1.67% of what will be needed to reach the 2030-target (Global CCS Institute, 2018).

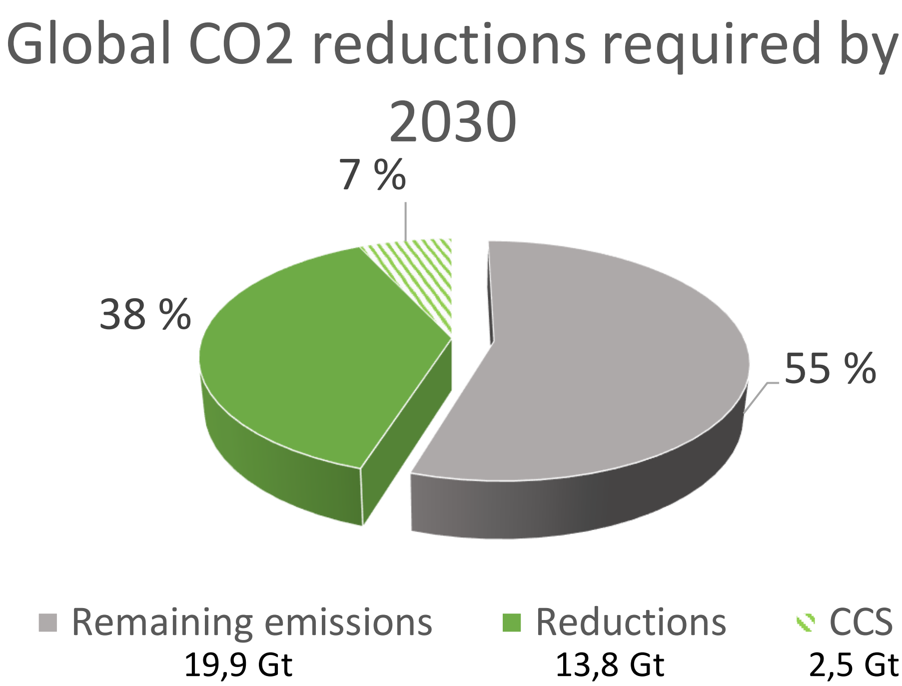

Figure 2 - Necessary CO_2 reductions in 2030 from 2017 levels. Data: (IPCC, 2018); Global Carbon Atlas

While some governments and experts say CCS is necessary and the best option to meet climate goals, other organizations and experts argue that CCS is a "false hope" and a diversion from the real solution (Greenpeace, 2012). For CCS to become a feasible solution in Norway, the external factors and frameworks influencing CCS need to be assessed, both politically, economically and technically. While there are many challenges for CCS both globally and in

[1] Non-ETS emissions are emissions not covered by the EU Emissions Trading System, i.e. agriculture, transportation, residential and waste (Regjeringen, 2019)

Norway, a general claim is that CCS is too expensive (Global CCS Institute, 2017). Development of a solid financial model for CCS can act as a catalyst towards other regulatory and political challenges, releasing funding and commitment.

1.2 The CO_2 pricing paradox

SINTEF published a report in 2018, investigating the possibilities and costs of the planned full-scale CCS project in Norway. The outcome revealed that the estimated cost of avoiding one tonne of CO_2 (capture, transport and storage) would be between 850-1330 NOK (SINTEF, 2018). Instead of capturing the CO_2, carbon credits can be bought through the EU emissions trading system (EU ETS) which allows a company to emit one tonne of CO_2 (European Commission, 2015). With an EU ETS price trading at 237 NOK (per 07.05.2019), you save between 613-1093 NOK per tonne CO_2 you emit by buying carbon credits, compared to the estimated cost of capture, transport and storage of one tonne CO_2. Emitting more CO_2 than you have quota for will result in a fine of 100 EUR/tonne CO_2, approximately 976 NOK (European Commission, 2015). Even at this price, emitting could be cheaper than capturing.

The estimated costs in the SINTEF report are based on the Norwegian full-scale CCS project, which will capture CO_2 from two independent sources; Norcem Brevik and Fortum Oslo Varme. Norcem Brevik is a cement factory and Fortum Oslo Varme a waste combustion facility, each estimated to capture around 400 000 tCO_2/year (Olje- og energidepartementet, 2016). Northern Lights is a project collaboration between Equinor, Shell, Total and Gassnova and will consist of the transportation and storage phase for the full-scale project as illustrated in Figure 1 (Equinor, 2018).

Price for capturing CO_2 will vary depending on the industry, emission quantity and CO_2 concentration in the emissions (Wilcox, 2012). Different industries have different costs and CO_2 concentrations. To better understand the actual costs, one would have to look at a specific emission source and map the emission quantity and the estimated capture costs. By mapping the big emission sources in Scandinavia and the industry-relevant cost of CO_2 avoided, AS Norske Shell can get an overview over the potential sources where CCS would be economically viable and developed a business case to transport and store the CO_2 through the Northern Lights project.

But it is not enough to just look at the costs. There are several other factors that must be in place for CCS to become an important industry in Norway. Political, legal, social and technological aspects can all affect the industry. If those are not in place, investing in CCS carries high financial risk. This leads to the main question for the thesis; *What is the potential for CCS as a new industry in Norway?*

To be able to answer this, three research questions have been formed:

1. How does political and economic frameworks facilitate the establishment of a CCS industry in Norway?
2. Is CCS technology mature enough to be commercialized?
3. What capture potential exists from large emitting sources in Scandinavia?

1.3 Constraints

Due to time and resource constraints, it is necessary to limit the scope of the report to a feasible size.

This report is written in cooperation with AS Norske Shell, who is currently working with Equinor, Total and Gassnova to develop the Northern Lights project. Hence the report will focus on Norwegian laws and regulatory frameworks. This thesis will focus on emission sources in Scandinavia with annual emissions above 700 000 tonnes CO_2 within the iron and steel, cement and ammonia production industries. These energy-intensive industries have been selected because CCS is the only option to cut their emissions while maintaining production (Engen & Whiriskey, 2014). Capturing CO_2 will be more cost efficient from large emission sources, thus a limit of 700 000 tonnes CO_2/year has been set. Smaller emission sources will most likely be too costly for CCS, and therefore the focus is directed towards sources that may be realistic for Shell to include in their Northern Lights project (Olje- og energidepartementet, 2016).

1.4 Structure of the Report

The thesis consists of seven chapters. Chapter 2 will explain the choice of theoretical framework we adapted to answer the research questions. The theory is split into two sections; part I and part II.

- Part I – PESTEL analysis[2]
- Part II – Mapping of the potential in Scandinavia

Part I is presented in Chapter 3 and comprises the PESTEL analysis and ends with a short briefing of the PESTEL results in chapter 3.7. This constitutes the theoretical foundation which will be discussed further in Chapter 6. Part II and supporting theoretical concepts are presented in Chapter 4. This chapter also ends with a brief presentation of the results which are discussed in Chapter 6.

Chapter 5 explains the methodology used, how we have gathered data and self-reflecting criticism. Chapter 6 constitutes the discussion which is based on findings presented in Chapter 3 and 4 and lays the foundation for the conclusion in Chapter 7. Finally, we will end the thesis with a recommendation for future research, which can contribute to further develop the concepts studies in this thesis.

[2] PESTEL is an analysis assessing these external factors; political, economic, social, technological, environmental and legal aspects and how these can affect the phenomenon investigated

2. Theoretical framework

The first research question "How does political and economic framework facilitate the establishment of a CCS industry in Norway?" will be answered through a PESTEL analysis. By assessing political decisions, funding and agreements across shifting Norwegian governments, a better understanding of how well supported CCS really is can be obtained. Is the support backed by actual funding, or simply encouraging statements and half-heartedly commitments? Are there incentives available for companies to encourage CCS investment? Has governmental support shifted between governments over time, and what does such political instability mean for investors?

Research question number two, "Is CCS technology mature enough to be commercialized?" can also be assessed using the PESTEL analysis, examining the different technologies and related costs, pros and cons in the technological chapter. What different types of technologies exist, and how well developed are they for use in the iron and steel, cement and ammonia industry? How much energy is needed for capturing the CO_2, and does that offset the benefit of removing CO_2 if additional costs will arise?

The third question, "What capture potential exists from large emitting sources in Scandinavia?" will be answered through a detailed mapping and analysis of large emitting CO_2 sources in Scandinavia. As environmental reporting on emissions are bound by law within the EU; Norway, Sweden and Denmark are required to publish annual emission data (Monitoring, reporting and verification of EU ETS emissions, n.d.). By connecting the CO_2 emissions with the relevant cost of capturing the CO_2, a storage operator can get an overview of how much CO_2 that can be stored at different locations at different costs.

2.1 PESTEL Framework

Understanding the potential for CCS as a new industry in Norway requires diverse knowledge within different fields and disciplines. To analyse this, the PESTEL framework is applied by assessing political, economic, social, technological, environmental and legal aspects.

PESTEL is an external analysis that examines the macro environment surrounding a company - or in this case, a new industry (Yüksel, 2012). It has two main functions:

1. Identification of the environment the relevant company or industry operates in

2. Provide information and data regarding future situations the relevant company or industry may find themselves in (Yüksel, 2012).

Each of the six elements is assessed to reveal threats and opportunities for the industry, based on two criteria: they are external factors in which the organization cannot influence, and they have the ability to impact the organization (Cadle, Paul, & Turner, 2010). Through this, the aim is to identify external forces that can influence industry; barriers that need to be solved and elements that are already in place and can provide opportunities for the industry. However, a PESTEL analysis is based on a holistic approach and cannot simply be summed up by looking at the six elements, as different elements have different impact and importance for different organizations and industries (Yüksel, 2012). Thus, when doing a PESTEL analysis, it is important to acknowledge the importance of the relevant elements and account for this in the discussion. The elements that make up the analysis and how they can affect CCS are listed below:

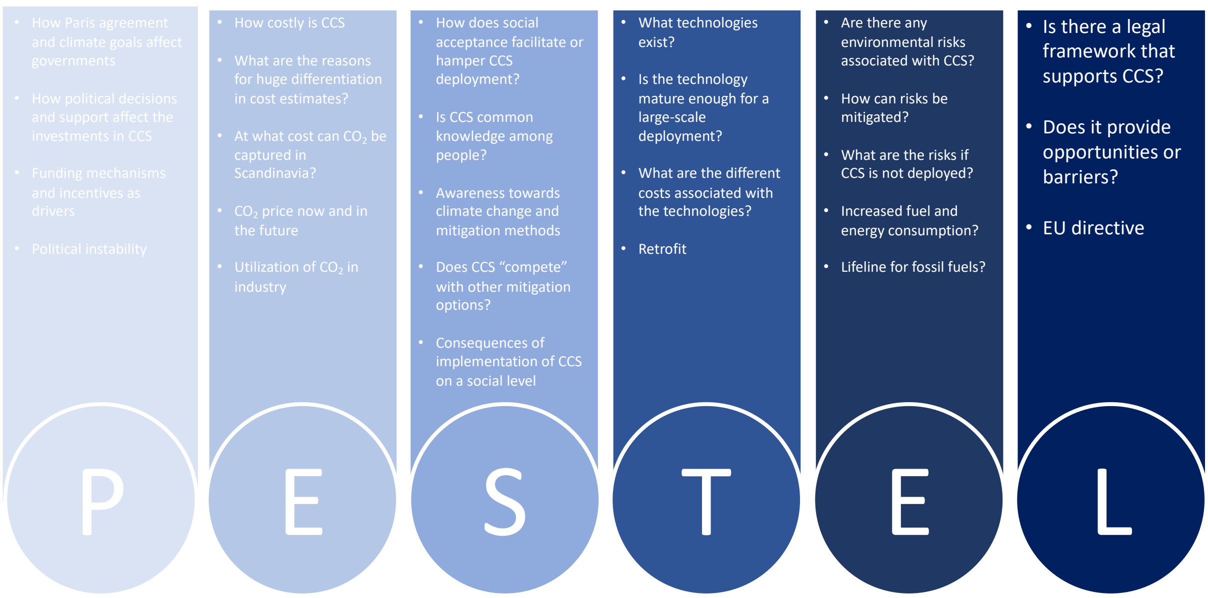

Figure 3 - PESTEL analysis and its contents

3. PESTEL analysis

3.1 Political climate

The political climate around CCS is changing. CCS has been here for decades, used in Enhanced Oil Recovery (EOR) since the 70's. Still, it was not until the IPCC Special Report on Carbon Capture and Storage in 2005 that the technology earned status as one of the main solutions to meet the climate goals. But even though CCS has been used successfully for decades, and is considered the cheapest method of meeting the climate goals (SINTEF, 2018), Global CCS Institute revealed in their "CCS Global Status Report 2018" that only 18 large scale CCS facilities are operating today around the world (Global CCS Institute, 2018). Considering that the same institution argues that we need 2500 facilities by 2040, the world is clearly behind schedule.

The 18 CCS facilities in operation have overcome demanding investment barriers, and the Global CCS Institute have mapped the different policies and project characteristics for all 18 facilities that have played a role in the investment decision (and the five facilities under construction, marked in light grey).

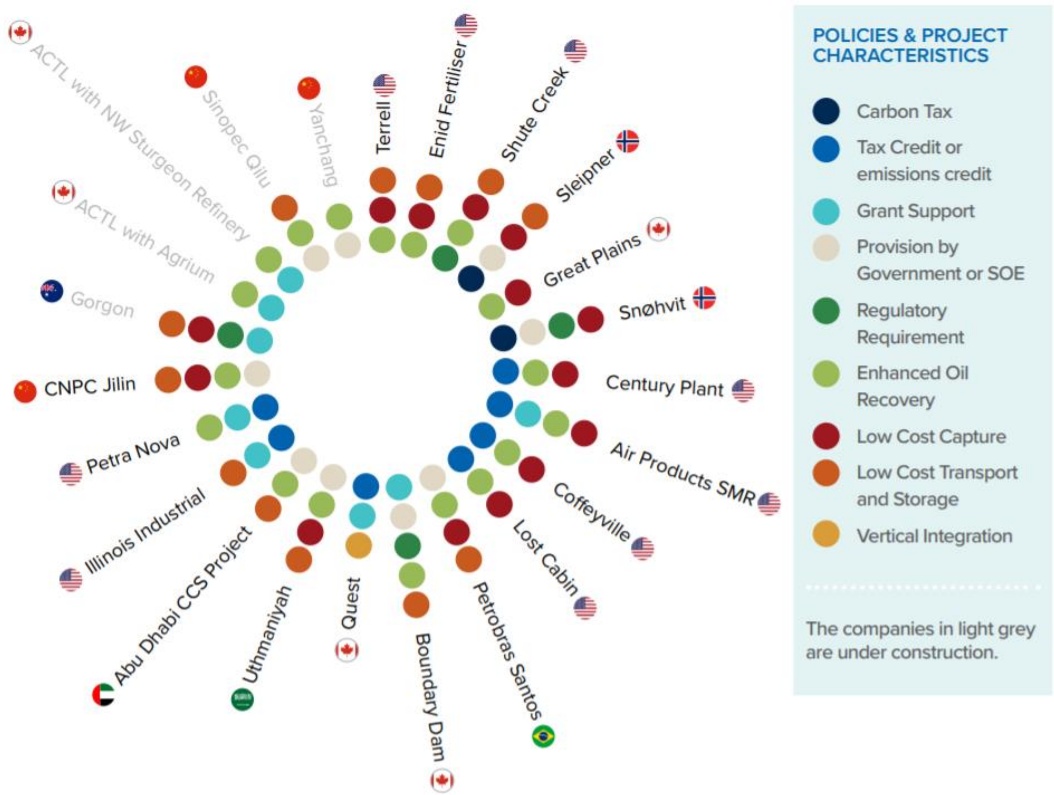

Figure 4 - Policies and project characteristics for operational CCS projects (Global CCS Institute, 2019)

14 out of the 18 facilities in operation use the captured CO_2 for EOR, a method which injects CO_2 into a reservoir to increase oil production. This will be further discussed in the economic Chapter 3.2.4.1. Tax credits are another important policy and have been critical for development for all US-based CCS projects through tax credits such as the 45Q arrangement, which provide US operators tax credits of 18 USD for each tonne CO_2 used for EOR, and 29 USD for each tonne CO_2 stored in geological formations. This amount will increase to 35 USD and 50 USD respectively, by 2026 and is a clear incentive for CCS and geological storage of CO_2 (Global CCS Institute, 2019).

In the EU, there is a policy for emission reductions. The European Union Emission Trading Scheme (EU ETS) was a GHG-mitigating strategy, promoting investments in clean technologies and low emissions. The price for one carbon credit (allowance to emit one tonne CO_2) is dependent on politics, supply and demand and provides a volatile price (European Commission, 2015). As of 07.05.2019, the quota price has in one year increased from 9.99 EUR to 24.32 EUR, a 143.4% increase (Business Insider, 2019). This price is vital for further deployment and investment in CCS, as increasing quota prices makes capturing CO_2 more desirable.

The EU ETS is a multi-nation collaboration, and an example of strategies CCS needs more of if it is to succeed. Political decisions across borders are lacking, and international collaborations are few. While some governments acknowledge CCS as a solution, others do not. Many environmental movements are against the technology, arguing that the cost of CCS will divert financial investment away from renewable energy such as solar and wind, and that CCS is an extension of a fossil fuel-based energy market (Kirchsteiger, 2008). Bäckstrand, Meadowcroft and Oppenheimer argue that one of the reasons behind the weak international collaboration is because international CCS politics is power driven by high emitting fossil fuel countries; like USA, UK, Canada and Norway. They claim that their motivation behind CCS support is based on prolonging their own fossil fuel industries rather than based on saving the climate itself (Bäckstrand, Meadowcroft, & Oppenheimer, 2011). Therefore, lack of international collaboration is present because less fossil fuel dependent nations don't have the same motivation and consider CCS a pure economic loss.

3.1.1 CCS Politics in Norway

Norway is one of the leading countries when it comes to CCS (Global CCS Institute, 2018). In 1996, Sleipner was the first facility to capture and store CO_2 in a dedicated offshore geological formation, avoiding the CO_2 taxation implemented by the Norwegian government in 1991 which only applies for the offshore industry (Global CCS Institute, 2018). In 2008, the Snøhvit facility became the second CCS facility in Norway, and the two combined is responsible for storing 1.7 Mtpa under normal operation (Norsk Petroleum, 2019).

In 2008, the Norwegian government supported the building of Technology Centre Mongstad (TCM). TCM is the world´s largest facility for testing and improving CO_2 capture technologies and aims to help reduce the cost and risks of CO_2 capture technology deployment by providing an arena where vendors can test, verify, and demonstrate proprietary CO_2 capture technologies. It is owned by Gassnova, Shell, Equinor and Total (Technology Centre Mongstad, 2010). In 2016, a feasibility study was undertaken by the Norwegian government, investigating the possibility of a full-scale CCS project – capturing CO2 from various sources and storing it offshore. Again, a partnership between the state, Equinor, Shell and Total emerged, where the three companies have responsibility for transport and storage of CO_2 through the Northern Lights project (Equinor, 2018).

