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Carbon Capture & Storage in the Cement Industry

A viable option for Sweden?

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"Coming together is a beginning;
keeping together is progress;
working together is success."
Henry Ford

Abstract

The Swedish government has set the goal of achieving carbon-neutrality by 2045. The production of cement currently accounts for 8% of CO_2 emissions worldwide, with a similar figure also true of Sweden. A clear government strategy is therefore needed to work with and provide support to the cement industry for decarbonisation. The most developed pathway for cement decarbonisation in the literature is through the application of CCS. However, the implementation of CCS has been problematic in projects globally. The largest barrier to CCS implementation is the cost. In Sweden, emitting carbon dioxide remains much cheaper under the EU ETS compared to the cost implementing carbon-abatement measures.

This thesis aims to explore the pertinent factors surrounding the political economy of CCS implementation, the economic feasibility of CCS implementation in the cement industry and discuss some of the important issues in the CCS debate that are relevant for Sweden. The political economy is valuable here because the interaction between the state and industry can help overcome the economic barriers to CCS implementation. This exploratory study serves as an important case study of the complexity of implementing CCS in an industrial context.

CCS, for most, is the only way to decarbonise the cement industry. Further research is needed into how best this transition could be catalysed through regulation and/or fiscal stimulus from the government. The cement value chain is unique in its structure and could lend itself to a lower cost of implementation for CCS than other sectors. Furthermore, when combined with bioenergy, CCS holds the potential for producing negative emissions. This is currently the only well-developed technology to achieve negative emissions. Further research is needed in order to establish the exact potential of CCS with bioenergy to harness negative emissions, a necessity in order to achieve complete carbon neutrality.

The government must capitalise on easy leverage points for CCS implementation, such as for the cement industry described in this research, as a first step to realising the potential of CCS.

Keywords: Carbon Capture & Storage; Cement; Political Economy; Decarbonisation.

Executive Summary

The Climate Act, passed by the Swedish government, on 15th June 2017 means that Sweden must achieve carbon-neutrality by 2045. Over the coming years and decades, regulating to encourage the decarbonisation of emission-intensive activities will become increasingly important for the government. One of the most carbon-emitting industries is the cement industry, accounting for some 4-8% of carbon emissions in Sweden at present. However, the cement production process is unique due to the fact that the 60% of the carbon dioxide produced is as a result of chemical reactions when processing the raw material, not just from the combustion of fuel. This problem is further complicated by the fact that cement is used to make concrete, one of the most consumed materials in the world. It is used in many types of buildings and infrastructure products and so much be of certain strength and quality. New products to replace cement will either be too expensive, not of a high enough quality to support infrastructure and/or the necessary materials are not readily available.

In light of this, an end-of-pipe solution for cement production that captures emissions before they are emitted into the atmosphere and stores them in bedrock could provide the solution. This technology is known as Carbon Capture and Storage (CCS) and is the subject of intense political debate around the world. The aim of this research, therefore, has been to add to the debate on whether or not CCS should play a role in the decarbonisation of the cement industry in Sweden. To do this, this research has three main components. The first is assess how the interplay between the state and market affects the implementation of CCS in the Swedish cement industry. The second is to assess the economic feasibility of introducing CCS during the cement production process. The third is to contextualise these findings in the current debate surrounding CCS in Sweden.

Ambitious new climate targets from the Swedish government, the threat of globalisation in the cement industry and international pressure are important unique drivers between the state and market that make CCS implementation in the Swedish cement industry more likely. Whilst there are many different political, economic and technical factors influencing CCS implementation, these are perhaps the most important for this particular case. Producing carbon-neutral cement is vital if Swedish cement is to remain competitive against foreign markets. The pressure to act on industrial emissions, coupled with Sweden's perceived status as a leader in climate mitigation following the Paris Agreement has put pressure on policymakers to act to reduce carbon emissions. However, the cost of CCS remains too high for the cement industry to take on the financial burden alone.

The unique structure of the cement value chain, the need to diversify and innovate in the cement industry, and a perceived market for carbon-abated cement support the argument that introducing CCS in the cement industry is economically feasible. Cement represents a low proportion of the final cost for the end-consumer of most construction projects so the cost of CCS could, in theory, be easily passed through the value chain. Consumers, especially in Sweden, are now looking for products with a low climate-impact. CCS is currently the only mature technology which will produce high-quality carbon-abated cement.

CCS technologies offers potential for emissions reductions in the cement industry, other carbon-intensive industries and for negative emissions through incorporation with Bioenergy (BECCS). An active government role is needed to regulate and invest in all these technologies to capitalise on their full potential for carbon dioxide abatement. To limit global warming to 2°C, compared to pre-industrial temperatures, CCS

must play a role in future climate mitigation efforts. The cost-effectiveness and carbon-reduction potential for this depend heavily on the role of the governing bodies to engage with the areas where it shows the most potential to overcome the economic barriers. The results from this study show that the cement industry is one of the key areas for an easier implementation of CCS and should be given political support accordingly.

The aim of this study was not to provide conclusive evidence for a specific course of action. However, it does give an overview of the possible points of action for decision-makers to decarbonise the cement industry. In this way, the audience for the study is relevant decision-makers. This could be policymakers at the top of government, industry managers responsible for decarbonisation strategies in the cement industry or consumers of cement who want to work towards decarbonising their supply chain to provide sustainable infrastructure. This study offers a holistic view of the debate surrounding CCS in the cement industry and provides an overview of the complexity of implementing the technology.

Direct recommendations are hard to offer for an exploratory study of this nature. However, this report does offers some recommendations accompanied by areas for further research. These are three key areas for further research found, which are:

- To help catalyse the uptake of CCS in the cement industry, the government could provide direct subsidies or develop procurement standards for public infrastructure to help de-risk the investment for the industry by immediately creating a market for carbon-abated cement. Further research is needed into these two scenarios including the costing of each and whether or not addressing procurement standards will be enough to incentivise CCS implementation.

- The role of BECCS will be vital in order to achieve zero-emissions by 2045. Further research is needed in order to determine the exact potential of this technology in Sweden, which could be sizeable given its large biomass sector. Research into the possibility for this technology to be commercialised is also needed.

- The government could take on the fiscal and regulatory responsibility for developing the transport and storage infrastructure necessary for the implementation of the full CCS value chain. Further research is needed into the potential of the two pathways for storage, either in the North Sea or in the Baltic Sea in order to determine the economic incentives and drawbacks for each pathway.

