Norwegian School of Economics

Bergen, Spring 2021

Combatting Climate Change with Carbon Capture and Storage (CCS)

An exploratory study on the implementation of CCS in the Norwegian iron and steel sector.

Amanda Jennings and Victoria Hordvik

Supervisor: Stein Ivar Steinshamn

Master Thesis, Economics and Business Administration, Business Analysis and Performance Management and Energy, Natural Resources and the Environment

NORWEGIAN SCHOOL OF ECONOMICS

Acknowledgements

This thesis is written as a part of our MSc in Economics and Business Administration, with majors in *Business Analysis and Performance Management* and *Energy, Natural Resources and the Environment*, at the Norwegian School of Economics (NHH). This thesis is written in the Spring of 2021.

First of all, we would like to offer our warmest gratitude to our supervisor, Stein Ivar Steinshamn, for his guidance and constant support throughout the course of the semester. We appreciate the help and encouragement you have given us, and do not believe we would have been able to produce the same result without your supervision. Second, we would like to thank Torleif Madsen at Compact Carbon Capture for valuable and candid advice given to us when first forming our thesis topic. We would also like to thank Endrava, for giving us extraordinary access to their database Capture Map, allowing us to access information about emission sites in Norway. Finally, we would like to thank our families, for unconditional support during the more hectic hours. This has been a challenging and rewarding process, and we are proud what we have achieved.

Norwegian School of Economics

Spring 2021

Amanda Jennings

Victoria Hordvik

Abstract

Today, Carbon Capture and Storage (CCS) is considered by many as the most credible and cost-effective method of combatting global warming and meeting the climate change targets. Despite this, CCS remains a novel technology within the Norwegian iron and steel sector. Thus, the aim of this thesis is to analyse the macroenvironment surrounding CCS for this sector. This is done to understand how well the Norwegian iron and steel sector is suited for CCS implementation, and to what extent government policies are necessary in order to accelerate development and deployment of the technology. The research questions are answered using a combination of the PESTEL framework and environmental economic policies.

PESTEL allows for the identification of opportunities and barriers in the market. The results from this analysis reveal that the Norwegian Government shows a high degree of commitment to CCS through specific projects and funding. However, as the cost of CCS exceeds the cost of carbon set by the EU ETS, CCS is not currently an economically viable abatement technology for the iron and steel case facilities. For this reason, government policies are necessary to boost development and deployment during a ramp up stage, until the cost of CCS falls or the price of carbon rises.

While it is clear that government involvement is required, which policies are most effective is less obvious. Yet, based on the PESTEL findings, it appears that policy attention should be directed towards decentralised and incentive-based policies instead of command-and-control policies. Furthermore, policies should not be implemented in isolation. Instead, a combination of policies is necessary to achieve the desired goals.

Keywords: *CCS, EU ETS, CO_2 Avoidance Cost, Price of Carbon, Environmental Policies*

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BECCS: Bioenergy with Carbon Capture and Storage

BF: Blast Furnace

BFG: Blast Furnace Gas

BOF: Blast Oxygen Furnace

CAPEX: Capital Expenditure

CC: Carbon Capture

CCS: Carbon Capture and Storage

CCUS: Carbon Capture, Utilisation and Storage

CO: Carbon Monoxide

CO_2: Carbon Dioxide

DACS: Direct Air Capture and Sequestration

ECCSEL: European CCS Research Infrastructure

EEA: European Economic Area

EOR: Enhanced Oil Recovery

EU ETS: European Union Emissions Trading System

EU: European Union

EUA: EU Allowance

FME: Centres for Environment-friendly Energy Research

GHG: Greenhouse Gas

H_2: Hydrogen

IEA: International Energy Agency

IPCC: International Panel on Climate Change

LB: Lower Bound

MAC: Marginal Abatement Cost

MSR: Market Stability Reserve

N_2: Nitrogen

NACE: European Classification of Economic Activities

NCCS: Norwegian CCS Research Centre

NCS: Norwegian Continental Shelf

NDC: Nationally Determined Contributions

OPEX: Operating Expenditure

R&D: Research and Development

t: Tonne

TCM: Technology Centre Mongstad

TGR-BF: Top Gas Recycling Blast Furnace

TRL: Technology Readiness Level

UB: Upper Bound

UNFCCC: United Nations Framework Convention on Climate Change

WGS: Water-Gas Shift Reaction

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) (2018) has recognised carbon capture and storage (CCS) to be a technological necessity in keeping down global temperatures. Climate change is one of the most pressing issues the world is currently faced with. Greenhouse gas (GHG) emissions from human activity have led to global warming of approximately 1°C above pre-industrial levels (IPCC, 2018). On this trajectory, global temperatures are predicted to increase at a rate which will result in a 1.5°C increase between 2030 and 2052. This could cause irreversible damage to the world as it is known today (IPCC, 2018). To prevent global warming of above 1.5°C, GHG emissions must be reduced by 40-50% on a global scale by 2030, and must be net zero by 2050 (Prosess21, 2021).

The Norwegian Government is currently dedicating vast amounts of resources towards reaching international climate targets, such as the Paris Agreement, and CCS has become a central point of interest. Likewise, the Norwegian process industry is taking note of the measures that need to be implemented in order to stay relevant in a low-carbon society. This has resulted in increased interest in CCS solutions through debates, research and investments (Prosess21, 2021). Although CCS has been utilised for several decades, there are still challenges connected to the feasibility and scalability of CCS. This is mainly a consequence of technical, commercial and economic challenges (Bui, et al., 2018), which need to be resolved for CCS to be fully successful. These challenges are a central part of this thesis. To explore the phenomenon of CCS and the issues related to its development in a case-specific study, two research questions will be answered. The first research question is:

To what extent does the economic and political environment support the implementation of CCS in the Norwegian iron and steel sector?

This research question allows for a broad analysis of the Norwegian CCS macroenvironment through the identification of barriers and opportunities in the iron and steel sector. These findings will then be used as a foundation to answer the second research question:

To what extent are government policies necessary in order to accelerate the development and deployment of CCS in the Norwegian iron and steel sector?

Findings from the analysis will be supplemented by theory to develop policies that aim to accelerate CCS development and deployment, as a measure to meet the required goals to prevent global warming of more than 1.5°C.

1.1. MOTIVATION FOR TOPIC

In a press release on September 21st 2020, the Norwegian Government proclaimed its commitment towards CCS research and deployment, through a project named Longship. The Government will assist the development of full-scale infrastructure required for CCS; capture technology, transport methods and storage facilities. The goal is to provide cost-effective solutions for full-scale CCS in Norway, with the assumption of technological dissemination onto international markets (Government, 2020). This project focuses on capture of CO_2 from two facilities only: Fortum Oslo's waste management plant and Norcem's cement plant. As such, the preliminary studies conducted for this project have largely been on cement and waste management. This has produced a gap in research towards other CO_2-emitting industries in Norway, who may also benefit from the Longship project in terms of technological advancements or transport and storage.

All industries need to reduce CO_2 emissions to reach climate goals (Størset, Tangen, Wolfgang, & Sand, 2018; Prosess21, 2021). It is therefore important to study sectors beyond cement and waste management in order to conclude whether deployment of CCS is feasible, and how policies must be developed to support CCS deployment. This study's aim is therefore to provide empirical evidence for the *Norwegian iron and steel sector* in order to evaluate CCS implementation through broad data collection and analysis. This is important for the iron and steel industry as it provides an analysis of different macroeconomic factors that can impact future investment decisions in CCS abatement technology. Likewise, it may provide guidance for policymakers on how to formulate future policies regarding CCS.

1.2. CONSTRAINTS AND ASSUMPTIONS

Due to time and resource constraints, as well as achieving an appropriate balance between depth and breadth, the authors chose to limit the scope of the thesis. The analysis and discussion will focus on CCS within the iron and steel sector in the Norwegian process industry to enable more case-specific and applicable analysis and conclusions. This entails focusing exclusively on CCS as a viable solution for the iron and steel sector to comply with environmental goals. Additionally, this study focuses on emission sites in the iron and steel sector that exceed emissions of 100,000 tonnes of CO_2 per annum, in order to provide insight into the largest emitters within this sector.

This study assumes Norwegian iron and steel to be an important and relevant sector to analyse in connection with CCS related abetment technology. The justification for this is that although the Norwegian iron and steel sector is small compared to international players, it remains an essential market by which demand is predicted to increase (Norsk Industri, 2016). Likewise, all industry sectors will need to reduce emissions, independent of size, to meet climate change mitigation targets.

1.3. THESIS STRUCTURE

Thus far, the thesis has introduced the research questions and motivation for this topic. Chapter 2 proceeds by presenting relevant background information and literature review. This is followed by an overview of the theoretical frameworks selected for this study in Chapter 3. Chapter 4 elaborates on the utilised methodology. A macroeconomic analysis of CCS in Norwegian iron and steel is then conducted in Chapter 5, where opportunities and barriers linked to CCS are uncovered. Based on Chapter 5, Chapter 6 analyses to what extent government policies can encourage the acceleration of CCS in Norwegian iron and steel. With this, Chapter 7 discusses these results and provides a detailed evaluation of possible policies. Chapter 8 concludes by emphasising the main findings from this study. Finally, Chapter 9 considers limitations to this study and areas for further research.

2. Background and Literature Review

This chapter presents insight into the Norwegian process industry and introduces the focus area of iron and steel as an appropriate industry case study. This provides the reader with a foundation for understanding the challenges iron and steel is facing in order to conform to low-carbon production. Furthermore, relevant research and literature is provided on CCS, and policies which are of relevance for the analysis in Chapter 5.

2.1. NORWEGIAN PROCESS INDUSTRY

Globally, the process industry accounts for approximately 32% of total emissions (Prosess21, 2021). In Norway, the process industry is responsible for approximately 23% (11.5 million tonnes) of the total 50 million tonnes of CO_2-equivalent[1] emitted (Prosess21, 2021). Relative to other nations, Norwegian industry has a comparative advantage in terms of having a small carbon footprint, as 98% of all electricity is generated by renewable energy sources (Government.no, 2016). Hydropower is the main contributor to this, and is also the primary source of energy in Norwegian process industry (Norsk Industri, 2016). Consequently, the process industry uses clean power in its energy-intensive production processes. It is the process-related emissions that arise from the manufacturing itself that contribute to a substantial share of the industry's CO_2 emissions (Normann, Skagestad, Bierman, Wolf, & Mathisen, 2019). Such process-emissions are difficult to address with simple actions such as improved production efficiency (IEA, 2016; Normann, Skagestad, Bierman, Wolf, & Mathisen, 2019). For this reason, technology such as CCS is required to maintain production levels and meet demand, whilst simultaneously upholding the social and regulatory requirements related to transitioning into a low-emission society (Norsk Industri, 2016). This makes CCS within the Norwegian process industry an interesting and challenging topic.

[1] CO_2-equivalent is a measure used to compare the emissions from various GHG based on their global warming potential (OECD, 2013).

The process industry involves several different activities. This thesis follows Statistics Norway's standard for industry grouping (SN 2007) to define what sectors make up the Norwegian process industry (Statistics Norway, 2016). The basis for this standard is the EU statistical categorisation of economic activity (NACE rev. 2). The main sectors that fall under the NACE code for process industries are: pulp and paper, refineries, chemical production including mineral fertilizers, non-metallic minerals including cement, lime and plaster, non-ferrous metals including aluminium, iron, steel and ferroalloys.

There are 29 facilities in Norway with annual emissions of above 100,000 tonnes of CO_2 that derive from the process industry. These have been identified and each emission site is depicted in Figure 1. For a more detailed overview of each emission site see Appendix A.

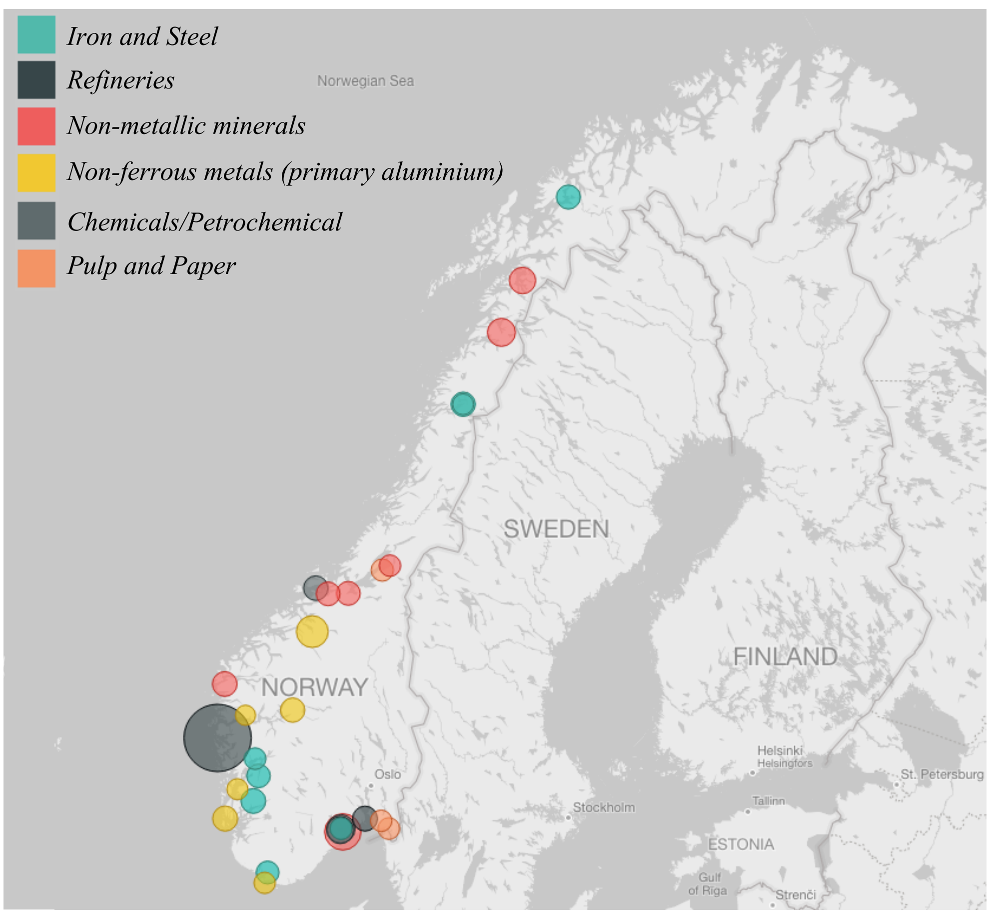

Figure 1: *Norwegian Process Industry. Source: (Endrava, 2021)*

The Norwegian processes industry is dispersed throughout the country. It employs approximately 25,000 people and has a turnover of NOK 200 billion (Prosess21, 2021). These sectors are of great national importance, and largely contribute to Norwegian export revenues, consumption and maintained value of hydropower energy, development of competence and the establishment of business clusters (Norsk Industri, 2016). All sectors supply material and products that are critical for complex, global value chains before reaching the end user (Prosess21, 2021).

Since 1990, the process industry in Norway has reduced its emissions by 41%, while the value created by the industry has increased (Prosess21, 2021). This indicates that emission reductions investments have been prioritised and overall efficiency has increased. Yet, the industry still lacks extensive measures to align with climate goals. For the process industry to remain competitive and relevant within a low-emission society, and still continue to increase export revenue over time, the production process is dependent on a significantly reduced CO_2 footprint (Prosess21, 2021).

CCS is recognised by many researchers and industry experts as today's most cost-effective method of reaching CO_2 mitigation goals and reducing global warming (Bui, et al., 2018; IPCC, 2018; Global CCS Institute, 2020). It is worth noting that other sources have opposing opinions and argue against its effectiveness, which is further discussed in section *5.4.3. Social Acceptance.* Nevertheless, the majority of research clearly suggests that CCS is the only technology currently capable of fully decarbonising the process industry (Norwegian Government, 2017; Global CCS Institute, 2018). This justifies the choice of CCS technology as the central CO_2 mitigating technology for this study. Thus, other technologies will not be commented on.

Despite years of ongoing research, the technology readiness level (TRL)[2] for many CCS solutions is still novel. There is no universally available CCS technology that is applicable across industries, and as such, each industry sector and facility require custom technology to reach its full potential

[2] TRL is a universal measurement system for assessing a technology's maturity level (Tzinis , 2021).

of CCS (Anantharaman & Seljeskog, 2011). Due to the scope of site-specific considerations associated with CCS, *one* sector is chosen as an industry case study, explicitly *iron and steel*.

2.1.1. Process Industry Case Study: Iron and Steel

Global industrial processes are dominated by iron and steel. Iron is at present the most produced metal, and is expected to continue to be an important building block in production of roads, infrastructure, cars, and more (Andresen & Gade, 2017). However, iron and steel is a small sector in Norway, and has therefore not been at the forefront of previous CCS feasibility studies. Nonetheless, as it is the goal of the Norwegian process industry to achieve net zero emissions by 2050 (Størset, Tangen, Wolfgang, & Sand, 2018), the iron and steel sector will need to need to reduce its emissions. If this is not possible to achieve through technologies such as CCS, the alternative is for facilities to shut down or change locations. This is a fundamental economic and environmental problem as it may lead to factories closing down in societies that depend on that industry, or carbon leakage as a result of production being transferred to countries with laxer environmental restrictions (Field & Field, 2017). This is not a desired outcome for Norwegian iron and steel, and as so it is assumed that Norway intends to continue with its current iron and steel production.

2.1.2. Norwegian Iron and Steel Sector

The following section will provide additional information on the case facilities and specific iron and steel processes. Throughout this thesis, the Norwegian iron and steel sector is presumed to compose of the facilities depicted in Figure 2 and Table 1 below.

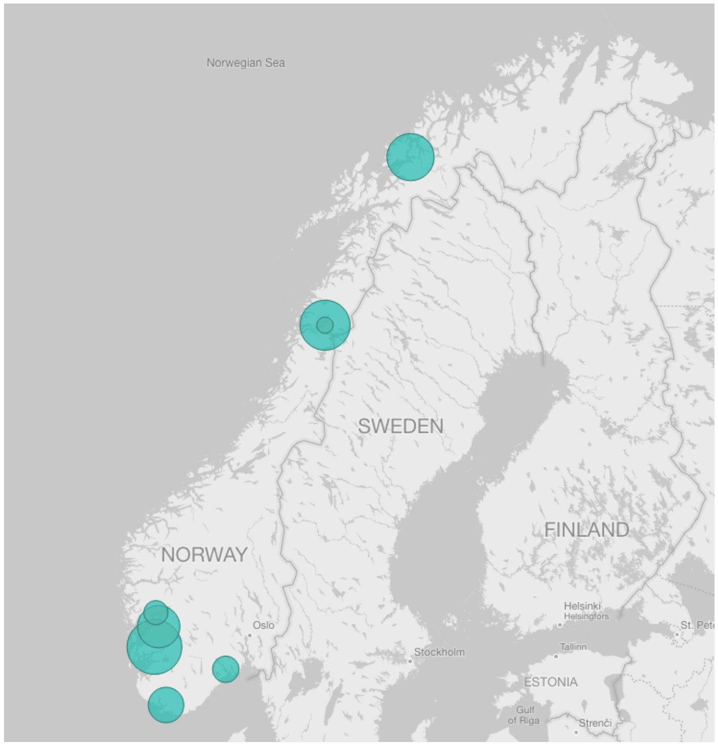

Figure 2: *Emission Sites in the Norwegian Iron and Steel Sector. Source: (Endrava, 2021)*

Table 1: *List of Norwegian Iron and Steel Facilities. Source: (Endrava, 2021)*

Emission Site	Sum of CO_2 2017 [t]	Estimated Capture Rate (LB)	Estimated Capture Rate (UB)	Distance to port (km)	Sailing distance to terminal (km)
Ferroglobe Mangan Norge AS	137,000	35%	80%	2	900
ELKEM ASA AVD BJØLVEFOSSEN	174,000	35%	80%	0	189
Eramet Norway AS, Porsgrunn	185,000	35%	80%	3	606
Eramet Norway Kvinesdal	228,000	35%	80%	0	410
TiZir Titanium & Iron AS	261,000	35%	80%	0	209
Finnfjord	284,000	35%	80%	0	1362
Elkem Rana AS	298,000	35%	80%	2	900
ERAMET NORWAY AS, Sauda	320,000	35%	80%	0	279
Sector	1,887,000	35%	80%	-	-

As seen in Table 1 above, each facility in the iron and steel sector had emissions between 140,000 – 320,000 tCO_2 in 2017. If facilities were equipped with carbon capture technology, it is assumed that each facility would have a lower bound (LB) capture rate of 35% and an upper bound (UB) capture rate of 80% of total released emissions (Endrava, 2021). All the facilities are located close to the coast, and the majority are located in Southern Norway. The sailing distance to CO_2 storage facilities can be studied using this information, which will be discussed later (see section *5.1.3. Suppliers of Transport and Storage*). In total, the facilities released 1,887,000 tCO_2 in 2017, which accounted for 17.39% of total emissions in the process industry[3] (see Appendix B, Table B.1). This implies that although the number of facilities is small, the contribution of industrial emissions is significant.

As previously stated, CO_2 emissions released from production are primarily due to the manufacturing process (Wiley, Ho, & Bustamante, 2011; Bui, et al., 2018), as well as indirectly through the use of electricity (Ho, Allinson, & Wiley, 2010). The processes involved in iron and steel production are further explained below.

Iron and Steelmaking Process

There are two main methods used to produce steel. These are based on either air-blown blast furnace or blast oxygen furnace (BF/BOF), or an electric arc furnace (EAF) (Norsk Stål AS, 2020). The difference between these methods is that BF/BOF rely on the use of iron ore, limestone and coke (a fuel made from coal), while EAF mainly uses electricity and scrap steel or metal (Norsk Stål AS, 2020). As Norwegian electricity comes from renewable hydropower, the thesis' focus is directed towards production processes that are more CO_2 intense; the blast furnace and blast oxygen furnace.

Most of global steel production is made by pig iron (Kuramochi, Ramírez, Turkenburg, & Faaij, 2011) through two main processes. First, pig iron is produced in the blast furnace by smelting iron ore with coke and limestone (IIMA, n.d.). The raw materials are added to the top of the blast furnace, and react with heated air blown in from the bottom (IIMA, n.d.). Second, the pig iron is

[3] "Total emissions in the process industry" refers to the total emissions from large emission sources, defined as >100,000 tonnes CO_2/year, and not total emissions in the process industry as a whole.

converted into crude steel in the blast oxygen furnace (Kuramochi, Ramírez, Turkenburg, & Faaij, 2011).

These two processes are the main sources of CO_2 emissions from steel production (Ho, Allinson, & Wiley, 2010). The production of pig iron also releases an off-gas known as blast furnace gas (BFG), which is a combination of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2) and nitrogen (N_2) (IIMA, n.d.). BFG contains about 25% CO_2 (see Appendix B, Table B.2), and is partly used in other processes around the iron and steelmaking plant. Studies have been conducted on how to apply carbon capture technology to remove CO_2 from the BFG, which will be discussed further in section *5.1.1. Capture Technologies.*

2.2. TECHNICAL EXPLANATION OF CCS

Carbon capture and storage is a complex, integrated process consisting of three distinct components: carbon capture, transport and storage (Rochon, et al., 2008). These three components are explained in greater detail below.

2.2.1. Capture

Depending on the CO_2 concentration and type of facility, there are traditionally three main systems for capturing CO_2 that are used in practice: pre-combustion, post-combustion and oxyfuel-combustion.