Although there is an interest in CCS from the Norwegian government, limited funding has been provided so far. The amount invested varies from year to year, and there has been substantially less invested in recent years (2017-2019) compared to 2013-2016. Even for their own full-scale project, the investments and support have been scarce. In 2017, minister of finance Siv Jensen proposed a 95% cut in the national state budget directed to the full-scale project, a reduction from 360 MNOK in 2017 to 20 million NOK in 2018. This was later revised and changed to 89 MNOK, but this is still a relatively small amount and could arguably demonstrate a lack of commitment (Det Kongelige Finansdepartement, 2018). A final investment decision for the full-scale project is expected to take place in 2020/2021.

The lack of commitment from the Norwegian government can be seen when looking at investments for CO_2-management over the last decade. It forms a clearly declining curve, peaking between 2010-2013. The peak period was under Jens Stoltenberg's second reign as prime minister from 2009-2013. After Erna Solberg became prime minister in 2013, funding has been declining and dropped 194% between 2013 and 2018.

Year	08	09	10	11	12	13	14	15	16	17	18	19
Special operating expenses	935	765	1368	1530	996	1165	15	5	45	4,8	4,5	
CLIMIT		81,8	81,8	80,8	80,8	80,8	200	200	255	225	182,5	186,5
Gassnova	60	70	91	92	92	93	154,3	113	142,3	437	107	126
Research services TCM DA					1088	1882	1877	1747	1806	617	195	208
Loan TCM DA				880	577	73	50	65				
Transportation of CO2									8			
Full-scale Mongstad		920	1822				28					
CO2 internationally		20	20	10	10	7	1	1				
Full-scale NORCEM											20	149
Grants for Gassco AS										30		
Total	**995**	**1856,8**	**3382,8**	**2592,8**	**2843,8**	**3300,8**	**2325,3**	**2131**	**2256,3**	**1313,8**	**509**	**669,5**

Table 1 - Governmental funding over the last 12 years. Numbers retrieved from National budget (2008-2019), section 1840 and 1833. (Ministry of Finance, 2008-2019)

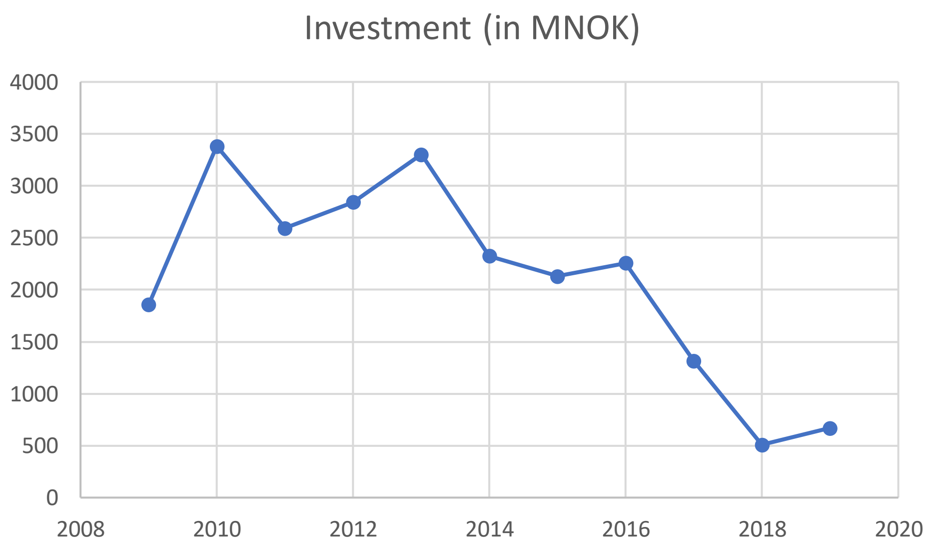

Figure 5 - Governmental funding over the last 11 years

Even though funding has been declining, Norway is still considered as a leading nation within carbon capture and storage technologies. The reasons for the supposedly high interest in CCS are outlaid by Tjernshaugen and Langhelle in their chapter "Technology as political glue: CCS in Norway" from *Caching the Carbon*. They argue there are four main reasons for Norway's interest:

1. Norway is a large petroleum nation, and CCS permits Norway’s petroleum production and their ambitions to be a leading environmentally friendly nation to coincide.
2. Building gas power plants on land was a heated debate in Norway in the 90’s, and the environmental organisation Bellona introduced CCS as a solution.
3. The CO_2 tax incorporated by the government in 1991, as well as European laws about CO_2 composition in gas for sale lead to the development of CCS on Sleipner and Snøhvit. These projects are deemed successful and stand as a political argument that CCS can be done.
4. Environmental parties have played a big part, where the industry has been in dialogue with environmental parties and convinced big NGO’s such as ZERO and Bellona to support CCS (Tjernshaugen & Langhelle, 2011).

The industrial structure in Norway as a large petroleum nation is a reason for why CCS is still a priority. It will allow Norway to continue with fossil fuel with a decreased environmental impact, and thus the energy industry in Norway will not require such a large and radical restructure into renewable energies. Marie Aalhus wrote a master thesis for NTNU on CCS politics in Norway between 1983-2016 and concluded that Norway’s interest and leading role within CCS is a consequence of international climate goals and agreements and a self-serving interest in maintaining production of fossil fuels - which accounts for 17% of Norway’s GDP and 43% of the total exports (Norsk Petroleum, 2018) (Aalhus, 2016) . The Global CCS Institute argues that Norway has taken a leading role within CCS, and that the policy framework for CCS in Norway is second to none, ahead of countries like United Kingdom and the United States (Global CCS Institute, 2018).

However, Oslo Economics and Atkins did a quality assurance report on the proposed full-scale project in Norway and found it not socioeconomically profitable, and thus the reserved governmental support continues (Atkins and Oslo Economics, 2018)

3.2 Economics

One of the biggest uncertainties with CCS is the economic aspect of the projects. For the operators, there are no clear incentives to implement CCS, as it is more expensive to capture/transport/store CO_2 than it is to emit it to the atmosphere. As of May 7th, 2019, the EU ETS price was 237 NOK, which is less than the estimated cost of CO_2 avoided for all industries (MARKETS INSIDER, 2019)(Appendix 1). McKinsey states that at current electricity prices, CCS is the most economical alternative for decarbonisation in the industry (McKinsey & Company, 2018). The report shows that the cost of decarbonisation in the ethylene, cement, iron and steel and ammonia industry ranges from USD 11 trillion to USD 21 trillion by year 2050. 50% to 60% of this represents operating expenses while the rest is capital expenses, i.e. building of CCS plants and infrastructure for transportation and storage (McKinsey & Company, 2018).

In 2017, four projects were added to the European list of qualified "Projects of Common Interest" (PCI), where three of these are associated to the Norwegian CO_2 storage facility in the North Sea. When a project qualifies, it can apply for funding from the "Connecting Europe Facility" (CEF). This is an infrastructure fund where 5.35 billion euros is available for energy projects, including CCS (SINTEF, 2018). Although initial investment costs are estimated to be large, quality assurance reports done by Atkins and Oslo Economics states the technological learning from the Norwegian full-scale project can reduce the cost of future projects with 3.5 billion NOK, equivalent to 14% of the cost of the full-scale project (SINTEF, 2018).

3.2.1 Future price of CO_2

Research done by SINTEF shows four different projections for future EU ETS price (Figure 6). The green line indicates the price that IPPC states is necessary to make it possible to reach the 2-degree goal. It shows that the price needs to increase to approximately 1500 NOK. This is an increase of almost 533% from today's price (SINTEF, 2018) (MARKETS INSIDER, 2019). It is therefore clear that incentives and regulatory measures need to be developed to facilitate the implementation of CCS in the industry (IEA and UNIDO, 2011). IPCC states that it will be 140% more expensive to reach the climate goals without CCS (SINTEF, 2018).

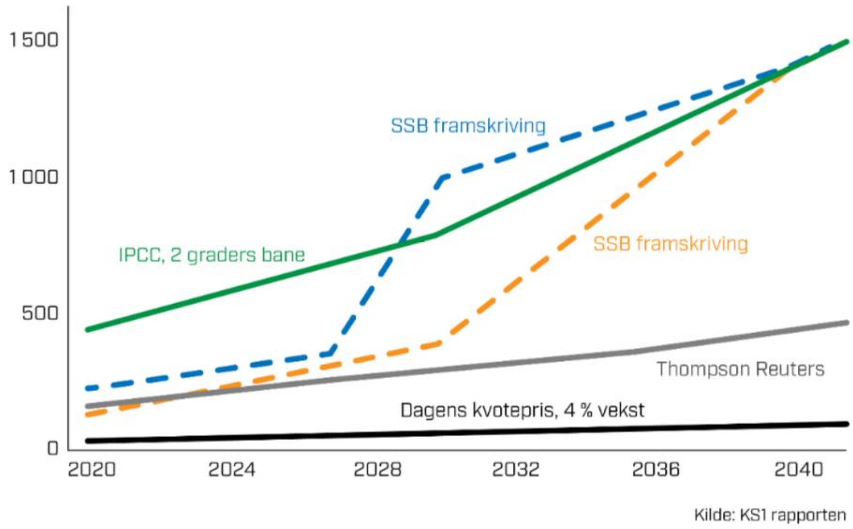

Figure 6 - Estimated future EU ETS price. (SINTEF, 2018)

In 2008 the EU ETS price was at its highest at approximately €30/tCO_2 (Refinitiv, 2018). Between 2009 and 2012 the total of EU allowances available was higher than the demand. The result of this was a surplus of emissions allowances (European Environment Agency, 2018). This led to a reduction in carbon price (€3/tCO_2 in 2013) and the incentive for investing in low-carbon alternatives was weakened (Refinitiv, 2018) (European Environment Agency, 2018). This increased the risk of carbon lock-in, where investments in technology that would make it harder for emission reduction in the future were made (European Environment Agency, 2018). In 2013 the surplus amount was at 2.1 billion allowances, but when the European Commission implemented the back-loading measure this amount was reduced to 1.78 billion in 2015 (European Commission, u.d.). A result of this measure was a rebalance of the supply and demand in the short-run, while at the same time reducing the price volatility. As a long-run measure, the Market Stability Reserve (MSR) was implemented in January 2019 (European Commission, u.d.). The MSR will strengthen the market stabilization reserve´s handling of the surplus of EU allowances (Regjeringen, 2018). From 2019 to 2023, 24% of the surplus shall be deposited in the reserve, while after 2023 the deposits will be reduced to 12%. From 2023, the part of the MSR that exceeds the total number of allowances auctioned in the ETS the year before should be permanently deleted (Regjeringen, 2018) (Refinitiv, 2018). This will increase the total emission cuts towards 2030 and help stabilize the EU ETS price on a higher level (Regjeringen, 2018) (Refinitiv, 2018). Refinitiv predicts that the average price from 2019 to 2030 will be €23/tCO_2, while for the first five years it will be €24/tCO_2 as of double working speed for MSR. They set an expected price of €26/tCO_2 in 2030 because of higher need for reduction in the industrial sectors (Refinitiv, 2018). As the price stabilizes the question that is left is to what price the carbon dioxide could be captured, transported and stored in the future.

3.2.2 Levelized cost and cost of CO_2 avoided

A CCS facility utilises more energy compared to a similar facility without CCS. It requires energy to capture, transport and store carbon dioxide. Definition of the two cost aspects, levelized cost and cost of CO_2 avoided are listed below and will be used in this section;

"Levelised cost of generation is the discounted lifetime cost of owning and operating a power plant expressed on a per unit of output basis ($/MWh, $/tonne, $/litre, $/J)" - Global CCS Institute.

(Global CCS Institute, 2010)

"The cost of CO_2 avoided reflects the cost of reducing CO_2 emissions to the atmosphere while producing the same amount of product from a reference plant. The cost of CO_2 avoided is expressed as a $/tonne of CO_2 not emitted with respect to the reference process. The cost of CO2 avoided must include the full chain of the process (capturing, transportation and storing)" – Global CCS Institute

(Global CCS Institute, 2009)

Research done by Global CCS Institute shows the levelized costs and the costs of CO_2 avoided for different industries in the United States. The numbers are presented in Table 2, and the study covers plants without CCS, first-of-a-kind projects (FOAK) and nth-of a kind projects (NOAK) (Global CCS Institute, 2017). Worth to mention is that labour costs are higher in Norway than in the US, so it is expected to be higher levelized costs for Norwegian plants. Another point is that the cost of CO_2 avoided in the table is not the same as the numbers used in Appendix 1. This is because Appendix 1 uses an overall average from different sources. This is explained in chapter 5. The key observations from the research are;

- The levelized cost for the different industries that implement a first-of-a-kind CCS project varies between a small increase of 2% in the natural gas industry, up to an increase of 68% in the cement industry.
- Natural gas, fertiliser and biomass to ethanol are already producing streams with a high concentration of carbon dioxide. At the moment this is vented into the

atmosphere, but because of this high concentration of CO_2, the delta cost between CCS and without is small. This cost is described by the "increase for FOAK w. CCS" in Table 2.

- Those industries that experience a higher incremental change in cost do not have CO_2 separation naturally included in the cycle like the ones mentioned above. Cement (68%) and Iron and Steel (30-41%) are industries that will experience the largest change because a lot of extra work and energy needs to be put in the cycle.
- The decrease in cost from a FOAK to a NOAK project ranges from 5-28%. This matches SINTEF´s estimation of a cost reduction of 14% from the full-scale project.
- The table also shows that the cost of CO_2 avoided will decrease for the nth-project, compared to the first one.

(Global CCS Institute, 2017)

	PC supercritical	Oxy-combustion supercritical	IGCC	NGCC	Iron and steel	Cement	Natural gas	Fertiliser	Biomass to ethanol
Levelised cost	USD/MWh	USD/MWh	USD/MWh	USD/MWh	USD/tonne	USD/tonne	USD/GJ	USD/tonne	USD/litre
Without CCS	75-77	-	95	49	280-370	101	3.75	400-500	0.40-0.45
With CCS – FOAK	124-133	118-129	141	78	114	69	0.061	13	0.018
With CCS – NOAK	108	107	102	62	95	58	0.058	12	0.017
Increase for FOAK w. CCS	60-70%	51-64%	45%	57%	30-41%	68%	2%	3-4%	4-5%
% decrease FOAK to NOAK	-13 to -19%	-9 to -16%	-28%	-21%	-17%	-16%	-5%	-8%	-6%
Cost of CO2 avoided (USD/ tonne CO_2)									
FOAK	74-83	66-75	97	89	77	124	21.5	25.4	21.5
NOAK	55	52	46	43	65	103	20.4	23.8	20.4

Table 2 - Levelized cost and cost of CO2 avoided with and without CCS in the US (Global CCS Institute, 2017)

The cost of capture varies a lot, based on different factors affecting the process. Interest rates, facility lifetime, fuel cost, technical factors related to plant design and operation will all influence the final cost of the project (IPCC, 2005). The selection of CCS capture technology will also affect the price, as well as the concentration of CO_2 in the steam where lower concentration usually causes higher capture costs (IPCC, 2005).

3.2.3 Energy consumption

Separating, transporting and storing CO_2 requires substantial work and consumes large amounts of heat and electrical energy. The energy demand depends on the concentration of CO_2 in the gas and the technology used. Studies done at Harvard states that the extra energy consumption from post-combustion could range between the lower bound of 11% up to a high bound 40%, with 29% as a good estimate (House, Zenz, Harvey, Aziz, & Schrag, 2009). The energy required to operate a CCS facility reduces the efficiency of the electrical generation and increases the demand for fuel. Hence, the total cost for fuel and energy will increase. McKinsey estimates in their report that the decarbonization of the iron and steel, cement, ammonia and ethylene industry will increase the demand for zero-carbon electricity per year from 6 EJ/y to 25-55 EJ/y by 2050 (McKinsey & Company, 2018).

3.2.4 Carbon dioxide utilization

A common way to write CCS where we include the utilization of carbon dioxide is CCUS - Carbon Capture, Utilization and Storage. The carbon capture process is of high interest in several industries, due to different applications for CO_2. An example is that 20% of the carbon dioxide separated in the process of making ammonia in Yara Porsgrunn is captured, condensed and delivered as food quality CO_2 (Appendix 4). Two other applications are EOR, which can provide extra revenue for the oil industry, and hydrogen production for natural gas with CCS, which has the potential to become a whole new industry. In the next sections, these two applications will be reviewed.

3.2.4.1 Increased oil recovery with help from carbon dioxide – EOR

Enhanced oil recovery is a technology where CO_2 is injected into the reservoir to generate better conditions for extracting more oil. As illustrated in Figure 4, 14 out of today's 18 operating facilities are used for enhanced oil recovery. SINTEF argues that the Norwegian full-scale project is probably too small to make EOR an income opportunity in the short run because it requires a stable stream of several million tonnes per year (SINTEF, 2018). In the long-run, it has the potential to increase the lifetime of the oil fields in the North Sea, where it can make use of already established infrastructure and increase the oil production with 4%, which for Norway represents an annual increased export value of 8 billion NOK (SINTEF, 2018). This is, of course, entirely dependent on the establishment of a CCS chain within the lifetime of the oil fields. CO_2-EOR calculations for 23 oil fields over 40 years in the North Sea is included in a study done by the Norwegian Petroleum Directorate. It estimates that 300 Sm^3 (≈1.9 billion barrels) extra oil can be produced. The export value of this is 680 billion NOK, given the export price for 2017 (SINTEF, 2018).

3.2.4.2 Hydrogen

The natural gas industry supplies the world with 22% of the energy used on a global basis today (IEA, 2018). The Hydrogen Council´s roadmap estimates that in the future hydrogen can supply 18% of the global energy needed (SINTEF, 2018). SINTEF argues that "*An investment in hydrogen from natural gas with CCS in Norway could potentially generate a turnover of 220 billion NOK in 2050 and between 25 000 to 35 000 jobs*" (SINTEF, 2018, p. 13). A prerequisite for this is that sufficient storage for carbon dioxide is established in the North Sea, according to the report. With sufficient storage and CCS, the energy intensive process of making hydrogen from natural gas can be done with minimal environmental impact. It also allows the natural gas industry in Norway to continue and contribute to clean energy (SINTEF, 2018). But like the future price of CO_2, the hydrogen price is also uncertain. Hydrogen produced from natural gas with CCS will have a higher market price because it requires energy and processing to produce the hydrogen. In the SINTEF-report, they assume a market price equal to twice the current price for natural gas, which requires customers to pay a higher price for hydrogen compared to natural gas (SINTEF, 2018).