In order to capitalise on the carbon-abatement potential that CCS has, it is important the government play an active role in each of these three areas.

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Abbreviations

CO_2 – Carbon Dioxide

IPCC – Intergovernmental Panel on Climate Change

IEA – International Energy Agency

CCS –Carbon Capture and Storage

2DS – 2°C Scenario for Global Warming from the IEA

NBS – National Bureau of Statistics for China

GWP – Global Warming Potential

BECCS – Bioenergy with Carbon Capture and Storage

GCCSI – Global Carbon Capture and Storage Institute

EOR – Enhanced Oil Recovery

UNFCCC – United Nations Framework Convention on Climate Change

EU ETS – European Union Emissions Trading Scheme

OECD - Organisation for Economic Co-operation and Development

UN – United Nations

UNEP – United Nations Environment Programme

EU – European Union

R&D – Research & Development

1 Introduction

1.1 Problem Definition

The emission of carbon dioxide (CO_2) into the atmosphere as the result of human activities is the leading cause of global warming. An increase in the CO_2 levels in the atmosphere intensifies the "greenhouse effect", trapping radiation close to the Earth's surface and raising temperatures worldwide. The combustion of fossil fuels and industrial processes have constituted 78% of the observed increase in CO_2 between 1970 and 2010 (IPCC, 2014). The warming of the atmosphere will cause shifts in the distribution of energy throughout the globe and has been linked to wide range of possible environmental changes. These include: increases in the number and magnitude of extreme weather events; rising sea levels; and changes in land coverage, among others. These changes will impact societies around the world and so have been the basis for international agreements to attempt to decarbonise the energy-production and industrial sectors that have released these emissions into the atmosphere. The need to decarbonise these sectors has led to the innovation of many new technologies including the production of renewable energy from water, wind, geothermal and solar sources, cleaner production methods in industrial processes and increases in energy efficiency. However, the current level of dispersion of these technologies in our energy and industrial systems will not reduce emissions enough in order to limit warming to only 2ºC, compared to pre-industrial temperatures (IEA, 2016; Rockström et al., 2017).

One of the new technologies that could help to decarbonise these sectors is Carbon Capture and Storage (CCS). The widespread implementation of CCS will help to reduce CO_2 emissions in order to limit global warming to 2ºC from pre-industrial levels (Rockström et al., 2017). The technology captures CO_2 at the point of production and sequesters it, usually in geologic formations both on- and offshore. However, whilst the technology is often included in climate mitigation models such as those proposed by the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC) and governments, including the US, Canada, Norway, Australia and the UK, there are still major barriers to the large-scale implementation of CCS. These barriers are considered by the Global CCS Institute (2016) and the IEA (2016) to primarily be political and economic in nature. The barriers for CCS implementation revolve around the "financial gap" created by the lack of incentive for industries to reduce their carbon emissions (Kern et al., 2015). In short, this means that the current price of releasing CO_2 into the atmosphere is still much lower than the investment required to achieve deep emission reductions. It is clear, therefore, that governments must play a role to overcome this gap. The exact role that the government plays here is the subject of much debate in the literature and indeed will depend on a number of factors relating to the political and economic structure of the country in question. According to the International Energy Agency (2016), this role should be concerted government incentives to catalyse the large-scale introduction of CCS and could include "mandates, direct or indirect subsidies, grants, tax credits, loan guarantees, feed-in tariffs, regulatory requirements, carbon pricing or taxes, or a combination of any of these" (IEA, 2016, p. 71).

One of the most emission-intensive industries globally in the cement industry - for every tonne of cement produced, 550kg of CO_2 is emitted as a by-product (Imbabi et al., 2012). Developing pathways to produce carbon-neutral, sustainable cement is, therefore, a key area for research in order to mitigate CO_2 emissions. The necessity of this research agenda is compounded by evidence from the IEA 2DS scenario, in which global warming is limited to 2°C. This scenario projects that there will be a rise in the demand for cement globally fed by the consumption of developing countries. These countries are predicted to be a significant source of emissions under this scenario in 2050. The emissions from the production of cement are largely from the calcination process during which limestone is heated, producing huge quantities of CO_2. Therefore, unlike many other sectors, the use of alternative fuels for energy will not result in deep emissions reductions. It is, therefore, necessary for researchers to find either alternative, sustainable means for the production of cement or alternative, sustainable products for the uses of cement.

As part of an effort to mitigate CO_2 emissions, the Swedish government took the unprecedented step of introducing a legally-binding target of zero greenhouse gas emissions by 2045 in June 2017. Currently, the cement industry in Sweden produces 5% of the total CO_2 emissions of the country (Tillväxtanalys, 2016). As Sweden seeks to reduce their overall CO_2 emissions, it is therefore vital that it develops a plan to decarbonise the cement industry. This will become increasingly important as the decarbonisation of other sectors progresses in the next decade and the cement industry's share of CO_2 emissions increases. One of the main ways in which production of cement can be made more sustainable and emissions deeply cut is through the application of CCS.

In light of this, the overarching aim of this thesis is to assess whether CCS is a viable option for decarbonisation of the cement industry in Sweden.

1.2 Background

1.2.1 The Cement Industry

History

Portland cement is the most commonly used cement in the world and is a basic constituent of concrete, mortar, stucco and most type of grout. Cement is a fine powder that is produced from cement clinker. Clinker is produced in cement kilns and is made up of lumps, which are a few millimetres in diameter, formed from the heating of limestone and other materials. The name Portland cement is derived from its similarity to Portland stone, a type of building stone quarried on the Isle of Portland in Dorset, England. Nowadays, concrete produced from Portland cement is the most widely-used construction material in the world by weight.

Cement production process

The production of cement is unique in the industrial sector. In order to fully understand why it is important to know the main steps of the production process for cement. At the beginning of the production process, limestone is heated to temperatures of between 600°C and 900°C, resulting in a conversion of the compound to calcium oxide compounds and carbon dioxide. The simplified stoichiometric equation representing the thermal decomposition of limestone is:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Following this, the calcium oxide (CaO) reacts with silica, aluminium and ferrous materials, to produce other minerals in the clinker. This is then mixed with a small amount of gypsum to form Portland cement, the most commonly-produced cement globally. From this equation, it is possible to see that there is a significant source of CO_2 resulting from heating of limestone. This goes someone way to explaining why cement is one of the few unique products where deep emissions reductions cannot be achieved by finding cleaner fuels and better energy efficiency.