Pre-Combustion Carbon Capture

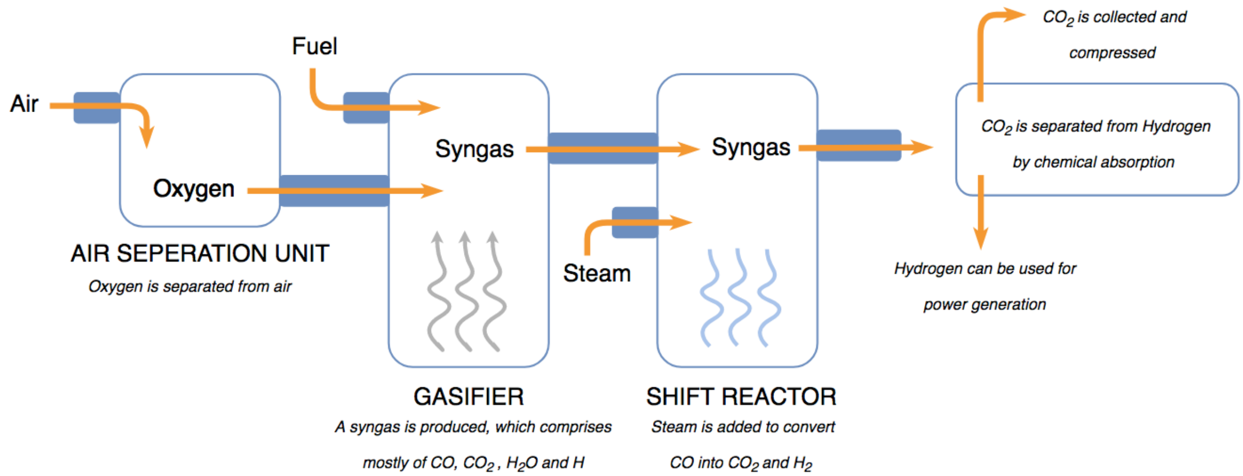

Figure 3: *Pre-Combustion Carbon Capture. Adapted from: (Chen, Vizzaccaro, Spagakos, & Loizou, 2018)*

Pre-combustion captures CO_2 prior to combustion. This is achieved through gasification. The oxygen necessary for the gasification process is generated in an air separation unit (WorleyParsons Services Pty Ltd, 2009), which is then injected into a gasifier to react with fossil fuels. This results in the production of a synthesis gas (syngas), which is composed of CO and H_2 (Rochon, et al., 2008). The CO then reacts with added steam in a catalytic reactor, which gives CO_2 and more H_2 (IPCC, 2005). Finally, the resulting CO_2 can be captured from a relatively pure exhaust stream using a physical or chemical absorption process (IPCC, 2005). The CO_2 is then dehydrated and compressed to supercritical conditions for future transport (WorleyParsons Services Pty Ltd, 2009). A by-product of this separation process is H_2, which can be used for a range of purposes, such as power generation in boilers, furnaces, gas turbines, engines and fuel cells (IPCC, 2005).

This approach produces BFG that has a higher CO_2 concentration (15 – 50%) than what is produced through post-combustion (Office of Fossil Energy, n.d.). This makes it easier and less costly to capture. A drawback of this approach is that it can only be applied to power plants and limited industrial plants. In addition, is cannot be retrofitted to existing plants, but has to be built simultaneously with the facility.

Post-Combustion Carbon Capture

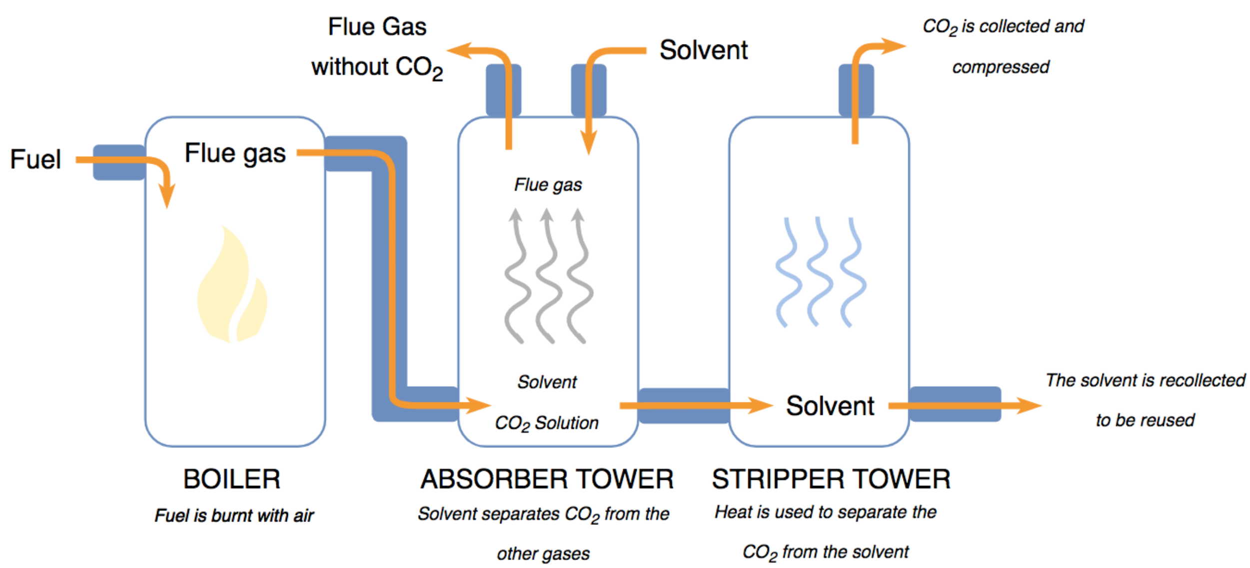

Figure 4: *Post-Combustion Carbon Capture. Adapted from: (Chen, Vizzaccaro, Spagakos, & Loizou, 2018)*

Post-combustion capture refers to the capture of CO_2 from the flue gases produced by the combustion of fossil fuels (IPCC, 2005). It therefore involves the capture of CO_2 *after* combustion. Fuel is injected into a boiler where combustion takes place. This produces an exhaust gas containing mostly CO_2, N_2, water vapour and oxygen, which is passed into an absorption tank (WorleyParsons Services Pty Ltd, 2009). A chemical sorbent process is then commonly used for CO_2 separation (IPCC, 2005). This reacts with the CO_2 contained in the flue gas (IPCC, 2005). The solvent containing CO_2 is then passed into another vessel, where conditions are changed in such a way that the solvent once again releases the CO_2. This separation can either be achieved through heating or a pressure decrease (IPCC, 2005). The solvent is reused in the step before (IPCC, 2005), while the CO_2 is cooled, dried and compressed for transport (Rochon, et al., 2008).

Today, this is the most diffused technology (Rochon, et al., 2008), as the technologies are suitable for retrofit application (WorleyParsons Services Pty Ltd, 2009). However, the CO_2 concentration from the flue gas streams is lower than with pre-combustion, at around 5 – 15% (Office of Fossil

Energy, n.d.). Relatively high solvent degradation rates also contribute to large equipment sizes, high solvent consumption and significant energy losses (WorleyParsons Services Pty Ltd, 2009). Identifying solvents with higher CO_2 absorption capabilities or higher degradation abilities would therefore reduce the capital and operating costs associated with this technology (WorleyParsons Services Pty Ltd, 2009).

Oxy-fuel Combustion Carbon Capture

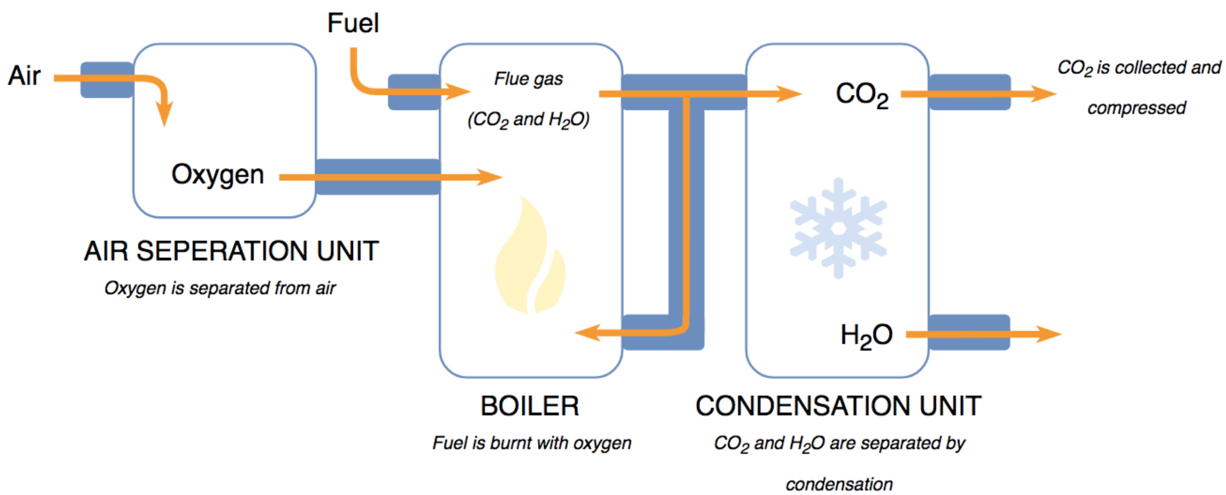

Figure 5: *Oxy-fuel Combustion Carbon Capture. Adapted from: (Chen, Vizzaccaro, Spagakos, & Loizou, 2018)*

Oxy-fuel combustion burns fossil fuels in a nearly pure oxygen-enriched gas mixture, instead of air (IPCC, 2005). The oxygen used is separated from other air components in an air separation unit, using techniques such as low temperature (cryogenic) air separation, membranes or chemical looping cycles (IPCC, 2005). The oxygen and fuel are then passed into an oxygen combustion boiler system, which generates a flue gas consisting of mainly water vapour and a high CO_2 concentration (WorleyParsons Services Pty Ltd, 2009). The CO_2 concentrations produced can exceed as much as 80% (Rochon, et al., 2008). Excess heat is also generated which can be used for various purposes, including power generation. The temperature in the oxygen combustion boiler system is very high, but the H_2O and CO_2 rich flue gas can be recycled back into the boiler to control this (IPCC, 2005). The flue gas is then passed into a condensation unit. The water vapour is condensed through cooling techniques, allowing the remaining CO_2 to be easily captured from the exhaust steam (WorleyParsons Services Pty Ltd, 2009; Norsk Industri, 2016). Once the water vapour is condensed, the CO_2 enters a capture and compression unit, where the CO_2 is collected and compressed for further transport to storage.

A benefit is that oxy-fuel combustion systems can be applied to both power plants and industrial sites (IPCC, 2005), however, there are no commercial applications as of today. A drawback of this approach is that the air separation unit has a very high power consumption, and therefore increases the site's levelized cost of energy (WorleyParsons Services Pty Ltd, 2009). This makes the process capital intensive, and it is therefore dependent on a low cost of producing oxygen (Rochon, et al., 2008).

2.2.2. Transport

Once the carbon has been captured and compressed, it needs to be transported to a suitable storage location. The most common options for transport include pipelines, ships, rail and road transport (Rochon, et al., 2008). What is most efficient depends on the location of emission sources. Pipelines are for instance currently used in the US, while no such infrastructure is available in Europe (Rochon, et al., 2008). Norway has some experience with CO_2 transport by ship as volumes of CO_2 are being transported by ship as a part of routine operations in the food industry (Norwegian Ministry of Petroleum and Energy, 2020).

2.2.3. Storage

The final stage of the CCS process is storage. This refers to the long-term isolation of CO_2 from the atmosphere (Rochon, et al., 2008). According to the Global CCS Institute (2020), geological storage resources for CO_2 appear more than sufficient to meet global requirements under any net-zero emissions scenario. Any formations that are sufficiently large and deeper than 800 meters, with adequate porosity and permeability, are potential storage sites if other impermeable rock formations prevent CO_2 from escaping (Global CCS Institute, 2020). CO_2 is then injected into these deep geological formations using technologies that have been used by the oil and gas industry (IPCC, 2005).

According to the Geological Survey of Norway, geological mapping reveals that Norway does not have suitable underground geological formations on land (Norwegian Ministry of Petroleum and Energy, 2020). It is therefore only possible to store CO_2 under the seabed on the Norwegian continental shelf (NCS) (Norwegian Ministry of Petroleum and Energy, 2020). Researchers estimate that 16,000 million tonnes CO_2 can potentially be stored here (Global CCS Institute, 2020). Norway thereby has the third largest geographical CO_2 storage potential worldwide, after the US and Australia with 205,000 and 16,600 million tonnes CO_2 storage capacity, respectively (Global CCS Institute, 2020).

2.3. CLIMATE POLICIES AND CLIMATE AGREEMENTS

2.3.1. EU Emissions Trading System (EU ETS)

The European Union Emissions Trading System (EU ETS) is the world's first and largest carbon trading market, operating in all EU countries including Iceland, Liechtenstein and Norway (EEA) (European Commission, 2020). The EU ETS covers CO_2 emissions from energy-intensive industry sectors such as iron and steel (European Commission, 2020).

The EU ETS is essentially a *cap-and-trade* system for emission allowances (European Commission, 2015). The EU sets a *cap* on the number of emission allowances (permits) in circulation, whereby permits may be *traded* amongst permit holders (European Commission, 2020). An emission allowance gives the holder permission to emit one tonne of CO_2.

The number of emission allowances allotted to an individual firm varies. At the end of each year, a facility must submit enough allowances to cover its level of emissions, as failure to do so results in sanctions and heavy fines (European Commission, 2020).

A finite number of allowances ensures that emissions attain sufficient monetary value. Likewise, economic incentives are created when the trading of allowances is endorsed. Through trade, market forces result in a flow of allowances away from facilities who abate at lower costs, and towards facilities who abate at higher cost. This forms a system where facilities will decide to reduce emissions when the cost of abatement is less than the cost of purchasing additional allowances. A robust carbon price therefore encourages investments in clean, low-carbon technologies (European Commission, 2020).

As of 2021, the EU ETS is currently within the initial stage of Phase 4 (2021 – 2030), which is the most aggressive phase since Phase 1 in 2005 (European Commission, 2020). Phase 4 aims to be an investment driver for industries by increasing the pace of the annual linear reduction factor[4] from 1.74% to 2.2%. (European Commission, 2020). This results in fewer emission allowances on the market, which will likely increase the price of emission allowances.

The effectiveness of the EU ETS has been criticised for failing to meet its goals, especially in Phase 1 and 2. This is due to long-term over-allocation of permits and volatile prices (Muuls, Colmer, Martin, & Wagner, 2016). To fight this, the Market Stability Reserve (MSR) was established in 2015 and introduced to the market in 2019, to maintain balance within the EU ETS. The aim is to stabilise the carbon price by extracting allowances from the market when there is a surplus, and injecting allowances into the market if (1) the allowance surplus drops beyond a certain point or (2) the price of allowances increases beyond a certain point for a consecutive period of time (European Commission, 2015).

[4] The annual linear reduction factor is the rate at which the emissions cap is decreased (European Commission, 2015).

2.3.2. Paris Agreement

The Paris Agreement is a legally binding international treaty on climate change, where the goal is to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels (United Nations, 2015; UNFCCC Secretariat, 2021). As a part of this agreement, member countries have to submit mandatory plans for climate action by 2020. These plans are known as nationally determined contributions (NDC's) which are submitted every fifth year to the UNFCCC secretariat. These plans will specify the actions each respective country will take to reduce their GHG emissions to reach the goals of the Paris Agreement and climate neutrality by the mid-century (UNFCCC Secretariat, 2021).

Norway's NDC report, submitted on the 7th of February 2020, updated and enhanced its national contributions to reduce emissions by at least 50%, and towards 55%, by 2030 compared to 1990 levels (Ministry of Climate and Environment, 2020). Norway has clear and ambitious climate goals, and many Norwegian standards and goals are more aggressive than other nations.

2.4. END OF CHAPTER 2

Chapter 2 has presented substantial background information regarding CCS and the iron and steel sector. With this, a short summary is included to clearly highlight the main points thus far.

Section	Main Points
Norwegian Process Industry	○ Thesis focus on emission sites with > 100,000 tCO_2/annum. ○ 29 facilities in the process industry. ○ 8 case facilities within the iron and steel sector. ○ Two main sources of CO_2 emissions in the iron and steel production process: blast furnace and blast oxygen furnace. ○ Facilities installed with carbon capture are assumed to have a LB capture rate of 35%, and an UB capture rate of 80%.
Technical Explanation of CCS	○ Pre-combustion carbon capture is capture *before* the combustion process. Cannot be retrofitted to existing facilities. ○ Post-combustion carbon capture is capture of flue gas *after* the combustion process. Can be retrofitted to existing facilities. ○ Oxy-fuel combustion carbon capture uses pure oxygen instead of air in the combustion process, which increases the CO_2 concentration in the flue gas. Can be retrofitted to existing facilities. ○ Norway has experience with CO_2 transportation by ship. ○ CO_2 can be stored under the seabed on the Norwegian continental shelf.
Climate Policies and Climate Agreements	○ The EU ETS allows facilities to buy and sell emission permits. ○ Facilities need to submit enough permits to cover their level of emissions. ○ The Paris Agreement defines 2°C (preferably 1.5°C) as the climate change goal. Norway is bound by this agreement and needs to submit a NDC outlining climate actions. ○ Norway has ambitious climate goals.

3. Theoretical Frameworks

This chapter will present the theoretical frameworks that will be used to study the research questions. First, the PESTEL framework will be reviewed, highlighting its appropriateness for this research. Second, theory on pollution control and environmental policies are presented, which will be used for studying developments for CCS in the iron and steel industry.

3.1. PESTEL

The PESTEL framework is chosen because it allows for a broad analysis of an industry, through studying the macroenvironment by which said industry is surrounded. The six macroenvironmental factors comprise of *Political*, *Economic*, *Social*, *Technological*, *Environmental* and *Legal*, and include both market and non-market aspects of strategy (Johnson, Whittington, Scholes, Angwin, & Regner, 2018).

PESTEL allows for analysis of factors that are indirectly associated with the industry by studying outside drivers that may have direct implications on the industry (Johnson et al., 2018). Studying a phenomenon through PESTEL can unveil underlying market prospects by determining key drivers of change (Johnson et al., 2018). The key drivers of change refer to the opportunities and threats that may assist or obstruct the implementation of CCS in the Norwegian iron and steel sector. As such, the framework provides a systematic study with a detailed and deep contextual understanding of the opportunities and barriers of CCS in Norwegian iron and steel.

As such, the PESTEL analysis will provide a thorough analysis for the first research question:

To what extent does the economic and political environment support the implementation of CCS in the Norwegian iron and steel sector?

PESTEL is traditionally applied to strategic analyses for corporations (Johnson et al., 2018). However, this framework has been adapted for this research to apply to study the potential of CCS within the Norwegian iron and steel sector. In addition, the order of the PESTEL factors discussed in the analysis is changed to TEPSEL. This is done because the authors feel it provides a better foundation to review the technology first.

Technological identifies the technology currently available (Johnson et al., 2018). Technological drivers of change include current suppliers of carbon capture technology, transport and storage on the Norwegian market today.

The *Economic* factor mainly studies traditional macroeconomic drivers (Johnson et al., 2018). The analysis will discuss costs associated with the implementation of CCS using case-specific calculations for the iron and steel sector. This section also discusses environmental economics and the trade-off that exists between cost of CO_2 abatement and the price of CO_2.

The *Political* factor considers the degree to which government intervention is visible in a certain market by studying the role of the state (Johnson et al., 2018). This factor will focus on drivers such as Norwegian and international policy actions that either support or oppose CCS deployment.

Social factors refer to cultures and demographics (Johnson et al., 2018). This section will investigate the end user's willingness to pay for carbon-free emissions and the social acceptance surrounding CCS. Additionally, this section explores how human capital and business ecosystems may influence deployment of CCS.

The *Environmental* factor studies environmental issues (Johnson et al., 2018). It will analyse the environmental risks and uncertainty associated with CCS, and the risks that may arise if CCS fails to be implemented.

Finally, *Legal* analyses existing legislative and regulatory frameworks (Johnson et al., 2018). The analysis will comprise of legal forces that build, support or limit CCS.

It is important to note that although the discussion is divided into separate factors, each factor is not independent of the others. For simplicity, the authors of this thesis will treat each factor separately, and discuss each driver of change under the PESTEL factor deemed most appropriate. The drivers of change included in the analysis do not represent the limit of possible discussion points. The results gathered from the PESTEL analysis will provide a solid foundation to discuss the second research question.

3.2. POLLUTION CONTROL: A GENERAL MODEL

The study of environmental economics reveals that markets will not necessarily act in the most socially efficient way (Field & Field, 2017). This is because market values and social values will likely not align with the perspective of environmental economics, thus creating market failures and externalities. In terms of attaining efficient levels of environmental quality, government intervention is necessary either through direct market interference or minor modifications that will create more efficient markets (Field & Field, 2017).

MAC as a Governmental Policy Instrument

Abatement costs are an analytical tool used for evaluating a polluting facility's ability to reduce the quantity of emissions being released into the environment (Field & Field, 2017). The *marginal cost of abatement* (MAC) is the *added* cost of achieving an additional one-unit decrease in the level of emissions.

In order to achieve cost-effective, socially efficient levels of emissions, the MAC curve assumes that the lowest possible abatement cost method has been adopted (Field & Field, 2017). The MAC curve holds different input assumptions and can be expressed in various ways depending on its context. Figure 6 illustrates a simple graphical representation of a MAC curve for polluting facilities, i.e., the iron and steel sector.

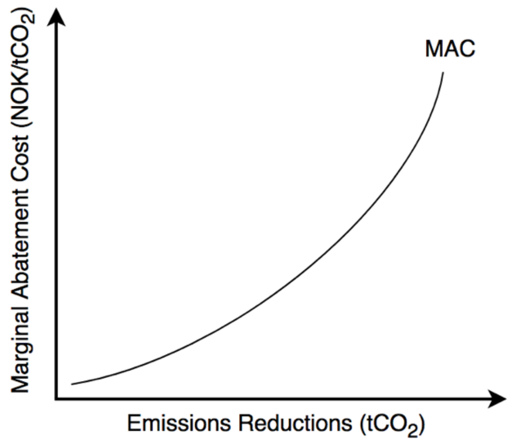

Figure 6: *MAC Curve*

Figure 6 is depicted with emissions reductions on the horizonal axis, illustrating that the marginal abatement cost increases as emission reductions increase. MAC curves are often used by policymakers and researchers to illustrate the technological and economic feasibility of abatement options for polluting firms (Ekins, Kesicki, & Smith, 2011). As such, it can be utilised as a policy tool for assessing climate mitigation options (Ekins, Kesicki, & Smith, 2011; Field & Field, 2017).

MAC as a Business Tool for Abatement Investments

The theory assumes that the marginal cost of abatement for a given pollutant will decrease with time and technological innovation, or n^{th}-of-a-kind technology implementation (Ekins, Kesicki, & Smith, 2011; Field & Field, 2017). Figure 7 depicts the perspective for a polluting firm with associated abatement costs for a given technology (CCS) and a given quantity (one tonne CO_2) of emissions reduction over time.

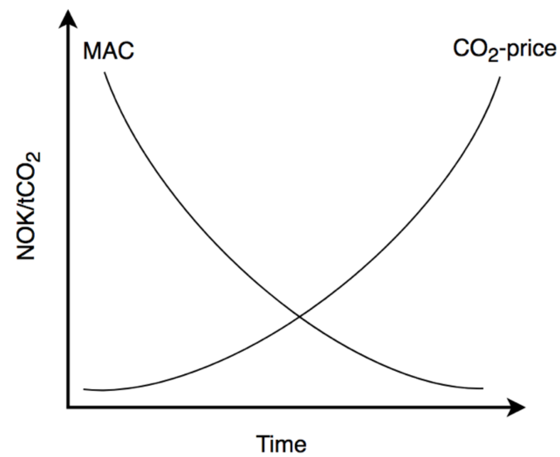

Figure 7: *MAC Curve Development Over Time*

The graph shows that as long as the price of carbon is less than the cost of abatement, profit maximising firms will choose to pay for carbon credits rather than reducing emissions. In addition, initial abatement investments will be extremely costly before technological innovation reduces abatement costs to the degree where new technology is implemented by all polluters. Government intervention is therefore needed to boost initial investments, until the cost of abatement equals the cost of carbon by natural means.