3.3 Social Studies

A lot of governmental funding has been put into research on CCS. Asbjørn Torvanger from CICERO argues that at this point it is more important to create a demand for CCS rather than tweaking the technology (Torvanger, 2019). A full commitment to CCS could lead to several

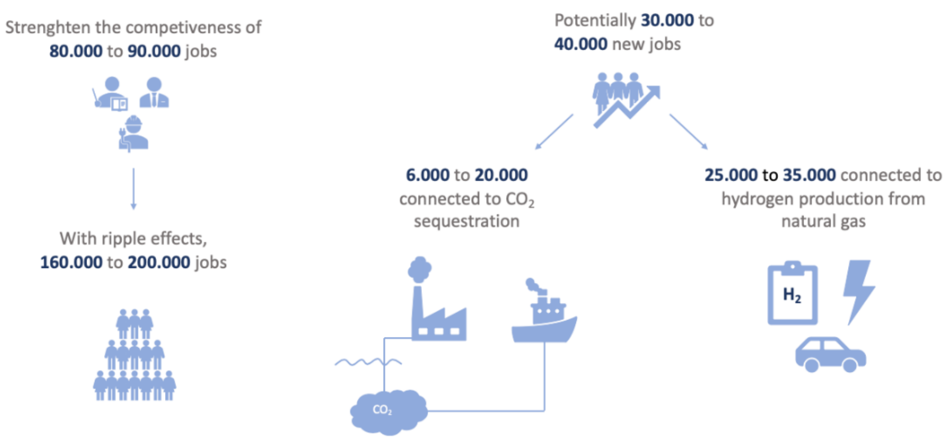

Figure 7 - The effect of full commitment to CCS in Norway in 2050. Data and inspiration from SINTEF (SINTEF, 2018)

positive “ripple effects”, where thousands of new jobs could be available, new industries may arise, and most importantly the world can reach its climate goals.

SINTEF states that an investment in carbon capture and storage in Norway will possibly strengthen the competitiveness of 80.000 to 90.000 jobs in the process industry, natural gas and the shipping industry in Norway. If jobs that are indirectly related to the industry are included, the actual number can be as high as 200.000. The initiative will also have the potential to create 40.000 new jobs within year 2050 (SINTEF, 2018). Between 6.000 to 20.000 of these will be connected to carbon dioxide sequestration and technology in Norway, while 25.000 to 35.000 will potentially be connected to hydrogen production from natural gas with CO_2 sequestration. If you sum up all the jobs directly and indirectly connected to these new industries, the total number of new jobs could be as high as 70.000 (SINTEF, 2018).

The attitude in the Norwegian community today is mainly determined by people´s perception of the risk of CCS and the knowledge of carbon capture and storage in general. Kristin Halvorsen from CICERO said this at CLIMIT SUMMIT 2019; “*I meet a lot of opposition to CCS when I go to Europe*”. Patrick Child from the EU Commission agreed upon this statement and followed up with saying that there lies a big task with making CCS accepted by the public in many EU countries (Brenna, 2019). A survey conducted by NORSTAT shows that 18% of the Norwegian population doubts that climate change is man-made (NRK, 2017). Another survey held by Eurobarometer states that 67% of the survey participants didn´t have any knowledge about CCS. The report also indicated that highly educated people and people with frequent use of internet had more information about CCS and had a higher tendency to see climate change as influenced by human activity. Eurobarometer´s survey also shows that the younger proportion of the population thought that the fight against climate change could benefit from CCS (TNS Opinion & Social, 2011). This proportion of the population is now starting to take action towards a greener future, where the Swedish climate activist Greta Thunberg is acting as a champion. A champion is “*a person who enthusiastically supports, defends, or fights for a person, belief, right, or principle”* (Cambridge Dictionary, 2019). Thunberg has followers all over the world and inspires thousands to fight against climate change. On August 20. 2018, Thunberg sat in front of the Swedish parliament with her posters, saying that this was the first school climate strike (The Guardian, 2019). She demanded that Sweden reduced their CO_2 emissions in line with the Paris Agreement, and was going to strike every Friday until they did so (Thunberg, 2019). On March 15. 2019, a worldwide demonstration took place where youngsters took to the street to fight for the climate. They strike to tell the politicians to take the future of the young generation seriously and treat climate change for what it is – a crisis (SS4C, u.d.). In Norway, the group “Natur og Ungdom” received 600 new members after the two climate strikes held 15th and 22 of March 2019. With the young generation showing initiative to reduce GHG emissions, this could be a driver for the implementation of CCS as a climate measure. MDG (Miljøpartiet de grønne) youth party also received new members after these demonstrations. Nationwide, they increased the member base with 30% in just one week (Selstø, 2019). One of MDG´s main fighting causes is that the oil and gas industry shall be phased out over a 15 year period and that Norway should be less dependent on fossil fuels (MDG, u.d.). CCS has received critics on this matter that if implemented it will continue dependency on fossil fuels. In Finland, studies show that some of the sceptical perceptions towards carbon capture and storage come from the belief that CCS commitment could reduce the investments in renewables and other low-carbon alternatives (Pihkola, et al., 2017).

To get an idea of how the public population has influenced earlier projects, Shell´s Barendrecht is a good example. In 2010 Shell announced that they were about to cancel the Barendrecht project, which was a project where they planned to store more than 10 $MtCO_2$ in onshore geological formations over a 25 years period. The reason the project was stopped was strong opposition from the local community, where the people feared the project would endanger the town and lead to lower house prices (Bellona, 2010). Another example of an unsuccessful project is the former Norwegian prime minister Stoltenberg´s proposed development of a full-scale CCS plant at Mongstad. The idea was presented in his new year’s speech in 2007 and was called the “moon landing” because of the investments that had to be made and the importance for Norway to lead the way for the rest of the world in carbon capture. In 2013 the government announced that the project would not be continued, which meant that the moon landing resulted in one of the ugliest political crash landings in the history, according to Frederic Hauge from Bellona (Reuters, 2013). The risks connected to the Mongstad facility were perceived to be too high, due to low carbon prices, economic slowdown in Europe and high development costs. The government stated that they were still committed to research in carbon capture, but that the Mongstad project would not be continued (Reuters, 2013). With the significant publicity the Mongstad project got, the failure of this project would risk weakening the public perception of CCS. Bellona state that the publics ability to influence the decision-making is crucial to their consent to a project. (Bellona, 2010). If carbon capture and storage projects are implemented successfully, people's perception of CCS can improve.

3.4 Technology

The capture of carbon dioxide is the first step in the CCS cycle. CCS-related patents, articles and inventions are growing globally, increasing the chance of making CCS economically viable (Luis Míguez, Porteiro, Pérez-Orozco, Patiño, & Rodríguez, 2018).There are three different methods that might be used for carbon capture; post-combustion, pre-combustion and oxyfuel-combustion. All three methods can achieve a capture rate exceeding 90% (Bellona, u.d.). Factors affecting which method should be used are the concentration of CO_2 in the gas, pressure of the gas stream and the fuel used (IPCC, 2005). In the following chapter, the three most used technologies will be presented, followed by a technological status of the three focus industries; ammonia, iron and steel and cement. (All figures in section 3.4 are inspired by (Bellona, u.d.))

3.4.1 Post-combustion

The most widespread method today is post-combustion, where CO_2 is separated from the gas stream after combustion. It is the choice for supercritical pulverized coal power plants and has been used in gas processing and refining for decades (IEA ETSAP, 2010). When burning fossil fuels (oil, coal and natural gas), you create an exhaust gas that contains different concentrations of CO_2. The liberated heat from the combustion in the power plant is converted to electric energy by steam-driven turbines (Global CCS Institute, 2012). After combustion, the exhaust gas with CO_2 enters a scrubber tank where a liquid solvent (usually mono-ethanol amine) and water are mixed with the gas. The solvent will react with the CO_2-molecules and trap the CO_2 in the solvent. The result is that the solvent-CO_2 mix sinks to the bottom of the scrubber tank, while the clean CO_2 free gas float at the top. The carbon dioxide-rich solvent is then heated in a regenerator, forcing the reactive bonds between CO_2 and the solvent to break (Bellona, u.d.). This is a process that requires a lot of thermal energy and is sensitive to the concentration of CO_2. The energy consumption decreases with 10% if the CO_2 concentration increases from 3 to 14% in volume (IEA ETSAP, 2010). The next step of the process is that the CO_2 gas then leaves through the top of the regeneration tank while the liquid solvent is recirculated and reused (Bellona, u.d.). This is the method used by Equinor at Sleipner. The technology is adaptable to different industries and can be used in both power plants and industrial plants (IPCC, 2005) (Bellona, u.d.).

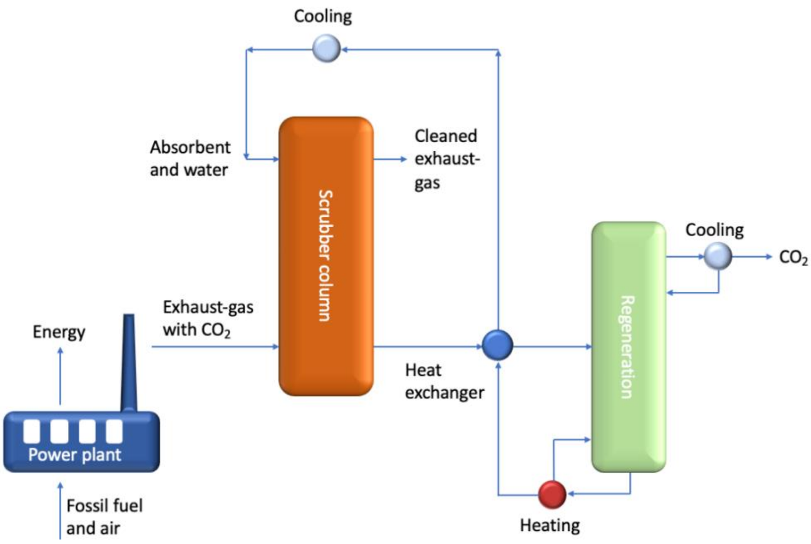

Figure 8 - Post-Combustion

3.4.2 Pre-combustion

This technology makes it possible to capture carbon dioxide before combustion. The technology can be utilized in coal-fired integrated gasification combined cycles and in natural gas combined cycles (IEA ETSAP, 2010). The first stage is to convert fuel into a gas containing carbon monoxide and hydrogen, also called synthesis gas or syngas (IEA ETSAP, 2010) (Bellona, u.d.). This can be done in two ways; the first option is through a steam reformer where fuel is mixed with steam (IPCC, 2005)(all formulas from (IPCC, 2005));

$$C_xH_y + xH_2O \rightarrow xCO + \left(\frac{x+y}{2}\right)H_2$$

The second option is through partial oxidation, where fuel is mixed with oxygen:

$$C_xH_y + \frac{x}{2O_2} \rightarrow xCO + (\frac{y}{2})H_2$$

To convert CO to CO_2, steam is added:

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

The next step is to separate hydrogen from carbon dioxide in the same way as CO_2 is separated from the exhaust gas in post-combustion. What is left is a hydrogen-rich fuel that could be used in tonnes of applications such as fuel for cars or boilers (Bellona, u.d.). The technology is not as adaptable to existing plants as post-combustion so the technology should therefore be built simultaneously with the plant. A positive note with this technology is that CO_2 concentration in the steam is higher than at post-combustion, making it easier and less costly to capture the carbon dioxide (IPCC, 2005) (Global CCS Institute, 2009) (Bellona, u.d.).

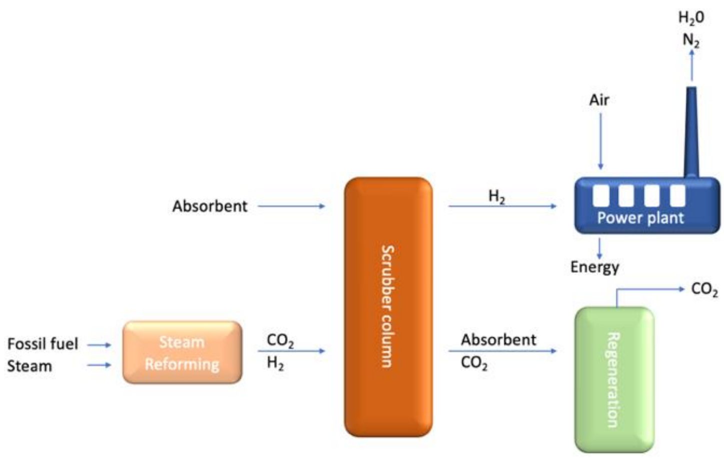

Figure 9 - Pre-Combustion

3.4.3 Oxyfuel-combustion

In oxyfuel combustion, fuel is burned with high-purified oxygen. As a first step, an air separation unit is used to remove the nitrogen from the air to produce pure oxygen Together with fuel, this is injected into a boiler where the combustion takes place (power plant) (Bellona, u.d.). The flue gas from this process consists of mainly water vapour and a high concentration of CO_2 (Global CCS Institute, 2009). Combustion with oxygen could result in concentration of CO_2 as high as 89% compared to normal power stations with 12 to 15% (acatech (Ed.), 2019). The combustion temperature is high, so the water vapour and CO_2 are recirculated to moderate this and to be slowly cooled leading the water vapour to condense, and leaves the CO_2 ready for dehydration, compression and transportation (IPCC, 2005) (Global CCS Institute, 2009). An advantage with oxyfuel combustion is that the flue gas contains a high concentration of CO_2, making it easier to capture the CO_2. If low-cost O_2 is available, it has the potential of becoming a cheaper alternative than both pre- and post-combustion (IEA ETSAP, 2010) (IPCC, 2005).

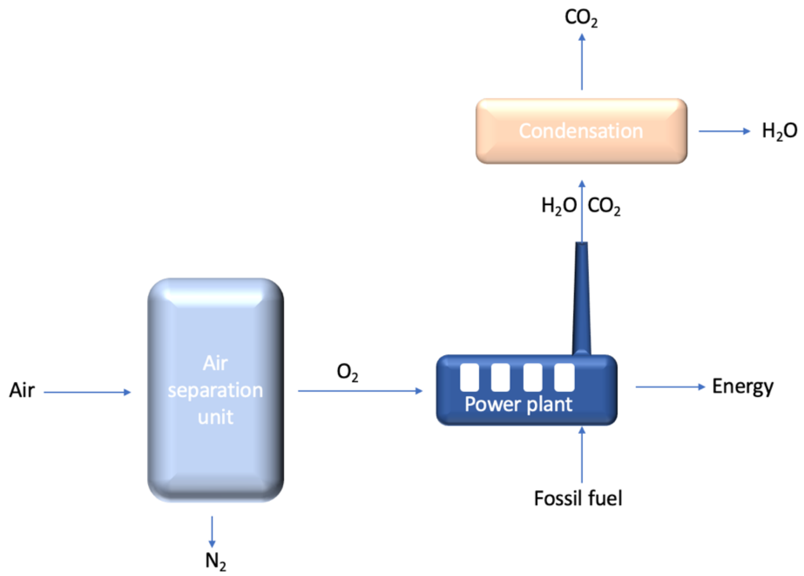

Figure 10 - Oxyfuel combustion

3.4.4 Cement Industry

McKinsey states that CCS is the sole decarbonization option that reduces cement process emissions at a sufficient level (McKinsey & Company, 2018). The cement industry makes up 5-6% of the global GHG-emissions (SINTEF, 2018). The main technologies for capture of carbon dioxide in the cement industry are post-combustion and oxyfuel-combustion. Pre-combustion is perceived as less efficient in this industry because it is unable to capture the amount of CO_2 that is produced during the heating process of calcium carbonate (IEA GHG, 2013). Old cement plants can be retrofitted to a post-combustion plant. It would not affect the core of the cement production, but sufficient space for CCS technology must be available (IEA Greenhouse Gas R&D Programme (IEA GHG), 2008). In oxyfuel-combustion, it is possible to retrofit the technology to existing plants, but core units in the plant need to be rebuilt. Oxyfuel-combustion is expected to have lower costs than post-combustion, and it could therefore be financially better to execute such a rebuilding of the plant (Kuramochi, Ramírez, Turkenburg, & Faaij, 2012). Oxyfuel-combustion is because of this considered to be available for the cement industry on a long-term scale where it represents a cheaper alternative than post-combustion. ECRA concludes that for post-combustion, both the power and thermal energy demand will double. With oxyfuel, it is just the power demand that double, while the thermal energy demand could be reduced (ECRA, 2018). In the cement industry, the oxyfuel technology still needs some R&D, but it is ready for demonstration (ECRA, 2018).

3.4.5 Ammonia industry

Ammonia is produced from methane and CO_2 is a by-product of the production. Because of the high concentration of CO_2, the separation process will be less expensive. A review of the ammonia production process can be useful to see why the concentration is so high (IPCC, 2005).

1. Purification of the feed
2. Primary steam methane reforming
3. Secondary reforming
4. Shift conversion of CO and H_2O to CO_2 and H_2
5. Removal of CO_2
6. Methanation (a process to remove small residual amounts of CO and CO_2)
7. Ammonia synthesis

The ammonia production process indicates that the CO_2 is already separated from the gas. The CO_2 is removed in a chemical or physical absorption process in step 5, where MEA (mono-ethanol-amine) is mostly used (Luis, 2016). Since the CO_2 is already separated, the cost of capture will be low compared to other industries. But the CO_2 is not necessarily available for storage since ammonia production plants are often connected with urea plants, capable of using 70-90% of the carbon dioxide (IPCC, 2005).

3.4.6 Iron and steel industry

Iron and steel stand for 10-15% of the total global industrial energy consumption, making it the largest energy-consuming manufacturer (IPCC, 2005). The outcome of producing one tonne of iron is one tonne of carbon dioxide (NORDICCS, 2015). All CO_2 emissions from a steel mill derive from combustion processes, and 80-90% originates from iron making, due to a carbon intense process with large energy requirements (NORDICCS, 2015). A consequence of this is that all three technologies (post-combustion, pre-combustion and oxyfuel-combustion) may be applicable where carbon dioxide can be captured both before and after combustion (NORDICCS, 2015). The EU ULCOS (Ultra-low CO_2 steelmaking) programme was initiated to reduce the carbon dioxide emissions in the iron and steel industry by as much as 50%. The four following technologies were identified in the program, but could only be achieved if combined with CCS (NORDICCS, 2015);

- Top Gas Recycling Blast Furnace (TGR-BF) – Deals with separation of the blast furnace gas. Top gas storage and separation devices are the main equipment in this technology. After the top gas has entered the device, it is separated into CO_2 and CO. The CO is returned to the blast furnace as a reducing agent, while the CO_2 is packaged or absorbed. The carbon emission could be reduced by 50% since the use of coke decreases (Fu, Tang, Zhao, & Hwang, 2014).
- HIsarna – Based on smelting. The sintering and coking process of the production are removed, resulting in a reduction of CO_2 emissions. It is a technology that allows coal to be partially substituted with biomass and natural gas. Has the potential of reducing the CO_2 emission with 70% (Fu, Tang, Zhao, & Hwang, 2014).
- ULCORED – Technology for iron ore pre-treatment. Natural gas or biomass gas are used to produce direct-reduced iron. Natural gas replaces the normal reducing agent in the gas purification process. Both the carbon emission and the cost decreases, as of the low cost of natural gas (Fu, Tang, Zhao, & Hwang, 2014).
- ULCOWIN/ULCOLYSIS – Iron and oxygen are produced, and there are no emissions of CO_2. It is based on direct electrolysis, different from the others where smelting is conventional (Fu, Tang, Zhao, & Hwang, 2014).

Research shows that post-combustion carbon capture and oxygen blast furnace with CCS in an iron and steel mill has the potential to reduce the CO_2 emissions significantly (NORDICCS, 2015). However, the cost of implementing these technologies are at the moment perceived as too high and encourages a step-by-step implementation of CCS in the iron and steel industry (NORDICCS, 2015).