The production of cement is associated with a number of environmental concerns. The process is very emissions intensive due to the chemicals and energy involved in the production process. These include emissions of NO_x, SO_x, particular matter and heavy metals (Gibbs, Soyka & Conneely, 2001) to the air and to wastewater. The release of these compounds can cause a wide variety of environmental problems, potentially leading to widespread and acute environmental degradation. For example, mercury can be produced during the heating of fuel and raw materials, potentially forming methylmercury which bioaccumulates in fish, is highly toxic and can severely damage the formation of the nervous system in infants.

Carbon dioxide emissions

The foremost concern, for the sake of this study, is the release of CO_2 as a result of cement production. CO_2 emissions are generated by carbonate oxidation during the cement clinker production process and from the combustion of fossil fuels in furnaces. The carbonate oxidation is very emission-intensive and is the largest non-combustion source of CO_2 in the industrial manufacturing sector. This represented around 4% of total global emissions in 2015 and combined with the emissions from combustion of fuel, the cement sector accounts for around 8% of global CO_2 emissions (PBL Netherlands Environmental Assessment Agency, 2016).

Out of the total emissions CO_2 emissions generated through the production of cement, 40% comes from the use of energy whilst the remaining 60% is produced as a by-product of the thermal decomposition of limestone. This means that even if energy efficiency and renewable energy measures were technically feasible and cement production was upgraded accordingly, the maximum CO_2 abatement that could be achieved is 40%.

Industry characteristics

Cement is a vital commodity for construction as the main constituent of concrete. It is normally produced in large, capital-intensive production plants in close proximity to limestone quarries. The size, capital-intensiveness, and need for raw material proximity are limiting factors to the number of cement production plants viable in any given country. In fact, the industry is one of the most capital-intensive in the world, with the ratio of investment cost to sales in the order of 2 to 3. Moreover, once these plants have been built, the capacity of each plant is very expensive to alter and would require significant investment. Geography, therefore, limits the number of competitors in any one location. Even in Europe, cement and concrete production is localised within countries or regions because of these limiting factors.

These factors have meant that, throughout Scandinavia, there is: 1 plant in Denmark, operated by Aalborg Portland; 2 plants in Finland and 2 in Norway, operated by Finnsementii and Norcem respectively; and 3 plants in Sweden, operated by Cementa AB (Rootzén et al., 2016). Most of these plants are located on the waterfront, with the cement product largely being transported by shipping. However, despite the capacity for regional trade and a few independent importers of cement, each respective market is dominated by the cement manufacturers in their own country. Despite continued globalisation of many markets, for the reasons already discussed, the cement market remains largely regional. However, it is continuously growing markets in China, India and Africa could threaten this.

Future Trends

The global amount of cement used from 1990 to 2010 and projected increase until 2050 is described by Imbabi et al. (2012), as shown in Figure 1.1. Global cement production is to increase constantly between 1990 and 2050, driven by the demand for infrastructure and housing in rapidly developing economies such as China and India.

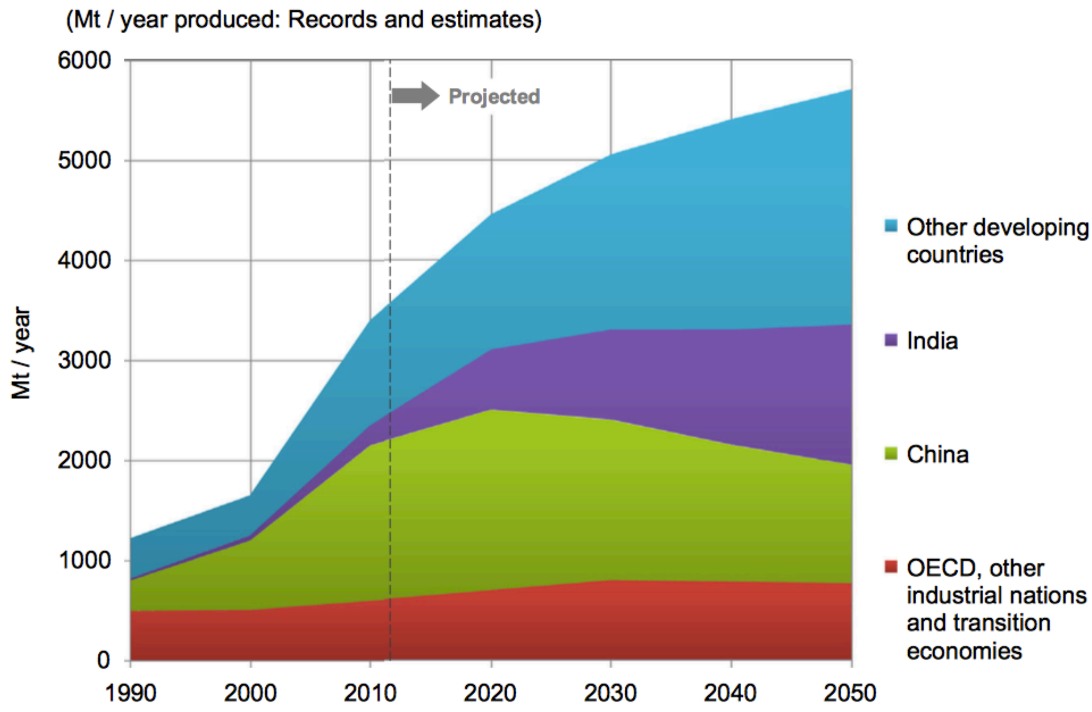

Figure 1.1 World Portland Cement Production 1990 – 2050

Source: Imbabi et al. (2012)

In 2015, China accounted for 58% of global cement production, with the EU-28 accounting for 4.4% of the total (NBA, 2016; PBL Netherlands Environmental Assessment Agency, 2016). However, the amount of emissions from the cement industry is not directly proportional to the amount of cement produced, as the share of blended cement, compared to traditional Portland cement, has increased in the overall amount of cement production. Blended cement contains considerably less clinker in the final product, instead replacing it by other materials like fly ash or blast furnace slag (PBL Netherlands Environmental Assessment Agency, 2016). This decoupling of emissions from cement with cement production means there is a large degree of uncertainty surrounding the projected amount of emissions from cement in the future.