The MAC curve is a simplified, yet useful model for policymakers and polluters to study pollution control (Field & Field, 2017). Limitations and weaknesses associated with the MAC curve should be taken into consideration when using the MAC curve for policymaking and should be combined with other policy decision-making tools. As such, additional policy instruments are presented below.

3.3. ENVIRONMENTAL POLICIES

This section will present alternative policies specifically intended for combatting pollution. These will be used as a foundation in the discussion of the second research question:

To what extent are government policies necessary in order to accelerate the development and deployment of CCS in the Norwegian iron and steel sector?

3.3.1. Decentralised Policies

Decentralised policies refer to policies that give the polluting parties privilege in choosing their preferred method of abatement (Field & Field, 2017). Two such policies include *liability laws* and *voluntary action*.

Liability Laws

By establishing liability laws, emission sources are made responsible for the damages caused, thereby internalising otherwise external effects (Field & Field, 2017). If found liable for environmental damage, a compensation payment would need to be paid. Liability laws can also be further divided into *strict liability* and *negligence*. Strict liability holds emitters liable and requires compensation for any and all damages caused by pollution, regardless of circumstances (Field & Field, 2017). Negligence is a slightly more lenient alternative, which only holds emitters liable if appropriate steps were not taken to prevent environmental damage from happening (Field & Field, 2017).

Voluntary Action

Voluntary action refers to pollution-control behaviour that arises without any need of formal or legal obligation (Field & Field, 2017). Two social forces that can encourage voluntary action include *moral suasion* and *informal community pressure*. Moral suasion aims to appeal to people's sense of civic morality, as opposed to using fines and threats (Field & Field, 2017). Informal community pressure attempts to influence polluters to reduce their emissions by inflicting indirect costs such as loss of reputation, loss of local markets (i.e., through boycotts), or loss of public reputation and thereby stock value for publicly owned firms (Field & Field, 2017). Information can be a powerful tool in these circumstances, for example by making emissions data easily and readily available for the public, in an attempt to mobilise public concern.

3.3.2. Command-and-Control

Command-and-control strategies ensure desired pollution-control behaviour through specific law-abiding policies (Field & Field, 2017). These laws are upheld by enforcement authorities such as courts or police, as well as through the use of inspections, monitoring, sanctions, fines or other penalties. A common form of command-and-control policy is relying on different types of environmental standards to mandate changes in polluting behaviour (Field & Field, 2017). Two environmental standards used are *emission standards* and *technology standards.*

Emission Standards

Emission standards set a fixed level or quantity of emissions that cannot be exceeded, which polluting facilities need to oblige to (Field & Field, 2017). This is typically expressed in terms of quantity of emissions per unit of time (e.g., one tonne CO_2 per week), total emissions, emissions produced per unit of output, emissions produced per unit of input, or the percentage removal of a pollutant (Field & Field, 2017).

Technology Standards

Technology standards forces emission sites to adopt certain technologies, techniques or practices (Field & Field, 2017). This may be certain equipment or operating practices that emitters have to utilise.

3.3.3. Incentive-Based Policies

Incentive-based policies work in such a way that authorities first set overall objectives and rules, while simultaneously ensuring sufficient amount of freedom for normal commercial incentives to lead emitters towards adopting cost-effective pollution-control technologies and procedures (Field & Field, 2017). There are three main types of incentive-based policies: *emissions charges (taxes)*, *subsidies,* and *market-based systems*.

Emission Charges (Taxes)

Emission charges, or emission taxes, is a method used to control emissions by requiring an emission site to pay a certain charge for every unit (e.g., per tonne) of released emissions (Field & Field, 2017). This harnesses a facility's desire to minimise costs, and thus gives an economic incentive to conserve on the amount of environmental damage produced, by locating the most cost-effective method of reducing emissions. A polluting facility will aim at progressively reducing emissions as long as the tax rate is above the marginal cost of abatement (Field & Field, 2017).

Subsidies

To produce the same economic incentive effect as taxes, a subsidy can also be utilised. For such a scenario, public authorities pay an emitter a certain amount for every unit (e.g., per tonne) of emissions reduced beyond a given benchmark (Field & Field, 2017). This creates a compensation system for reducing emissions. Environmental subsidies can take several forms including tax exemptions for utilising pollution-control equipment, reducing fines for facilities with extensive pollution-control plans, public grants to encourage environmental programs, or cost-sharing grants to cover a portion of the development and deployment cost (Field & Field, 2017).

Market-Based Trading Systems

Market-based trading systems are designed to work automatically through interactions between polluters (Field & Field, 2017). One common form of a market-based trading system is referred to as *cap-and-trade*. Here, a regulatory agency makes a centralised decision about the aggregate quantity of emissions deemed acceptable, and thereafter converts these allowances into permits that are distributed amongst the polluters (Field & Field, 2017). Decentralised market interactions then allow polluters to buy and sell these transferable discharge permits.

4. Methodology

This chapter describes the methodological framework by which this thesis is constructed, to answer the research questions. First, the research design is explained, followed by a discussion of the elements that align with the choice of research design, as well as a thorough review of reliability and validity measures.

4.1. RESEARCH DESIGN

Saunders, Lewis and Thornhill (2019) describe research design as a structure for how the study will be conducted, and a plan for answering the research questions. It is meant to guide the researchers from the research problem to empirical observation (Saunders, Lewis, & Thornhill, 2019). The purpose of this research is to conduct a feasibility study of CCS within the Norwegian iron and steel sector, through an extensive market analysis. This will act as the foundation for developing new policies that will assist in the implementation of CCS within this sector. Currently, there is limited research on this specific topic. This study is therefore constructed on a *mixed methods exploratory case study* research design to develop novel insights into the topic.

A mixed methods design combines elements of both quantitative and qualitative research. Simultaneously collecting and analysing both methods allow for more diverse viewpoints and interpretations (Saunders, Lewis, & Thornhill, 2019). The foundation of this thesis is built on the ability to use archival data from a variety of different sources. The use of secondary qualitative and quantitative data has allowed for thorough and critical analysis of policy and strategy statements from governments and industry participants. Likewise with scholar publications, which have been studied extensively in order to understand the technological, economic, political, social, environmental and legal drivers of CCS. As such, the authors have taken advantage of a *concurrent triangulation design* through collection of quantitative and qualitative data in the research, to critically compare the available data (Saunders, Lewis, & Thornhill, 2019).

Exploratory research designs allow for a flexible approach that tolerates modifications to the study as the research is being conducted (Saunders, Lewis, & Thornhill, 2019). This deemed useful when determining the choice of sector for this research, as the research focus was adjusted accordingly.

This study has used the Norwegian iron and steel sector as an *industry case subject,* to provide a deeper analysis of the phenomenon. A case study strategy has the capacity to generate insights from extensive and in-depth research of a phenomenon in its real life context, leading to rich, empirical descriptions and the development of theory (Eisenhardt, 1989; Dubois & Gadde, 2002; Graebner & Eisenhardt, 2007; Ridder, Hoon, & Baluch, 2014; Yin, 2018). The authors found a need for this research as the information openly available today is generally provided for a very broad-spectrum, and not case nor sector specific scenarios. The results from the macroenvironmental analysis in Chapter 5 can then be used to develop policy recommendations more coherent to this sector's needs. As such, a case study strategy creates more meaningful results as it can be specifically applied by facilities within Norwegian iron and steel. Saunders et al. (2019) state that combining secondary data with case studies is a good method of improving analyses where literature is missing.

4.1.1. Research Philosophy and Research Approach

The authors of this thesis follow a *pragmatic research philosophy* in the sense where the focus is directed towards making a difference for future organisational and political practises. Also, mixed methods designs are often associated with pragmatism. This type of research is initiated through realisation of a problem and aims to produce practical solutions to enrich future practise (Saunders, Lewis, & Thornhill, 2019). Pragmatism usually combines facts and values, subjectivism and objectivism, rigorous and accurate information, and various contextualised understandings (Saunders, Lewis, & Thornhill, 2019). Saunders et al. (2019) state that pragmatism entails an analysis of different theories and ideas in terms of their actions and practical consequences within specific concepts, which is coherent with this study's format. As such, reality is of great importance in pragmatic research philosophy, as knowledge and practical effects of ideas need to be exhausted for the correct actions to be successfully applied (Saunders, Lewis, & Thornhill, 2019).

A combination of an *inductive* and *abductive* research approach is used in this thesis. Induction aims at providing an understanding of a phenomenon by analysing the available data. This may result in explanations of concepts that were not previously predicted, such as new conceptual frameworks or theory (Saunders, Lewis, & Thornhill, 2019). As this research aims to analyse data to understand the drivers of CCS development in order to suggest appropriate policy, it can be argued that an inductive approach is utilised. Also, the thesis moves from data collection to exploring possible policies which is coherent with an inductive approach. Combining an *abductive* approach to the research means obtaining data that is sufficiently detailed for exploring the phenomenon, to identify and explain themes and patterns regarding CCS development within iron and steel. The results are then integrated into an overall conceptual framework, thereby building relevant policies for CCS deployment. Although the recommended policies are not tested in real life as a part of this thesis, established theory is used to provide evidence for its effectiveness.

4.1.2. Research Objective

This study's findings have the objective of, firstly, providing a clear and broad understanding of the current economic and political situation of CCS, and secondly, apply this knowledge to design appropriate policies for further implementation of CCS in iron and steel. This way, the research provides a strong foundation for industry participants and policymakers to develop policy that will aid the current development and deployment of CCS.

The research is unique in the sense that current research on this topic lacks specific alignment between the iron and steel sector and politics, and the research method applied aims to fill this gap.

4.2. DATA COLLECTION PROCESS

The research is based on a mixed methods design, mainly comprised of raw and compiled secondary qualitative and quantitative data. The secondary data includes surveys, documents and other multiple-source data, ranging from industry reports to government publications and academic literature from open access databases. The primary data in this study is mainly collected though unstructured interviews and meetings. Further detail on this is given in section *4.2.1 Data Sources*.

To gain a thorough understanding of the complexities affecting industry, policy and CCS, the authors dedicated considerable time towards studying relevant reports, scholar articles, and industry material. Additionally, informal talks with industry experts were conducted to supplement secondary data findings. The following sections explains the data collection process in further detail.

4.2.1. Data Sources

Exploratory studies require considerable observation and information gathering to convert findings to build solid explanations (Ghauri & Grønhaug, 2005). The case study in this thesis merges data from several different sources and combines qualitative and quantitative data. This method is often utilised to provide deeper understandings of the dynamics of the case (Saunders, Lewis, & Thornhill, 2019). By studying numerous data sources, the authors also take advantage of triangulation of evidence, which has been used as a method of validating the given explanations.

Primary Data

The collection of primary data has been conducted though e-mails, unstructured interviews and conversations with industry representatives and CCS experts. Unstructured interviews are often used in exploratory studies, as this allows for a higher degree of participant contribution, which in turn can help uncover new perspectives (Saunders, Lewis, & Thornhill, 2019).

The conversations with industry experts were an important part of the preliminary research. It involved talks with Norwegian developers and suppliers of CCS solutions, and e-mail correspondence with CCS experts from the Global CCS Institute. The Global CCS Institute is the world's leading think tank of CCS, whose main mission is to accelerate the deployment of CCS around the world (Global CCS Institute, 2021). This provided a better understanding of the problems currently faced by the industry in connection with CCS today, as well as insight into additional information sources. It also helped with narrowing the research topic to provide more industry specific results.

Correspondence between the eight focal iron and steel facilities was also initiated. This resulted in unofficial correspondence with the CFO of Elkem, which provided valuable understandings of the future prospects for iron and steel in correlation with CCS projects and necessary policies.

Secondary Data

Most of the thesis' analysis is built on secondary data sources. Utilisation of secondary data allows for gathering vast amounts of different data types in a short timeframe (Saunders, Lewis, & Thornhill, 2019). This has been advantageous for this research as it allowed for a broad macroenvironmental analysis from a variety of different literary sources, which is evident in the PESTEL analysis Chapter 5. For example, studying industry and government reports provided information about past, current and future prospects and strategies regarding CCS. Scholar articles gave superior insight into the technical and socioeconomic aspects of CCS within the iron and steel sector, and highlighted the main challenges that need further attention. Additionally, data from research case studies provided essential cost data used for comparison in this thesis, as there is a scarcity of Norwegian industry specific scholar articles found during the literature review stage of this study.

Additionally, *grey literature* has been utilised, which are literature sources produced by all levels of industry, corporations, academics and government, but are not controlled by commercial publishers (Saunders, Lewis, & Thornhill, 2019). For example, through information by the Intergovernmental Panel on Climate Change (IPCC), Global CCS Institute, the International Energy Agency (IEA), and the Ministry of Petroleum and Energy (MPE). These sources have, amongst others, been used as supplementary information on cost data for iron and steel industries. This was of great importance as these additional sources were able to show consensus in the information and validate certain assumptions that were made.

Moreover, extraordinary access was given to the *Endrava Capture Map* database, for more detailed industry research. Capture Map is a uniquely designed tool for locating large CO_2 emission sources in Europe (Endrava, 2021). Endrava's data on industry emissions in Norway originally derives from the Norwegian Environment Agency's databases. Accumulation of data from Endrava's Capture Map and scholar articles on industry and CCS technology costs, enabled the authors to calculate sector specific CCS costs for Norwegian iron and steel facilities.

4.3. DATA ANALYSIS

This section provides details on how the collected data was used for analysis and how specific calculations were made in relation to cost calculations for the iron and steel facilities.

4.3.1. CO_2 Cost Calculations for Iron and Steel

In order to provide detailed evaluations of the feasibility of CCS for the iron and steel sector in section *5.2.2. CO_2 Avoidance Cost*, extensive cost analyses were conducted. Calculating a representative CO_2 avoidance cost for Norwegian iron and steel involved reviewing academic literature regarding the cost of CCS applied to the other case studies in the iron and steel sector. Cost estimations were collected from multiple sources in order to produce a substantial overview, which was then used to compute an industry average CO_2 avoidance cost.

To compare cost estimation data made in different currencies and years, cost conversion and escalation was necessary. Costs were first converted into NOK in the respective cost year using annualised mean exchange rates gathered from the Central Bank of Norway (Norges Bank, 2021). Following this, the NOK costs were escalated from their respective cost years to the year of comparison, chosen to be 2021, by applying a cumulative inflation rate (Inflation Tool, 2021).

4.3.2. Research Quality

The quality of the research design is of great importance to research studies as it reduces the chance of wrongful conclusions and recommendations (Saunders, Lewis, & Thornhill, 2019). The quality highly depends on the reliability and validity of a study (Saunders, Lewis, & Thornhill, 2019). As such, this section elaborates on how the authors have controlled for reliability and validity throughout the research period, in order to provide high quality research.

Reliability

Reliability varies with the degree to which replication of the research provides equal results, if the same study was replicated by other researchers (Saunders, Lewis, & Thornhill, 2019). The literature often distinguishes between *internal* and *external reliability*. Internal reliability refers to the degree of consistency throughout the research period, and external reliability refers to the ability to receive equal results if outside researchers follow the same methods of data collection and analysis (Saunders, Lewis, & Thornhill, 2019).

The authors have controlled for internal reliability by conducting the analysis in a research team with more than one researcher. This decreases the possibility of researcher error or bias. Likewise, the researchers have maximised the degree of consistency through following identical methods of data analysis, thorough discussions of interpretations of findings, and clear research objectives.

Similarly for external reliability, this study is built on a vast number of reliable information sources. This ensures that other researchers would, with a high degree of certainty, find the same information and thus develop the same conclusions as in this study. What is possible, however, is that new discoveries on this research topic may reveal new findings, such as technology and cost developments, or a change in political or social views on CCS. Comparably, when using secondary data, this has the disadvantage of providing old, or poor-quality data and information, as external researchers tend to have little control over this (Saunders, Lewis, & Thornhill, 2019). In order to alleviate this threat to the extent of our ability, the authors of this thesis confirmed information through various, unrelated old and new sources, and industry experts.

Compared to self-collected data, an advantage of using secondary data is that it is often readily available for other researchers. This entails that the data and the findings from this study are more openly available for public scrutiny (Saunders, Lewis, & Thornhill, 2019). Likewise, literature from acknowledged journals and government organisations are likely truthful and reliable, as their reputation and continued existence depends on it (Saunders, Lewis, & Thornhill, 2019). This helps enhance the study's external reliability.

Validity

Validity refers to the appropriateness of measures used to study the phenomenon in question (*measurement validity*), the precision placed on the analysis of the results (*internal validity*), and the ability to generalise the results (*external validity*) (Saunders, Lewis, & Thornhill, 2019).

In order to adhere to measurement validity, the authors studied a range of technological, economic, political, social, environmental and legal drivers for CCS, which would allow for the development of appropriate policies when combined with environmental economics theory from *3.2. Pollution Control: A General Model*. Likewise, when calculating avoidance costs for the iron and steel facilities, cost data from several acknowledged scholars from the field was used. The results from this were used to compute an industry average, as CCS costs are extremely case sensitive, and costs may vary depending on the methods deployed at each facility. This precaution was taken to control for measurement validity.

This thesis is heavily dependent on literature sources produced by experts with high level of accuracy. In order to attain a high level of appropriate archival data, considerable amount of time was dedicated to thoroughly review available reports and literature. This was especially the case for archival data made available by industry and CCS experts, as the authors had to understand the document's original research purpose. As described in section *4.2.1. Data Sources*, triangulation of evidence was utilised as a method of validating the literature. Triangulation is the action of using more than one source of data and data collection method throughout the research (Saunders, Lewis, & Thornhill, 2019). The aim of this approach is to decrease the possibility of one source giving inaccurate information, which highly strengthens the internal validity of this thesis.

External validity is often difficult to control. However, through the use of various research methods combined with conventional environmental economics theory, the authors adhere to external validity. This is because the policy recommendations are constructed using the macroenvironmental drivers found in the PESTEL analysis and are anchored to environmental theory. Thus, following the same methodology as presented in this study should provide the same results. Yet, it is important to note that drivers studied in this research may differ with time and preference.

By providing a detailed description of this study's context, research questions, methodology, interpretations and conclusions, the authors generate generalisability for the reader. As such, the reader can judge the transferability of this research to other settings the reader may be interested in researching. This transmits to the external validity of this study. Additionally, utilisation of the mixed methods design enhances credibility and generalisability as more complete knowledge is produced (Saunders, Lewis, & Thornhill, 2019).

5. Analysis of PESTEL

This chapter will present the macroenvironmental analysis of CCS in Norway, with focus on the iron and steel sector. The analysis follows the PESTEL framework, as presented in Section *3.1 PESTEL*. The aim of this chapter is to investigate the first research question.

5.1. TECHNOLOGICAL

Optimal capture technology is highly site-specific. Thus, this section begins by introducing existing general technologies that are relevant for the iron and steel sector. Carbon capture (CC) suppliers in Norway will then be commented on. Finally, this section covers details for transport and storage infrastructure under development for CCS in Norway today.

5.1.1. Capture Technologies

CO_2 emissions released at process facilities, such as iron and steel, tend to be dispersed across several emission points throughout the production process. This makes fitting CO_2 capture technology challenging (Ho, Allinson, & Wiley, 2010). Despite having several emission points, the main source of CO_2 emissions in iron and steel production stem from the two processes explained in section *2.1.2. Norwegian Iron and Steel Sector*: the blast furnace (BF) and basic oxygen furnace (BOF). McKinsey & Company (2009) found that that direct carbon emissions, primarily from the BF and BOF, make up 84% of total iron and steel GHG emissions. The BF is where most capture technology research has been focused (Leeson, Mac Dowell, Shah, Petit, & Fennell, 2017), and will for this reason also be the focus onwards in this thesis.

As previously mentioned, studies have been conducted on how to apply post-combustion capture technology to remove CO_2 from the blast furnace gas (BFG) before it is reused as an energy source around the steel mill (Wiley, Ho, & Bustamante, 2011). Kuramochi, Ramírez, Turkenburg and

Faaij (2011) are amongst researchers that have assessed CO_2 capture technologies at iron and steel facilities. Some of these technologies will be presented below.

Blast Furnace: Add-on CO_2 Capture

The first technology discussed requires no modification to the BF, but is a form of *add-on CO_2 capture*. Recall that BFG contains circa 25% CO_2. This gas flows through expansion turbines, where the add-on technology can either (1) capture the gas directly through chemical or physical absorption, or (2) capture the gas after the conversion of CO to CO_2 (explained below). Less than half of the carbon contained in the gas is captured, as the remaining fraction is in the form of CO.

Blast Furnace: Integrated CO_2 Capture

A second capture technology applicable to the iron and steel sector has a higher capture rate, but requires modification of the BF. This is *process-integrated CO_2 capture*, based on Top Gas Recycling Blast Furnace (TGR-BF) technology (Kuramochi, Ramírez, Turkenburg, & Faaij, 2011). TGR-BF relies on separation of the off-gases, such that useful components can be recycled, while the CO_2 can be captured (Tsupari, Arasto, Kärki, Sihvonen, & Lilja, 2013). Due to recycling, the flue gas concentration is higher than that of a regular BF (~35% CO_2), thereby making the carbon capture process less energy intensive (Leeson, Mac Dowell, Shah, Petit, & Fennell, 2017). Carbon capture from the flue gas is achieved using solvent chemical absorption (Kuramochi, Ramírez, Turkenburg, & Faaij, 2011; Tsupari, Arasto, Kärki, Sihvonen, & Lilja, 2013). The remaining flue gas is then recycled into the base of the BF as a reducing agent (thereby also reducing the need for coke) (Leeson, Mac Dowell, Shah, Petit, & Fennell, 2017).

Shift Conversion of CO to CO_2

In order to reduce the energy penalty of CO_2 capture, a method is to convert the CO present in the BFG into CO_2 (Ho, Allinson, & Wiley, 2010). This uses pressurisation and water-gas shift reaction

(WGS) to concentrate low partial pressure CO_2, into a more concentrated stream (Ho, Allinson, & Wiley, 2010). In the WGS reaction, steam is reacted with the flue gas under high temperature and high pressure. A physical absorbent is then used for CO_2 capture (Ho, Allinson, & Wiley, 2010).

In principle, it is possible to retrofit all CO_2 capture technologies explained above to existing iron and steel facilities (Kuramochi, Ramírez, Turkenburg, & Faaij, 2011). However, although different capture technologies applicable for iron and steel facilities have existed for some time, they are still not commercially in use. This suggests that barriers to wide-scale deployment exist beyond the technology itself. In addition, little innovation in the type of technology has been seen over the years. The study by Kuramochi, Ramírez, Turkenburg, & Faaij was conducted in 2011, but continues to be referenced in several more recent works.

5.1.2. Producers of CC Technology

While there are several producers of CC technology in Norway today, these are at various stages of development. Each producer offers different technological features and possibilities for retrofitting. For example, Compact Carbon Capture is in a demonstration stage, and has technology that is unique in its size and scalability (Madsen, 2021). This is a benefit for the case facilities that have little space available for CC technology. Aker Carbon Capture, however, state that their technology can be applied to emissions from various sources, including process industries (Aker Carbon Capture, 2021). This is beneficial, as there is currently no technology made specifically for the iron and steel sector. However, since the Norwegian iron and steel sector is small and more research has been done in this area abroad, Norway has an opportunity to learn from other more experienced countries.