3.5 Environmental

As profitable business cases have been hard to develop for CCS, the technology is mainly driven by environmental concerns and not profitability (Jonassen, 2018). Even though it is said to be a climate solution, and both IPCC and IEA argue that the Paris agreement is impossible without CCS, many environmental organizations are unsupportive of the idea and deliberately work against it (Conniff, 2018).

Greenpeace published a report in 2008, named “CCS The False Hope”, where several reasons were given for why CCS was a diversion rather than a solution for the climate. Arguments against CCS focused on the following (Greenpeace, 2008):

- CCS cannot deliver in time
- CCS use too much energy
- Leakage probabilities
- Prolonged period of fossil fuels
- Too expensive

Greenpeace argues that money spent on CCS is money lost on renewables, saying “*The promise of CCS diverts attention away from sustainable energy solutions and risks locking the world into an energy future that fails to save the climate*.” (Greenpeace, 2008, p. 37). These claims are not only relevant for Greenpeace, as they conclude the same issues that most organisations against CCS agrees on (NOAH Friends of the Earth Denmark). The Dutch national R&D programme for CCS, CATO, has made an argument map for CCS in the Netherlands (Appendix 3: Argument map CCS) by including the most common arguments for and against CCS and reveals that Greenpeace´s arguments are supported by other organisations as well.

In 2016, an estimated 18.2% of total global energy consumption originated from renewable energies, and 79.5% from fossil fuels (REN21, 2018). With increasing population, energy levels are expected to almost double within year 2050 compared to year 2000 (Shell, 2019). Figure 11 below shows the Sky scenario built by Shell, where a possible pathway of reaching the Paris-agreement is presented (Shell, 2018). Even though electrification is estimated to increase rapidly towards the end of the century, fossil fuels will remain an important energy source.

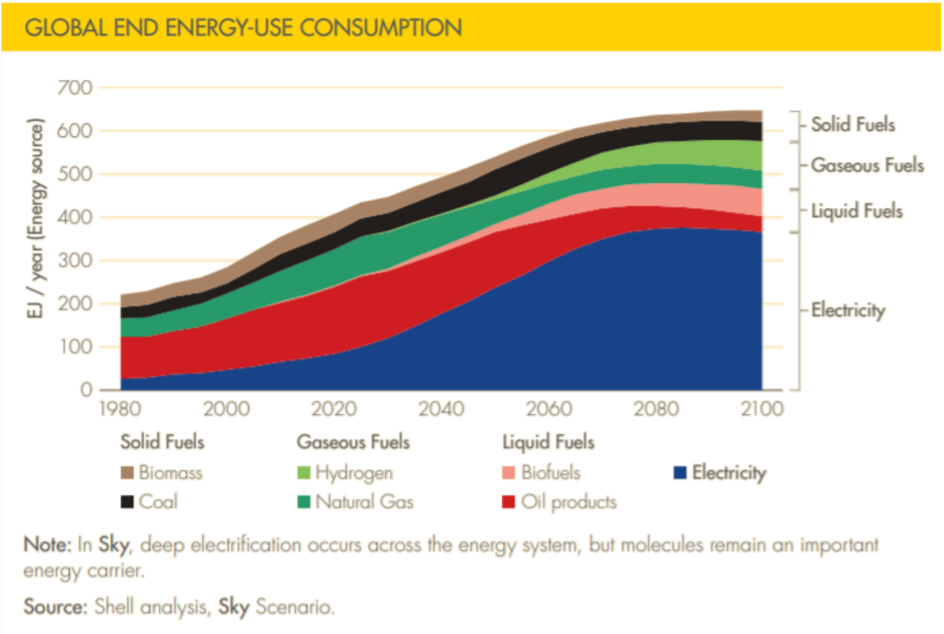

Figure 11 – Sky scenario by Shell. Global end energy-use consumption (Shell, 2018)

3.5.1 Environmental liabilities for CO2 storage

Another risk for CCS involves the injection and storage of CO_2. In Norway, geological formations offshore are considered for storage, and Northern Lights will use the Johansen-formation south of Troll as their storage location (Equinor, 2018). CO_2 will be injected through pipelines into the reservoir and naturally trapped in an impermeable layer called caprock which stops the CO_2 from exiting the reservoir. The risk is that the CO_2 manages to escape the storage site and leaks into the ocean and enters the atmosphere. Supercritical, gaseous or liquid CO_2 may escape through the following scenarios (IPCC, 2005):

- Through the pores in the caprock (e.g. shales) if the relative permeability and capillary entry pressure exceeds the pressure of which CO_2 can enter the storage
- Through fractures, holes and openings in the caprock
- Through human-made faults, such as poorly abandoned wells

Escaping CO_2 can enter water aquifers, ocean water and air (IPCC, 2005). The main risk offshore is leaked CO_2 mixing in with ocean bottom sediments, and if it is lighter than the surrounding water, it can resurface and reach the atmosphere (IPCC, 2005). The CO_2 can either stay in a separate phase (e.g. liquid) or dissolve into the ocean and cause biological damage to the areas affected. If it is kept in a separate phase, it can form a CO_2 plume on the surface, endangering offshore workers as storage sites can be based near offshore fields (IPCC, 2005). The European research project ECO2 organized a field study to investigate CO_2 leakage in the ocean and the effects on the surroundings and concluded that CO_2 leakage dramatically affected the ecosystem and its inhabitants (Molari, et al., 2018). Massimiliano Molari who led the study claimed: "*Most of the animals inhabiting the site disappeared due to the effect of the leaking* CO_2", and revealed that the long term effects were severe: "*Even a year after the* CO_2*-vented sediment had been transported to undisturbed sites, its typical sandy sediment community had not established*" (Molari, et al., 2018).

The consequences of a big CO_2 leak in a human environment are well documented through the events at Lake Nyos in Cameroon, 21st of August in 1986 (Kling, et al., 1987). CO_2 that had been stored naturally in the lake's hypolimnion was released after a small earthquake disrupted the water layers in the lake. About 300 000 – 1.6 million tonnes of CO_2 were released to the air. The fact that CO_2 is denser than air ensured that the CO_2 formed a cloud on the ground which flowed down from the volcanic lake and hit the village below. The villagers who got exposed to the gas died of carbon dioxide asphyxiation, resulting in more than 1700 fatalities and the death of 3500 livestock (Kling, et al., 1987). When being exposed to CO_2 levels above 5%, the central nervous system (brain and spinal cord) will be depressed and eventually fail, leading to death (Renewable Fuels Association). Being exposed to leaked, purified CO_2 from CCS, the high concentration would possess a huge threat to living organisms, including humans.

With the severe risk to marine life, human life and ecosystems in case of a leakage, it is important to assess the total risk by identifying and quantifying the consequences for the event happening, multiplied by the probability of the event occurring (Gleick & Holdren, 1981). This indicates that the total risk is a product of two inputs; consequences and probability. With consequences likely to be severe, studies on leakage probabilities are important. The total risk is site-specific, and in Norway, the Norwegian Petroleum Directorate has been developing a map of potential storage sites with site-specific data needed to conduct a risk assessment (Norwegian Petroleum Directorate, 2019). With the assumption of careful site selection, operation and monitoring, IPCC's special report on Carbon dioxide Capture and Storage (IPCC, 2005) claims that:

- It is very likely the fraction of stored CO_2 retained is more than 99% over the first 100 years.
- It is likely the fraction of stored CO_2 retained is more than 99% over the first 1000 years.

This means that the probability of a leak is very low, hence minimizing the total risk of offshore CO_2 storage. This evidence is backed up by the successful CCS facilities in Norway; Sleipner and Snøhvit, who has been capturing and storing CO_2 offshore successfully for decades (Norsk Petroleum, 2019).

3.5.2 Storage Potential in Norway

The global annual CCS capture rates of 40 Mtpa of CO_2 is just a tiny fraction of the 2300 Mtpa CO_2 that IEA claim needs to be captured in 2040 in order to reach the 2-degree Celsius target (IEA, 2019). To accommodate for all this CO_2, storage options need to be available. Some examples of potential storage reservoirs are oil and gas fields, abandoned oil and gas fields and saline aquifers (Norwegian Petroleum Directorate, 2014). These are geological formations commonly found on the Norwegian Continental Shelf, providing a potential for Norway as a storage location both nationally and internationally.

The Norwegian Petroleum Directorate's atlas and mapping over potential storage locations indicate that there is a storage capacity of approximately 86 Gt CO_2 in Norway (Norwegian Petroleum Directorate, 2014). This is equivalent to 40% of the storage potential in northern Europe (SINTEF, 2018). In an interview with Equinor regarding the Northern Lights project, Stuart Haszeldine - professor in carbon capture and storage at the University of Edinburgh – said "*On a world basis, there's capacity for over 200 years with today's levels of CO_2 emissions globally. The North Sea is very well explored, and Norway can store their CO_2 there for 1000 years."* (Equinor, 2018)

The Global CCS Institute have ranked several countries and given them a "storage indicator", which is based on "*a country's geological storage potential, maturity of their storage assessments and progress in the deployment of CO_2 injection sites*" (Global CCS Institute, 2018, p. 30). Their report indicates that Norway's storage assessment is among top three in the world - together with Canada and the United States (Global CCS Institute, 2018). SINTEF has argued that Norway can take a 40% share of the European CO_2 storage market, creating an estimated 2000 – 10 000 jobs, depending on the deployment level of CCS (SINTEF, 2018).

3.6 Legal

Law and regulations still represent a critical obstacle in a government's political response in support of a CCS project. In the last couple of years, several jurisdictions all over the world have changed the legislation and enacted a regulatory framework to support the activity (Global CCS Institute, 2018). Other less developed countries are also taking steps towards a framework that supports the deployment of a full-scale integrated project. Global CCS Institute has developed a map that shows the legal position within the CCS technology. From CCS-LRI (CCS Legal and Regulatory Indicator) it comes forward that United States, United Kingdom, Australia, Canada and Denmark (Band A) has a well-established regulatory framework for CCS, where there exist specific laws that cover most of the CCS-cycle. The remaining countries (Band B and C) has still some work to do to establish a well-defined and specific regulatory framework that covers the CCS-cycle (Global CCS Institute, 2018).

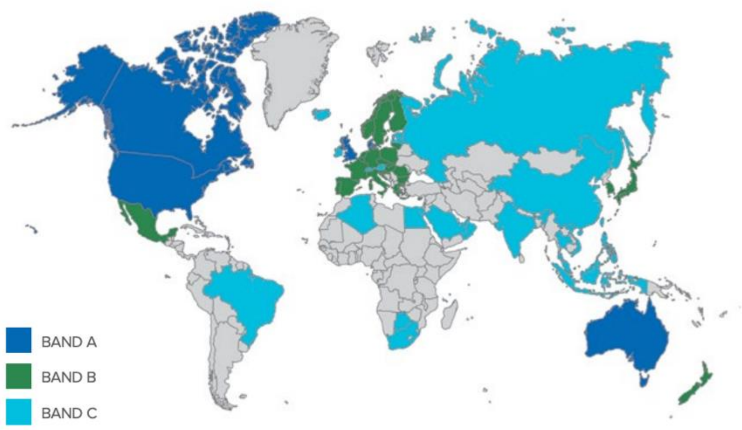

Figure 12 - Global Legal Development (Global CCS Institute, 2018)

Within the EU, the main regulatory framework is decided by the EU Directive on Geological Storage of Carbon Dioxide (Directive 2009/31/EC). If an EU member country shall implement a CCS project, it needs to be executed according to the Directive. It mainly concerns regulations for safe geological storage and doesn´t cover the capture and transportation part of the cycle in detail. In storage, it deals with all part of the cycle, from the selection of storage site (Article 4), Exploration permits (Article 5), Storage permits (Article 6), Operation, Closure and Post-closure obligations. The Directive also covers responsibility and transfer of responsibility. Although Norway is not a part of the European Union, they have still implemented the EU CSS Directive because they are a part of the European Economic Area (EØS) (EU DIRECTIVE 2009/31/EC , 2009).

The main legal question concerning CCS is the long-term liability issue, such as leakages from the storing sites and the impact it will have on the environment. Who has the responsibility for a possible leakage in 50 years? The long-term security to storage sites is critical for the viability and credibility of CCS as a climate solution. EU Directive Article 18 states that when a storing site is closed, it shall be transferred to the competent authority on its own initiative, or on request from the operator, if and only if the following criteria are met;

a) *All available evidence indicates that the stored CO_2 will be completely and permanently contained;*
b) *A minimum period, to be determined by the competent authority has elapsed. This minimum period shall be no shorter than 20 years, unless the competent authority is convinced that the criterion referred to in point (a) is complied with before the end of that period;*
c) *The financial obligations referred to in Article 20 have been fulfilled; [this involves a financial contribution from the operator to the competent authority to cover at least the anticipated costs of monitoring for 30 years]*
d) *The site has been sealed and the injection facilities have been removed.*

(EU DIRECTIVE 2009/31/EC , 2009)

All jurisdiction requires a specific amount of years before the liability is transferred from the operator to the competent authority. As can be seen from Article 18 b), the EU Directive sets the minimum years to be 20 years. France and Germany have chosen to disregard this and has implemented a minimum 30 years before handover, while the Americans require a minimum of 50 years or the alternative time approved by the director (International Energy Agency, 2011) (40 CFR § 146.93, 2011). The world lacks experience with closed CO_2 storage sites, so many consider this timeframe to be arbitrary at this point (International Energy Agency, 2011). Another aspect of the liability is the economic contribution that must be made by the operator to cover long-term stewardship of the storage sites. The financial security is covered in Article 19 in the EU Directive and requires the storage operator to prove they have adequate funding in place to deal with all obligations that may arise during their permit time, and that these costs can be met. This will act as a deposit to cover all costs, including accidents and leaks, and will be periodically adjusted over the permit lifetime to account for varying risk levels during operation. The financial security is needed from the time of application for storage permit to the time the responsibility is transferred to the competent authority (EU DIRECTIVE 2009/31/EC , 2009).

This implies that all risks regarding storage will be carried by the operator until Article 18 is met. If an accident were to occur, and CO_2 leaked from the authorized storage area, the operator will have to pay for the amount of CO_2 leaked through giving up or buying EU ETS carbon credits for the ETS price present at the time of leakage. As the ETS price is a volatile price, regulated by politics, supply and demand, there is no way of knowing what the price will be decades into the future. Estimations in Figure 6 predicted a price of 1500 NOK/tonne CO_2 in 2040, and if a big leakage were to occur, resulting in 50 million tonnes CO_2 escaping the storage area this would incur a cost of 75 000 000 000 NOK. Of course, the ETS price may be lower, and the leakage can be smaller or higher, point being that there's a lot of uncertainty and consequently high risk. Chief investment officer in GFG Alliance, Jay Hambro, talked about the financial risks in an interview with BusinessGreen, saying: "*The reality is until someone finds a solution for CCS that deals with the long-term risk I don't think anyone can take it forward. There's a lot of people, including us, who stand ready to do it, but you simply can't insure that. And as a corporate you need to look after your risk.*" (Cuff, 2018). So it seems that the industry needs a framework to share some of this risk, which can enable increased interest from operators and help drive the industry forward.

3.6.1 Insurance Policies

A meeting was held in The Hague, Netherlands, on March 20th on behalf of OGCI (Oil and Gas Climate Initiative). The purpose was to gather important CCS players from the oil and gas industry, the insurance industry and government officials to discuss the barriers associated with offshore CO_2 storage in Europe and look at what insurance policies are already in place and what needs to be established in the future.

It became evident that there were in fact insurance products available for some parts of the value chain, especially costs related to production halt due to leakage or similar events.

However, these products will cover a maximum period of three years and are not able to cover larger periods of time, such as decades. The main reason the insurance companies was unwilling to carry more risk was because of the difficulties in quantifying the risk. As CCS projects are scarce and long-term data is lacking, the insurance companies will need more risk data, especially on geological risk, to develop adequate insurance products. (Source: Appendix 2 - OGCI Workshop on Carbon Storage Risk and Liability – The Hague, 20 March 2019).

ClimateWise is an insurance industry leadership group put together to support the insurance industry in understanding risks and opportunities associated with climate change mitigation methods (University of Cambridge, 2019). In 2012, the possibility of an insurance product for storage operators was assessed and published in the "Managing Liabilities of European Carbon Capture and Storage" report (ClimateWise, 2012). The potential for an insurance market for CCS was acknowledged, but they claimed development was held back due to "*lack of available risk management solutions for a small number of nonetheless significant liabilities that are largely created by the EU CCS Directive*" (ClimateWise, 2012, p. 8).

Furthermore, the financial security obligations in the EU Directive was highlighted as a large barrier for operators aiming to invest in CCS, along with the uncapped liability the operators face in case of a CO_2 leakage. A possible solution to this was expressed, saying that the government must cap the CO_2 leakage risk and that the following risk transferring insurance product could be made and mitigate the uncertainties related to storage (ClimateWise, 2012). An illustration of elements of a CO_2 leak that could be covered through insurance was made and shown in Figure 13.

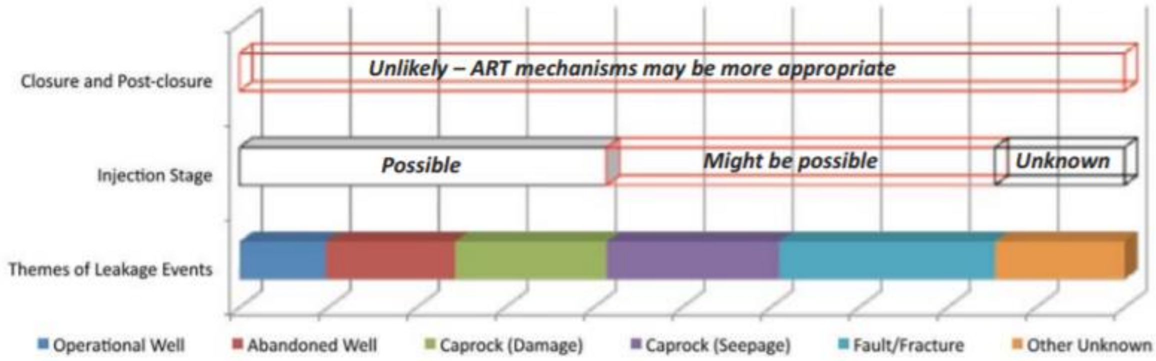

Figure 13 - Insurance cover presented by ClimateWise (ClimateWise, 2012)

The figure shows that insurance was only possible during the injection stage and that an insurance product covering the closure and post-closure of a storage site was deemed unlikely. For post-closure accidents, such as leaks, the future ETS price will be very important for the risk-sharing parties. The uncertainty of the future ETS price is currently preventing insurance companies from developing effective products and remains a barrier for the industry according to the chief executive of the Carbon Capture and Storage Association, Luke Warren: "*The very obvious one is what the future price of carbon is. It's impossible to tell what that will be, because that's effectively something that is determined by government policy. So that's one risk where you would expect that government would have to find a way of being able to share that with industry,*" indicating that the government would have to carry some of the risks in the early phase of CCS deployment: *"I think government will have to play a role early on, certainly, and then over time as this sector starts to develop you can imagine insurance capacity starting to be made available for some of these risks*" (Cuff, 2018).