The majority of cement produced in the Nordic countries is made from grey clinker, however between 5% and 10% of cement produced is white clinker. Grey Portland cement is used primarily for projects which require a high performance because of its durability, whilst white Portland cement is used for projects based on the high aesthetic value of white concrete (Aalborg Cement, 2004).

A sustainable cement industry

Deep emissions reductions for cement can only be achieved either by making the production process more sustainable or finding a sustainable alternative for the uses of cement in the construction sector. This could be achieved through any combination of the following mechanisms:

1. Through using alternative materials in the production process to reduce the amount of emissions produced.

2. Capturing the carbon dioxide emissions, transporting them and storing them in geologic reserves.

3. Finding alternatives for cement in the construction sector, as well as its other uses around the world (Tillväxtanalys, 2016).

In order for Sweden, therefore, to achieve deep emission reductions in the cement industry, in line with its commitment to zero net-greenhouse gas emissions by 2045, it is important to follow any number of the previous mechanisms as a political priority. However, there are caveats to each of the three. For example, whilst there are some alternative sustainable substitute-materials to produce cement, they are either too expensive or produce a lesser standard product. Moreover, there are some alternative materials to cement that can be used in certain construction projects, especially in a forest nation like Sweden. However, the supply of alternative building materials is not as universal as cement and are not available globally in their supply. For capturing emissions, the low cost of emitting CO_2 means that capturing carbon has not yet become economically viable.

Lifecycle Perspective

Understanding some key issues in the lifecycle of cement can help to achieve a better understanding of the exact environmental impact of the product from cradle-to-grave, not just during the production process. The environmental impact associated with the lifecycle of cement and its products is large and diverse. Apart from those already discussed, transport has been found to constitute 5% of the total Global Warming Potential (GWP) of the concrete and cement value chain (Li et al., 2014). In addition to this, a current area of research concerns understanding the lifecycle of a concrete structure. Over its lifecycle, concrete reacts with CO_2 in the air and has been found to sequester it. Possan et al. (2017) measured the amount of carbonation that had taken place on a large concrete dam in Brazil and found that carbonation had taken place over the whole structure. There has not been a lot of research conducted in this field yet but there are signs the concrete and cement can be chemically altered in order to maximise the carbonation process and therefore maximise the amount of CO_2 absorbed by a concrete structure over its lifetime.

1.2.2 Carbon Capture & Storage

According to the Carbon Capture & Storage Association, CCS is "a technology that can capture up to 90% of the CO_2 emissions generated from the use of fossil fuels in electricity generation and industrial processes, preventing the CO_2 from entering the atmosphere." (The Carbon Capture & Storage Association, 2017). CCS has potential applications in wide range of power-generating, industrial and standalone projects. Projects range from the first commercial BioEnergy with Carbon Capture and Storage (BECCS) plant, which is operating as of March 2017 in Illinois (Mooney, 2017), to the capturing of CO_2 from the processing of natural gas in the Sleipner project in Norway, which has been operating for more than 20 years.

The Global CCS Institute recognises 38 large-scale projects, either in operation or under construction, globally (Global Carbon Capture and Storage Institute, 2016). When their 2016 annual report was published, 15 large scale projects capturing and storing CO_2 were in operation globally, with a joint capacity of capturing 30 million tonnes of CO_2 per annum. Three more large scale projects were due to begin in the US at the beginning of 2017, raising global capacity to 35 million tonnes per annum. Throughout 2017, the Institute believes that with the addition of projects currently expected to be operational in Canada and Australia, the total number of operational large-scale CCS projects will reach 21 producing a CO_2 storage capacity of 40 million tonnes per annum. This number of projects is over twice the number of operational facilities in 2010, when there were 10 (Global Carbon Capture and Storage Institute, 2016).

There are three stages that are pertinent infrastructure considerations when discussing the policy matrix regarding CCS. These involve the capture of CO_2, either prior to or after combustion of the fuel, transportation of the CO_2 to a suitable storage site, and the process of the storage of the CO_2 to a suitable geologic formation.

History

In the early 1970s, CO_2 was first pumped into the oil aquifers in the United States (US) for Enhanced Oil Recovery (EOR), ensuring the maximum yield of oil from oil fields. By pumping CO_2 into these oil reservoirs, in a process known as miscible flooding, more oil is released from the bedrock in which it is held. The CO_2 naturally dissolves in the oil, increasing the displacement rate of oil from the interstitial spaces in the bedrock through reducing the surface tension between oil and water. CO_2 is the ideal gas to use for this because it is cheap, relative to alternatives and when dissolved in the oil, it reduces the oil's viscosity. However, it wasn't until the Sleipner project in Norway came online in 1996 that CCS was implemented primarily as a measure to reduce the amount of CO_2 entering the atmosphere (IEA, 2016). This project was, at least, partly stimulated by the carbon tax implemented by the Norwegian government in 1991.

In 2001, the UNFCCC (United Nations Framework Convention on Climate Change) requested a report from the IPCC on CCS which was published in December 2005. This report stated that:

- CCS represented a potential 15-55% of mitigation effort to 2100, in terms of CO_2 mitigation;
- the energy required for CCS equipment was considerable, increasing energy consumption by 10-40% in any given application;
- there would be no substantive deployment of CCS unless a CO_2 price over 25-30 USD/tonne CO_2 was introduced;
- and that risks involved were comparable to industrial activities at the time but more pilots were needed in order to fully understand the risks

(IPCC, 2005)

After this report, there was a "surge of commitment and desire to implement" CCS (Cozier, 2017) because the report made it clear that the widespread dispersion of the technology would be essential if global temperatures were to be kept within "safe" limits. The IEA (2016) state that there was over 30bn USD in public funding announced and a pledge from the G8 to build 20 new large-scale CCS demonstration projects. This momentum, they say, decreased as "CCS deployment proved to be more complex, expensive, and politically challenging than anticipated" (IEA, 2016). This resulted in just less than 10% of this publicly committed money to actually be invested in CCS projects between 2007 and 2014. This was compounded by the economic stress from 2008 onwards, in which safer, less expensive options were more attractive. These included renewable energy and new energy efficiency measures (IEA, 2016).