5.1.3. Suppliers of Transport and Storage

The previously mentioned Longship project will provide full-scale CCS infrastructure within Norway. The transport and storage components are provided by Northern Lights, which are handled by Equinor, Shell and Total (Gassanova, 2020). CO_2 will be transported by ship from the capture sites to an intermediate onshore storage terminal located in Øygarden in Western Norway (Gassanova, 2020). From Øygarden, CO_2 will be transported approximately 100 – 110 km by pipeline and injected 2,600 – 3,000 meters underneath the seabed in the North Sea for permanent storage (Gassanova, 2020; Northern Lights, n.d.).

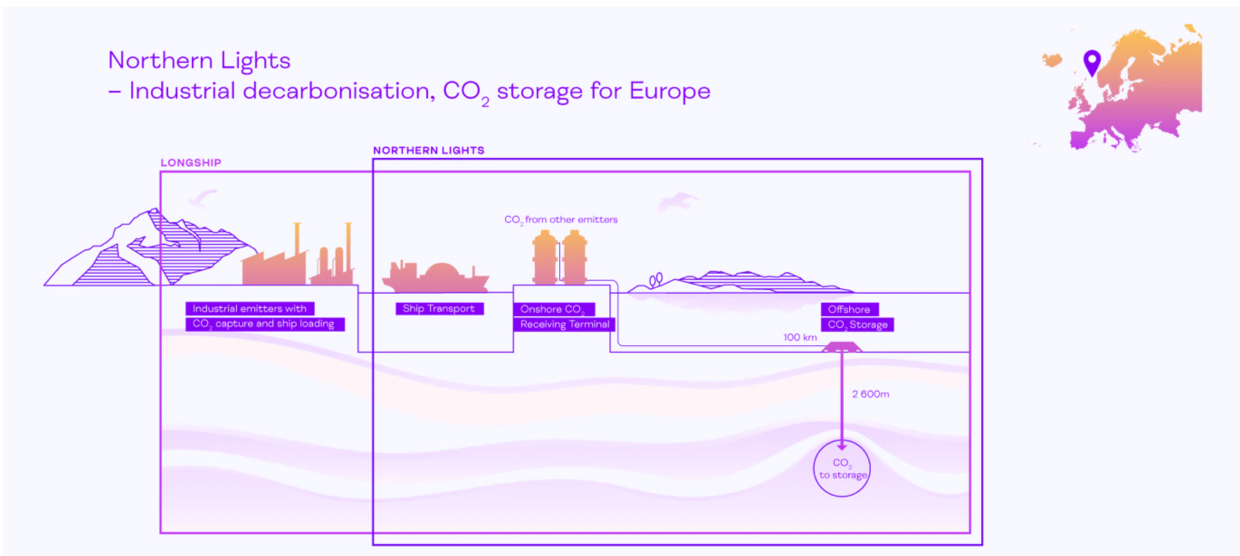

Figure 8: *Longship and Northern Lights Project: Full-Scale CCS Infrastructure. Source: (Northern Lights, n.d.)*

Although the Northern Lights storage terminal is currently being developed for the Longship project, it aims to be the first cross-border and open-source CO_2 transport and storage infrastructure network (Northern Lights, n.d.). This means that iron and steel facilities participating in carbon capture will also be able to utilise this infrastructure. The identified iron and steel emission sites, seen in Figure 2 under section *2.1.2. Norwegian Iron and Steel Sector,* clearly shows a wide dispersion of facilities across the country. Simultaneously, the facilities are located close to the coast, which make ships the best mode of transport for the case facilities. Currently, the storage terminal is being developed to hold a storage capacity of 1.5 million tonnes of CO_2 per year, with an eventual capacity increase of 3.5 million tonnes per year, if storage demand increases (Northern Lights, n.d.). This infrastructure therefore provides iron and steel with good transport and storage opportunities.

5.1.4. Summary of Technology Analysis

Technological Advancement

Advantages and disadvantages related to the technical aspects of carbon capture technologies is not the focus of this thesis. However, it is made clear from the multiple investigated case studies that CC is possible, showing that there are opportunities for CC in iron and steel facilities. Yet, slow innovation does act as a threat for further development of the technology. Nevertheless, Norwegian iron and steel facilities can adapt knowledge from international case studies, to locate technological developments applicable for specific Norwegian processes.

Furthermore, Kuramochi, Ramírez, Turkenburg, & Faaij (2011) find that post-combustion technologies can be retrofitted, which is highly relevant for this study's case facilities. This acts as a large opportunity because there are currently no publicly announced plans to build new iron and steel plants in Norway, and a retrofitting solution is essential.

Suppliers of Infrastructure and Technology

Other opportunities derive from the Northern Lights project. This project means that iron and steel facilities may have accessible transport and storage infrastructure, which is essential for reducing risk and managing disposal of the collected CO_2. The costal locations of the case facilities also increase the opportunity of being able to utilise the available ship transport.

A large threat is that the technology is clearly very complex. In addition, due to site-specific characteristics such as size and space, technology would require customisation in the majority of cases.

5.2. ECONOMIC

In order to realistically analyse the future potential for CCS, studying economics of CO_2 avoidance cost is essential (Simbeck & Beecy, 2011). This section studies the economic feasibility of CCS in the Norwegian iron and steel sector by first identifying the cost components of CCS, and thereafter comparing the iron and steel industry average avoidance cost with the EU ETS price of carbon. This will be discussed in light of the environmental economics theory outlined in section *3.2. Pollution Control: A General Model*.

5.2.1. Cost Components of CCS

To determine the cost of abatement, it is helpful to first understand the three main cost components that make up a CCS system. These are; capture, transport, and storage.

Capture Costs

The capture component of a CCS system involves both the separation and compression of CO_2, and is often considered the largest part of the CCS costs (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). Employing a CO_2 capture system requires both additional annual capital expenditure (CAPEX) due to the required CCS investment, as well as additional operational expenditures (OPEX) due to the extra processes it necessitates (Arasto, 2015). OPEX may include increased energy requirements, steam, cooling water, maintenance, labour costs, and other utilities (Garðarsdóttir, Normann, Skagestad, & Johnsson, 2018).

It is important to acknowledge that the cost of capture may vary greatly between similar applications. This is due to a variety of different factors, such as size, space, age, unit type, temperatures, CO_2 concentration, and if the technology needs to be retrofitted (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018; Norwegian Ministry of Petroleum and Energy, 2020). This is supported by a Swedish case study by Garðarsdóttir, Normann, Skagestad, & Johnsson (2018), which investigated the investment costs related to the implementation of nth-of-a-kind CC and CCS in two separate emission sources with near-identical gas flows, but different CO_2 concentrations. The comparison was made between a steel mill with a flue gas CO_2 concentration of 30%, and a pulp mill with a flue gas CO_2 concentration of 13%.

The study found that in absolute terms, the CO_2-rich source (steel mill) required larger investments in several CAPEX-intensive process components and equipment (Garðarsdóttir, Normann, Skagestad, & Johnsson, 2018). However, in specific terms (cost/tCO_2 captured), the increased volume of CO_2 captured resulted in economies of scale. Capturing ~ 800 ktCO_2/year from the CO_2-rich source rather than ~ 400 ktCO_2/year from the CO_2-lean source gave a 23% reduction in the specific CAPEX (Garðarsdóttir, Normann, Skagestad, & Johnsson, 2018). These findings reveal that for higher CO_2 concentrations, a larger share of the total cost is allocated to OPEX, because economies of scale assist in lowering the CAPEX (Garðarsdóttir, Normann, Skagestad, & Johnsson, 2018; Madsen, 2021). This implies that a CC investment decision for CO_2-rich emission sources become highly OPEX driven, while CO_2-leaner sources need to consider both CAPEX and OPEX (Madsen, 2021).

Although exact figures for the CO_2 concentration at the Norwegian iron and steel case facilities were inaccessible for this research, background and literature review revealed that average CO_2 concentration for iron and steel facilities in general is 25% (see section *2.1.2. Norwegian Iron and Steel Sector*). This is slightly less than the steel mill used in the case study above, but it implies that the Norwegian iron and steel case facilities do not need to give as much attention to the CAPEX portion of the total cost in a potential CCS investment decision. This can make implementation more economically reasonable and worthwhile than for other process industry sectors, since more CO_2 can be captured for the same investment cost.

Transportation Costs

The second cost component of CCS is transport. Kjärstad, Skagestad, Eldrup, & Johnsson (2016) examine the costs associated with CO_2 transport via ship versus offshore pipelines in the Nordics, as a function of volume and distance. Onshore pipelines were excluded from the investigation due to probable local opposition and demanding terrain. As Nordic emission sites are relatively small (100 kt – 1000 ktCO_2/year), and because CO_2 often has to be transported over long distances (>300 km) to storage sites, CO_2 transport by ship is found to be the most cost-competitive option. This is because the cost of travelling by sea is relatively insensitive to distance (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). As such, ships are also the selected mode of transport in the Northern Lights collaboration.

Currently, arrangements have been made to invest in three CO_2 ships for transport in the Northern Lights project (Norwegian Ministry of Petroleum and Energy, 2020). Although no specific estimates are publicly available for the cost of transporting one tonne of CO_2 one kilometre, it is reasonable to assume that the cost will decrease when a ship carries increased CO_2 volumes, due to economies of scale. To avoid the financial risk of underutilisation, operators will likely search for other facilities to form emission clusters where CO_2 can be collected. Here, the iron and steel case facilities could be attractive candidates, as they are located near the coast. The majority of facilities are also located in Southern Norway, along the route between Oslo/Brevik (where the ships will collect CO_2 in the Northern Lights project) and Øygarden (the location of the intermediate onshore storage terminal). If clusters can be formed between nearby iron and steel facilities, CO_2 could be collected from fewer designated points along this same route. This would reduce the cost of transport for all involved parties. This encourages collaboration and incentivises the case facilities to become early participants of the cluster. Once transport volumes begin to reach capacity, transport prices can be expected to increase.

Storage Costs

Within this analysis, only ocean storage at the Northern Lights terminal is considered. The cost of ocean storage is a function of offshore distance and injection depth (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). The Norwegian Government have stated that a gradually decreasing share (from 95% to 80%) of the operating costs at the Northern Lights storage terminal will be covered, for a period of up to 10 years (Norwegian Ministry of Petroleum and Energy, 2020). Again, no exact estimates are given for the cost of storing one tonne of CO_2. Yet, the Government support granted for CO_2 storage implies that a storage operator has the ability to offer storage to polluting facilities at a lower cost. If this storage infrastructure becomes available to additional polluting facilities, this could act as a large opportunity for the iron and steel case facilities.

5.2.2. CO_2 Avoidance Cost

Identifying these cost components provides a foundation for estimating the costs of a fully integrated CCS system for a polluting facility. However, estimating the overall cost of abatement requires more than simply adding the individual cost components together. This is because the *CO_2 captured* differs from the *atmospheric CO_2 avoided* during the production process (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). For cost analyses, it is therefore important to distinguish between cost of CO_2 captured and cost of CO_2 avoided.

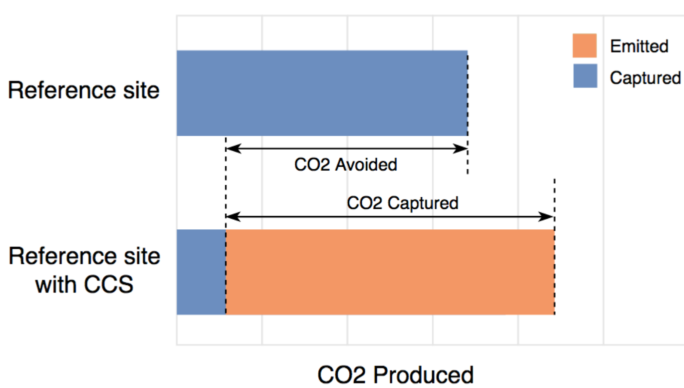

Figure 9: *CO_2 Captured vs. CO_2 Avoided. Adapted from (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018).*

To understand the difference between CO_2 captured and CO_2 avoided, it can be helpful to picture a facility with and without CCS. When CCS is implemented, additional energy is required for each of the three components. Consequently, CO_2 emissions also increase per unit of output (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). This means that more CO_2 will be captured in cases with CCS, simply because more CO_2 is being emitted in the process. This represents an efficiency loss. As the cost of CO_2 captured is calculated based on the *CO_2 captured per unit of output*, this means that the larger the efficiency loss, the lower the CO_2 capture cost (Simbeck & Beecy, 2011).

On the other hand, the cost of *CO_2 avoided* is calculated based on the *reduction of CO_2 emissions to the atmosphere, per unit of output* (Simbeck & Beecy, 2011). Here, the larger the efficiency loss (i.e., higher CO_2 emissions from CCS), the lower the emissions 'avoided' during production, and the higher the CO_2 avoidance cost (Simbeck & Beecy, 2011). Since the CO_2 avoidance cost penalises efficiency loss in this way, it means that it will always be higher than the CO_2 capture cost (Leeson, Mac Dowell, Shah, Petit, & Fennell, 2017; Dadhich, Dooley, Fujii, Hohmeyer, & Riahi, 2018). In accordance with current environmental policies and the aim of reducing GHG into the atmosphere, this thesis is interested in calculating the CO_2 avoidance cost as this gives a better representation of the true costs.

To calculate a representative CO_2 avoidance cost estimate for CCS in the Norwegian iron and steel sector, an industry average has been calculated from cost estimates found in existing literature and case studies (see section *4.3.1. CO_2 Cost Calculations for Iron and Steel* for an explanation of the method used). Table 2 presents a collected overview of estimated CO_2 avoidance costs for CO_2 capture, transport and storage found in the iron and steel sector, specifically.

Table 2: *CO_2 Avoidance Cost Estimates from Literature*

Reference	Cost year	Currency	CO_2 avoidance cost estimate in cost year	CO_2 avoidance cost in NOK escalated to 2021 values
(IPCC, 2005)	1990	USD	35	425.32
(Huijgen, Comans, & Witkamp, 2007)	2007	EUR	77	823.62
(Ho, Allinson, & Wiley, 2010)	2008	AUD	74	454.26
(Ho, Allinson, & Wiley, 2010)	2008	AUD	56	343.77
(Ho, Allinson, & Wiley, 2010)	2008	AUD	74	454.26
(Ho, Allinson, & Wiley, 2010)	2008	AUD	39	239.41
(WorleyParsons Services Pty Ltd, 2009)	2009	USD	52	414.84
(Global CCS Institute, 2009)	2009	USD	47	374.95
(Wiley, Ho, & Bustamante, 2011)	2011	AUD	71 – 100	497.29 – 700.41
(Kuramochi, et al., 2011)	2011	EUR	40 – 65	377.63 – 613.65
(Kuramochi, et al., 2011)	2011	EUR	30	283.22
(Kuramochi, et al., 2011)	2011	EUR	30 – 55	283.22 – 519.24
(Arasto, et al., 2013)	2013	USD	60 – 100	420.87 – 701.45
(IEA, 2013)	2013	USD	50	350.73
(IEA, 2013)	2013	USD	75	526.09
(IEA, 2013)	2013	USD	85	596.24
(IEAGHG, 2013)	2013	USD	74	519.08
(IEAGHG, 2013)	2013	USD	81	568.18
(IEAGHG, 2013)	2013	USD	57	399.83
(Garðarsdóttir et al., 2018)	2015	EUR	81	831.36
(Bui, et al., 2018)	2018	USD	65.1 – 119.2	564.09 – 1032.86
(Bui, et al., 2018)	2018	USD	54 – 88	467.91 – 762.51
(Johnsson, Normann, & Svensson, 2020)	2020	EUR	80 – 135	871.04 – 1469.87
(McKinsey & Company, 2009)	2005 (for 2030)	EUR	25	200.18
(McKinsey & Company, 2009)	2005 (for 2030)	EUR	27	216.20

Table 2 confirms that large differences and uncertainty exist in the potential CO_2 avoidance costs faced by emission sites even within the same sector. This is because the cost estimates and underlying case studies are based on different economic assumptions, and each facility has different site-specific conditions and characteristics. This proves that no single estimate is a perfect representation of the costs that could arise for the case facilities in this thesis. This justifies the use of an industry average as a representative CO_2 avoidance cost for the Norwegian iron and steel case facilities.

Based on the figures presented in Table 2, the industry average is found to be ~ 541 NOK/tCO2 or **563 NOK/tCO_2** without the low 2030 cost projections made by McKinsey in 2005. Given an industry average of 563 NOK/tCO_2, Tables 3 and 4 show the calculated total avoidance cost for each of the case facilities. The calculations are based on facilities' individual emissions data, and the expected lower bound (LB) and upper bound (UB) capture rates presented in Table 1 under section *2.1.2. Norwegian Iron and Steel Sector*. At the LB, facilities are expected to be able to capture only 35% of their total emissions. At the UB, facilities are expected to be able to capture 85% of their total emissions. The total avoidance costs calculated for each of the LB and UB scenarios have been distributed across the different CCS cost components. This is done using Al-Fattah et al.'s (2011) suggested cost distribution shares of; 70% capture, 20% transport 10% and storage.

Table 3: *Distribution of CO_2 Avoidance Cost to CCS Components: Lower Bound Capture Rate*

Emission Site	Total CO_2 Avoidance Cost LB	Capture	Transport	Storage
Ferroglobe Mangan Norge AS	26,991,365	18,893,955	5,398,273	2,699,136
ELKEM ASA AVD BJØLVEFOSSEN	34,281,003	23,996,702	6,856,201	3,428,100
Eramet Norway AS, Porsgrunn	36,448,193	25,513,735	7,289,639	3,644,819
Eramet Norway Kvinesdal	44,919,935	31,443,955	8,983,987	4,491,994
TiZir Titanium & Iron AS	51,421,505	35,995,053	10,284,301	5,142,150
Finnfjord	55,952,902	39,167,031	11,190,580	5,595,290
Elkem Rana AS	58,711,143	41,097,800	11,742,229	5,871,114
ERAMET NORWAY AS, Sauda	63,045,523	44,131,866	12,609,105	6,304,552
Sector	371,771,569	260,240,099	74,354,314	37,177,157

Table 4: *Distribution of CO_2 Avoidance Cost to CCS Components: Upper Bound Capture Rate*

Emission Site	Total CO_2 Avoidance Cost UB	Capture	Transport	Storage
Ferroglobe Mangan Norge AS	61,694,548	43,186,183	12,338,910	6,169,455
ELKEM ASA AVD BJØLVEFOSSEN	78,356,579	54,849,605	15,671,316	7,835,658
Eramet Norway AS, Porsgrunn	83,310,156	58,317,109	16,662,031	8,331,016
Eramet Norway Kvinesdal	102,674,138	71,871,896	20,534,828	10,267,414
TiZir Titanium & Iron AS	117,534,868	82,274,408	23,506,974	11,753,487
Finnfjord	127,892,347	89,524,643	25,578,469	12,789,235
Elkem Rana AS	134,196,899	93,937,829	26,839,380	13,419,690
ERAMET NORWAY AS, Sauda	144,104,053	100,872,837	28,820,811	14,410,405
Sector	849,763,587	594,834,511	169,952,717	84,976,359

Each of the case facilities have very different total CO_2 avoidance costs, depending on their levels of emissions. Although this is to be expected, the cost calculations from the tables are only meant as indicative. The reason for this is that site-specific factors are not considered beyond total emissions. For example, the iron and steel facility 'Finnfjord' has the furthest sailing distance to the Northern Lights storage terminal (see Table 1 under *2.1.2. Norwegian Iron and Steel Sector*), and would therefore likely need to allot a larger share of the total costs to transport. Since the calculations are based on a fixed distribution, this is not captured in the results. Other site-specific considerations that could influence the true cost faced by each individual facility in Norway include higher labour (and thereby OPEX) costs, different levels of excess heat, fuel and energy prices, CO_2 concentration in the BFG, or plant design and operation.

5.2.3. Price of Carbon

In the following two sections, the industry average CO_2 avoidance cost for one tonne of CO_2 will be compared with the current and predicted future prices of carbon, to determine whether CCS within iron and steel is currently economically feasible.

As explained in section *3.2. Pollution Control: A General Model*, if the cost of CCS is above the price of carbon, the case facilities will simply continue to emit and pay for carbon credits. This means that whether or not the case facilities choose to invest in CCS technology is greatly dependent on the current and future prices of carbon set by trading systems such as the EU ETS or carbon taxes.

At present time (date: 16th April 2021), the price at which carbon is traded is 44.33 EUR (EMBER, 2021), which is equivalent to 444 NOK at today's exchange rate. This is an all-time high, signalling that the price of carbon is on the rise. This is supported by the drastic development in the EU allowance (EUA) price since 2018, as seen in Figure 10 below. As much as a 471% increase is evident since January 1st, 2018.

Figure 10: *Price of Carbon in EU ETS. Source: (EMBER, 2021)*

If the price continues to rise on this trajectory, this could significantly impact the possibilities for CCS within the Norwegian iron and steel sector.

According to analyses done by Atkins & Oslo Economics (2016), the carbon price needs to increase to approximately 2000 NOK/tCO_2 by 2050 in order to achieve the emissions reductions necessary to reach the 2°C target. This reflects the optimal CO_2 price, based on the assumption that all countries choose the cheapest possible method of abatement per tonne CO_2. This also implies that even higher prices would be needed to reach the new 1.5°C target. Based on data from 2016, Atkins & Oslo Economics calculated predictions for future carbon price development. These price projections revealed that expected development was far below the optimal level.

Today, the development can be expected to be on a steeper projection than the price paths predictions made in 2016. The annual linear reduction factor decreases supply which may continue to drive up the price, but the Market Stability Reserve's implementation in 2019 will also likely contribute to stabilising the price through removing excess allowances from the market. Nevertheless, to reach the 2000 NOK/tCO_2 optimal price by 2050 from today's price of 444 NOK/tCO_2, yet another 350% increase is needed.

5.2.4. Socioeconomic Emission Level

The current market price for CO_2 emissions is not high enough to reflect the marginal cost of using carbon abating technology. Given the current carbon price of 444 NOK/tCO_2 and the industry average avoidance cost of ~ 563 NOK/tCO_2, this means that a facility emitting CO_2 would save approximately 120 NOK/tCO_2 by buying more allowances relative to the cost of capture. This difference may be even more drastic in reality, as several of the cost expectations that make up the industry average are based on the assumption of n^{th}-of-a-kind CCS facilities (see section *8.1. Limitations to this Study*). First-of-a-kind facilities, such as Norwegian iron and steel, will likely have to bear more costs and risk associated with early development and application (Norwegian Ministry of Petroleum and Energy, 2020).