3.7 PESTEL Results

The PESTEL analysis has revealed both barriers and drivers towards the establishment of a CCS industry in Norway. There are clear incentives and opportunities that encourage investments in CCS, but there are still a lot of barriers that hamper CCS deployment that needs to be assessed and solved for CCS to become more attractive for investments. As the information in the PESTEL analysis is comprehensive and detailed, a summary figure is made for easier visualisation by including the main drivers and barriers derived from the analysis. These findings will make up the basis in which will be further debated in Chapter 6.

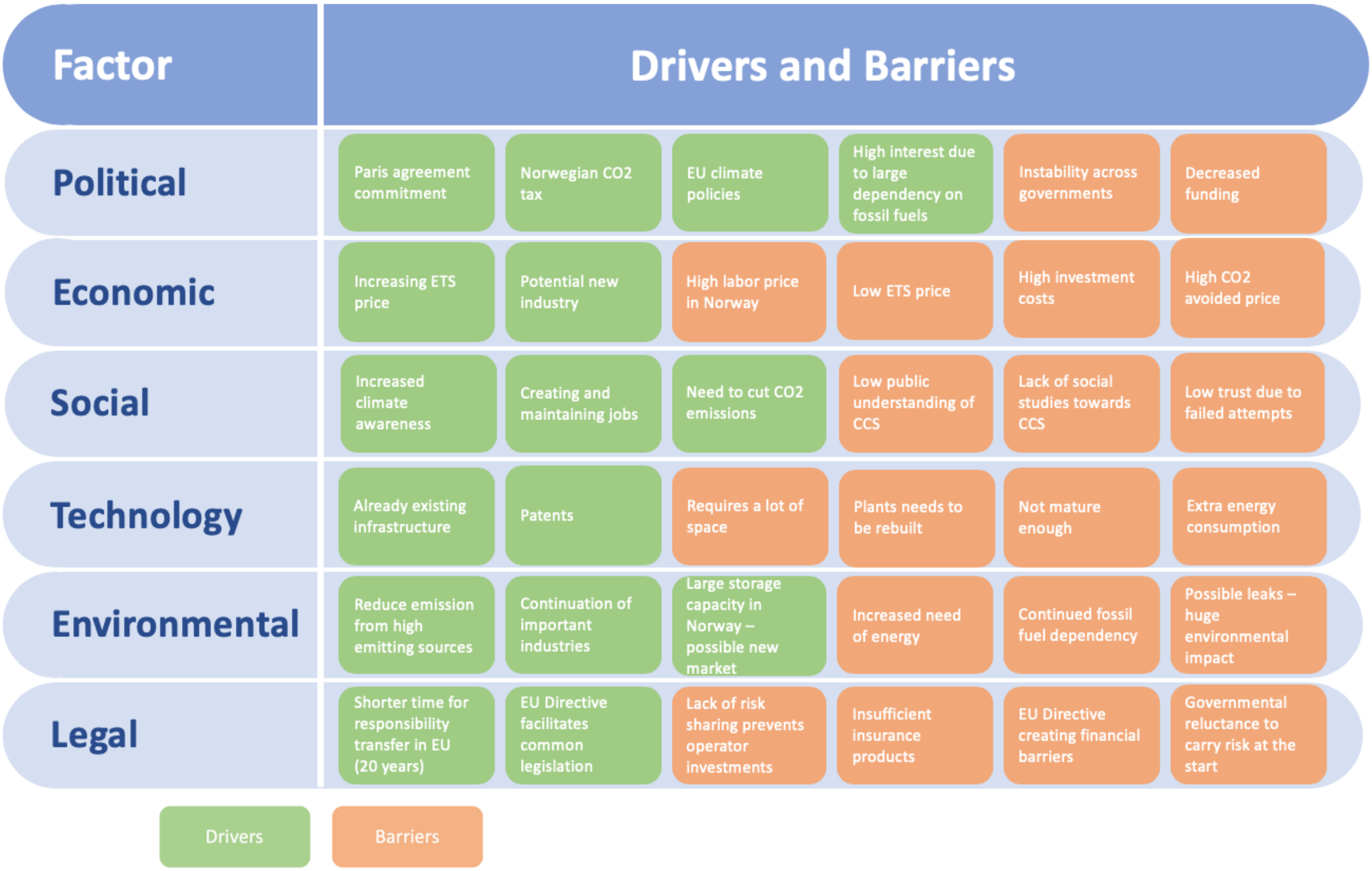

Figure 14 - PESTEL results

4. Mapping the Potential – high emitting sources in Scandinavia

External factors can facilitate and assist CCS development in Norway - but if the business case is lacking and economic profit is unlikely, private investments are likely to be absent. For a storage operator to start investments, customers are needed. The storage operator will store CO_2 from various sources and gain payment for the quantity of CO_2 they store. Therefore, large amounts of CO_2 will be needed to cover their costs and increase their profit. Large amounts of CO_2 emissions will also incur a lower price per tonne CO_2 captured at the facility. The Northern Lights project will transport CO_2 by ship from the emitting source to the temporary storage facilities at Mongstad before it is injected through pipelines into the storage reservoir (Equinor, 2018). Transportation will add costs for the operator, and thus having customers close to the temporary storage location will be cheaper than transporting CO_2 for customers further away. So, for the Northern Lights project, attractive customers would be high emitting sources relatively close to Mongstad.

Some industries may see a shift towards more climate-friendly solutions, e.g. oil and gas can invest in natural gas and renewables and thus lower their emissions. However, industries like iron and steel, cement and ammonia production cannot cut their emissions on a quantity that is required to meet the climate targets and still maintain production without implementing CCS. This implies that these industries are especially prone to adapt CCS and become potential customers for Shell and the Northern Lights project. If the requirements are put together, potential customers are:

1. High emitting sources
2. Relatively close to Mongstad and accessible by ship
3. In the iron and steel, cement or ammonia production industry

This is the basis of the potential analysis. In Appendix 1 "Scandinavian CO_2 sources", all sources within Scandinavia with annual CO_2 emissions surpassing 100 000 tonnes are included for easier future work. However, as the cost of capture will be lower at high emitting CO_2 sources and based on the three criteria mentioned above, a special focus will be directed towards iron and steel, cement and ammonia industries with annual CO_2 emissions > 700 000 tonnes and accessible by ship.

4.1 Costs and CO_2 Concentration

The cost of CO_2 avoided will vary across industries and depends on the CO_2 concentration in the excess gas to be captured. High purity CO_2 streams will be less costly to capture, as more CO_2 will be captured by the amine solution used to bind up the CO_2 (Hansson, Hackl, Taljegard, Brynolf, & Grahn, 2017). The CO_2 concentration is often similar across the same industries, e.g. the cement industry is usually exposed to a CO_2 concentration around 20-25% as the methods of making cement is quite similar from company to company (IEA Greenhouse Gas R&D Programme (IEA GHG), 2008). The ammonia production process requires a different method, where a high purity CO_2 stream is produced with a CO_2 concentration around 97-100% and thus the cost of capture is estimated to be lower for ammonia production compared to cement. To account for this variation, contact has been made to all sources in Scandinavia within the three chosen industries and emissions exceeding 700 000 tonnes of CO_2/year. The purpose is to map their different CO_2 emitting sources and connect each source with a CO_2 quantity and the CO_2 concentration in that specific source. In case of unavailable data, an estimated industry standard has been made by investigating literature data and taking the average values from these as shown in Appendix 1 and presented in Table 3.

Industry	Iron and Steel	Cement	Ammonia
Average cost of CO2 avoided [NOK/t]	590	907	249
Average CO2 concentration	22%	22%	99%

Table 3 - Average cost of CO2 avoided and CO2 concentrations based on literature. Data from Appendix 1.

These data will be used where site-specific data was unavailable to create a most likely scenario. For future work, Appendix 1 "Scandinavian CO_2 sources" can easily be used to update specific data to get more accurate cost estimations of CO_2 avoided for the specific emission source. This data can further be used to map potential customers, calculate transportation costs and generate an NPV for site-specific sources.

4.2 Results - Scandinavian emissions

The results show that there are currently six sources that fit the three criteria mentioned above. From the following, only one source (Yara) has a high purity CO_2-stream (CO_2 % vol > 90%), while the other sources are in the low to medium range with 15-22% CO_2 concentration.

The majority of the emissions are located in Sweden, which accounts for 4,26 Mt CO_2. Aalborg Portland A/S is the single largest source and the only Danish source on the list. The two facilities in Norway were both initially planned to be part of the Norwegian full-scale project, but after Yara cancelled their involvement only Norcem Brevik remains.

Company	Industry	Emissions (tCO_2/year)	CO_2 % vol	Country
Aalborg Portsland A/S	Cement production	2 050 000	22 %	Denmark
Cementa AB, Slitefabriken	Cement production	1 740 412	22 %	Sweden
SSAB Oxelösund AB	Iron and steel production	1 462 246	22 %	Sweden
SSAB EMEA AB i Luleå	Iron and steel production	1 058 000	22 %	Sweden
Norcem Brevik	Cement production	877 700	22 %*	Norway
Yara Norge, Yara Porsgrunn	Ammonia production	827 000	99 %*	Norway
Total emissions (tCO_2/year)	**8 015 358**			

*Table 4 - Scandinavian sources within iron and steel, cement and ammonia production with annual emissions > 700.000tCO2. * indicating site-specific data obtained.*

If all sources within the same industries are considered, the total annual emissions rise to 12 Mt CO2 and are presented in Figure 15. This implies that 67% of total emissions across the three industries originate from the focus facilities in Table 4. With a 90% capture rate from iron & steel and cement, and a 100% capture rate from ammonia, the total capture potential from Table 4 facilities equals 7 296 522 t CO2/year. As a comparison, the largest industry in Scandinavia is included (paper and pulp), which emits around 23 Mtpa.

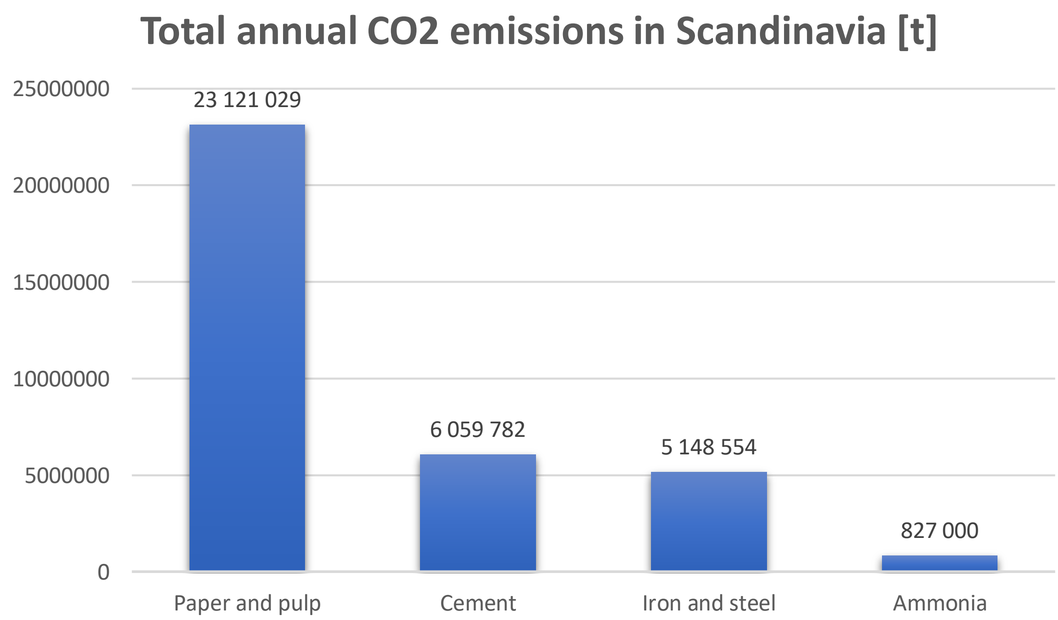

Figure 15 - Total annual emissions in Scandinavia by sector

4.2.1 Offshore transportation and storage costs

A report by McKinsey assessed the different costs associated with transport and storage onshore and offshore. The report showed that offshore transport is approximately 40% higher compared to onshore transport (McKinsey & Company, 2008). They argued that one tonne CO_2 could be transported offshore at a price of 6 EUR in 2008, the equivalent to 76 NOK/tonne CO_2 today. As for storage, the cost difference is larger. Storing one tonne CO_2 offshore was estimated to be 82% higher than onshore, resulting in a cost of 12 EUR in 2008, equal to 152 NOK/tonne CO2 today. Together, transportation and storage of one tonne CO_2 offshore equal a cost of: $76\frac{NOK}{tCO_2} + 152\frac{NOK}{tCO_2} = 228\ \frac{NOK}{tCO_2}$.

Other sources share the cost of CO_2 avoided across the following; the cost of capture (70%), transport (20%) and storage (10%) (Al-Fattah & Duncan, 2012). By using the cost of CO_2 avoided numbers from Table 3, the total cost of capturing, transporting and storing the capture potential mentioned will be 5 353 752 590 NOK.

This results in a total cost for the operator (given 30% of the costs are transportation and storage) of $5\ 353\ 752\ 590\ NOK * 0{,}3 = 1\ 606\ 125\ 777\ \ NOK$.

To make a profit, the operator would need a payment above $\frac{1\ 606\ 125\ 777\ NOK}{7\ 296\ 522\ t\ CO_2} = 220{,}12\frac{NOK}{tCO_2}$.

Both estimates are relatively close to one another, differing only 7,88 NOK or 3.5%. Using McKinsey's estimates, the total cost of transportation and storage will be $7\ 296\ 522\ \text{t}\ CO_2 * \frac{228\ NOK}{t\ CO_2} = 1\ 663\ 607\ 062\ NOK$.

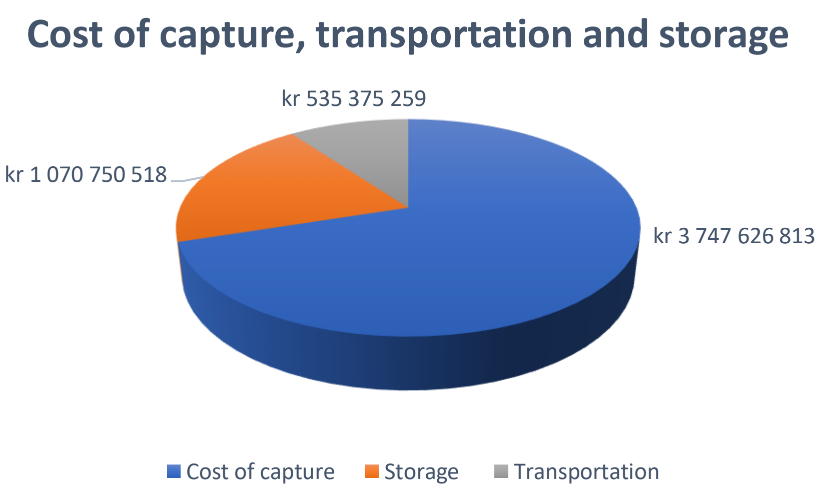

Figure 16 - Cost of CO2 avoided from relevant sources in Scandinavia

5. Method

The purpose of empirical research is to provide knowledge. This chapter is therefore meant as a description of how we have proceeded to derive this knowledge. A challenge with research is that it may be biased as the research is continuously guided by the researcher, and thus contain the researcher's own values and perceptions to some degree. It is argued that there is therefore no perfect research process as all such processes are subject to weaknesses, errors and deficiencies (Jacobsen, 2005). The aim of the method is not to deny any weaknesses and shortcomings, but to highlight and reveal possible weaknesses in the results and argue how choices may have affected them.

We can distinguish between deductive and inductive approach, where the deductive approach is tied up with a theory and data is then gathered to test this theory. The Inductive approach is concerned with new theories arising from the data (Jacobsen, 2005). As for this thesis, we will test if there is a foundation for CCS as a new industry in Norway and use data to test this hypothesis. A deductive approach is thus most suitable for this thesis. A challenge with deductive research is that you know what you are looking for, and so there is a bigger chance of being biased and overlook important data that does not coincide with the researcher’s own thoughts. The reliability and validity then become essential to avoid bias and will be discussed in the reliability and validity section.

5.1 Quantitative vs Qualitative method

Usually, we distinguish between two ways of collecting data; qualitative and quantitative methods. The problem statement of the thesis should decide which of them to use. The method tells us something about how we should address our work to obtain or verify knowledge (Dalland, 2010). A qualitative method wishes to go in depth to gain a deeper insight of a phenomenon, while a quantitative method collects data that can be quantified or expressed using numbers. A mix between these two is called triangulation (Thagaard, 2002).

5.1.1 Quantitative method

The methods´ intention is to present the most accurate reflection of the quantitative variation, where it approaches the task with a broad perspective and collects some information from many aspects. Its purpose is to test the correlation between hypothesis and facts. Verifiability is therefore an important aspect in this type of research because one wants to obtain and document evidence for the specific theory or hypothesis. A characteristic feature with quantitative methods is that the data are numbered, as the analysis deals with the valuation of quantities and sizes. The researcher sees the phenomena from the outside and strives for neutrality and distance. The data used in the research are mainly collected through surveys or systematic and structured observations. (Dalland, 2010) (Samset, 2015)

5.1.2 Qualitative method

Compared with the quantitative method, the qualitative goes more in depth to collect as much information as possible about specific aspects. It wants to bring out what´s special or different and gives a more comprehensive understanding of a phenomenon. Information and data are collected through interviews that are flexible, without any fixed answers and through unstructured observations (Dalland, 2010). The research deals with subjective assessments such as attitudes, opinions, behaviours and cognitive processes that cannot be quantified (Kothari, 2004). The researcher looks at the phenomena from the inside and acknowledges influence and participation. Such research is difficult to verify, but very important for the development of theories and hypothesis. Because a lot of the data collected is subjective, it should be crosschecked with reliable sources. (Samset, 2015)

In this thesis, both qualitative and quantitative research has been used to collect data and information, hence a triangulation approach has been used.

5.2 Secondary vs primary data

Data observed, constructed or collected from first-hand experience is categorized as primary data. Secondary data is categorized as data that has already been gathered by someone else. (Jacobsen, 2005). Our secondary data is obtained from different articles, literature and studies with both qualitative and quantitative approaches. Because of the broad context of the CCS industry, we based the information primarily on secondary data. However, we used secondary data to produce primary data when constructing the declining government funding curve. Secondary data was also the basis on which we constructed a lot of the primary data used in the second part of the thesis; mapping the potential in Scandinavia.

A qualitative method was used to obtain some of the primary data. Through open dialogues with relevant people and through the participation at the OGCI´s climate discussion in The Hague, information was collected. During part II of the thesis, we planned to collect quantitative data from six different facilities that emit carbon dioxide in the cement-, iron and steel- and ammonia industry. Only two of them responded, which forced us to collect these relevant data from already existing documents (secondary data). Combining all this secondary data into an industry average provided us with new primary data.