However, since the UNFCCC Paris Agreement in 2015, there has been a renewal in the interest of CCS. The interest has been stimulated by the fact that climate models predict that keeping within a temperature rise of 2ºC will require the deployment of CCS to some extent from 2020 onward (IEA, 2016; Rockström et al., 2017). The IEA (2016) highlights need to for pilot projects, especially where the case for CCS can be more easily made, and there are no alternatives for deep emissions reductions.

Capture

There are many technological pathways currently being developed to capture CO_2, with a large proportion of these having a high technology readiness level (Araújo and de Medeiros, 2017). For industrial applications, CO_2 can be separated in a variety of ways, including before, after and during the production of CO_2. In the pre-combustion pathway, CO_2 is separated from H_2 (hydrogen); in the post-combustion pathway CO_2 is separated from N_2 (nitrogen); and in the oxy-combustion pathway CO_2 is separated from H_2O (water) by burning hydrocarbons in pure oxygen (Adams & Davison, 2007).

The post-combustion pathway is the most developed of the three, is the closest to large-scale realisations, and is preferred for retro-fitting. During post-combustion capture, the CO_2 is dissolved in a solvent solution and chemically or physically bonded to the solvent, depending on the type of solvent uses. The former gives a higher selectivity and lower hydrocarbon losses, but the regeneration of the solvent is much harder. (Araújo and de Medeiros, 2017). This technology was considered mature even in 2005 (IPCC, 2005) with further advancements having been made since in terms of the scalability of the technology. However, there is evidence that the amine solution, used as a solvent can have adverse effects on environmental and public health if not dealt with correctly (SEPA, 2015). A commercial project using this technology exists in the 110MWe Boundary Dam coal-fired power plant in Saskatchewan, Canada which captures approximately 1 million tonnes of CO_2 annually. The plant, however, has not progressed without some problems. For example, whilst 90% of CO2 is captured only half this stored - the rest is lost though processing in the oil field and the capturing process ("SaskPower Boundary Dam CCS: Financial Report & Analysis", 2015).

The pre-combustion pathway reforms fossil fuel to synthesis gas, hydrogen, and carbon monoxide before a water-gas shift reaction (the reaction of carbon monoxide with water) forms hydrogen and CO_2 (Araújo and de Medeiros, 2017). The hydrogen is then purified and can be used as fuel and the CO_2 can then be captured. The synthesis gas is then used as the fuel to provide power. The first fully integrated coal-based pre-combustion large-scale system was the Kemper County-Mississippi Power Plant in the US. The project was first announced in 2006 but did start operation to August 2016. However, since operations began there have been many technical and financial issues. The cost of the plant has risen from a projected 1.8bn USD to 7.5bn USD. This led the operators of the plant to cease operation on the gasification faction of the process and the plant will now be powered by natural gas (Kelly, 2017).

In oxy-fuel combustion, air is replaced by oxygen during the combustion of the fuel. In most applications, the oxygen is diluted with recycled flue gas to reduce the combustion temperature and to increase the volume in order to push the energy through the heat transfer operations. Oxy-fuel combustion is the least developed of the three options and has not yet been commercialised, therefore posing a greater technical risk than the other two options. There are, however, proposed projects using the technology, for example, the White Rose plant in North Yorkshire which was only partially constructed due to a withdrawal of funding from the Drax Group and UK government (Araújo and de Medeiros, 2017).

Transport

Transport of CO_2 by pipeline is a mature technology, with CO_2 being transported for over 40 years for EOR in pipelines in the US. When the IPCC first published its special report on CCS in 2005, it detailed knowledge of pipeline transport extensively largely based on the experience of the American EOR pipelines. Since then, only significant update has been the demonstration of an offshore pipeline as part of the Snøhvit project (IEA, 2016).

Following this, there has been a significant amount of research into the feasibility of pipelines in Canada, Europe and Australia (IEA, 2016). This includes regional distribution hubs and offshore pipelines. If there is a joint investment into a common pipeline transport infrastructure for this will significantly reduce the cost of implementing CCS for individual projects. If a hub of projects were to use a common transport infrastructure, the cost of transporting the CO_2 would be significantly reduced for each individual actor.

Transport of CO_2 by shipping is the most cost-effective form of transporting CO_2 over distances longer than 2400km (IEA, 2016). The process of transporting it is very similar to shipping Liquefied Petroleum Gas (LPG), produced from processing natural gas, and is now a mature technology with expertise in the United States and the North Sea. For example, Mærsk Tankers is further developing the technology on behalf of Mærsk Oil, who have multiple depleted oil fields in the North Sea and are developing EOR opportunities here ("CO_2 Shipping", n.d.) In comparison to pipelines, shipping offers much more flexibility in terms of the volume of CO_2 transported because pipelines must maintain a constant pressure. Therefore, it represents a good option for building CO_2 hubs before they are ready to be connected to pipeline infrastructure (IEA, 2016). Shipping of CO_2, therefore, can act as a transition technology so that companies can begin to capture CO_2 before a common pipeline infrastructure is agreed upon.

Storage

Captured CO_2 is stored by injection in the geological subsurface, sequestering it long-term from the atmosphere. In theory, this process is analogous to natural gas being trapped in hydrocarbon pools for millions of years before any recent extraction. There are two major categories of a suitable geologic site for storage of CO_2, which are: old fossil fuel fields and saline aquifers. On top of this suitable sites must be sufficiently porous and permeable to allow CO_2 injection at the desired rate and be able to hold the desired volume. These two constraints are known as injectivity and storage capacity respectively. Additionally, storage sites should be chosen to avoid compromising other sedimentary basin resources including groundwater, hydrocarbons and geothermal energy. Sedimentary basins in this way represent a large economic asset and in-depth surveys of surrounding geologic strata should be conducted before a site for carbon storage is selected. Protecting surrounding economic assets in the bedrock in this way is known as containment security (Underschultz et al., 2016).

In order for CO_2 injection to achieve the desired injectivity, storage capacity and containment security, two physical processes, must be considered in the potential site. These are the unintended migration of CO_2 and the increase of formation pressure. If unintended vertical or horizontal migration of CO_2 occurs, it could comingle with a hydrocarbon reservoir or enter a coal seam. By designating a site for geologic storage of CO_2 and injecting CO_2 into it, there is an immediate limit on any future use of that stratum which could be used, for example, for geothermal energy. Injecting CO_2 into a saline aquifer will cause the reservoir pressure in the aquifer to increase, and could force saline water into freshwater aquifers. Conversely, increased reservoir pressure could provide extra pressure to depleted oil and gas fields that have had their pressure reduced through extraction or even limit the dropping of groundwater levels in overused aquifers (Underschultz et al., 2016).