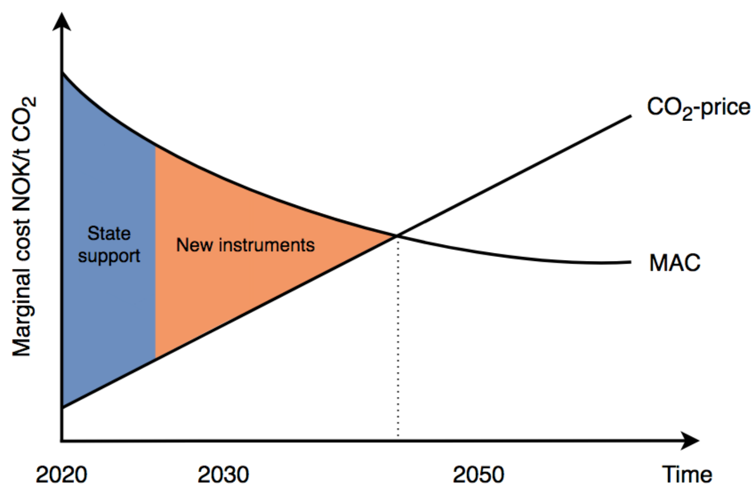

Figure 11: *Estimated Development of CO_2-price and MAC Curve. Adapted from (Stub, Skriung, Post-Melbye, & Holm, 2019)*

The gap between the CO_2 avoidance cost and price of carbon prevents the industry from achieving a socially efficient level of emissions, as illustrated in Figure 11 above. The price of emitting carbon is lower than the socioeconomic costs associated with such emissions, which results in a negative externality (Zapantis, Townsend, & Rassool, 2019; Norwegian Ministry of Petroleum and Energy, 2020). It is not before the MAC decreases or the price of carbon increases, that it becomes profitable for iron and steel facilities to invest in CCS. This is currently a huge barrier for

CCS development in the iron and steel sector, as well as any other polluting sectors where the MAC exceeds the CO_2-price.

Furthermore, it may become more profitable to be a second-mover in the market. This is because the costs of CCS are expected to fall in cases where capacity utilisation increases, solutions in the chain are optimised, or technology improves (DNV GL Energy, 2020). As the benefits of CCS are shared by many while the costs are borne by few, it can be said that the technology shares characteristics to that of a public good and positive externality (Norwegian Ministry of Petroleum and Energy, 2020). If the market is left to its own devices, too little of this technology will be employed, and too little will be abated. With government intervention in the form of monetary aid, regulatory support or other incentive schemes, initial investments will be encouraged until the cost decreases by means of innovation and efficiency. Therefore, it is imperative for governments to be involved in CCS deployment, as depicted in Figure 11.

5.2.5. Summary of Economics Analysis

Cost Components of CCS

Applying CCS technology increases both the total CAPEX and OPEX. However, due to economies of scale, the CAPEX-share of the total costs becomes less significant for the case facilities. If the facilities also have operating and maintenance processes in place that can be shared with the new CC technology, it can dampen the economic burden of installing CCS in the existing sites. This presents an opportunity for lower marginal abatement costs.

Large initial investments are required for transport and storage infrastructure during the ramp up phase. Because it is possible that these two components will be underutilised during the first years until the number of facilities that participate in CO_2 capture increases, a barrier is the decision of who should carry the financial risk of underutilisation. However, if the Government provides financial aid in this area, it could enable operators to offer cheaper transport and storage until utilisation increases. If clusters are formed, the case facilities could be attractive users of the existing infrastructure, as the majority are located along the same Southern route as the Northern Lights project plans to sail.

Socioeconomic Emission Level

There is large uncertainty in the cost estimates related to the implementation of CCS. A reason for this is that avoidance costs are highly case-specific. Based on an industry average, it is possible to see that this exceeds the current price of carbon, thereby weakening the economic incentive for the case facilities to invest in carbon capture. Each facility's CO_2 avoidance cost is the minimal price of carbon required to realistically consider CCS. To account for the added capital and risk that CCS entails relative to simply purchasing carbon credits, it would presumably need to be even higher. This is a significant cost barrier associated with CCS. In addition, although the cost of CCS is expected to decrease in the years to come, how quickly learning-by-doing will lower these costs is uncertain. This encourages a 'wait-and-see' attitude, by which facilities prefer to enter the market when the costs are lower, and expertise has increased. Therefore, to encourage first-of-a-kind projects, government intervention is necessary to reach the socioeconomic level of emissions.

5.3. POLITICAL

Norway's Government has been heavily involved in CCS since the 1990's through various initiatives. The Government's interest in CCS initially derived from the oil and gas industry to be utilised as a measure for emission reductions and enhanced oil recovery (EOR) (Gassnova, 2020). This involvement has evolved into additional environmental strategies and international environmental treaties with clear focus on aiding the nation towards a zero-emission society. The following section analyses national and international political factors that have influenced CCS development within Norway, and its impact on the iron and steel industry.

5.3.1. Norwegian Policy Frameworks and Incentives

Norway's NDC's and overall climate target is to achieve a reduction of 50% (and towards 55%) in emissions by 2030, compared to emission levels in 1990. The *Norwegian Climate Strategy for 2030* (Norwegian Ministry of Climate and Environment, 2017) gives a thorough overview of different plans for reaching the 2030 target. With regard to the process industry, roadmaps have been developed that focus on the long-term technological developments essential for reducing emissions from process production. Discussions between government and the process industry have resulted in the constellation of *Prosess21*. This is to act as a strategic forum for sustainable growth and development for the process industry in combination with emission reduction strategies.

The Government proposed a white paper in 2017 (approved by the Solberg Government), dedicated solely towards process industry. The white paper states that the Government will strive for a "*greener, smarter and more innovative industry*" by which "*Norway will be a world leader in industry and technology*" (Ministry of Trade, Industry and Fisheries, 2017). In this white paper, the Government states that facilitating green growth in existing industry exposed to international competition will be challenging. This is especially the case for iron and steel, as this is a small sector compared to international iron and steel. It is therefore essential that small sectors receive government aid, if the government is to fulfil its promise of facilitating growth in existing Norwegian industry while pushing for strict climate goals and preventing carbon leakage (Ministry of Trade, Industry and Fisheries, 2017).

Researchers at the Global CCS Institute argue that the policies currently in place are insufficiently designed to meet emission reduction goals (Zapantis, Townsend, & Rassool, 2019). To support their argument, Bui et al. (2018) state that the lack of financial funding and supportive government through policy and legislative frameworks are the key reasons for the slow advancement of CCS. They argue that there would currently be more CCS projects at a commercial stage if these aspects were given more attention. In addition to policies directly related to process industries, the

Government is also heavily devoted to its Longship project. It is apparent that Norway's formulation of environmental policy is contributing to the development of this unique full-scale CCS project. However, direct financial funding towards the iron and steel industry is still not evident. As such, current policy settings regarding the iron and steel sector does not support private business investments within CCS (Global CCS Institute, 2020). This may result in slower deployment of CCS within this sector. As such, appropriate incentives and legislation are essential for private iron and steel investors to take part in separate CCS projects.

5.3.2. Norwegian Government Research Facilities and CCS Projects

The Norwegian Government has executed targeted work for CCS application through policy instruments that have been designed to support the development of CCS projects. The key governmental entity responsible for CCS policy and technological development is Gassnova SF, established in 2005. Gassnova administers several CCS initiatives on behalf of the Norwegian state, including Technology Centre Mongstad (TCM), CLIMIT, and the Longship Project. Norway is also involved in Centres for Environment-friendly Energy Research (FME), the European CCS Research Infrastructure (ECCSEL), Norwegian CCS Research Centre (NCCS), and more (Norwegian Ministry of Petroleum and Energy, 2020). An example of a successful Norwegian Government CCS project is TCM, which has been operational since 2012. TCM is viewed as one of the world's largest test facilities today continuously working on the development, testing and qualification for CCS technology (Norwegian Ministry of Petroleum and Energy, 2020). With this experience, TCM has contributed to reducing both costs and risks associated with full-scale CCS (Norwegian Ministry of Petroleum and Energy, 2020). Likewise, research by CLIMIT has resulted in more efficient technology and contributions to the safety and reduced risks associated with CCS, whereas ECCSEL and FME have developed international collaborations and research on capture, transportation and storage (Norwegian Ministry of Petroleum and Energy, 2020). These engagements show an obvious commitment by Norwegian Government.

Norway's political involvement in CCS has received support and resistance, and has resulted in both successful and abandoned projects. Jens Stoltenberg's '*moon landing*' proposal for full-scale CCS in 2007 was heavily criticised due to insufficient technology testing plans, as well as high risk and costs estimations, resulting in plans being terminated in August 2013 (Gassnova, 2020). Yet, the Government pledged to continue their work towards full-scale CCS, though a new and improved strategic plan was necessary (Gassnova, 2020).

As stated, the Norwegian Government is investing massive resources towards the development of policies and projects involving CCS (Norwegian Government, 2017; Norwegian Ministry of Petroleum and Energy, 2020). The most recent, and largest, initiative is the full-scale CCS Longship project. Longship has the goal of contributing with information and experience that will further result in new jobs, technological development, cost reductions, international collaborations and full-scale CCS infrastructure (Solberg, 2020; Norwegian Ministry of Petroleum and Energy, 2020). For example, Norwegian national regulations have allowed for testing of geographical storage sites for CO_2, which is now an essential part of Longship. Longship is also projected to act as a catalyst for increased international interest in CCS (Norwegian Ministry of Petroleum and Energy, 2020). The Longship project assumes that other countries will take note of Norway's involvement within CCS, which will lead to increased international CC projects. Norway plans to boost such interest through their CO_2 storage facility, which holds the capacity to store CO_2 from international sources. This way, the project may generate income from storing CO_2 from European sources. These are conditions that the Government deems essential for Longship's long-term success (Norwegian Ministry of Petroleum and Energy, 2020).

It is obvious that the Norwegian Government has interest in increasing private CCS investments, in Norway and internationally, in order to strengthen their investments in the Longship project. Yet, focus on the iron and steel sector (and other emitting industries) is insignificant compared to that of Fortum Oslo waste management plant and Norcem's cement plant. In the initial stages of CCS involvement, it makes economic sense to focus on the most feasible projects. However, this results in a lack of resources and innovation in industries that also need development, such as iron and steel, and this can act as a barrier and competitive disadvantage for the industry.

5.3.3. Fiscal Policy

Carbon Tax

Norway has a long history of ambitious climate policies. The main policy tool used in Norway is a carbon tax, introduced in 1991 (Bruvoll & Larsen, 2002). Bruvoll and Larsen (2002) concluded that the effect carbon tax had on emission reductions was merely modest. This was due to extensive tax exemptions for the process industry and inefficient differentiation of tax rates for specific sectors, such as iron and steel. The lack of CO_2 taxation within process industries eventually resulted in experimentation with a Norwegian CO_2 quota system, which fused with the EU ETS system in 2008 (Bruvoll & Dalen, 2009). Further analysis of the EU ETS system is given in section *5.3.5. Emission Trading Schemes*.

The Global CCS Institute (2020) argues, however, that the carbon tax has been the main driver of CCS development in Norway. The implementation of the carbon tax resulted in a significant value of CO_2, giving Norwegian industries an economic incentive to avoid CO_2 emissions. From an international perspective, the Global CCS Institute (2020) claims that the value of CO_2 emissions is currently insufficient and acts as one of the main barriers towards further development of CCS. As such, Norwegian iron and steel has less opportunity to learn from international technological advancements.

The Government's current long-term plans involve a threefold increase of the carbon tax by 2030. The Government believes that an increase from circa NOK 590 to 2000 of emitting one tonne of CO_2 equivalents will provide stronger incentives for industries to reduce their emissions. Theory provides strong evidence that a tax increase will lead to emissions reductions (Kolstad, 2011; Field & Field, 2017). A tax increase may therefore result in synergy effects within CCS for process industries as more market players invest in abatement technology, which can eventually be adapted by iron and steel at a lower cost. However, tax increases are usually not welcomed by voters, and a large tax increase may negatively impact the iron and steel sector by increasing industry costs as CCS adaptation may be slow, and harm international competitiveness.

National Budget

The CCS projects and initiatives established by the Norwegian Government have been possible through clear political goals and fiscal policy. However, national monetary investments in CO_2-management and CCS have stagnated over time, and the effect of this is evident on the development of CCS.

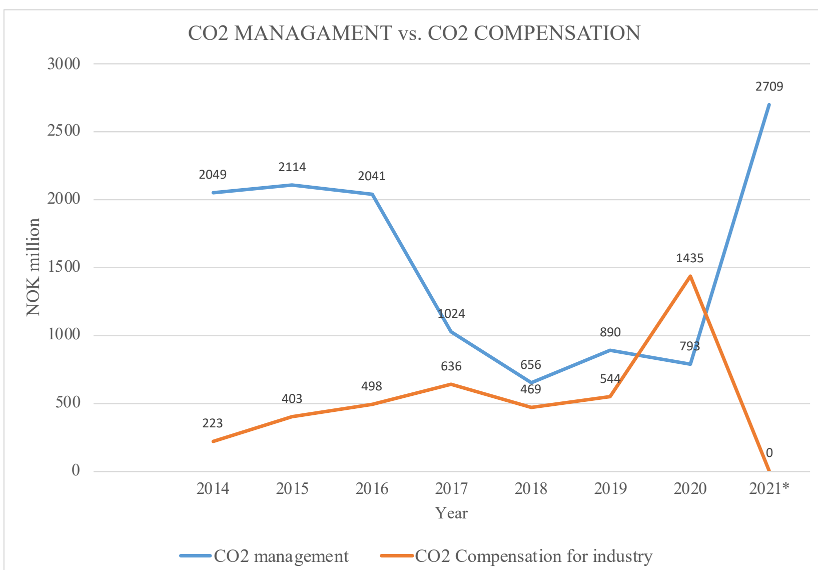

Figure 12: *Government Investments in CO_2 Management and Compensation. Derived from: National Accounts 2014-2020; National Budget 2021, sections 1840; 142074.*
2021 taken from National Budget*

Figure 12 (see Appendix C for specific budget line explanations) provides a historical overview of government investments derived from the Norwegian national accounts. It shows direct government investments towards CO_2 management and CO_2 compensation for process industry[5]. This data is included in the analysis to provide a clearer understanding of the Government's dedication towards CO_2 mitigation, over time. Total funding has fluctuated since 2014, and the rise in past couple of years is due to increased funding towards preventing carbon leakage through CO_2 compensations, rather than increasing government funding towards CO_2 management. This shows a lack of commitment towards direct CO_2 prevention since 2014, however, as of 2021, the Longship project will receive substantial monetary funding, as suggested by the 2021 budget.

Realisation of CCS requires excessive amounts of capital. Private investments are most likely to occur where direct injection of capital is provided through, for example, direct grant funding (Bui, et al., 2018; Global CCS Institute, 2020). Although the Government portrays evidence of interest in CCS, funding has been limited to this date. The lack of funding may be due to insufficient plans for establishing where monetary resources are most efficiently allocated. Even so, the Government and Norwegian Parliament has portrayed interest in CCS in the national budget since 2014, with realisation though the current Longship project (Ministry of Finance, 2020).

In the relative short-term, national and international funding is deemed essential for initiating large scale CCS investments. However, due to limited government budgets, public spending will not be sustainable in the long-term and is dependent on private investments (ZERO, 2013).

5.3.4. International Government Policy

Norway's involvement in several international climate legislations gives the Norwegian Government the opportunity to formulate international legislation and goals, and encourage neighbouring countries' involvement in CCS. To illustrate this, the Norwegian Government recently proposed that the EU increase its efforts, by which the European Commission has

[5] "CO_2 compensation" is financial compensation distributed to energy-intensive industry sectors, thereby iron and steel, that are exposed to carbon leakage. The compensation period is valid from 2013 – 2020 (Lovdata, 2013).

responded by suggesting increases in their emission reduction climate targets for 2030 from at least 40% to 55% (Norwegian Ministry of Petroleum and Energy, 2020). For CCS to become a competitive climate policy, international involvement is essential (United Nations, 2015; Norwegian Ministry of Petroleum and Energy, 2020). International cooperation may also create synergies that can enhance the Norwegian iron and steel sector's CCS capabilities.

Norway's strong global relations and political position within international networks is assumed to benefit Norway's investments in CCS, in the event that international interest and projects for CCS spikes (Norwegian Ministry of Petroleum and Energy, 2020). This is especially relevant for Norway if success in promoting conglomeration within the Longship project is achieved. Encouraging foreign participation will result in Norway being able to receive higher returns on their investments on CCS projects, critical for its long-term success (Norwegian Ministry of Petroleum and Energy, 2020). However, if demand for storage space from foreign participants increases significantly over time, this may negatively impact the iron and steel industry's storage possibilities, unless a binding contract with the Norwegian Government is made.

Other systems of tax incentives, such as the 45Q tax credit arrangement in the US, have also incentivised CCS initiatives. As an example, the US, who has the highest number of CCS facilities in the world, has implemented attractive tax credits (45Q tax) in connection with the opportunity to sell captured CO_2 to EOR. This has been two of the key drivers for CCS involvement in the US (Global CCS Institute, 2020; Pareto Securities, 2020). The effectiveness of the 45Q has been heavily debated as the 45Q goes against the goal of reducing overall industrial CO_2 production. Instead, the 45Q creates a demand for capturing CO_2 which consequently increases the demand for producing CO_2 (Madsen, 2021). As such, there is no incentive for finding solutions and developing technology that will result in decreased CO_2 production. The Norwegian Government and iron and steel sector currently have the opportunity to study international cases in order to improve their own efforts towards CCS and locate specific drivers for investments in CCS deployment.

5.3.5. Emission Trading Schemes

Economists argue that setting a price on emissions is the most cost-effective method of abating GHG (Borenstein, 2012). Carbon markets and the EU ETS are examples of this. As explained in section *2.3.1. EU Emissions Trading System (EU ETS)*, the EU ETS is essentially an international GHG mitigation strategy, aimed at reducing emissions at the lowest possible cost. The European Commission will continue with free allocation of emission allowances to support international competitiveness and limit carbon leakage. This may prove important for iron and steel during the low-carbon transition by providing adequate time for the development and adaptation of new CCS technologies. This also reduces the likelihood of iron and steel facilities located in Norway to move facilities to other counties with fewer policy restrictions, which is the principal of carbon leakage. Lastly, the European Commission aims to aid industries with financial investment challenges for emission reductions by initiating low-carbon funding mechanisms (European Commission, 2020). This may support the development of CCS within the Norwegian iron and steel industry, where Norwegian government funding lacks. This is particularly important from 2021, as the Norwegian Government's CO_2 compensation fund period has ended (as depicted in Figure 12).

Historically, the EU ETS has had moderate effect as low economic growth in Europe has resulted in high distribution of allowances (Norwegian Government, 2017). This created a surplus of emission allowances, resulting in low carbon prices. Due to low allowance prices and inefficient allocation of free allowances towards process industries, critics argue that the EU ETS is inefficiently reducing GHG and will fail to meet climate targets in the required time (Klemetsen, Rosendahl, & Jakobsen, 2016). Onarheim et al. (2015) argued that neither the current EU ETS price nor the future predictions of carbon prices was sufficient enough to stimulate the capital-intensive investments within CCS.

As mentioned in *5.2.3. Price of Carbon,* the price of carbon is trading at an all-time high. If carbon prices continue to rise, this will create stronger incentives for CO_2 mitigation investments, which will put pressure on Norwegian iron and steel. However, too high carbon prices may lead to decreased competitiveness for Norwegian iron and steel, when trading on the much larger international iron and steel industry.

5.3.6. Political and Regulatory Stability

Other identifiable drivers which may influence CCS within Norwegian iron and steel are variations in political and regulatory stability. As the above analysis portrays, the Norwegian Government has historically shown dedication towards environmentally cautious policies. Although government funding has fluctuated, it is reasonable to assume that political dedication towards environmentally friendly policies will continue, as this has historically been the case for all main Norwegian political parties the past decades (Lipponen, et al., 2017). Yet, it is difficult to predict how future policies may be formulated in the case of a new government constellation, which occurs every four years in Norway. Also, new government assessments may suggest that resources allocated towards other climate mitigating solutions results in improved cost-benefit analyses. Likewise, slow economic growth or recessions may threaten political stability towards CCS. An additional potential threat may be a change in government perspective from long-term to short-term, as this would likely result in government investments towards projects that provide short-term returns, in contrast to CCS projects. Still, the fundamental political support remains strong. Similarly, governmental change in other countries may also affect the development of CCS which may impact Norwegian iron and steel both negatively and positively.

With regard to regulatory stability, CCS development may be hindered due to existing regulations. An example of this was the London Protocol which initially held regulatory obstacles that restricted transboundary transportation of CO_2, making it impossible for countries to trade CO_2 with countries where CO_2 storage was possible. The London Protocol has now been modified to allow for international trade of CO_2, as long as the purpose of the trade is for geological storage (Global CCS Institute, 2020). This will act as a lesser barrier for countries without full-scale CCS infrastructure to capture CO_2, and acts as an advantage for the Norwegian Northern Lights project which can now accept international CO_2. Similar regulatory obstacles may delay development within CCS as regulatory change may take time and meet resistance by contract members.

5.3.7. Summary of Political Analysis

Clear commitment through regulations and frameworks

Currently, Norway has clear policies and frameworks that signal involvement within CCS on a general level. There is a lack of frameworks that are formulated specifically for the iron and steel industry. This acts as a barrier as clear frameworks are needed in order to improve CCS involvement. Also, many political incentives have resulted in research and demonstration projects, but few political incentives have resulted in actual implementation or commercial development.

Government involvement and the Longship Project

The Government's current dedication of resources towards Longship and other initiatives to meet NDC's and Paris Agreement goals may result in funding towards additional CCS projects, such as CCS development within iron and steel. However, the opposite effect may occur if resources are solely dedicated towards Longship, excluding other industries. Yet, the Longship project provides other opportunities that the iron and steel sector may adapt such as international cooperation, CCS networks and hubs, knowledge transfer, reduced risks and costs, and CO_2 storage opportunities. The expected synergy effects from Longship are numerous. With infrastructure in place and as costs decrease, the economic incentives of private investments in CCS will likely increase. This will invite more players onto the market, thereby creating a more commercially feasible environment for CCS. Risk and liability in connection to CCS projects will likely decrease if Longship proves its success.

Government involvement in CCS projects creates positive associations with CCS and shows true dedication towards CCS as a solution to solve climate change. Additionally, knowledge and useful data is developed, providing obvious opportunities. However, Longship focuses primarily on the most feasible industries within CCS. This will result in further cost reductions with regard to CCS within those specific industries. This is a barrier for iron and steel as iron and steel facilities lack readily available technology that can be adapted easily and at low costs.

Fiscal policy

Although the EU ETS has the goal of being an investment driver for CCS, the introduction of a higher carbon tax, in combination with EU ETS may decrease global competitiveness within iron and steel as long as CCS infrastructure or readily available technology is missing.

Political and regulatory stability

Political and regulatory stability will act as opportunities, whereas political and regulatory instability may act as barriers for iron and steel within CCS. Norwegian iron and steel has the advantage of a relatively stable government.

5.4. SOCIAL

This section analyses the identified social macroeconomic forces that are assumed to impact CCS within the Norwegian the iron and steel sector. First, the willingness to pay for CCS and drivers for social acceptance. Then, focus is dedicated towards Norway's educational level and CCS knowledge hubs.

5.4.1. Willingness to Pay for CCS

Facilities will experience significantly high costs in the scenario of installing CCS equipment. This increase will ultimately result in an increase in product prices for the end consumers. The degree to which consumers are willing to pay for this increase will depend on factors such as the consumer's reservation price, income effect and substitution effect (Hanemann, 1991). Studies conducted on the end user's willingness to pay for higher electricity prices due to CCS implementation revealed that there are groups of consumers who show altruistic support towards

CCS regardless of higher prices (Tcvetkov, Cherepovitsyn, & Fedoseev, 2019). The threat for CCS deployment lies with the consumers of iron and steel who are not willing to pay for the additional resources required for carbon-free metal production.

The capital-intensive nature of CCS projects heavily relies on funding. During demonstration projects or initial phases of CCS instalments, government funding is essential (Tcvetkov, Cherepovitsyn, & Fedoseev, 2019). In the long-term, as demonstration projects mature and technological feasibility improves, willingness to pay amongst institutional and private investors is expected to increase and eventually become the leading source of funding for CCS (Global CCS Institute, 2020). For such a reality, the economic feasibility of CCS must be proven to exist. As such, thriving capital markets may also act as an opportunity for CCS development in that sense private and public investments are made in the long-term to show evidence of support.