5.3 Empirical vs Conceptual Research

Empirical research is primarily based on observations and available data, where the researcher can conclude on the basis of this data. Results derived from experiments or empirical studies are considered the strongest form of confirmation or denial to hypothesis and theories (Samset, 2015). In some cases, empirical data can be hard to find. Future assumptions are abstract and lack empirical data, and thus a more abstract approach is needed.

Conceptual research is a methodology that focuses on a concept or theory that explains or describes the chosen question (Enago Academy, 2018). Instead of doing research and base results on pure data, conceptual research supports a more abstract way of describing a phenomenon, such as "how is the phenomenon caused?" and "how can the future affect the phenomenon?" By combining both empirical and conceptual research, we obtain the scientific method (Enago Academy, 2018). This method involves both empirical data and conceptual assumptions to investigate the phenomenon, and it is this approach we will use in this thesis as the potential for CCS can be described both through existing factors and future scenarios.

5.4 Reliability and validity

The reliability and validity of the thesis are important if the results are going to be useable. This is however two different aspects with different definitions. One can have reliable data with no validity at all. The aim is to provide both high reliability and validity. Reliability reflects on how consistent the research is (Samset, 2015). For example, if the data is considered to be consistent over time, one can test the reliability by doing a test-retest reliability measure. This is done by conducting the same research within the same boundaries and one should get approximately the same results time after time. If the data is consistent, independent of who's doing the research, it can be said that the research is reliable. Reliable research is unbiased, and the researcher must be objective and avoid personal opinions and values when conducting the research (Samset, 2015).

The validity of the research concludes how well the research describes what it is intended to describe (Samset, 2015). Do the methods used really answer your question? One measure to judge the validity is by looking at the test-retest reliability. This will indicate if the validity is on point or if your data is off target. You can obtain different mixtures of reliability and validity, which is represented in Figure 17.

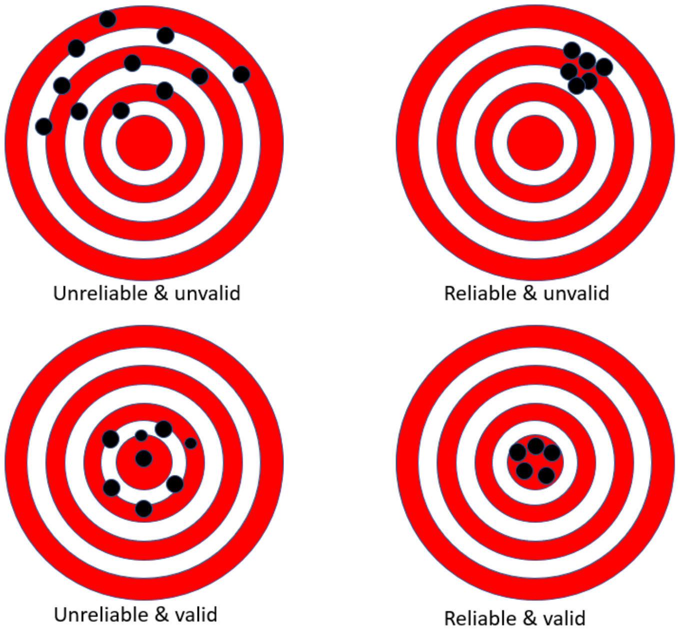

Figure 17 - Reliability vs validity

A gathered cluster indicates that the data is consistent and reliable, whereas its position on the target represents its validity. The closer the cluster is to the centre, the more valid the research is. Good research should be reliable and valid, and therefore be in the lower right category from Figure 17.

5.5 Requirements for sources

Data from the analysis is primarily based on literature findings and research articles from a wide range of sources to include different views, opinions and aspects. Reliable sources and big organizations such as IPCC, IEA, Global CCS Institute and SINTEF were mainly used for facts, together with science articles and existing research on the relevant topics. The articles were mainly found through Google Scholar to ensure reliable research material. IPCC and IEA are objective and transparent organizations considered as very reliable and without biased opinions, while other sources as the Global CCS Institute and Greenpeace might have more biased opinions. This is included to contain both sides and diverse views on CCS and its implications.

5.6 The Research Process

5.6.1 Part I

As this thesis' main purpose was to investigate the potential for CCS as a new industry in Norway, a wide spectrum of knowledge within several different disciplines was needed. The three research questions were formed as a tool to answer the main question by assessing political, economic, technical and commercial aspects. We needed a framework which included all relevant aspects that could influence CCS as a new industry, and furthermore investigate if there was a commercial foundation for the industry in terms of potential customers. A solid framework would not be enough if no potential business case was possible. Hence the thesis was divided into two parts;

- Part I: assessing the external framework that can influence the industry
- Part II: mapping the potential for CO_2 storage in Norway.

In the early stages of the thesis, a wide range of investigative measures were done to better understand the context of CCS and its challenges. Conversations and meetings were held with CCS relative parties, including Eva Halland and Aslaug Eskeland Janssen from the Ministry of Petroleum and Energy, Asbjørn Torvanger from CICERO and Kim Bye Bruun, Christiaan van der Eijk and Emil Yde Aasen from Shell. These meetings gave us a better understanding of what challenges the different parties thought was important. As for the legal element, a lot of information was gathered from the OGCI climate meeting in The Hague, Netherlands. The information contained results from interactive group discussions and revealed legal and insurance elements already in place, and what needs to be done in the future to make CCS attractive. A summary was given to the attendees and included as Appendix 2 and became the basis for a lot of the legal and insurance data.

From the meetings, a large variation in challenges arose. Some pointed on technical challenges, others on economic, environmental and legal challenges. To account for the variation, a PESTEL analysis was chosen as the framework to assess the external elements surrounding CCS. As the PESTEL analysis comprises a wide sector of elements, information from a lot of different sources was necessary.

5.6.2 Part II

All emission sources above 100 000 tCO_2/year in Scandinavia were obtained to check the total potential for CCS as an industry. Databases containing these numbers were located, and all sources inserted into an excel sheet to get a good overview of all facilities. To be able to use such data, it is a prerequisite that the numbers are obtained from reliable sources. The Norwegian emission numbers are obtained from The Norwegian Environment Agency´s web page (Norskeutslipp.no), while the Swedish and Danish were obtained from Naturvårdsverket (Naturvardsverket.se) and the European Pollutant Release and Transfer Register (prtr.eea.europa.eu). The numbers used in this thesis are the most recent numbers from these specific databases, where the Norwegian, Swedish and Danish emission numbers are from 2017, 2018 and 2016 respectively. It would have been possible to obtain all the numbers from the European Pollutant Release and Transfer Register, but because these numbers were from 2016, we decided to use more updated numbers for Sweden and Norway. The numbers used are the total amount of CO_2-emissions from the plants, and not CO_2-equivalents as we are interested in capturing CO_2 only.

Different literature has been used to find an average for carbon dioxide concentration in the flue gas from different industries, as well as the cost of CO_2 avoided in the relevant industries. The sources used are presented in Appendix 1. The reason why we checked different sources is because this number varies widely, and therefore, an overall average has been utilized throughout this thesis. The variation in price for the ammonia, iron and steel and the cement industry is presented in Figure 18. The price obtained from sources is normally presented in USD or € with a specific reference year. The conversion to NOK has been done according to today's currency, and not at the time the reports were published.

In consultation with Shell; ammonia, cement and the iron and steel industry were chosen as our main focus for this part. Our focus facilities; Yara Porsgrunn, Norcem Brevik, Aalborg Portsland A/S, Cementa AB, SSAB Oelösund AB, SSAB EMEA AB were all contacted as they represent large emitters (>700 000 tCO2/y) inside the three relevant industries. The aim was to find the %vol CO_2 in the different emission sources/outlets at each plant, and the amount of CO_2 that is emitted through the various outlets. The concentrations were compared with the numbers obtained from reports to check the reliability of the sources. Yara Porsgrunn and Norcem Brevik are the only ones we got specific numbers from. For those who did not respond, the overall average is used as a reference.

In Appendix 1, a calculation tool is presented where the amount of CO_2 emitted from the different industries is summed up and multiplied with the specific price of CO_2 avoided and the estimated capture rate for the specific industry. The results indicate the potential in the industry, with both cost of CO_2 avoided and the amount of CO_2 available for capture. The calculations in section 4.2.1 are done with use of numbers from Appendix 1. The results were compared with McKinsey´s estimates to check the validity and deviations between our calculations and literature. The results we got from the calculations are presented in Figure 16.

5.7 Criticism of the method

When using such a large spectrum of sources, the chances are that some of the information is biased, wrong or inaccurate. The fact that cost estimates varied so much from different reports also indicates that there is large uncertainty regarding CCS - which is illustrated in Figure 18, where a flat curve would mean no variation.

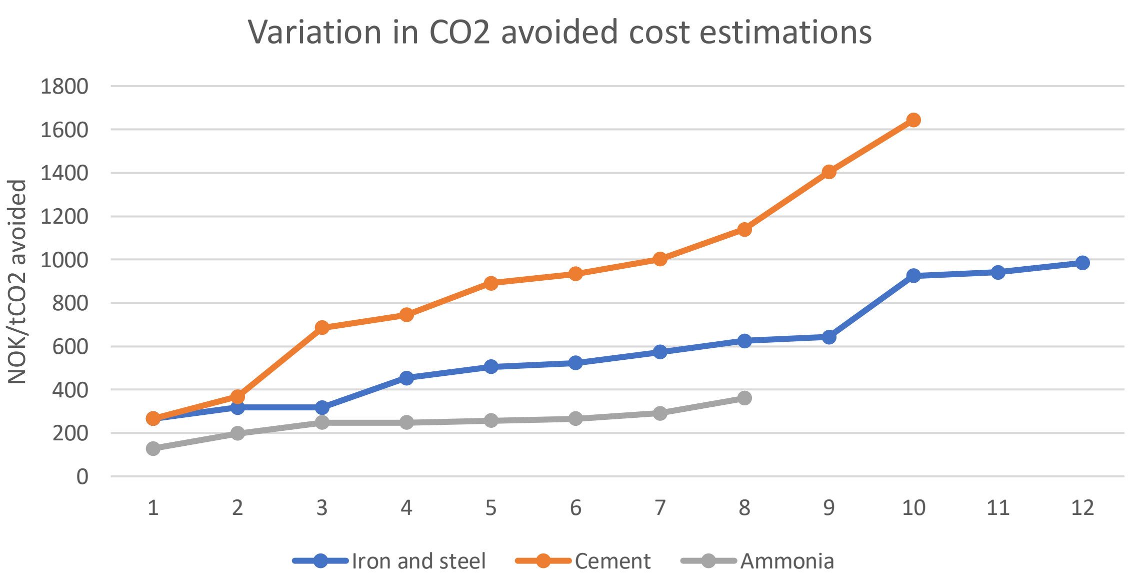

Figure 18 - Variation in CO2 avoided cost estimations found in literature

This uncertainty was accounted for by taking the average value as mentioned, but due to the wide range of reported data, the actual outcome may differ a lot from the averages used in the cost estimations. Costs are likely to differ across facilities, also within the same industry.

So, generalizing the CO_2 avoidance cost for different industries is a large, but necessary assumption as it depends on site-specific factors like costs of building the CCS plant, electricity price, labour costs, excess heat in the system etc. This would be too much uncertain data to account for in this thesis, hence the generalization is made to make a realistic average across industries. The capture rates can also vary across facilities and may differ a lot depending on the technology used. A change in capture rates will affect the numbers and the total costs. However, the excel sheet can easily be modified to account for this by updating capture rates for the industries which will automatically adjust the potential capture numbers.

As for the broad context of the PESTEL analysis, it had to be limited to a feasible size. Some important aspects may have been overlooked or neglected here, as we had to focus on the aspects we thought were the most important for the CCS industry in Norway.

5.7.1 Source critics

Some of the sources used are relatively old, with the Carbon Capture and Storage report from IPCC dating back from 2005. Although research on CCS has been relatively limited, technology and certain aspects have changed over the years. We have tried to limit the use of this source to only include up to date facts and supplied with newer research when necessary. However, the CCS industry is rapidly changing, and some facts may be outdated by the time of reading.

As the environment surrounding CCS is changing so fast, a lot of the material used is based on reports from organizations rather than books. This results in a lot of different sources, and it has been evident that different research may show different results on the same topic. This is largely down to the uncertainty that comes with CCS as so few projects have been completed. With more sources comes higher risk of contaminating the thesis with biased or inaccurate information, but this is a risk we tried to mitigate through using trustworthy organisations and check different sources for the same information. Over the course of this thesis, we have gained a fairly deep understanding of the CCS industry, and lots of information is consistent through different reports. We are therefore in a good position to close out information that doesn´t conform with most research. However, basing so much of the information on literature findings and secondary data, there is a risk that some of the information may be wrong or inaccurate.

6. Discussion

This chapter will present and discuss how well-suited CCS is as a new industry in Norway, based on the results from the PESTEL analysis and the Scandinavian CO_2 mapping. Divided into sub-chapters, all the different elements from the PESTEL analysis will be discussed with a focus on the findings in Figure 14 – PESTEL results. Furthermore, the numbers from the Scandinavian CO_2 mapping will be thoroughly discussed to see if there is any potential for the industry at all. At last, the three research questions will be discussed and together make up the foundation of the conclusion.

6.1 Politics

It is imminent that political support is the key for CCS is to succeed. We can distinguish between international politics and national politics. International politics can play a vital role when assessing challenges as global warming. Although a few nations make up a large proportion of the global CO_2 emissions, this is a global problem that needs global collaboration. The Paris agreement exemplifies this; a huge collaboration which requires several parties to come up with an actual plan and continuously renew this into even more ambitious goals. How well a nation is doing will be assessed every fifth year from 2023, and thus make it easier to quantify the development and discover faults and improvement areas (United Nations Association of Norway, 2018).

Another example of international climate friendly politics is the EU ETS. This is a measure that can regulate the price of CO_2, and thus influence the attractiveness of CCS (European Commission, 2015). The CO_2 price has been volatile since its beginning, falling below 5 EUR several times (MARKETS INSIDER, 2019). When the cost of emitting one tonne CO_2 is less than 5 EUR, the need for expensive CCS facilities and capture rates more than ten times that amount is unacceptable for most companies. You could make considerable savings from buying one EU ETS credit compared to capture the same amount of CO_2. However, the EU ETS price is currently increasing at a relatively fast pace, which makes CCS projects more desirable. The EU ETS goal is to make investments in less carbon heavy technologies more attractive by steadily increasing the CO_2 price. How the CO_2 price behaves in the coming decades will therefore influence the commercial attractiveness of CCS. If the CO_2 price rises above 1000 NOK/tonne CO_2, it will become more desirable to capture the CO_2 than to emit it, and thus create an incentive to implementing CCS equipment, either to new facilities or by retrofitting existing ones.

The 45Q arrangement is an example where national politics can influence the CCS or CCUS industry. From Figure 4, one can observe that all the US CCS projects are characterized by using the CO_2 for EOR. Furthermore, 6 out of 9 US facilities are influenced by the national tax credit system, 45Q. The EOR business in the US is so big that companies capturing the CO_2 benefits from selling the CO_2 to EOR, compared to geological storage. Since CCUS for EOR has been successfully operating in the US for decades, the new incentivizing 45Q arrangement will enhance the profitability even more. The capturing company will receive either 35 USD/t + the selling price (15-30 USD/t) or 50 USD if they store it geologically (Global CCS Institute, 2019). When profitability is increasing, investments are increasing. Incentivizing legislations as this shows that national politics can be just as important as international collaboration.

6.1.1 Norwegian CCS politics

In Norway, national politics has incentivized low carbon operations since 1991. A CO_2 tax was implemented for the petroleum industry on the Norwegian continental shelf (Global CCS Institute, 2018). The decision resulted in the CCS projects at Sleipner and Snøhvit. They have become a symbol that shows CCS can be done, and that CO_2 can be stored geologically offshore in a safe way. From Figure 4, we can see that only 4 out of 18 operating CCS facilities do not use the CO_2 for EOR. The reason why EOR is not used in Norway is primarily because the amount of CO_2 available in Norway is insufficient for EOR, where larger quantities of CO_2 are needed (SINTEF, 2018). The CCS projects in Norway seems to be driven by the urge of avoiding the CO_2 taxation, and not profitability from selling CO_2. Until now, all the projects discussed in this section have been characterized and motivated by economic profit or less expenses. Lately however, the focus has diverted from using CCS to recover more oil to take advantage of CCS as a tool for reaching climate goals.

The Stoltenberg government’s belief in CCS was supported by funding from the Norwegian state, labelling CCS as part of a solution to the climate change and as a technology Norway could develop and share globally. The second Stoltenberg reign invested around 14 billion NOK into CO_2 mitigating measures, with the Mongstad facility being the largest project (Ministry of Finance, 2008-2019). As the government election in 2013 resulted in Erna Solberg being the new prime minister, the project was cancelled due to low carbon price, dim interest for the technology and a tougher economy. The perception of CCS hit a hard wall, as billions of kroner had been diverted to an unsuccessful project. The focus on CCS diminished, and funding declined from 3,38 billion in 2010 to 669,5 million in 2019.

This illustrates how changing governments can have a huge impact on the CCS industry. The decreased funding from Solberg can be viewed as a smart political decision, as people's perception of CCS was at a low. Throwing billions more into this "failed" technology could potentially impact the next election. This is also relevant for today's situation. The government's commitment to the full-scale project is still unclear. The investment decision will be taken somewhere between 2020/2021 and can again influence the upcoming election in 2021. Huge investments into a technology most people don't know much about, or associate with failed attempts, can be risky. Hence, spreading knowledge around CCS and its importance for climate change can be an effective strategy for gathering support for future investments. A full-scale project will be a starting point, but more mitigating efforts need to be done if the goal of 40% reduction cuts of CO_2 is to be accomplished by 2030.

Norway is in a position where CCS is beneficial to the nation because it offers a prolonged period of fossil fuels and a strategy to reach the climate goals. Therefore, the incentives for Norwegian politicians to support CCS is present. However, there is no guarantee that CCS will be supported after a new election in 2021.

6.2 Economics

Many of the previous failed CCS projects have been concluded due to lack of economic funding. The Mongstad project is a prime example where we see that it received large support during the first years but was eventually shut down (Reuters, 2013). Big investments were made, and for many this might be regarded as a sunk cost, but all the work that was put into the project resulted in increased knowledge. Today, Mongstad is the world's biggest test centre for testing CCS technologies. The knowledge obtained after the full-scale project will most likely result in cost savings in future projects. With high commitment to CCS, SINTEF argues that 3.5 billion NOK will be the estimated savings after the first full-scale implementation in Norway (SINTEF, 2018). This number will vary depending on the industry, but as we can see from Table 2, there is a clear tendency that the costs will decrease after the first project (Global CCS Institute, 2017). Norway has three projects that are put on the PCI list, allowing them to apply for funding from the CEF. This is a way to lower the total cost of the project (SINTEF, 2018).