Storage of CO_2 in geologic formations has received much attention for potentially being environmentally damaging because of the risks of leaks of CO_2 from the formation. In their report "20 Years of Carbon Capture and Storage," the IEA (2016) say that the safety of CO_2 storage was the subject of an issue of the International Journal on Greenhouse Gas Control. In this special issue, it was shown that the majority of CO_2 storage is safe, as long as storage sites are selected with the appropriate amount of attention and managed well with a suitable monitoring scheme (Gale et al., 2015). Moreover, Jones et al. (2015) have helped show some of the important implications that need to be taken into consideration should there be a leak of CO_2. They research in this area shows that, generally speaking, the impacts of CO_2 leakage are diffuse in both space and time. In addition to this, surface expression of leaks usually occurs in isolated, small areas (Jones et al., 2015).

Cost of CCS

The IEA state that policy supporting this type of technological implementation on the scale required cannot be reactive but must be proactive, updated as the technology matures and as the markets change. In addition, as technologies develop the need for political and financial support must also develop. Technological development describes the process through which a technology progresses between the research and development stage; the first pilots; and then, the development stage (Jaffe, Newell & Stavins, 2002). Pilot CCS projects inherently carry risks, are very capital intensive, and offer nearly no commercial value whatsoever beyond progressing through the technical learning curve. The only way to address this is ensuring that supportive policy mechanisms are proactive in their approach, with the support increasing greatly during the early development phase. The large-scale deployment of CCS technology will result in cost reductions when moving through the learning curve. This means that once knowledge is gained about the installation and appropriate configuration of the best systems, the overall uncertainty and cost of installing CCS will reduce. The overall cost per amount of CO_2 captured will, therefore, decrease overtime, largely due to the knowledge gained from installing the various technological applications of CCS (IEA, 2016).

The application of CCS technologies in cement reduction has been reported by Newell and Anderson (2003) to reduce carbon emissions of CO_2 by 65-70%. These different methods are highly variable in cost (Rootzén et al., 2016). When CCS is used in conjunction with other emission prevention methods, it can greatly reduce or even nullify the emissions from cement manufacture (Ali et al., 2011). Rootzén et al. (2016) highlight that under the current price of emission for the EU ETS, there is little incentive for private investment in production processes to lower the amount of CO_2 produced in carbon intensive industries, including cement manufacturing. However, their study of the value chain surrounding cement, and derived concrete, show that implementing investment in CO_2 abatement for the cement industry will have little effect on the current cost-structure. Their results show that the even at the most extreme abatement investment the cost to contractors in the building sector could rise by only 1-2% (Rootzén et al., 2016).

Withdrawal of Support

The implementation of CCS policy has undergone a loss of momentum in recent years. The Global CCS Institute says that there is significant evidence to suggest that this reluctance to work with CCS indicates a reflective period by governments to rethink their approaches to CCS (Global Carbon Capture and Storage Institute, 2016). For policy development, minimising the perceived risks surrounding the transportation and storage of CO_2 is key to catalyse investment into CCS in industrial settings. For the United Kingdom, it is widely accepted among a wide group of stakeholders that CCS must play an important role in a "least-cost" approach to British decarbonisation.

For every commercial application of CCS that has been constructed or operationalised since 2010, there have been two cancelled projects. A recent example of political uncertainty is in the UK, where 1 billion GBP worth of investment was withdrawn at the end of 2015. This was largely due to the money being an easy cost-saver in an economically sensitive time, and arguably because of the slowdown in CCS globally. Politically, the money was easy to cut because of the lack of public backlash, even if there was some industry-led backlash. Another example of when financial incentives have not worked is for uptake of CCS is in America, where the funding for the FutureGen 2.0 oxy-fuel with CCS project in Illinois was withdrawn because the project was not likely to be able to use the funds allocated to it within the six-year target it was given. The design of this fiscal stimulus, therefore, did not support a new innovative technology and did not take into consideration the flexibility needed when working with projects using young technology (IEA, 2016).

The withdrawal of political support for CCS has been, arguably, symptomatic of the political uncertainty surrounding the technology. The case for political uncertainty is supported by the fact that just 1 in 3 planned large-scale CCS projects planned in 2010 made their way from conceptualisation to realisation and to operation worldwide (IEA, 2016). A large portion of these projects was able to sell the captured CO_2, to processes like Enhanced Oil Recovery, which covered a lot of the cost installing the carbon capture technology. The political uncertainty surrounding the issue is even though in the IPCC's Fifth Assessment Synthesis Report (IPCC, 2014) most climate models show that the amount of emissions reductions required could not be met without CCS. Moreover, the cost of mitigating climate change would rise by an average of 138% should CCS not be implemented on a large-scale (GCCSI Institute, 2016). Modelling for the IEA (2014), an organisation known for their conservative estimates regarding transitioning technologies (e.g. renewables), shows that CCS can contribute up to 13% of cumulative emission reductions up until 2050 in a 2°C warming scenario. This number should, therefore, be viewed as a baseline, as the technological capacity of CCS to reduce carbon emissions will only increase.

Environmental Issues

CCS technologies constrict the emission of CO_2 in the atmosphere, thereby reducing the contribution of that source of CO_2 to anthropogenically-forced global warming. However, it does not work to reduce the emissions of sulphur dioxide, nitrogen oxides and particulate matter that are associated with the combustion of fossil fuels and other traditional fuels. Moreover, the application of CCS has been found to increase the energy consumption of power plants by 10-40% to account for the energy-intensive process of post-combustion carbon capture (IPCC, 2005). Since only carbon is captured during this process, this would mean an additional 10-40% of other emissions being released into the atmosphere. This is certainly the case for the application of CCS to power-generating plants. As described previously though, this study considers capturing carbon for the cement industry, where CO_2 is produced inherently in the chemical reaction in the production process, not just the combustion of fuels. It should, therefore, be stated that CCS should not be viewed as the only option to deal the production of CO_2 from fuel combustion. This could include measures such as increased energy efficiency and electrification of the cement kiln which will allow for the incorporation greener fuels. However, these measures can only reduce the carbon emissions from fuel combustion and do little to reduce the emissions from the calcination reaction.