Willingness to pay largely correlates with the willingness to accept (Hanemann, 1991). The social acceptance related to CCS is therefore studied in the following section.

5.4.2. Social Acceptance

CCS and Environmental Awareness

For successful large-scale technological deployment, such as CCS, wide social acceptance is required (Gough & Mander, 2019). Studies by Pietzner et al., (2011) and Whitmarsh et al., (2019) show that Norway's public awareness of CCS is high compared to other European countries. This is largely due to Norway's involvement with CCS throughout the decades and generally high environmental awareness. Yet, the same study found that almost 40% of the Norwegian population (survey data collected between 2009-2010) did not recognise the topic of CCS. This shows that there is an opportunity to educate the population on CCS, as the lack of awareness may result in opposition for extensive CCS projects.

There is a lack of updated literature on the social perception of CCS in Norway. However, the Government's involvement in the Longship project and other environmental commitments have resulted in reoccurring media exposure on the topic of CCS in major national media houses. This makes it possible to assume that Norway's public awareness has increased since 2009/10. This awareness is likely accompanied with positive CCS associations as the Norwegian Government has displayed public support towards CCS as a realistic and efficient method towards climate mitigation goals, as is made evident in section *5.3. Politic*s (Tcvetkov, Cherepovitsyn, & Fedoseev, 2019). If, however, new studies showing that public opinion of CCS is negative, this may hinder investment decisions and slow down the development of CCS within Norwegian industries and the iron and steel sector.

An opportunity for CCS within Norwegian iron and steel is the current level of environmental awareness in Norway. The high level of environmental awareness results in environmental action being taken at governmental, corporate and municipal level. The strong evidence of CCS as a cost-effective solution (Bui, et al., 2018; IPCC, 2018; Norwegian Ministry of Petroleum and Energy, 2020) therefore acts as an opportunity towards CCS development. However, barriers also arise, as critics of CCS often argue that resources allocated towards CCS result in a lack of resources towards other climate change mitigation solutions, such as renewable energy and carbon-free industrial processes (Greenpeace, 2015; Pihkola, et al., 2017). Likewise, some communities have contradictory beliefs towards the science of global warming and may believe climate mitigation technologies to be without purpose.

Public Opinion

Researchers state that positive public opinion is important for CCS development because government and business decision-making will, to some degree, be influenced by public opinion (Bui, et al., 2018). Public opinion of CCS is therefore crucial for the future success of Norwegian CCS within iron and steel.

Recent studies show that support for CCS implementation in Norway, on a local and national level, receives high support amongst the Norwegian population (Whitmarsh, Xenias, & Jones, 2019). This positive public opinion may therefore influence further government policy related to CCS, and will unlikely result in drastic changes in government initiatives towards CCS in the case of electing a new government constellation. Likewise, iron and steel facilities do not need to fear that large investments in CCS will result in strong opposition from stakeholders. However, if public opinion is dramatically altered, governments and facilities may face challenges related to CCS investments. This shows that opportunities are created when public opinion is positive, whereas barriers are created when public opinion is negative.

Negative public CCS perceptions may derive from being influenced by sources perceived as trustworthy. Social acceptance of CCS therefore also depends on corporate and governmental opinion. For example, Greenpeace is a perceivably trustworthy environmental non-governmental organisation that believes CCS is a diversion rather than a long-term solution. Greenpeace (2015) argues that the main goal of CCS is to alleviate environmental pressures off heavily polluting facilities, resulting in further continuation of oil extraction and extending the dependence of fossil fuels. This is also the case for certain nations, such as Germany and the Netherlands, whose governments have repeatedly criticised CCS due to high risks and storage challenges, which has resulted in low public support for CCS (Tcvetkov, Cherepovitsyn, & Fedoseev, 2019; Whitmarsh, Xenias, & Jones, 2019). As such, organisations and governments that actively criticise CCS will lead to lower social acceptance (Tcvetkov, Cherepovitsyn, & Fedoseev, 2019).

Safety and Risk

Social acceptance of CCS may be reinforced though strengthened safety and risk assessments, communicated clearly and effectively to the public. Literature reviewed by Tcvetkov et al. (2019), reveal that there are mixed perceptions of how safe CCS solutions are, especially related to CO_2 storage and geological CO_2 leakage. Likewise, Whitmarsh et al. (2019) state that public acceptance of CCS is influenced by the unknown long-term safety concerns. As such, the safety concerns associated with CCS solutions may act as a barrier (Pihkola, et al., 2017). Low social acceptance towards CCS may also be due to previously failed attempts with CCS in Norway, such as Jens Stoltenberg's moon landing, as well as generally little understanding or education of the CCS technology.

5.4.3. Human Capital

Education

Pietzner et al.'s (2011) study revealed that survey respondents with a higher educational background showed a higher level of CCS awareness, signifying that education is an important driver under the social factor.

The general educational level within Norway is amongst the highest in the world. Taking advantage of this is a clear opportunity for Norwegian iron and steel in order to be pioneers of new CCS solutions to reduce costs and increase capture efficiency. For example, the iron and steel sector can initiate collaborations with educational institutes in order to develop interest and expertise at an earlier stage of education. Likewise, developing university-level courses on CCS may result in a more specialised future workforce. This is needed to meet the expected demand from future CCS projects within Norway. This also applies to curricula beyond the engineering and geological aspects of CCS, such as social studies and economics, as this is currently acting as a barrier. Achieving this may act as an opportunity by educating different schools of thought on CCS.

Employment

It is important to communicate the positive ripple effects that may adhere from CCS deployment, such as an increase in jobs. Reports published by SINTEF (2018) have estimated that full-scale infrastructure investments within CCS will create jobs both during and after construction, which benefits Norway's workforce. Yet, there are concerns that employment will mainly come from other countries (Norwegian Ministry of Petroleum and Energy, 2020).

5.4.4. CCS Ecosystems

Clusters and Hubs

As CCS ecosystems emerge, there will be an increased demand for knowledge and resource sharing. The development of CCS clusters and hubs can become a huge opportunity for the relatively small Norwegian iron and steel sector. CCS clusters are beneficial for risk and cost reductions by sharing investments in infrastructure and transport of carbon (Global CCS Institute, 2020). As discussed in section *5.2.1. Cost Components of CCS,* the geographical location of iron and steel facilities in Norway are closely located to sea transportation methods, which means that transportations costs may be shared between the industry.

Interdependency Risk

Although utilisation of economies of scale through clusters will significantly reduce risk and the unit cost of CO_2 storage and transport, specific infrastructure for iron and steel may result in challenges (Zapantis, Townsend, & Rassool, 2019). For example, if CO_2 storage facilities or CO_2 transport operators become inoperative, a high dependency on single distributers of such services may therefore be a barrier.

5.4.5. Summary of Social Analysis

Awareness and trust

As the general population becomes more educated on environmental issues and the topic of CCS becomes more widespread, the willingness to pay and social acceptance towards CCS solutions can have several positive synergies. One example is through an increase in private investments towards CCS related companies which will create a more stable market and further growth opportunities for CCS. Currently, the Norwegian population has a very positive attitude towards CCS, and environmental conscious solutions in general, which strengthens the opportunity for further CCS implementation. The problem lies in the trust towards CCS to be a reliable or even possible solution for climate change due to previously failed attempts with CCS.

Education and employment

Other issues arise when the public lacks knowledge and education. This is a long-term issue which effectively will negatively impact the development and deployment of CCS technology if there is no focus on CCS within education or in established polluting corporations. Education is needed to provide better public understanding and future interest in CCS. Simultaneously, the implementation of CCS should be viewed as a means of job creation in contrast to job destruction.

Clusters and hubs

Cooperation between polluting sectors and developers of CCS technology can create important expansion opportunities for CCS through amalgamation of infrastructure and knowledge sharing. This is especially true for iron and steel, as collaborations will strengthen their competitiveness on the international market.

5.5. ENVIRONMENTAL

This section studies the environmental risks associated with CCS and the risks that may arise if CCS fails to be implemented. These environmental drivers emphasize the significant uncertainties connected to CCS.

5.5.1. Environmental Risks with CCS

An environmental risk largely discussed by critics of CCS (see also section *5.4.2. Social Acceptance*) is related to the potential risk of geological CO_2 leakage. Although the risk of leakage from a storage site is extremely small, it is not non-existent (Global CCS Institute, 2020). To assess the total risk, it is useful to study the consequences of leakage and the probability of leakage occurring.

In the event that carbon leaks from an offshore storage site through, for example, fractures in the rock formation, CO_2 can migrate laterally or up towards the surface of the water. Depending on the rate of CO_2 leakage, it can then either dissolve into the water, or reach the ocean surface (IPCC, 2005). If the CO_2 dissolves into the water, it can be corrosive to the ocean floor and harmful to marine ecosystems. If larger amounts of CO_2 reach the surface layer and surrounding atmosphere, it can be dangerous to offshore platform workers, as well as other humans, animals and nature. Although CO_2 is a natural component of air, it is hazardous in excessive amounts. Therefore, an episodic and localised leakage (for example due to an earthquake), will have more of an impact per unit CO_2 released than minor continuous seepage from different points (IPCC, 2005).

When it comes to the probability of leakage, IPCC (2005) find that more than 99% of the CO_2 stored is expected to be retained for the first 1000 years. However, Greenpeace (2008) argue that these numbers only apply for storage location that are properly selected, designed and managed. Nevertheless, the IPCC (2005) implies that although the consequences of a potential leak can be severe, the probability of this occurring is small enough to be considered safe. In Norway, safe storage has been demonstrated beneath the seabed on the Norwegian continental shelf since as early as 1996 (Norwegian Ministry of Petroleum and Energy, 2020). The continental shelf is extensively explored, and reservoir simulations and monitoring programmes have been utilised to check that storing CO_2 is safe (Norwegian Ministry of Petroleum and Energy, 2020).

Another closely related environmental risk associated with the CCS storage component, relates to routine operation of the facility and injection well maintenance (IPCC, 2005). As CCS is still a relatively novel technology, countries have limited knowledge of managing CO_2 injection for the explicit purpose of reducing GHG (IPCC, 2005). However, as mentioned, Norway already has operational CO_2 storage facilities (Sleipner and Snøhvit), and is committed to further development though Northern Lights (Global CCS Institute, 2020). Norway also has relevant knowledge and experience from closely related operations in oil and gas industries (Norwegian Ministry of Petroleum and Energy, 2020), and is considered one of few countries to have sufficient geological resources for storage and full-scale CCS deployment (Consoli, 2018). Such a foundation can be an argument for why Norway is well positioned to handle operation and maintenance of new storage facilities.

Finally, a third environmental risk is associated with the argument that CCS prolongs the fossil fuel industry, and the consequences of this. With increased governmental support and focus directed towards CCS, less economic resources and political attentional are being invested in renewables (Emily Rochon, et al., 2008). Although Norway produces almost all its electricity using renewable energy, petroleum-based research still receives almost five times more funding than renewable energy research (Emily Rochon, et al., 2008). Furthermore, in the eyes of funding, CCS is considered a part of renewable energy research (Emily Rochon, et al., 2008). However, according to Prosess21 (2021), renewables alone are unable to realise climate change mitigation or reverse the current course.

5.5.2. Environmental Risks without CCS

Without CCS technology, global warming will continue to impact natural and human ecosystems, both directly and indirectly (IPCC, 2018). In addition, global energy demand is expected to grow as a result of increasing populations and quality of living (Norsk Industri, 2016). Shell (2013) believe that renewables can account for up to only 40% of the global energy demand by 2060. This highlights the need for fossil fuels to sustain increased demand, but with a reduced carbon footprint. Furthermore, the production and maintenance of renewables in themselves are reliant on fossil fuels (Prosess21, 2021). Finally, the Global CCS Institute (2020) support a combined approach by saying that a renewables-only approach will disrupt the production of vital fossil fuel goods, such as medicine.

In addition to an increased demand for energy on a national and global scale, Norsk Industri (2016) predict an increase in the demand for low-carbon process industry products. This means that value must be created at the same time as emissions are reduced. If this is not possible through technologies such as CCS, the alternative is that industrial plants will need to be shut down. This risks carbon leakage through moved production, thereby increasing overall global carbon emissions (Norsk Industri, 2016). The Norwegian process industry is unique in that it is highly energy efficient, and well positioned to meet demands in a low-emission society with CCS (Norsk Industri, 2016).

5.5.3. Summary of Environmental Analysis

Continued use of fossil fuels

Although associated with critique, an opportunity with CCS is that it allows for the continued use of fossil fuels, but with a dampened effect on the environment. This is important when a predicted increase in energy demand and population, is combined with the goal of maintaining value creation in a low-emission society.

Pre-existing experience

Furthermore, Norway's well-explored continental shelf, former experience with CO_2 storage and industrial knowledge from the petroleum industry, makes Norway well-equipped to handle the operation and maintenance of new storage facilities. It is also reasonable to assume that this provides valuable insight when assessing and selecting new geological locations for ocean storage.

Risk of leakage

A significant barrier to CCS is the potential risk of leakage. Since the probability of this is very small, storage is considered safe for the purpose of this thesis. Norway's aforementioned experience is a factor that hopefully decreases this probability even further. Another interesting question is who should be liable for the cost of leakage, should such an event occur. This will be discussed in Chapter *5.6. Legal*.

Opportunity cost

A final drawback of CCS is that less investment can be directed to other climate solutions such as renewable energy. This thesis does not focus too heavily on the advantages and disadvantages of CCS compared to other emission-mitigating solutions, as there are several. However, there is consensus in that CCS is a necessary next step, and the environmental benefits of CCS seem to outweigh the environmental risks associated with CCS.

5.6. LEGAL

This section will take a closer look at the CCS-specific legislative and regulatory frameworks in Norway today. If weak legal frameworks surround CCS, it can lead to uncertainty about government commitment and reduce the urgency for facilities to implement the technology.

The Global CCS Institute (2018) developed an indicator to compare and assess the status of national legal and regulatory regimes for CCS. A global overview of the results can be seen below. At the time of this assessment, Norway scored in Band B with a total CCS Legal and Regulatory indicator score of 40 out of 87.

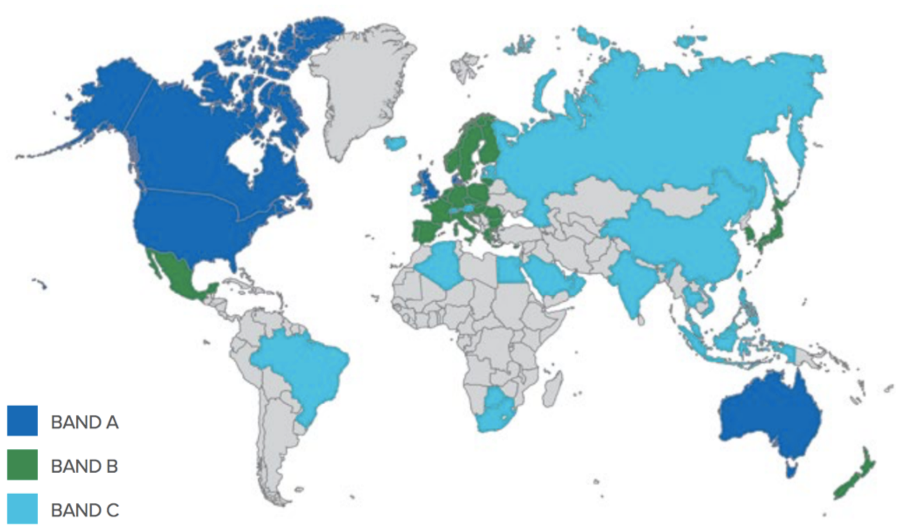

Figure 13: *Legal and Regulatory Indicator - Global Rank Map. Source: (Havercroft, 2018)*

Although no country-specific conclusions were drawn, the report states that despite continued development of demonstration and commercial-scale projects, limited progress had been made in terms of legislative activity for the technology (Havercroft, 2018). To understand the extent this applies to Norway, an overview of the CCS-specific frameworks will follow.

CCS Directive

A central legislative framework that Norway is subject to is the 2009 EU CO_2 Storage Directive, also known as the CCS Directive. This focuses on the storage component of CCS, and specifies extensive requirements that must be met before accepting a storage site. This Directive dictates that no geological storage is possible without a storage permit to confirm that prior analysis has been made into the risk of leakage and damage to human health and the environment (European Commission, n.d.). The Directive covers additional aspects such as closure and post-closure obligations (e.g., monitoring), demands financial security from the operator to prove that adequate funding exists to cover the cost of obligations arising under the permit, and makes sure that third-parties (potential users) gain access to storage sites and transport networks (DIRECTIVE 2009/31/EC, 2009). In addition, it suggests that a transfer of responsibility from the operator to a competent authority can occur after a minimum period of 20 years, given that certain criteria is met (DIRECTIVE 2009/31/EC, 2009). To ensure permanent closure, a financial contribution is also required from the operator to the competent authority before this transfer can take place, to cover anticipated future costs of storage (DIRECTIVE 2009/31/EC, 2009).

National Regulations

Responsibility for upholding different parts of the CCS Directive in Norway is delegated to the Ministry of Petroleum and Energy (MPE), the Ministry of Labour and Social Affairs (MoL), and the Ministry of Climate and Environment (Norwegian Ministry of Petroleum and Energy, 2020). The MPE is given authority over exploration and exploitation of subsea geological formations with respect to transport and storage, and the use of these formations for CO_2 storage (Henriksen &

Besche, 2012). Those considering conducting storage activities must apply for surveying, exploration and exploitation licences from the MPE (Norwegian Ministry of Petroleum and Energy, 2017). The MoL regulates safety issues related to transport and storage of CO_2 to the subsea geological formations on the continental shelf (Henriksen & Besche, 2012). In February 2020, the Petroleum Safety Authority (under the MoL), issued new regulations regarding CO_2 safety, including general requirements for material and information, the use of recognised standards, design and use of facilities, documentation and reporting, and the need for consent for certain activities (Petroleum Safety Authority, 2020). Finally, the Ministry of Climate and Environment handles environmental issues, and jointly addresses the financial guarantees submitted by the potential operator together with the MPE (Agerup, n.d.).

If a licensee chooses to develop a subsea reservoir into a location for injection and storage of CO_2, copies of a development and operation plan, impact assessment, and safety and work environment plan shall be submitted to all three ministries (Norwegian Ministry of Petroleum and Energy, 2017). Finally, consent for injection and storage of CO_2 is given by the MPE and MoL (Norwegian Ministry of Petroleum and Energy, 2017). Transfer of responsibility from the operator to the MPE can occur after a minimum of 20 years, unless the MPE is convinced that the stored CO_2 will remain permanently enclosed before this time (Norwegian Ministry of Petroleum and Energy, 2017). A financial contribution shall also be made by the operator to the state, as stated by the CCS Directive, which should be large enough to cover 30 years' worth of anticipated monitoring expenses (Norwegian Ministry of Petroleum and Energy, 2017).

In terms of liability of pollution damage caused by discharges or CO_2 emissions from the storage site, regulation states that the licensee is liable regardless of guilt. The responsibility can only be reduced if the damage is caused by unavoidable circumstances (e.g., natural occurrence or act of war) (Norwegian Ministry of Petroleum and Energy, 2017). The MPE also requires that licensees ensure reasonable insurance coverage for all activities conducted in accordance with the regulations (Norwegian Ministry of Petroleum and Energy, 2017).

Overall, although these three ministries together make up a regulatory framework for transport and storage of CO_2, Norway does not have a streamlined CCS framework. Instead, it considers the development and deployment of CCS on a case-to-case basis (Baker & McKenzie, 2009). It is also understood that various CCS activities will be subject to general Norwegian laws, but the extent of this depends on case-specific circumstances (Henriksen & Besche, 2012). This can result in confusion for the case facilities, in that sense there are no clear guidelines of which general laws would be applicable.

5.6.1. Summary of Legal Analysis

Research suggests that the legislative and regulatory status for CCS in Norway is somewhat limited. This can confirm the findings given by the Global CCS Institute (2018). It appears that the majority of regulations in place today are mainly directed towards CO_2 storage, with less focus on the capture and transport components. In addition, it is assumed that CCS will fall under general Norwegian laws, but which laws that apply to CCS and to what degree can be considered confusing for facilities considering implementation. Since the deployment of CCS is currently considered on a case-to-case basis, making specific CCS laws could signal greater commitment and promise. The main concern of many is also the aspect of liability. With a high degree of liability, less incentive exists to establish new storage sites, which in turn affects CO_2 storage capacity, and potential cross-risk in the entire CCS chain (see section *5.4.4. CCS Ecosystems*). Risk sharing laws of CO_2 storage liability could potentially alleviate this problem.

5.7. END OF CHAPTER 5

This concludes the PESTEL macroenvironmental analysis of CCS within the Norwegian iron and steel sector. Based on these findings, Chapter 6 proceeds by analysing governmental policies that can aid CCS development. All findings from Chapters 5 and 6 are then evaluated and concluded in Chapter 7.

6. Analysis of Government Policies

On the basis of the macroenvironmental analysis presented above, the following chapter will analyse potential environmental policies that may encourage development and deployment of CCS in the Norwegian iron and steel sector. This is done to discuss the second research question.

This chapter assumes CCS to be an essential technology for reducing emissions from Norwegian production. In order to explore to what extent policies must be implemented, this analysis will be grounded in the environmental policies described in section *3.3. Environmental Policies*.

6.1.1. Decentralised Policies

Liability Laws

Liability laws make a facility liable for environmental damages caused. Liability laws can be further divided into *strict liability* and *negligence*.

Liability laws and compensation payment from the individual facilities can work in the same way as an emission tax. Liability laws can also be placed on operators of CO_2 storage to increase the availability of infrastructure. According to the IEA (2013), governments cannot focus on CO_2 capture without also giving equal attention to CO_2 storage. This is because for the iron and steel sector to adopt CCS, they must know that a commercial model exists for CO_2 transport and storage.

Liability laws can be used to reduce the concerns associated with who is financially liable for leakage during transport and storage. Today, the regulations regarding liability for pollution damage are strict. Forming a clear differentiation between strict liability and negligence may help ease this concern. This would create a form of risk-sharing system between the operator and government. When monitoring is difficult, this policy ensures that operators take appropriate steps to prevent storage leakage, while at the same time the operators are not punished beyond what is reasonable.

A challenge with liability laws is that it can be difficult to measure damage and fault, thereby also making it difficult to assign blame and determine the exact amount of compensation required from each party. This implies that although more lenient liability laws could lead to more operators supplying transport and storage infrastructure, it may be difficult to achieve in practice due to large-scale and technically complicated cases.

Voluntary Action

Voluntary action encourages facilities to engage in pollution control without any formal regulations. Two social forces that can lead to voluntary action are *moral suasion* and *informal community pressure.*

To appeal to a facility's sense of morals, the Government needs to clearly define the benefits of utilising CCS to reduce emissions. Establishing a simple, stable and well-functioning market or networking platform for CCS components would also make it simpler for facilities (potential users) and suppliers (operators) to connect. This would lower the hurdles linked to voluntary action. A risk of this approach is, however, 'moral free-riding', where less morally sensitive facilities enjoy the benefits of other's commitment to carbon capture.

Using informal community pressure is perhaps an even more effective tool than moral suasion. Norway has a good foundation for using this decentralised policy approach, as the Norwegian population is already environmentally conscious (see section *5.4.2. Social Acceptance*). By making facilities' emission data more easily and readily available for the general public, public awareness and interest can be increased, further pressuring CCS employment. This way, facilities may feel more conscious of own emissions, and voluntarily enforce steps to abate for the sake of maintaining their reputation. Information is thus a powerful tool in this scenario.