The investment cost is a certain barrier against CCS implementation. The McKinsey report estimates that decarbonisation of the four industries; iron and steel, cement, ethylene and ammonia will cost between 11 to 21 trillion USD globally up until 2050. This equals 0.4 to 0.8% of the worlds GDP every year (McKinsey & Company, 2018). As the EU ETS price is lower than the CO_2 avoided cost, it is hard to see this concept as profitable. On top of that the energy penalty of an average facility with post-combustion of 29% results in higher operational costs, making it less profitable (House, Zenz, Harvey, Aziz, & Schrag, 2009). It should also be mentioned that labour costs in Norway are high compared to other countries, which incurs higher costs. But what makes Norway a suitable location for CCS is that there are good storing facilities. If the facilities in Scandinavia are connected through infrastructure investments or CO_2 transport solutions, making the inflow of CO_2 much higher, there are possibilities of utilizing this for EOR. This can potentially ensure an annual income of 8 billion NOK (SINTEF, 2018). This can also make it easier to defend the concept and creates an economic incentive when it is shown that it can potentially increase the annual revenues of the O&G industry in Norway by 4% (SINTEF, 2018).

With a CCS industry in place, energy-intensive processes such as hydrogen production from natural gas reforming can be done with less environmental impact. With renewable energy destined to rise, hydrogen production with CCS can become another important industry for Norway, potentially giving Norway a turnover of 220 billion NOK in 2050 and provide 35 000 jobs (SINTEF, 2018).

The EU ETS measures like back-loading and MSR are trying to make the price less volatile and stabilize it on a much higher level (European Commission, u.d.). This could act as a driver for operators, where it becomes an economic incentive to implement CCS if the ETS price reaches an acceptable level.

6.3 Social studies

The lack of focus on the social aspects of CCS has resulted in low awareness from the general population. The obvious driver for carbon capture is that we need to cut down CO_2 emissions and that it needs to happen in a relatively short time period (Pihkola, et al., 2017). As it comes forward from the surveys conducted by Norstat and Eurobarometer the knowledge about CCS and the climate change in general is relatively low (TNS Opinion & Social, 2011) (NRK, 2017). A result is a negative/neutral mindset regarding CCS where a "not in my backyard" way of thinking may occur. CCS has the potential to increase climate awareness, but to do so, the knowledge of CCS needs to be increased and general concerns addressed. Greta Thunberg is acting as a champion and inspires the young generation. This is exactly what CCS needs. A champion that encourages people to fight and believe in the cause. This can create publicity and increase knowledge about carbon capture and storage.

CCS is a new industry where there are uncertainties concerning most parts of the project. People need evidence that proves that CCS is feasible and safe. They may not have this before the first full-scale facility is implemented. As mentioned earlier, the crash landing of the Mongstad project resulted in reduced interest and the public perception became more negatively focused (Reuters, 2013). If the full-scale project becomes very costly or fails, it will seem daunting for future investors (Atkins and Oslo Economics, 2018). Although the cost will vary widely depending on the type of industry, the cost level of the first project will influence the general belief in CCS as a technology to reduce GHG emissions. The lower the cost, the more it will demonstrate that CCS is a relevant technology for the future fight on climate change (Atkins and Oslo Economics, 2018). As Norway goes forward as an example with a full-scale project, it could lead to other countries losing or gaining interest when they see the final costs (Atkins and Oslo Economics, 2018). On the other hand, a new industry means new jobs. A full commitment to carbon capture and storage in Norway will have the potential of creating thousands of new jobs and strengthen existing ones (SINTEF, 2018). In a world where digitalization occupies more and more jobs, this represents an opportunity for a new industry in Norway. By implementing CCS, the competitiveness of the O&G industry in Norway will be strengthened as it enables O&G extraction with less emissions. New jobs can also be created, where a new industry such as hydrogen production from natural gas with CCS arises. This industry alone can create up to 35.000 jobs (SINTEF, 2018).

What people need to understand, is that CCS will not be implemented primarily to save the O&G industry and lead the attention away from renewables, but it can also contribute to reduced global warming. Whether or not people are positive towards it remains to be seen, but they should at least have knowledge of the potential of the technology.

6.4 Technology

The technology has been there for some time, but on a large-scale CCS represents an underdeveloped industry where a lot of research and development is still needed. The three technologies we have focused on in this thesis have the potential of capturing 90% of the CO_2 from industrial facilities (Bellona, u.d.). It is possible to reach a higher rate, which automatically leads to higher energy consumption and costs. Post-combustion represents the technology that is most used today because of its ability to be retrofitted to existing facilities and industries (Global CCS Institute, 2009) (Bellona, u.d.). But retrofitting an existing facility is complicated, and not all facilities have sufficient land acreage to enable such developments, making retrofits difficult and costly. An alternative to retrofits is oxyfuel combustion when a new plant is constructed. The estimated capture cost is lower for oxyfuel than it is for post-combustion, and therefore it is important to consider long-term opportunities rather than short-term costs when making investment decisions (Global CCS Institute, 2009).

CCS can be economically challenging when considering the low efficiency and high energy penalty. A goal should be to improve the technology to reduce the energy penalty, which will lower the cost and demand for extra fuel, thus making the technology more sustainable (Pihkola, et al., 2017). The race for valuable patents will help drive the development of the technology in the right direction. Although the technology is present today, it is not efficient enough to encourage large scale deployment of CCS due to the increased costs (House, Zenz, Harvey, Aziz, & Schrag, 2009).

6.5 Environmental

Many environmental organisations are against CCS (Conniff, 2018). This opens up for a debate on whether CCS is actually helping the environment, or if it is merely a tool for prolonging the fossil fuel industry. But the opinions are very divided. Different environmental organisations have different views – from Bellona and Zero who supports it, via Greenpeace who's against it, to the ones in the middle who thinks it may contribute in the future but needs improvement (WWF, Worldwatch Institute, Sierra Club) (Conniff, 2018). However, most ENGO's seem to agree that CCS should not be used to prolong the life of fossil energy carriers.

A lot of the arguments against CCS are being discussed in other sections. This section will focus on the environmental liabilities. The fact that 79.5% of the worlds energy consumption in 2016 originated from fossil fuels indicates that the world is dependent on fossil fuels to sustain its population (REN21, 2018). As the energy demand is expected to double within year 2050, compared to year 2000, it becomes clear that fossil fuels will have a part to play in the future (Shell, 2019). At least until renewable industries, such as wind and solar energy are big enough to overtake the energy demand. The Sky scenario built by Shell clearly shows the expected energy trends in the future – replacing a lot of fossil fuels with electricity (Shell, 2018). Getting there requires a steady transition in which fossil fuels will play an important role. And since the trajectory of global warming is pointing in the wrong direction, this continued fossil fuel dependency needs to be addressed as soon as possible if the Paris-agreement goals shall be met. The emissions need to drop significantly, and CCS is a key technology for doing just that, according to IPCC and IEA (IEA, 2019) (IPCC, 2018).

CCS is considered the only sufficient technology to cut large emissions from industrial plants, while maintaining production (Engen & Whiriskey, 2014). With increasing population and fast-growing cities, industries as iron, steel and cement are likely to increase production as well. But capturing the CO_2 is not enough – it still needs to be safely injected and stored.

Injection and storage of CO_2 can possess a huge threat to the surrounding environment (IPCC, 2005). A leakage, either during injection or during the storage lifetime can be critical to the surrounding ecosystem, animal and human life. As the storage potential in Norway is located offshore, some of these risks are reduced due to the absence of human activities in some of these areas. However, leaked CO_2 can act in the same way as the incident in Lake Nyos – forming a gaseous cloud of high purity CO_2 on the surface (IPCC, 2005). Passing ships, offshore facilities and other life in the area will then be endangered of carbon dioxide asphyxiation. The leakage can also be trapped on the ocean floor, destroying ecosystems and marine habitats (Molari, et al., 2018). Although these risks possess a huge threat if occurred, the probability of occurrence is deemed so low that it is considered safe (IPCC, 2005). Decades of offshore petroleum activities have provided deep knowledge into geological reservoirs, their behaviour and the risks involved. Monitoring equipment is well developed and can discover abnormal behaviour in time to implement mitigating measures. Hence, offshore CO_2 storage is considered safe – and Norway has got a lot of it.

6.5.1 – Norwegian storage capacity

With an estimated storage capacity of 86 Gt CO_2, the Norwegian continental shelf can potentially offer a future business opportunity (Norwegian Petroleum Directorate, 2019). Equivalent to 40% of northern Europe's CO_2 storage capacity, Norway has a unique opportunity to create a new market if CCS deployment reaches the desired levels outlaid by IPCC. Storage capacity is critical in order to reach climate goals in line with the Paris Agreement. By being a first mover within full-scale CCS deployment, SINTEF argues that Norway can take at least 40% of the European storage market. This will not only create thousands of new jobs; it can also generate significant revenues and thus lower the total costs associated with CCS (SINTEF, 2018). Considering that the Global CCS Institute ranked Norway's storage indicator as number one in Europe, it is likely that the thorough storage assessment can provide an advantage compared to other nations with great storage capacities, as the UK (Global CCS Institute, 2018). The Norwegian Petroleum Directorate's atlas over storage locations represents a benefit for Norway if CCS is to be deployed at a large scale. And by being a first mover, Norway can influence this outcome and take even bigger shares of the storage market.

6.6 Legal

Based on this research, the legal requirements are currently acting as an obstacle against CCS investments. The idea behind the EU Directive is generally good. Standardizing certain requirements can simplify the complexity of handling CO_2 and promote cross-border cooperation. A general set of rules can be helpful if the elements within the Directive are helpful. However, if the elements within the Directive creates more barriers than drivers, the outcome becomes negative.

The fact that the operator must ensure a financial security to cover all expenses for the lifetime of the stewardship, including potential leaks, is not encouraging operators to invest in CCS (EU DIRECTIVE 2009/31/EC , 2009). This will incur a large amount of money that will act as a deposit for the operator and can therefore not be used until the liability transfer occurs, after 20 years. Some companies may not last 20 years, and a lot of companies cannot cope with such big deposits over such a long period.

The lack of risk-sharing between operators and the competent authorities (in this case the Norwegian state) is currently causing reluctance from operators and other investors. From the OGCI climate meeting in The Hague, it was imminent that the lack of risk-sharing alternatives is the biggest barrier for operators aiming to invest in storage (Appendix 2). A common risk-sharing method is using insurance companies, but the insurance products towards CCS are currently insufficient. This is partly because of the EU Directive, and partly because of little knowledge about offshore CO_2 storage. Signing up for the responsibility of a CO_2 storage site is equivalent to signing an uncapped check, as a potential leak must be paid for by EU ETS credits at the price relevant at the time of leakage. Since there is no way of knowing the EU ETS price in 20 years, there is no way of knowing what the incurred costs might be. This uncertainty is causing operators, insurance companies and governments to avoid storage responsibility and thus hamper the CCS development.

A compromise could potentially contribute to a solution, where a three-part risk sharing method is implemented as a public-private partnership. If the risk is shared between the operator, insurance company and the competent authorities, the barrier for operating a storage site would be reduced. If the competent authorities carried a part of the risk for the first projects, experience and knowledge could result in data necessary for insurance companies, storage operators and other investors to invest in storage. By carrying the risk in the early phase, successful projects could lead to adjustments in the EU Directive, lowering the financial security needed and relaxing the constraints of reliability transfer between the operator and competent authorities. As mentioned, unsuccessful projects in the early phase can act as an end to all storage investments and potentially CCS investments. But if the Paris-agreement is to be fulfilled, some risks will have to be taken.

If the EU Directive is not relaxed, the risk is that no one takes on the responsibility of CO_2 storage. A solution can be to update the current EU Directive to better facilitate for CCS deployment, without the experience of previous projects. By relaxing the financial security requirements in Article 19, the barrier towards CCS storage can be affected. The financial requirements in case of a leakage also act as a barrier, both for operators and insurance companies. Instead of paying for the amount of leaked CO_2 by giving up EU ETS credits at an unknown price, one could sign a deal with an agreed upon price or cap the price. By doing this, the check for insurance companies now has a specific number they can relate to.

Nevertheless, the legal jurisdictions in the EU Directive should adapt to a more operator-friendly approach and contribute as a driver rather than a barrier if CCS shall succeed as a new industry in Norway.

6.7 Part II – Discussion: Mapping the potential in Scandinavia

The mapping of CO_2 sources in Scandinavia was made to indicate whether there is a sufficient market for CCS in Norway. Since the costs related to CCS is one of the key barriers towards it, economies of scale can ensure that the overall costs can be reduced if there are large quantities of CO_2 available for capture and storage. With a focus on the three aforementioned industries, consisting of six facilities with annual emissions > 700 000 t CO_2, the numbers revealed that these six companies accounted for 67% of the emissions related to those industries in Scandinavia. Thus, the majority of Scandinavian emissions within iron and steel, cement and ammonia could be captured and stored from implementing CCS equipment on these six facilities. With the relevant capture rates, an estimated 7,3 $MtCO_2$ can be captured annually from these facilities. This equals approximately 10% of all the CO_2 emissions from Scandinavian sources > 100 000 tCO_2/y and would make a considerable contribution to the emission reductions needed to maintain the Paris agreement. The Norwegian CO_2 reductions from these focus facilities account for approximately 3.5% of total Norwegian CO_2 emissions in 2017 (Energi og Klima, 2019). From sources included in Appendix 1, the Norwegian focus facilities make up around 11.3% of the Norwegian emissions. This indicates that sources excluded in this list (offshore petroleum sector, transportation, agriculture, etc.) make up a large proportion of the total CO_2 emissions. Out of a total 43,7 Mt CO_2 emissions in Norway in 2017, the industry list accounts for 13.6 Mt CO_2. This indicates that there may be a potential for CCS, and indeed GHG-reductions, in other areas than the chosen industries included in Appendix 1.

Figure 15 illustrates that the cement and iron & steel industries have far more emissions than the ammonia industry, and they are also the costliest. With an average CO_2 avoidance cost of 907 NOK/tCO_2, the cement industry is the most expensive industry of the three. Ammonia is the cheapest industry, but only account for 0,83 $MtCO_2$ per year (Yara Porsgrunn is the only ammonia facility in Scandinavia). Furthermore, three of these facilities are operating in Sweden, two in Norway and one in Denmark. As all facilities are near the coast, CO_2 transport by shipping is possible.

This is the capture potential and the relevant cost of CO_2 avoided:

Industry	Capturable CO_2 [$MtCO_2$]	Total cost of CO_2 avoided [NOK]
Cement	4,2	3 809 697 552
Iron and steel	2,27	1 337 751 617
Ammonia	0,827	206 303 420

Table 5 - Capture potential and cost of CO2 avoided in focus facilities

The total cost of CO_2 avoided from the six facilities will add up to 5,354 billion NOK. Transportation and storage will account for around 1,606 billion. With such large quantities of CO_2, in combination with a high uncertainty towards the cost of CO_2 avoided (especially for the FOAK projects), these numbers can vary widely. These numbers are therefore best used as an indication of potential quantities of CO_2 available, as the cost and technology can be expected to change over the coming years.

Due to the high cost related to the cement industry, it can be recommended to start with less expensive industries such as ammonia and iron & steel. The FOAK projects need to demonstrate that CCS is feasible, both technically and financially. The success or failure of the first CCS projects can possibly affect the whole industry. Therefore, starting with CCS in an industry where the expected costs of CO_2 avoided is low can be a strategically smart move. Demonstrating that CCS can be profitable and done at a lower cost than the EU ETS price and carbon tax, can spread enthusiasm for the technology in the media and affect people's opinion of it.

As Yara has cancelled their involvement in the full-scale CCS project, no other ammonia facilities are available for CCS in Scandinavia. There are however, other low-cost industries, depending on the technology used. Natural gas processing can use a technology where high purity CO_2 streams are generated, lowering the cost of CO_2 capture. Hydrogen also incurs a low cost, where IPCC argues it can be as low as 2 USD/t CO_2 avoided (IPCC, 2005). As natural gas is an important industry in Norway, this could be a focal point for CCS deployment and thus enable hydrogen production.

The industry with most emissions in Scandinavia is the paper industry. With annual emissions of approximately 23 Mt CO_2, this is by far the largest emitting industry – outranking the second most emitting industry, waste combustion, with its 10,4 Mt CO_2. All paper industries included in Appendix 1 are located in Sweden, the largest emitting country in Scandinavia.

With their self-proclaimed goal of being carbon neutral by 2045, CCS investments for the paper industry could be of high interest (Government Offices of Sweden, 2017). With their high emissions, ambitious goals and Norway's storage potential, this can arguably make a potential business partnership. Based on the collected data, it could drastically reduce Scandinavian CO_2 emissions and provide the Northern Lights project with large amounts of CO_2 to store.

In general, the Scandinavian emissions offers a potential for CO_2 capture and storage. There are large emitting sources within iron and steel, cement and ammonia where all of them are accessible by ship. The quantities are of a magnitude that can ensure profit and lower the total cost of CCS due to the principles of economies of scale. In a future scenario, CCS can be used in other industries as well. Paper and pulp make up 23 Mt alone, and could be a feasible industry for CCS deployment (Onarheim, Santos, Kangas, & Hankalin, 2017). With an interconnected pipeline system, the additional cost for a source to connect will be lower. Again, FOAK facilities will incur a higher cost than NOAK facilities, so it may be worth considering long term gains instead of short-term costs. However, one will be dependent on the future CO_2 price to rise and incentives to be established before most companies can justify the expense of CCS equipment. Today, the expense is too high for companies in Scandinavia to invest in CCS without governmental backing or incentives - but the potential in terms of CO_2 amount and accessibility is present.

6.8 Discussion: Research questions

Based on the discussion, we now have a better foundation for answering the three research questions. The arguments above are used to present a short and concise answer to the research questions.

1. *How does political and economic framework facilitate the establishment of a CCS industry in Norway?*

This question can be divided into two parts; political and economic. The political framework in Norway is characterized by instability. Due to changing governments, CCS support can be expected to vary from one government to the next. The declination of CCS support from the current Solberg reign is evident, and the investment decision for the full-scale project in 2020/2021 will define Norway's commitment to CCS. The upcoming election in 2021 can affect this decision and creates a political tension towards CCS. The governmental reign from 2021 will have to deploy CCS at a large scale if the Paris agreement targets for 2030 are to be met, so this election will be of great importance on whether Norway facilitates for CCS deployment or not. The political situation is thus regarded as risky for current CCS investments. The lack of political urgency is primarily down to economic barriers towards CCS.

The economics behind it are estimating that the full-scale project will not be economically profitable and can incur a deficit of 20.7 billion NOK (SINTEF, 2018). This could incur a high cost of CO_2 avoided, and with the EU ETS price being so low, CCS cannot compete. If the EU ETS price is lower than the cost of CO_2 avoided, companies have few incentives to invest in CCS equipment. The EU ETS price is, however, expected to rise in the future. This can have a huge effect on CCS, as a high EU ETS price can make CCS a cheaper alternative; promoting investments for CCS equipment.

Together, this constitutes a decision that while the political and economic framework have the potential to facilitate for CCS deployment in the future, the current situation is that political and economic incentives are needed before CCS investments become feasible for industry players. The Paris agreement commitment is a driver towards CO_2-mitigating technologies, but if CCS will be a part of that remains to be seen.