1.2.3 The Political Economy

The political economy investigates the relationship between that state and market (Gamble et al., 1996) and "how the interaction between the two contributes to outcomes in either sphere" (Kern et al., 2016). Of primary concern when implementing a new technological regime at the national level is the relationship that exists between policymakers and private enterprises. A cement CCS project will require significant commitment from both the government and from a private industry because of the infrastructure and investment required.

Decarbonisation of industrial processes is an important part of Sweden's climate goals. It is important to foster quick transitions to a low-carbon economy and industrial sector in the light of the 2015 Paris Agreement. This was a major global commitment to limit the warming effect of anthropogenically-produced CO_2. This commitment has signalled international political will to address the issue preventing a transition to a low-carbon economy and provide infrastructure investment to catalyse the transition (Kern et al., 2016).

The need for a transition of our energy systems away from fossil-fuels is well documented. Forces such as resource depletion, a changing climate, economic development and energy security are forcing governments and energy suppliers to innovate the way in which our economies are fuelled (Verbong & Loorbach, 2012). However, the need for a transition of our industrial sector away from fossil fuels is also vitally important, largely as a result of the same four forces. Globally, the industrial sector is responsible for 25% of greenhouse gas emissions and the sector is expected to continue to grow well into the coming decades as a result of the growing economies of developing countries.

As part of these transitions, innovation needs to be nurtured in global economies. Ideas for how society can transform their fossil-fuel based energy production and industries need to be given space and funding to be piloted and implemented. Proponents of innovation in these areas must be involved in political spheres to: maintain resources (capital, material etc.); lobby for favourable institutional change and broader contextual changes and work with or argue against proponents of incumbent systems or competing innovative systems (Raven et al., 2016). To implement new innovative systems therefore, it is important to understand how technological innovation systems compare to often politically powerful incumbent socio-technical systems. In addition, it is also important to consider how the risks and benefits of the low-carbon innovations themselves are distributed, and what effects this could have on the development of the technology (Raven et al., 2016).

On the side of the government, deliberate governing of innovation and technological systems is gaining more traction, especially in Europe. This is also true for governing for a more normative outcome, such as sustainability. Turning experimentation policies in niches that would require radical destabilisation, and reformation of incumbent regimes will inherently face large amounts of opposition. This opposition could include barriers such as: social norms, technological design and vested economic interest amongst others.

A CCS project in the cement industry in Sweden could be seen as a technological demonstration, a process of social learning whereby not only are technological uncertainties overcome but a knowledge base about the technology is developed. This can increase public confidence in the technology as well as increase the economic feasibility of the production of carbon-abated products (Kern et al., 2016a).

1.3 Research Questions

CCS is an option for the decarbonisation of the cement industry in Sweden. The aim of this thesis is to explore the factors that could affect the implementation of CCS for the cement industry in Sweden. This involves the interaction between political parties, economics, industry and societal actors.

To do this, the following research questions will be addressed:

1. What are the political economy barriers to CCS implementation in the cement industry in Sweden?

2. What is the economic feasibility of implementing CCS in the cement industry in Sweden?

    a. What does the cement-value chain look like?

    b. Is there a market for carbon-abated cement in Sweden?

3. What are the trends for the future of CCS in the cement industry and how should this be addressed by the Swedish government?

1.4 Limitations and Scope

There are many limitations at all levels of this research. However, they do not undermine the overall aims of this thesis by adding to the debate of all three areas covered by the research questions. At the core of this reasoning is the exploratory nature of this research, which is seeking to understand the political and economic implications of implementing CCS for the decarbonisation of the cement industry in Sweden. However, there were some heavy limitation, that if were not present would have made the research process easier and improved the reliability of the results. First, the author does not speak Swedish. Some issues arose especially when trying to understand policy documents produced by the Swedish Government and conducting interviews where the interviewees were not fully accustomed to discussing the ideas and concepts in English.

The scope of this research is delineated to the application of CCS for the cement industry in Sweden. It is therefore one specific technology, for one specific sector, in a confined geographic location. This scoping allows for a wide-range of topics to be discussed throughout this study. This is important given that there are many aspects and perspectives to consider when implementing technological change. This selection of this scoping was based on the information shown throughout Chapter 1 of this study. Scientific evidence points towards CCS being the only option to fully decarbonise the cement industry and Sweden has set ambitious goals to achieve carbon-neutrality by 2045. The results may be generalisable for other specific cases that concern CCS implementation and/or decarbonisation of industry in other developed economics with ambitious climate goals.

The debate surrounding CCS is very politically sensitive, owing, at least in part, to CCS technologies association with the continued use of fossil fuels. It should be noted that in this report the focus is not on whether CCS should be used a technology to enable the continued use of fossil fuels. Instead, the focus is on the potential for CCS in an industrial setting in which, evidence claims, there are no credible alternatives to achieve full decarbonisation. Therefore, this is not a study analysing the potential role that CCS could play in a transition to a low carbon society but rather it seeks to analyse the potential applications of CCS for the decarbonisation of the cement industry in Sweden.

1.5 Ethical Considerations

This research has been undertaken without funding for the completion of the author's Master of Science qualification. Academic integrity was maintained throughout the process, with the author making careful consideration to avoid plagiarism and maintain confidentiality during the interview process. For the collection of primary research in this report, expert interviews, each interview was recorded with the permission of the interviewee. Where they are directly cited in this report, it has been confirmed with each expert that this is the case. However, more often than not, the primary data from interviews has been used to verify and triangulate secondary sources of information.

1.6 Audience

This research will be useful to a number of societal actors who are interested in finding out about the current debate surrounding CCS, the decarbonisation of the cement industry and how interplay between the state and the market in Sweden affects technology dispersion. For policymakers, it provides a case study for some of the decisions that may be necessary to take if the ambitious goal of carbon-neutrality by 2045 is to be reached. For academia, this should be viewed as a case-study for socio-technical transition management. It also adds to the hotly contested debate for whether CCS implementation is at all feasible.

1.7 Outline

This thesis is structured as followed:

Chapter 1 is the Introduction and has presented the problem that this research attempts to address. It also provides a full background into the Cement Industry, CCS and the concept of the political economy – the key concepts at the centre of the paper.