6.1.2. Command-and-Control

Emission Standards

An emission standard command-and-control policy requires facilities to limit themselves to a fixed level or quantity of emissions. To make sure the standard is being met by each of the case facilities, the Government could use inspections, monitoring, sanctions, fines or other penalties. By setting an emission standard, the Government could ensure that the climate goals will be met. It is also a way of demanding removal, versus continuing to allow facilities to emit and simply pay for extra carbon credits.

There are also disadvantages with using this method to incentivise use of CCS. First, the Government has no control over what abatement techniques are being used. Second, this method would force facilities to reduce their emissions to a given limit, without incentivising abatement beyond this. It is also difficult to know where to set this limit, and whether this limit should be the same for each of the case facilities. If the limit is set too low (i.e., the policy is too strict), this could increase the risk of carbon leakage. Finally, this policy approach is dependent on a high degree of monitoring, which would have to be conducted by different regional authorities, since the case facilities are spread across the country. This could potentially lead to unsatisfactory monitoring in certain regions, or even bribery leading to data fabrication of CO_2 emissions.

Technology Standards

Another command-and-control policy is technology standards. Here, the Government could simply demand that facilities install CCS within a certain timeframe. Benefits of this approach include that it ensures quick adoption, and that it would apply uniformly across all of the iron and steel facilities. Apart from the time and resources that would have to go to enforcement and inspection, this approach would require less resources from the Government in terms of monetary aid and other situation-specific policies.

A drawback of a universal technology standard is, however, that it could be politically unpopular. This is because it does not take into account differences in emission levels, and would treat all facilities the same. A facility emitting less than other facilities may consider this unfair. Another serious drawback is that this approach would eliminate any incentive for further R&D. If facilities were required to use today's CCS technology, there would be no reward for finding superior approaches or improving the existing technology. CCS development would halt, and as would the economic, technological and environmental benefits innovation would bring.

6.1.3. Incentive-Based Policies

Emission Charges (Taxes)

Emission taxes are a policy that would require the case facilities to pay a certain charge for every unit of emission released. As discussed in section *5.3.3. Fiscal Policy*, Norway has been using carbon taxes since 1991. It was also found that extensive tax exemptions are given to the process industry, which means that the tax has only contributed to modest reductions. Increasing this tax and making it applicable to all sectors can give facilities increased economic incentive to avoid CO_2 emissions.

The Norwegian Government intends to increase the carbon tax by 2030, which is positive for reducing emissions. In addition to motivating facilities to cut emissions, this would generate government revenue that could in turn be used to further stimulate CCS development. In contrast to a technology standard which hinders R&D, facilities would now have an incentive to continue researching for better and more cost-effective ways to improve capture technology. This is because a facility's R&D efforts would lead to a greater reduction in their total pollution control-related costs (abatement cost + tax payments) (Field & Field, 2017). Whether this policy directly results in increased use of CCS solutions within the case facilities is less certain. CC technology in Norway is also produced by external suppliers and not the iron and steel facilities themselves, which makes this push-for-innovation argument less applicable for the iron and steel sector.

Similar to the command-and-control standards, a relevant question is at what rate to set the emission tax. If the rate is too low, it is possible that facilities will not consider it worthwhile to conduct R&D, locate and install CCS, or operate and maintain the technology, as opposed to simply paying for carbon credits. If the rate is too high, the Government could risk losing voters over a politically unpopular decision, or risk carbon leakage. This policy also involves a response delay, as facilities need time to respond to the tax rate before the Government knows whether the policy has been effective or if the tax needs to be adjusted.

Subsidies

Instead of forceful policies for CCS investments through direct regulations in terms of emissions quantities and use of technology, or higher CO_2 prices through taxation, the Norwegian Government can also attempt to pull CCS investments through subsidisation. Subsidisation can take several forms. For example, it can be given directly to iron and steel facilities when installing CC technology, to producers of CC technology, to suppliers of transport and storage, or to R&D institutes. Subsidisation can include paying facilities per unit of emissions reduced, capital grants, tax exemptions or cost-sharing plans.

Facilities may be motivated to install CCS if awarded with financial returns for every unit (e.g., tonne) of emissions reduced. An example is the 45Q tax credit in the US discussed in section *5.3.4. International Government Policy*. While this approach has the potential of giving the desired effect and has resulted in CCS installations in the US, the Government has little influence over what abatement techniques are used by polluting facilities. In addition, it can risk leading to perverse incentives. That is, if facilities know that profits can be made by capturing more CO_2, it gives financial incentives to produce more CO_2.

Financial support in the form of capital grants or tax exemptions can alternatively be given to facilities for the procurement and installation of CC technology. This would help bridge the gap between the price of CO_2 and the MAC curve (see section Figure 11 under *5.2.4. Socioeconomic*

Emission Level) during the ramp up stage. The IEA (2013) argue that government focus should be on demonstration and early development, and this approach encourages first-of-a-kind projects. Once the MAC curve falls by natural means (such as technological development or more users), financial aid can be reduced.

Bridging the gap between the price of CO_2 and the MAC curve can also be done by providing grants or tax exemptions to CC suppliers. This way, the technology can be sold to polluting facilities at a lower cost. This approach would be less specific to the iron and steel sector, but would allow for cheaper installation across all industries. It would, nevertheless, benefit the iron and steel sector, in that it could improve knowledge-sharing, infrastructure-related insights and allow for transport sharing between clusters.

Next, by creating cost-sharing plans with potential operators of transport and storage, it could help mitigate the financial risk related to potential underutilisation during the ramp up years (see section *5.2.1. Cost Components of CCS*). It is possible that more actors of transport and storage will enter the market if it is believed it is possible to hedge oneself against less demand during the first years, and reap the benefits of increased demand in the near future. If this approach is used in combination with the *negligence* liability law discussed earlier, operators are spared much of the financial risk connected to both underutilisation and potential leakage. If the Government increases the availability of infrastructure by encouraging more suppliers of transport and storage, this reduces cross-chain interdependency risk for the iron and steel case facilities (see section *5.4.4. CCS Ecosystems*).

Finally, subsidisation can also be given to R&D institutes. This would help accelerate the development of technology, possibly bringing down the MAC curve at a faster pace. This could also help increase the possibilities for retrofitting, which is a necessary requirement for the iron and steel case facilities.

A major drawback of subsidisation as an environmental policy is that it involves a trade-off. Critics of CCS, such as Greenpeace (2008), highlighted this by stating that investments towards CCS is resources lost on renewables. Subsidisation requires resources from the national budget, which implies that less government revenue is available to spend on other aspects of society. This may include investment in renewables, but also education, infrastructure, health systems, and more. Another potential risk arises when actors believe there is an opportunity for financial gain from subsidies upon entering the iron and steel sector. If more actors enter the market, total emissions will increase, rather than decrease, leading to inefficiencies in the market.

Market-Based Trading Systems

The EU ETS is an example of a cap-and-trade market-based trading system, which Norway is subject to. This has proven to be an effective policy in allocating emissions to polluters who have high costs associated with abatement. As the Market Stability Reserve now removes excess supply of allowances, the future carbon price should be less volatile. An advantage of this policy is that a centralised agency can decide the annual rate at which the quantity of allowances is reduced. This is currently being increased from 1.7% to 2.2%. While this policy reduces the risk of carbon leakage as polluters are given time to adjust to fewer allowances, it is slow at showing results. Critics therefore fear that this policy is not sufficient on its own to meet the climate goals, which acts as a major disadvantage. Likewise, this policy may decrease Norwegian iron and steel's global competitiveness as CCS retrofitting and CCS infrastructure-technology is not currently in place.

6.1.4. Additional Policies

The policies above are largely aimed at accelerating short-run changes in CCS utilisation. One important aspect brought up in section *5.4.3. Human Capital* was the role of education. While short-run development should be prioritised first, it is also important for the Government to invest in high-quality CCS-related education. This raises awareness amongst futures scholars, politicians and leaders, hopefully contributing to continued use of capture technology over time. CCS engagement can also be created by, for example, inviting students to participate in projects at the Norwegian CCS Research Centre or Test Centre Mongstad.

Finally, as government funding and commitment was also found to vary over the years in section *5.3.3. Fiscal Policy*, the Government could consider signing long-term agreements with the EU to avoid CCS-related setbacks in the case of a change in government constellation.

6.2. END OF CHAPTER 6

Chapter 6 has reviewed a range of environmental policies that the Government could employ to accelerate CCS implementation. These policies will be evaluated in the following chapter.

7. Discussion

Previous chapters have analysed opportunities and barriers, and specific government policies applicable to the iron and steel sector. The findings are discussed and evaluated in this chapter.

7.1. PESTEL RESULTS

In terms of opportunities, there are clearly positive prospects in relation to the Government's involvement in constructing full-scale CCS infrastructure. The case facilities can potentially be integrated to this CCS infrastructure due to their geographical locations. Through well-defined delegation of authorities and storage potential, this provides reduced risk, uncertainties and possible cost reductions for the case facilities. This is further supported through trustworthy and stable Norwegian political and corporate institutions, creating a leeway for developing CCS ecosystems though clusters and hubs. The fact that education and environmental awareness is robust increases the chances of amplified demand for low-emission goods, thus increasing the willingness to pay for environmental goods. Also, the ability to retrofit CCS technology in facilities contributes to reducing CCS barriers for energy-intensive and fuel-dependent industries. Investigations prove that it is technologically possible to retrofit CCS in existing case facilities. Moreover, Norwegian CCS research centres prove that n^{th}-of-a-kind CCS technology will result in reduced costs and risk. Finally, the recent developments in increased carbon prices provides interesting prospects for future expansion possibilities for abatement technology, such as CCS.

Despite obvious political commitment, a lack of sector-specific incentives and funding is apparent. A main barrier is the current insufficient value of carbon emissions by which the abatement cost of CO_2 avoided exceeds the price of carbon. Economists have already concluded that setting a sufficient value on emissions is the most cost-effective method of emission reduction, suggesting that increasing the value on carbon would promote investments in CCS. Likewise, the profound complexity of customised CCS technology obstructs accurate cost estimations, as well as implementation. Simultaneously, the lack of knowledge and trust in CCS technology hinders current implementation. Insufficient emphasis on the legal aspects concerning capture, transport and storage also increases cross-chain risks, as full-scale CCS needs to be fully functional for success. Subsequently, the barriers may prove so significant that the consequences outweigh the benefits, resulting in a justifiable trade-off from investments in CCS to alternative abatement technologies.

To what extent these drivers reflect economic and political support for the implementation of CCS in Norwegian iron and steel is dependent on the pending obliteration of the most significant barriers, and especially how technical and cost prospects mature. The PESTEL framework does not indicate numerical weighing of each factor. With the current findings from the PESTEL results, the authors therefore assume that the opportunities compensate for the barriers in the case of implementing CCS. The main findings are also summarised in Figure 14.

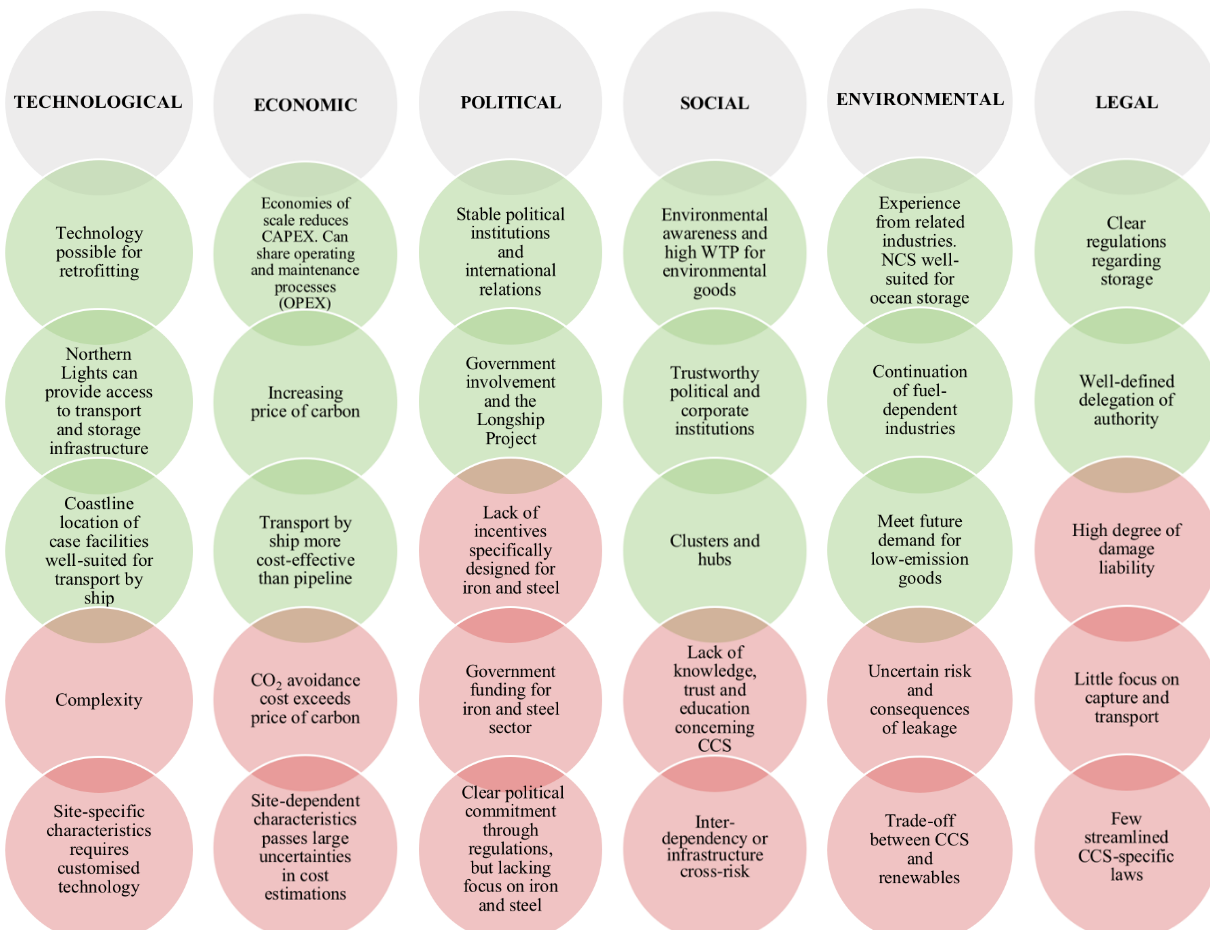

Figure 14: *Main Opportunities and Barriers from PESTEL Analysis*

7.2. POLICY EVALUATION

Which policies are best suited depend on what phase overall CCS progress is in. Today, a finite number of CCS projects are operational. For this reason, the Government is currently amid a CCS ramp up stage. Policies should therefore be focused on achieving more widespread development and deployment of CCS across industries, including iron and steel.

Making the public aware of the importance of CCS is a huge first step in incentivising deployment. This is because it can trigger voluntary action, despite the fact that CCS is not presently cost-competitive. Likewise, it can encourage small-scale private investments, leading to more stable financial markets for CCS solutions. Despite the costs that would go towards press releases, media coverage or other information channels, this approach requires almost no government resources. The aim is to use information as a tool to pressure facilities into using CCS. According to Field & Field (2017), policymakers often underestimate the effect of internet connectedness, social media, public morality and civic virtue. In addition, an environmental policy relying on voluntary action has the potential to create widespread spillover effects. That is, the more facilities that invest in CCS, the more the remaining facilities will feel pressured to do so as well.

An issue that remains with voluntary action is *first-mover disadvantage*. First-of-a-kind projects are more costly due to the lack of experience and undeveloped technology. The Government therefore also needs to employ policies that make the technology more commercially viable. Here, subsidisation can be a useful instrument. To avoid perverse incentives linked to payment per unit CO_2 reduced, subsidisation should be given in the form of capital grants or tax exceptions for CCS. This also defines which specific technology the subsidisation is for, providing the Government with some control over the abatement technologies being used. A drawback of this method, which needs to be considered, is that it extracts government revenue from other causes. However, it is possible to use subsidisation for a limited time to encourage use of CCS during the ramp up phase, until the MAC curve falls by natural means. This way, first-movers are rewarded, while second-movers enter the market simply because this makes sense economically.

In addition to subsidising the installation and implementation of CCS for first-movers, the Government could provide capital grants to R&D institutions. This would hopefully contribute to accelerating technological developments and make retrofitting technology cheaper, which would bring the MAC curve down faster. Once the marginal cost of abatement equals the price of carbon, facilities will favour CCS. Subsidising CCS in this way also signals the Government's support for the technology. If claims are made about the importance of CCS to the public in an attempt to stimulate voluntary action, it is important for the Government to show their commitment as well.

With regard to carbon taxes already in place in Norway today, fewer exemptions should be given. If all sectors are to reduce their emissions, all sectors should be subject to emissions-sanctions. The Norwegian Government has already expressed intentions to increase the carbon taxes. While doing so, it is important that taxes are not set too high. The iron and steel sector has already decreased in size in Norway over the years, and the goal is not for the production for remaining facilities to be shut down or move. Furthermore, if carbon taxes are applied in combination with subsidisation, it is possible that investing in CCS becomes more appealing, as the facility's total pollution control-related costs increases from pre-existing MAC to MAC plus the tax payment. This effect is amplified with continued increase in carbon prices in the EU ETS.

As stated by the IEA (2013), *"CCS deployment can only move as quickly as the slowest developing part of the CCS process."* This means that in order to accelerate deployment of CCS in the iron and steel sector, the Government also needs to turn its attention towards the transport and storage components. Here, well-defined liability laws that promote risk-sharing in unavoidable leakage cases can help encourage operators to take on the financial risk of supplying transport and storage. As it is difficult to assign blame in such technically complex cases, the Government would need to ensure that significant monitoring systems are implemented.

Finally, command-and-control policies are effective in that the Government can simply demand the desired outcome. However, a major disadvantage is that facilities have no incentive to go beyond the set standard, and no incentive to continue to perform R&D and innovate. In addition, difficulties arise in terms of where to set the standards, whether to set uniform standards and the economics of enforcement. Finally, setting emission or technology standards are forceful policies. For this reason, the next government constellation may want to appeal to voters by removing such unpopular regulations, which would be inefficient for environmental progress. This study therefore considers these policies as poor methods for encouraging use of CCS.

Overall, it is clearly not possible to apply one policy in isolation and different policies should be used in combination to make CCS more attractive. Applying decentralised policies in combination with incentive-based policies, creates less risk and fewer economic challenges for facilities to employ CCS as first-movers. Utilisation of such policies, as opposed to stricter command-and-control policies, also reduces the risk of carbon leakage. Today, government focus should be directed towards policies that help accelerate CCS development and deployment in the ramp up phase. This can justify increased government expenditure in the form of subsidisation, which can be reduced as CCS becomes more widespread. However, to facilitate future CCS engagement, the Government should expedite its commitment by investing in relevant education and by committing to long-term agreements.

8. Conclusion

This thesis has explored the following research questions in an attempt to evaluate CCS as a means for the iron and steel sector to reach the current environmental goals:

To what extent does the economic and political environment support the implementation of CCS in the Norwegian iron and steel sector?

To what extent are government policies necessary in order to accelerate the development and deployment of CCS in the Norwegian iron and steel sector?

The thesis was formed as a pragmatic, exploratory case study. This entailed reviewing sufficient quantities of data to deliver conclusions that may impact future organisational and political practises. This provided central insights into the economic and political support environment for CCS implementation. Currently, economic conditions do not incentivise the instalment of CCS for the iron and steel sector. Yet, price prospects suggest that the value of CO_2 may increase to better represent the damages caused by emissions. The political environment for CCS is generally strong, though attention on the iron and steel sector lacks. Thus, the political environment must be adjusted to effectively assist the implementation of CCS in the iron and steel sector.

The thesis' research reveals that financial funding and government support policies would greatly aid CCS progression. As such, decentralised and incentive-based policies should be implemented, by which a combination of policies are necessary to achieve the desired environmental goals.

The degree to which these results reflect the true setting for CCS in the iron and steel sector depend on the assumptions set for this thesis and future progress. Nevertheless, the analysis suggests that Norway has the potential to become a leading user of the technology. Therefore, the thesis concludes that there is significant value in the Norwegian Government aiding the acceleration of CCS development in all industry sectors, large and small.

9. Limitations and Future Research

9.1. LIMITATIONS TO THIS STUDY

When conducting this thesis, some simplifications and assumptions have been made that could act as limitations to the study.

Use of Industry Average Costs

The industry average CO_2 avoidance cost that was used as the basis for the total cost calculations and analysis in *5.2.2. CO_2 Avoidance Cost* and *5.2.3. Socioeconomic Emission Level*, is likely lower than it would be in reality. This is because many of the case studies used to find the industry average assumed n^{th}-of-a-kind facilities or mature technology. Some of the cost estimations were projections for future costs, and may therefore have assumed more rapid cost development than has actually occurred. If this is the case, a larger gap currently exists between the marginal abatement cost and the price of carbon. This would mean that more government support would be needed in terms of both R&D and widespread deployment. This could result in the CCS technology being less worthwhile than is estimated in this study, due to the increased opportunity costs created for the Government.

In addition, the use of an industry average is a highly simplified method of calculating the CO_2 avoidance cost. This assumes that each facility is faced with the same costs, which is not representative. In reality, costs will be extremely case-specific, which is why so much uncertainty is already associated with the technology.

Evaluation of PESTEL Results

The PESTEL framework does not provide measurements or numerical implications for evaluating the identified opportunities and barriers. As such, the theory does not indicate how to weigh an opportunity against a barrier. Consequently, assumptions have been made about the importance of different drivers for the iron and steel sector. Researcher bias may lead to false impressions of the identified opportunities outweighing the identified threats. As such, the discussion of government policies could be based on false conclusions and assumptions about the market, without adequate quantitative data to inform where support should be directed.

Data Sources

The thesis primarily uses secondary data. This is a limitation because the sources used can be either outdated or written specifically for other case studies. Supplementary primary data could add insight into emission quantities, specific cost components and the overall iron and steel sector. Increased participation from industry experts from iron and steel would allow for conducting more specific and accurate cost calculations, beyond what this thesis accomplished. This could have resulted in new or different findings and conclusions.

9.1. FUTURE RESEARCH

There are several areas where the findings of this study could be further developed. First, this thesis focuses solely on CCS as a solution for climate change mitigation. This was done intentionally to limit the scope of the study. However, it may be interesting to compare the economic feasibility and advantages of CCS relative to other technologies, such as additional renewable solutions, hydrogen, carbon capture with utilisation and storage (CCUS), bioenergy with carbon capture and storage (BECCS) or direct air capture and sequestration (DACS). This might lead to different conclusions about where government policies and support should be directed, and how allocation of resources should be prioritised in the short-run.

Additionally, in terms of the theory used, this thesis depicts a simple MAC curve to portray the problems faced by polluters. By studying all available abatement technology options for the entire process industry, a more technology-detailed MAC curve could be created. This may prove helpful for the industry as a whole on the choice of abatement technology, and for policymakers as it provides more detailed information than a simplified MAC curve.

Another area for future research would be to create a roadmap for policy implementation, highlighting a timeline for when different policies should be put into effect. This could more clearly guide large scale CCS deployment over time.

Finally, as the CO_2 avoidance cost estimates are currently based on a universal industry average cost/tCO_2 rather than separate costs/tCO_2 for each case facility, it would be interesting to conduct a sensitivity analysis to see how the overall costs could be expected to vary under different site-specific conditions. However, this would require extensive participation from the industry, as well as disclosure of sensitive corporate information. Complementary research could include surveying end users' willingness to pay for carbon neutral iron and steel products. Such research would add a large degree of accuracy and reliability to the results.