2. Is CCS technology mature enough to be commercialized?

Although the technology has been present for decades, there are still some flaws that need to be addressed if CCS shall contribute as much to the Paris agreement as IPCC argue it should. Firstly, the energy penalty that comes with the technology is significant. A 29% increase in energy consumption with post-combustion is costly and can prove too much for many companies (House, Zenz, Harvey, Aziz, & Schrag, 2009). The total carbon footprint will also diminish if the CCS plants require much more energy. This increases costs, which is mentioned as one of the main barriers for CCS deployment. If CCS would be financially viable, CCS equipment still needs a lot of space. Newly built plants could be built with integrated CCS equipment, but existing facilities would need to be retrofitted, commonly by the use of post-combustion technology. This is very space consuming and can exclude many facilities from getting CCS.

Oxyfuel-combustion is a technology that looks promising, but in need of further development before being mature enough at a commercial scale (ECRA, 2018). So, although pre-combustion and post-combustion are technologies that already exist on a commercial scale, there are still flaws that should be solved for the technology to reach the desired level of commercialization.

3. What capture potential exists from large emitting sources in Scandinavia?

There is a potential for CCS to become a large industry in Norway when we look at potential emission sources in Scandinavia. When expanding outside Norway, the increasing amount of CO_2 emissions can provide a business opportunity for operators aiming to store CO_2 in Norway. The increased volume can lower the costs and enhance profitability. The fact that most big Scandinavian emission sources are located near shore enables CO_2 transportation by shipping, and the infrastructure could be built to facilitate for easier interconnecting if other sources want to store their CO_2 in the future.

If other industries than iron and steel, cement and ammonia are included, the volume increases substantially. With ambitious climate goals, the Scandinavian countries could find CCS as a solution and thus contribute to further development. But despite the combined CO_2 volume increase, the individual sources are relatively small at a global scale. The highest emitting source from the chosen industries is Aalborg Portsland A/S with approximately 2 Mt

CO2 annually. As cost of CO_2 avoided will be lower at large emitting facilities, this indicates that capturing the CO_2 from the relatively small Scandinavian sources can be too expensive. Building a CCS plant for a facility emitting relatively low quantities CO_2 will be expensive and increase the cost of CO_2 avoided. The high cost of CO_2 avoided prevents companies from investing in CCS. Without the economic and political incentives mentioned, CCS will likely be undeployed for most facilities. If no CO_2 is captured, there is no CO_2 to store, and thus the whole potential of a CCS industry in Norway diminish.

7. Conclusion

The purpose of this thesis has been to investigate whether there is a potential in Norway for CCS to become a new industry. The findings are primarily based on existing legislation, as well as a comprehensive literature study. This is complemented by extensive quantitative secondary data gathering to map large industrial emitters in Scandinavian.

The findings show that there are certain elements that facilitate for CCS deployment, while other elements are creating barriers that needs to be solved for CCS to become a new industry in Norway. The main reasons for CCS are Norway's climate goals and commitment to the Paris agreement, the offshore storage potential and the existing knowledge and technology towards CCS and offshore operations. There is also a potential for sub-industries as hydrogen production and EOR, which can enhance the profitability of CCS. The possibility of cooperation with Sweden and Denmark can enable CCS at a large scale and provide enough CO2 needed to drive the costs down through the economies of scale principle.

However, economic and responsibility-legislations in the EU Directive are currently creating barriers for carbon storage. These laws will have to be relaxed, and the responsibility needs to be shared between storage operators, government and insurance companies if the investment risk levels is to drop to an acceptable level. This is a technology that can help Norway to reach its climate goals, and thus the government should contribute to the development through risk-sharing and creating incentives for the industry. As much as companies needs incentives to invest in CCS, politicians need incentives to fund it. People's perception of CCS in Norway is currently low due to lack of knowledge and the failed attempt at Mongstad. Increased general knowledge of CCS and its importance for reaching the Paris agreement goals can act as a catalyst for investments and justify political support. The investment decision in 2020/2021 for the full-scale project will determine if CCS will become a priority in Norway, or if focus will be diverted to other mitigating solutions. Economically it will be expensive, but it is worth considering that it is regarded as the cheapest method of reaching the climate goals (SINTEF, 2018). With an adequate public-private partnership and financial incentives for industry players to invest in carbon capture and storage, CCS can become a new industry in Norway, create thousands of new jobs and contribute to the GHG-reductions needed to meet the Paris agreement.

Further Research

The focus of this thesis has been on the external framework that influence or have the potential to influence the CCS industry in Norway. The field of CCS spans much wider, but including all aspects in the thesis was difficult and we would limit the opportunity for us to provide detailed analysis of our focus areas. We have therefore concentrated on the elements we thought were most important and relevant for Norway in developing a CCS industry. A more in-depth approach towards some of the elements in the PESTEL analysis would most likely reveal information of importance, particularly related to technological and/or social factors and could be a master thesis alone.

As for the mapping of Scandinavian CO_2 sources, a comprehensive foundation is laid that can easily be updated with new, more detailed information. An idea is to continue to investigate relevant CO_2 sources and update with source-specific data as CO_2 concentration, number of CO_2 outlets and the respective magnitudes. By doing this, a more realistic cost estimation of each facility can be accomplished. All data in Appendix 1 can be manipulated and can potentially provide an accurate database for Scandinavian CCS costs.

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Appendix 1 – Scandinavian CO_2 Sources

See attached Excel file – “Scandinavian CO2 Sources”.

Appendix 2 - OGCI Workshop on Carbon Storage Risk and Liability

OGCI Workshop on Carbon Storage Risk and Liability – The Hague, 20 March 2019

The workshop brought together around 35 participants, including regulators from the Netherlands, Norway and the UK, insurers and project finance and industry players, with the aim of brainstorming how carbon storage risks and liabilities can best be managed – both now and once a commercial CCUS industry is up-and running.

We discussed four scenarios, focusing on offshore carbon storage risk in Europe:

1. Injected CO2 escapes the store and permeates the sub-surface
2. Leak of CO2 into the atmosphere with no immediate damage to human or animal life
3. Leak of CO2 into the atmosphere with damage to human or animal life
4. CO2 leakage during transport or temporary storage

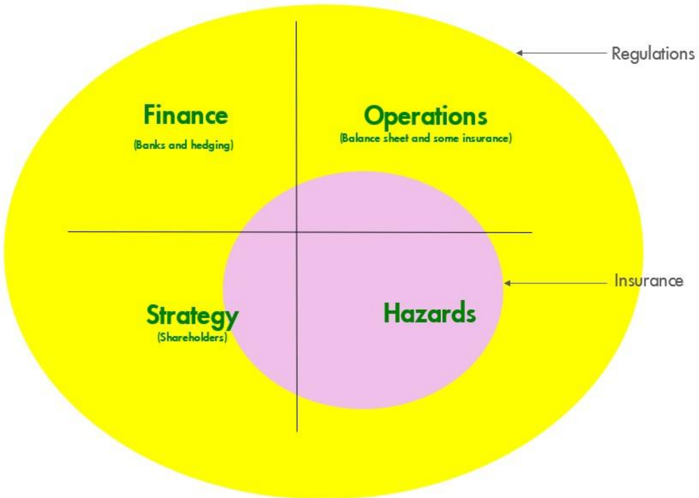
We explored how each of these scenarios could play out, focusing on impacts, who could make claims, how compensation might look and what wider implications there might be for governments, industry and public perception. We then looked at the suitability of current regulations and insurance products for managing risks and liabilities in each of the scenarios, and discussed what else is needed to get CCUS off the ground, and what might make sense once the industry is operating at scale.

<u>The current situation:</u>

The EU Carbon Storage Directive and national legislation regulates activity in storage and pipeline transport, but there are gaps and weaknesses. In particular, the EU directive treats CO2 storage more strictly than E&P operations and requires an onerous upfront financial security requirement that cannot currently be covered by insurance.

Insurance products exist that can address carbon injection, loss of containment and business interruption for third parties, but these are not sufficient to cover financial security and have limits, especially on term length. There is also too little data available to quantify risk well.

There is too little emphasis on managing risks through capital markets, shareholders and company processes. The insurance industry is good at covering hazards, but only touches on operational, strategic and financial risk. We discussed the importance of managing risks through balance sheets/company processes (operational risk), shareholders (strategic risk) and hedging (financial risk).



<u>What is needed to get a CCUS industry running at scale:</u>

- **Collaborate more**: this workshop is a good start, but more collaboration is needed between industrial players, project finance, insurance, regulators, capital markets
- **Adopt a CO2 mindset**: it is very useful to leverage current analogies with hydrocarbons, but be aware of the differences of dealing with this specific gas
- **Consider whether longer-term insurance policies are possible:** currently the maximum is three years which is too short to cover risks, but long-term policies are unlikely to be available
- **Quantify risk:** the lack of data makes risk quantification hugely difficult, especially on geological risk (requires 1-2 projects per reservoir)
- **Work on regulations and standards for transport (beyond pipelines) and transfer**: offshore storage will require transport, and although regulations exist already for pipelines, they will also be needed for trucking, shipping and transfer
- **Clarify what level of leakage is acceptable**: Currently zero leakage is permissible which makes risks extremely high. Is <1% acceptable, for example
- **Evolve storage regulations:** regulators to consider if financial security requirements can be relaxed after X projects

<u>Next steps:</u>

OGCI to look at ways to enable more dialogue about liabilities and risk management among these groups, possibly in smaller, country-based groups and involving capital markets players too.

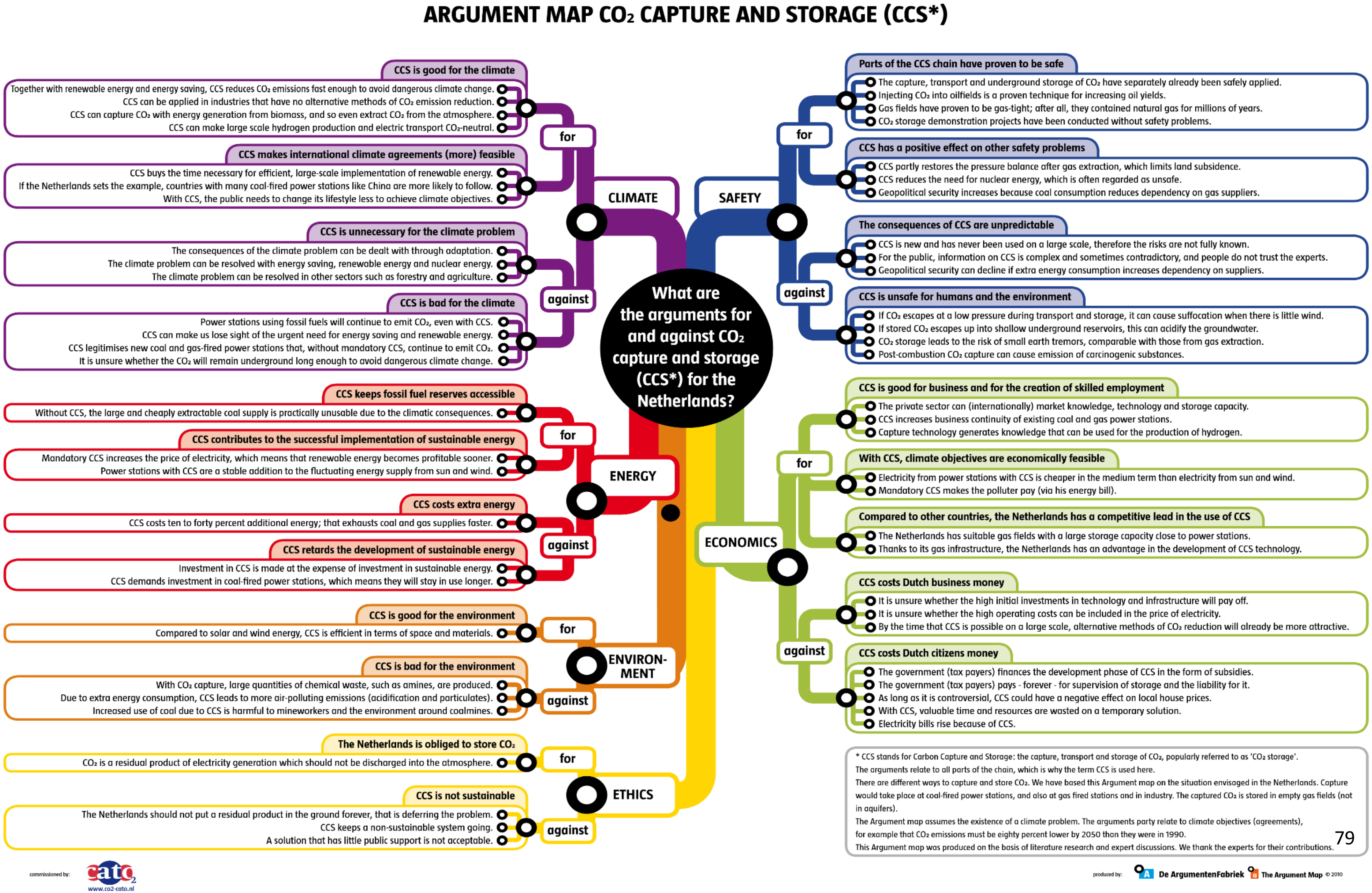
Operators to provide clarity on what is needed from regulations. Regulators are willing to look at regulations but ask operators to be clear on exactly what is needed from them, bearing in mind the important of public acceptance for them.

Insurers to explore more suitable policies and risk quantification with operators – and clearly establish the potential but also the limits to insurance in CO2 storage.

We look forward to hearing your feedback and thoughts on how you would like to take this dialogue further.

This summary was written by OGCI and does not necessarily reflect the views of all participants.

Appendix 3 – CCS Argument Map



Appendix 4 – Emails from Yara Porsgrunn and Norcem Brevik

Yara Porsgrunn mail [Date: 11.03.2019]

Hei

Yara Porsgrunn har en ammoniakkfabrikk i Porsgrunn.

Den benytter etan, propan og butan som hoved råstoff. Generering av CO_2 er helt avhengig av produksjonsnivået av flytende ammoniakk i fabrikken.

Antar man at fabrikken kjører for fult vil den generere ca. 1036 kt CO_2/år.

Denne CO_2-gassen vil komme ut via:

- Utslippspunkt 1: Røykgass, ca. 330 ktCO_2/år (ca. 10-15 vol % CO_2 i røykgassen)
- Leveranse produkt: CO_2 fanget, kondensert og levert som matvare kvalitet, 209 ktCO_2/år (renhet > 99,8 mol % CO_2)
- Utslippspunkt 2: CO_2-gass ventilert via pipe, ca. 282 kt CO_2/år (renhet ca. 8-10 vol % CO_2)
- Utslippspunkt 3: CO_2-gass ventilert til atmosfære via skorstein, ca. 215 kt CO_2/år (renhet 96-98 vol % CO_2)

Utslippspunktene 1,2 og 3 er på forskjellige geografiske punkter.

Det som er angitt som leveranse produkt er flytende CO_2 som blir levert via Praxair (nå Nippon) til det norske og skandinaviske marked. Dette er flytende CO_2 som blir levert til brusprodusenter, bryggeri etc.

Anlegget som lager matvarekvalitet CO_2 har ikke kapasitet til å kondensere mer enn ca. 200-220 kt CO_2/år.

Hadde dette anlegget hatt mer kapasitet, kunne det også ha kondensert mengden gitt i utslippspunkt 3.

Norcem Brevik mail [Date: 06.03.2019]

Hei

Som du sikkert kjenner til er vi midt i FEED-studien på CCS-anlegg for sementfabrikken i Brevik.

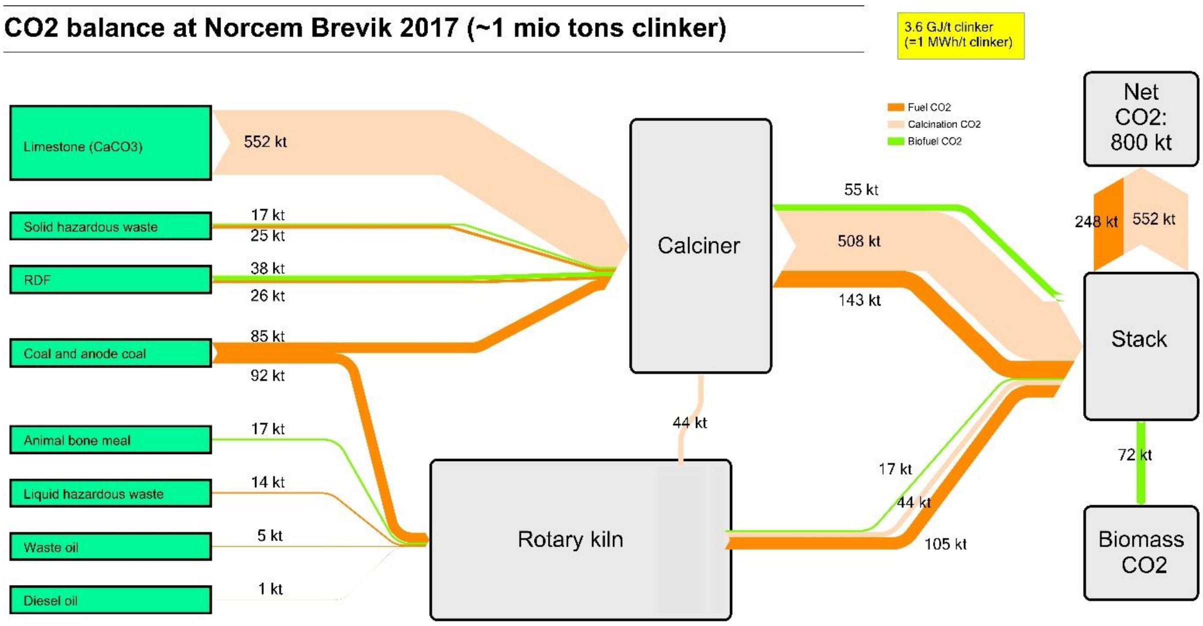
I tabellen under er tallene for røykgassen som inngår som design basis for CCS-prosjektet. Håper du finner svaret på det du trenger der (Utslippet er altså gjennom to parallelle strenger som i prinsippet er identiske):

Table 3: Preheater flue gas exit values recommended as design values for the Feasibility study:

Parameter	Unit	String 1	String 2
Preheater exit temperature	°C	386	386
Preheater exit pressure	mbarg	-80	-80
Preheater exit gas flow rate	Nm³/h	132 250	132 250
Preheater exit gas flow rate	t/h	182 410	182 410
Preheater exit N_2 concentration	vol%	61.42	61.42
Preheater exit CO_2 concentration	vol%	22.22	22.22
Preheater exit O_2 concentration	vol%	7.03	7.03
Preheater exit H_2O concentration	vol%	9.33	9.33
Preheater exit dust concentration	g/Nm³	50	50

[63]

Vedlegger også til informasjon et Sankey-diagram som sier noe om CO2-ens opprinnelse i prosessen



Appendix 5 - CCS as a new industry in Norway – Pros and Cons

CCS as a new industry in Norway