10. References

Agerup, M. K. (n.d.). *Norway: Legal and regulatory CCS framework [PowerPoint slides]*. (Ministry of Petroleum and Energy) Retrieved from https://iea.blob.core.windows.net/assets/imports/events/3/2.1_Agerup.pdf

Aker Carbon Capture. (2021). *Products and Solutions*. Retrieved from Aker Carbon Capture: https://www.akercarboncapture.com/technology/products-and-solutions/

Al-Fattah, S. M., Barghouty, M. F., Bureau, G., Dabbousi, B. O., Fillacier, S., Le Thiez, P., . . . Royer-Adnot, J. (2011). *Carbon Capture and Storage: Technologies, Policies, Economics, and Implementation Strategies.* Boca Raton: CRC Press.

Anantharaman, R., & Seljeskog, M. (2011). *CO2 capture from industry and offshore: Opportunities and challenges.* Trondheim: SINTEF Energy Research .

Andresen, S. R., & Gade, H. (2017). *Kunnskapsgrunnlag for utforming av klimapolitikk for industrien.* Miljødirektoratet.

Arasto, A. (2015). *Techo-Economic Evaluation of Significant CO2 Emission Reductions in the Iron and Steel Industry with CCS.* Juvenes Print.

Atkins & Oslo Economics. (2016). *Kvalitetssikring (KS1) av KVU om demonstrasjon av fullskala fangst, transport og lagring av CO2.*

Baker & McKenzie. (2009). *Strategic Analysis of the Global Status of Carbon Capture and Storage - Report 3: Country Studies, Norway.*

Borenstein, S. (2012). The Private and Public Economics of Renewable Electricity Generation. *Journal of Economic Perspectives*, 67-92.

Bruvoll, A., & Dalen, H. (2009). *Pricing of CO2 emissions in Norway Documentation of data and methods used in estimations of average CO2 tax rates in Norwegian sectors in 2006.* Oslo: Statistics Norway.

Bruvoll, A., & Larsen, B. M. (2002). *Greenhouse gas emissions in Norway. Do carbon taxes work?* . Oslo: Statistics Norway, Research Department.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., . . . Maitland, G. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science*, 1062-1176.

Burrows, J. (2021, Februrary 18). Student Thesis. London: Client Engagement Manager Global CCS Institute.

Chen, K., Vizzaccaro, M., Spagakos, M., & Loizou, S. (2018). Carbon capture and storage technologies for the sustainable use of fossil fuels. Newcastle upon Tyne.

Consoli, C. (2018). *CCS Storage Indicator (CCS-SI).* Global CCS Institute.

Dadhich, P., Dooley, J., Fujii, Y., Hohmeyer, O., & Riahi, K. (2018). *IPCC Special Report on Carbon dioxide Capture and Storage.* Intergovernmental Panel on Climate Change.

DIRECTIVE 2009/31/EC. (2009). DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006. *Official Journal of the European Union*, 114-135.

DNV GL Energy. (2020). *Potential for reduced costs for carbon capture, transport and storage value chains (CCS).*

Dubois, A., & Gadde, L.-E. (2002). Systematic combining: an abductive approach to case research. *Journal of Business Research, 44*(7), 553-560.

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review, 14*(4), 532–550.

Ekins, P., Kesicki, F., & Smith, A. Z. (2011, August). Marginal Abatement Cost Curves: A call for caution. *Climate Policy, 12*(2), 219-236.

EMBER. (2021). *Daily EU ETS carbon market price (Euros)*. Retrieved from ember-climate.org: https://ember-climate.org/data/carbon-price-viewer/

Emily Rochon, E., Bjureby, E., Johnston, P., Oakley, R., Santillo, D., Schulz, N., & Goerne, G. v. (2008). *False Hope: Why carbon capture and storage won't save the climate.* Amsterdam: Greenpeace International.

Endrava. (2021). *captureMap*. Retrieved from captureMap: https://www.capturemap.no/

European Commission. (2015). *EU ETS Handbook.*

European Commission. (2020). *Emissions cap and allowances*. Retrieved April 2021, from ec.europa.eu: https://ec.europa.eu/clima/policies/ets/cap_en#:~:text=Stationary%20installations&text=In%20phase%204%20of%20the,linear%20reduction%20factor%20of%202.2%25.

European Commission. (2020). *EU Emissions Trading System (EU ETS)*. Retrieved from https://ec.europa.eu/: https://ec.europa.eu/clima/policies/ets_en#tab-0-0

European Commission. (n.d.). *A legal framework for the safe geological storage of carbon dioxide*. Retrieved from European Commission: https://ec.europa.eu/clima/policies/innovation-fund/ccs/directive_en#:~:text=The%20directive%20on%20the%20geological,entire%20lifetime%20of%20storage%20sites.

Field, B. C., & Field, M. K. (2017). *Environmental Economics: An Introduction.* New York: McGraw-Hill.

Garðarsdóttir, S. O., Normann, F., Skagestad, R., & Johnsson, F. (2018). Investment costs and CO2 reduction potential of carbon capture from T industrial plants – A Swedish case study. *International Journal of Greenhouse Gas Control*, 111-124.

Gassanova. (2020). *The CCS chain*. Retrieved from CCS Norway: https://ccsnorway.com/%20full-scale-capture-transport-and-storage/

Gassnova. (2020). *The Gassnova Story*. Retrieved April 2021, from Gassnova: https://gassnova.no/en/the-gassnova-story#Too_much_uncertainty

Ghauri, P. N., & Grønhaug, K. (2005). *January 2005 Pervez N. GhauriPervez N. GhauriKjell GrønhaugKjell Grønhaug Research Interest 639.4 Citations 1,190.* Harlow: Financial Times Prentice Hall.

Global CCS Institute. (2018, March 28). CCS: A solution to climate change right beneath our feet. *Submission to the UNFCCC from the Global Carbon Capture & Storage Institute*. Global CCS Institute.

Global CCS Institute. (2020). *Global Status of CCS 2020.* Melbourne: Global CCS Institute.

Global CCS Institute. (2021). *About us*. Retrieved April 2021, from Global CCS Institute: https://www.globalccsinstitute.com/

Gough, C., & Mander, S. (2019). Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS. *Current Sustainable/Renewable Energy Reports*, 116–123.

Government. (2020, September 21). *Longship – Carbon capture and storage — Meld. St. 33 (2019–2020) Report to the Storting (white paper)*. Retrieved from https://www.regjeringen.no: https://www.regjeringen.no/en/dokumenter/meld.-st.-33-20192020/id2765361/

Government.no. (2016, May 11). Renewable energy production in Norway. Oslo, Norway. Retrieved from https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/#:~:text=In%20Norway%2C%2098%20percent%20of,of%20most%20of%20the%20production.

Graebner, M. E., & Eisenhardt, K. M. (2007). Theory building from cases: Opportunities and challenges. *Academy of Management Journal, 50*(1), 25-32.

Greenpeace. (2015). *Carbon Capture SCAM (CCS): How a False Climate Solution Bolsters Big Oil.* Washington: Greenpeace USA.

Hanemann, M. W. (1991). Willingness to pay and willingness to accept: how much can they differ? *The American Economic Review, 81*(3), 635–647.

Havercroft, I. (2018). *CCS Legal and Regulatory Indicator (CCS-LRI).* Global CCS Institute.

Henriksen, D. E., & Besche, A. d. (2012). *The legal framework for carbon capture and storage in Norway*. Retrieved from Practical Law: https://content.next.westlaw.com/0-521-9178?__lrTS=20210213015049208&transitionType=Default&contextData=%28sc.Default%29

Ho, M. T., Allinson, G. W., & Wiley, D. E. (2010). Comparison of MEA Capture Cost for Low CO2 Emissions Sources in Australia. *International Journal of Greenhouse Gas Control*, 49-60.

Huijgen, W. J., Comans, R. N., & Witkamp, G.-J. (2007). Cost evaluation of CO2 sequestration by aqueous mineral carbonation. *Energy Conversion and Management*, 1923–1935.

IEA. (2013). *Technology Roadmap: Carbon Capture and Storage.* Paris.

IEA. (2016). *Nordic Energy Technology Perspectives 2016.* Paris.

IEAGHG. (2013). *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill).*

IIMA. (n.d.). *Pig Iron Production - Blast Furnace Route*. Retrieved from International Iron Metalics Association: https://www.metallics.org/pig-iron-bf.html

Inflation Tool. (2021). *Inflation calculator - Norwegian Krone*. Retrieved from Inflation Tool: https://www.inflationtool.com/norwegian-krone/2007-to-present-value?amount=588

IPCC. (2005). *Carbon Dioxide Capture and Storage.* New York: Cambridge University Press.

IPCC. (2018). *Special Report: Global Warming of 1.5°C.* Intergovernmental Panel on Climate Change.

Johnson, G., Whittington, R., Scholes, K., Angwin, D., & Regner, P. (2018). *Fundamentals of Strategy.* Harlow, UK: Pearson.

Johnsson, F., Normann, F., & Svensson, E. (2020). Marginal Abatement Cost Curve of Industrial CO2 Capture and Storage – A Swedish Case Study. *Frontiers in Energy Research, 8*(175).

Kjärstad, J., Skagestad, R., Eldrup, N. H., & Johnsson, F. (2016). Ship transport - A low cost and low risk CO2 transport option in the Nordic countries. *International Journal of Greenhouse Gas Control*, 168-184.

Klemetsen, M. E., Rosendahl, K. E., & Jakobsen, A. L. (2016). *The impacts of the EU ETS on Norwegian plants' environmental and economic performance.* Oslo: Statistics Norway .

Kolstad, C. D. (2011). *Intermediate Environmental Economics.* New York: Oxford University Press.

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2011). Comparative Assessment of CO2 Capture Technologies for Carbon-Intensive Industrial Processes. *Progress in Energy and Combustion Science*, 87-112.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. (2017). A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pult and Paper Industries, as well as Other High Purity Sources. *International Journal of Greenhouse Gas Control*, 71-84.

Lipponen, J., McCulloch, S., Keel, S., Stanley, T., Berghout, N., & Berly, T. (2017). The politics of large-scale CCS deployment. *Energy Procedia*, 7581–7595 .

Lovdata. (2013, September 26). *Forskrift om CO_2 -kompensasjon for industrien*. Retrieved May 2021, from Lovdata: https://lovdata.no/dokument/SF/forskrift/2013-09-26-1160

Madsen, T. (2021, February 10). Online Conversation with Torleif Madsen about CCS Master Thesis. *Zoom Meeting*. (V. Hordvik, & A. Jennings, Interviewers)

McKinsey & Company. (2009). *Pathways to a low-carbon economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve.*

Ministry of Climate and Environment. (2020). *Norway - NDC Update.* Norwegian Government, Ministry of Climate and Environment. Oslo: NDC Registry.

Ministry of Finance. (2020, September 25). Prop. 1 S (2020 –2021) Proposisjon til Stortinget (forslag til stortingsvedtak). *FOR BUDSJETTÅRET 2021, Statsbudsjettet 2021*. Oslo, Norway: https://www.regjeringen.no/contentassets/3a26510c180f4657ae1d1892ef96e6d8/no/pdfs/prp202020210001guldddpdfs.pdf. Retrieved from Regjeringen:

https://www.regjeringen.no/contentassets/3a26510c180f4657ae1d1892ef96e6d8/no/pdfs/prp202020210001guldddpdfs.pdf

Ministry of Trade, Industry and Fisheries. (2017). *A greener, smarter and more innovative industry.* Norwegian Government, Ministry of Trade, Industry and Fisheries. Oslo: Ministry of Trade, Industry and Fisheries.

Muuls, M., Colmer, J., Martin, R., & Wagner, U. J. (2016). *Evaluating the EU Emissions Trading System: Take it or leave it? An assessment of the data after ten years.* Imperial College London, Grantham Institute. London: Imperial College London.

Norges Bank. (2021). *VALUTAKURSER*. Retrieved from Norges Bank: https://www.norges-bank.no/tema/Statistikk/Valutakurser/?tab=all

Normann, F., Skagestad, R., Bierman, M., Wolf, J., & Mathisen, A. (2019). *Reducing the Cost of Carbon Capture in Process Industry.* Porsgrunn: SINTEF.

Norsk Industri. (2016). *Veikart for prosessindustrien.*

Norsk Stål AS. (2020). *Norsk Stål*. Retrieved from Grønnere – Stålproduksjon i dag: https://www.norskstaal.no/om-oss/miljoe-og-baerekraft/groennere-staalproduksjon-i-dag?fbclid=IwAR1KkzDx9NvoaHMEeGKSY19BOJJ5SAKtTawQ9ot1EDvjLYQ-YazeYareNMM

Northern Lights. (n.d.). *What we do*. Retrieved from Northern Lights: https://northernlightsccs.com/what-we-do/

Norwegian Government. (2017). *Better growth, lower emissions – the Norwegian Government's strategy for green competitiveness.* Government.no.

Norwegian Ministry of Climate and Environment. (2017). *Norway's Climate Strategy for 2030: a transformational approach within a European cooperation framework.* Norwegian Government, Norwegian Ministry of Climate and Environment. Oslo: Norwegian Ministry of Climate and Environment.

Norwegian Ministry of Petroleum and Energy. (2017). *Regulations relating to exploitation of subsea reservoirs on the continental shelf for storage of CO_2 and relating to transportation of CO_2 on the continental shelf*. Retrieved from Norwegian Petroleum Directorate: https://www.npd.no/en/regulations/regulations/exploitation-of-subsea-reservoirs-on-the-continental-shelf-for-storage-of-and-transportation-of-co/

Norwegian Ministry of Petroleum and Energy. (2020). *Longship – Carbon capture and storage, Meld. St. 33 (2019–2020) Report to the Storting (white paper).* Norway: Norwegian Ministry of Petroleum and Energy.

OECD. (2013). *Carbon Dioxide Equivalent*. Retrieved from OECD: https://stats.oecd.org/glossary/detail.asp?ID=285

Office of Fossil Energy. (n.d.). *Pre-Combustion Carbon Capture Research*. Retrieved from Energy.gov: https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd/pre-combustion-carbon

Onarheim, K., Mathisen, A., & Arasto, A. (2015). Barriers and opportunities for application of CCS in Nordic industry - A sectorial approach. *International Journal of Greenhouse Gas Control*, 93–105.

Pareto Securities. (2020). *Aker Carbon Capture, Initial Coverage: The missing piece of the puzzle.* Oslo: Pareto Securities Research.

Petroleum Safety Authority. (2020). *REGULATIONS RELATING TO SAFETY AND WORKING ENVIRONMENT FOR TRANSPORT AND INJECTION OF CO2 ON THE CONTINENTAL SHELF (CO2 SAFETY REGULATIONS).*

Pietzner, K., Næss, R., Reiner, D. M., Cismaru, D., Anghel, S., Schumann, D., . . . Koukouza. (2011). Public Awareness and Perceptions of Carbon Dioxide Capture and Storage (CCS): Insights from Surveys Administered to Representative Samples in Six European Countries. *Energy Procedia*, 6300-6306.

Pihkola, H., Tsupari, E., Kojo, M., Kujanpää, L., Nissilä, M., Sokka, L., & Behm, K. (2017). Integrated sustainability assessment of CCS – Identifying non- technical barriers and drivers for CCS implementation in Finland. *Energy Procedia*, 7625 – 7637.

Prosess21. (2021). *Prosess21 Hovedrapport.* Oslo: prosess21.no.

Ridder, H.-G., Hoon, C., & Baluch, A. M. (2014). Entering a dialogue: Positioning case study findings towards theory. *British Journal of Management, 25*(2), 373–387.

Rochon, E., Bjureby, E., Johnston, P., Oakley, R., Santillo, D., Schulz, N., & von Goerne, G. (2008). *False Hope: Why Carbon Capture and Storage Won't Save the Climate.* Amsterdam: Greenpeace International.

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students.* Harlow: Pearson.

Shell. (2013). *New Lens Scenarios: A Shift in Perspective for a World in Transition.* Shell. Retrieved April 2021, from shell.no: https://www.shell.no/energi-og-innovasjon/the-energy-future.html

Simbeck, D., & Beecy, D. (2011). The CCS Paradox: The Much Higher CO2 Avoidance Costs of Existing versus New Fossil Fuel Power Plants. *Elsevier, Energy Procedia*, 1917–1924.

Solberg, E. (2020, September 21). The Government launches 'Longship' for carbon capture and storage in Norway. (Government.no, Interviewer)

Statistics Norway. (2016). *Standard for næringsgruppering (SN)*. Retrieved from Statistics Norway: https://www.ssb.no/klass/klassifikasjoner/6

Størset, S. Ø., Tangen, G., Wolfgang, O., & Sand, G. (2018). *Industrielle muligheter og arbeidsplasser ved CO2-håndtering i Norge.* SINTEF. SINTEF.

Stub, S. Ø., Skriung, C. S., Post-Melbye, A., & Holm, M. (2019). *New business models for carbon capture and storage.* Zero Emission Resource Organisation (ZERO).

Tcvetkov, P., Cherepovitsyn, A., & Fedoseev, S. (2019). Public perception of carbon capture and storage: A state-of-the-art overview. *Heliyon*, 1-28.

Tsupari, E., Arasto, A., Kärki, J., Sihvonen, M., & Lilja, J. (2013). Costs and potential of carbon capture and storage at an integrated steel mill. *Energy Procedia*, 7117-7124.

Tzinis , I. (2021, April 1). *Technology Readiness Level*. (NASA) Retrieved from Nasa.gov: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

UNFCCC Secretariat. (2021). *The Paris Agreement*. Retrieved from United Nations Climate Change: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United Nations. (2015). *Paris Agreement.* Paris: United Nations.

Whitmarsh, L., Xenias, D., & Jones, C. R. (2019). Framing effects on public support for carbon capture and storage. *Palgrave Communications, 5*(1), Article number 17.

Wiley, D. E., Ho, M. T., & Bustamante, A. (2011). Assessment of Opportunities for CO2 Capture at Iron and Steel Mills: An Australian Perspective. *Energy Procedia*, 2654–2661.

WorleyParsons Services Pty Ltd. (2009). *Strategic Analysis of the Global Status of Carbon Capture and Storage - Report 2: Economic Assessment of Carbon Capture and Storage Technologies.*

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods (6th edn).* London: Sage.

Zapantis, A., Townsend, A., & Rassool, D. (2019). *Policy Priorities to Incentivise Large Scale Deployment of CCS.* GCCSI.

ZERO. (2013). *Policy instruments for large-scale CCS.* Oslo: ZERO.

11. Appendix

11.1. Appendix A

Table A.1: *Industry points of emission in Norway with >100,000 tonnes of CO_2 per year. Source: (Endrava, 2021)*

Emission Site	Process Industry Sector	Sum of CO_2 2017 [t]	Estimated Capture Rate (LB)	Estimated Capture Rate (UB)
Hydro Aluminium, Høyanger	Aluminum	104,000	70%	90%
Sør-Norge Aluminium	Aluminum	142,000	70%	90%
Alcoa aluminium, Lista	Aluminum	160,000	70%	90%
Hydro Aluminium, Årdal Metallverk	Aluminum	300,000	70%	90%
Hydro Aluminium, Karmøy	Aluminum	336,000	70%	90%
Hydro Aluminium, Sunndal	Aluminum	660,000	70%	90%
Yara Norge, Yara Porsgrunn	Chemical production	487,000	50%	90%
Equinor ASA avd.Tjeldbergodden Metanolfabrikk	Chemical production	312,000	NA	NA
NORETYL AS	Chemical production	432,000	50%	70%
Ferroglobe Mangan Norge AS	Iron and steel	137,000	35%	80%
ELKEM ASA AVD BJØLVEFOSSEN	Iron and steel	174,000	35%	80%
Eramet Norway AS, Porsgrunn	Iron and steel	185,000	35%	80%
Eramet Norway Kvinesdal	Iron and steel	228,000	35%	80%
TiZir Titanium & Iron AS	Iron and steel	261,000	35%	80%
Finnfjord	Iron and steel	284,000	35%	80%
Elkem Rana AS	Iron and steel	298,000	35%	80%
ERAMET NORWAY AS, Sauda	Iron and steel	320,000	35%	80%
Norcem Kjøpsvik	Non-metallic minerals	401,000	70%	90%
Norcem Brevik	Non-metallic minerals	878,000	70%	90%
NorFraKalk	Non-metallic minerals	167,000	70%	90%
Wacker Chemicals Norway	Non-metallic minerals	274,000	NA	NA
Elkem Thamshavn	Non-metallic minerals	277,000	NA	NA
Elkem Bremanger	Non-metallic minerals	319,000	NA	NA
Elkem Salten	Non-metallic minerals	476,000	NA	NA
Borregaard AS, avd. spesialcellulose	Pulp and paper	166,000	70%	90%
Norske Skog Saugbrugs	Pulp and paper	178,000	70%	90%
Norske Skog Skogn	Pulp and paper	203,000	70%	90%
Esso Norge, Slagentangen	Refinery	330,000	45%	70%
Equinor avd. Mongstad raffineri	Refinery	2,360,000	45%	70%

11.2. Appendix B

Table B.1: *Total Emissions per Process Industry Sector*

Process Industry Sector	Sum of CO_2 2017 [t]	CO_2 Concentration	Fraction of Total Emissions
Aluminum	1,702,000	1%	15.69%
Chemical production (ammonia)	1,231,000	97-100%	11.35%
Iron and steel	1,887,000	25%	17.39%
Non-metallic minerals (cement)	2,792,000	20-25%	25.74%
Pulp and paper	547,000	14%	5.04%
Refinery	2,690,000	8%	24.79%
Total emissions for process industry	10,849,000	-	1

Table B.2: *Average CO_2 Concentration for Iron and Steel Sector from Literature*

Process Industry Sector	CO_2 Concentration (LB of estimation)	CO_2 Concentration (UB of estimation)	Type of Off-Gas
(Kuramochi et al., 2011)	17%	25%	Air-Blown Blast Furnace
(Kuramochi et al., 2011)	35%	NA	Top Gas Recycling Blast Furnace
(Kuramochi et al., 2011)	25%	35%	Smelting reduction
(Leeson et al., 2014)	35%	NA	Top Gas Recycling Blast Furnace
(Endrava, 2021)	22%	NA	Basic iron and steel
(Garðarsdóttir et al., 2018)	30%	NA	Power plant iron and steel
(Garðarsdóttir et al., 2018)	20%	25%	Other stacks
(IPCC, 2005)	15%	16%	Oxygen steel furnace
Average	25%		

11.3. Appendix C

Table C.1: *Government investments in CO2 management. Source: National Accounts 2014-2020; National Budget 2021, sections 1840; 142074*

Year	2014	2015	2016	2017	2018	2019	2020	2021*
CO2 Management								
Longship							236.0	2275.0
TCM	1720.9	1649.0	1587.5	515.6	193.0	199.6	180.0	165.0
R&D	200.0	199.8	239.6	199.2	182.1	186.5	160.0	164.0
Gassnova, Admin.	108.3	131.3	160.3	284.1	118.6	128.8	108.8	105.0
Other	19.6	133.9	53.5	25.1	162.2	375.5	108.0	
Sum	**2048.8**	**2114.0**	**2040.9**	**1024.0**	**655.9**	**890.4**	**792.8**	**2709.0**
CO2 Compensation for Industry	**222.7**	**402.5**	**497.9**	**636.4**	**469.2**	**544.0**	**1434.7**	**0**
Total	**2271.5**	**2516.5**	**2538.8**	**1660.4**	**1125.1**	**1434.4**	**2227.5**	**2709.0**

2021 taken from National Budget*