Chapter 2 presents the Methodology used for the completion of the research. This includes some rationale, the introduction of the conceptual framework and a full description of the methods used.

Chapter 3 contains the findings and analysis that is pertinent to answer RQ1, where the political economy of CCS for the cement industry in Sweden is discussed.

Chapter 4 contains findings and analysis that is pertinent to answer RQ2, where the economic feasibility of CCS for the cement industry is discussed by analysing data from the value chain of cement and the possibility of a market for carbon-abated cement.

Chapter 5 is a Discussion of the research process and reliability of the results. It also discusses some of the important topics that came up during the course of the research that are pertinent to answer RQ3, alongside data from the Chapter 3 and 4.

Chapter 6 provides conclusions to the research, as well as some policy implications of the research. There are also some reflections on the research.

2 Methodology

2.1 Research Rationale

The research for this paper is exploratory in nature and is focussed around the three research questions described previously. All the research questions have been approached using a triangulation method by combining a literature analysis with expert interviews. However, the style in which they have been answered varies within the text of this thesis. Research question one has been answered through analysing the case of CCS for the decarbonisation of the Swedish cement industry through a political economy framework. The second research question has been addressed through a discussion around the unique value chain of the cement industry and the opinion of important stakeholders and experts of the trends are predicted for the future. The final research question has been addressed more implicitly, drawing on different aspects put forward throughout this thesis drawing on a wide variety of literature and expert interviews. The research is largely inductive in nature and exploratory, with the aim to provide an overview of new research and political paradigms surrounding CCS, innovation in the cement industry and governmental policy.

2.2 Conceptual Framework

The conceptual framework for this study consists of three main sections. Each of these three sections corresponds to a respective research question discussed in Chapter 1. The first section assessed the political economy of CCS in Sweden; the second sought to understand the economic feasibility of introducing CCS in the cement industry; and the third discusses some of the major trends regarding CCS broadly in the Swedish context. This framework is shown in Figure 2.1.

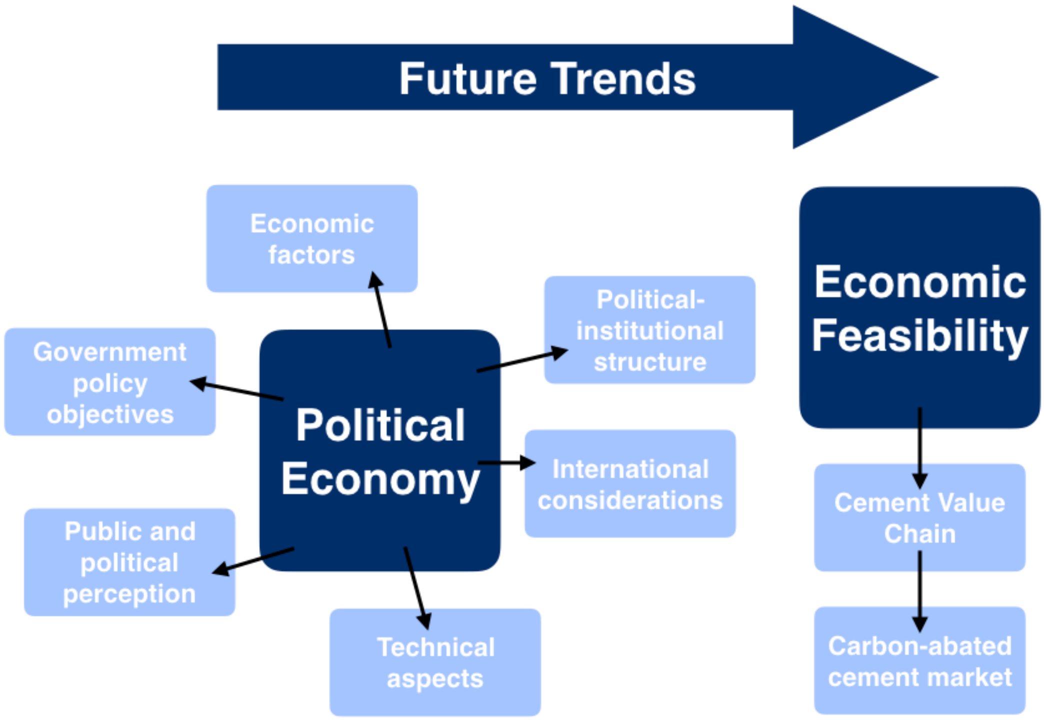

Figure 2.1 Conceptual Framework

Source: Own Source

The political economy framework that addressed RQ1 for this study has been developed based on previous literature surrounding the political economy of CCS (Kern et al., 2016; Meadowcroft & Langhelle, 2009; Torvanger & Meadowcroft, 2011) and the political economy literature more generally (Hayward, 1998; Meadowcroft, 2005). The conceptual framework developed was used to analyse the potential of CCS for the cement industry in Sweden. Exact definitions used in the framework are shown in Table 2.1. This framework shows the six areas within the political economy framework that will serve to analyse the feasibility of the introduction of CCS in the cement industry in Sweden based on an analysis of the political economy literature listed above. This type of framework is common and is employed by Kern et al. (2016) and Meadowcroft & Langhelle (2009) successfully to analyse the relationships between economics, politics and social institutions for CCS. The government policy objectives section describes the policies of the government that aim to achieve the country's energy and policy goals. This can include general climate and energy policy direction (e.g. emissions targets, energy security concerns and regional development). Economic factors considered include the financing of the implementation, general macro-economic trends, resource availability, fuel type and availability of public finances. Political-institutional factors that have been considered include the characteristics of the Swedish political system. The section on public and political opinion analyses the perspectives of the general public and politicians. The section on international considerations analyses the influence of global trends in politics and markets surrounding CCS that could impact decisions made in Sweden.

None of these six areas should be considered stationary or static, and this framework recognises the interdependence that these factors have on each other. For example, government policy objectives could be influenced by international commitments made when signing United Nations treaties. This framework focuses specifically on factors that affect the Swedish cement industry, offering a complementary perspective to multi-level innovation and technological development studies. The results obtained will be a useful case study on the political feasibility of applying CCS to the industrial sector, but will not provide a large amount of evidence supporting the implementation of CCS in other sectors (e.g. the power sector) or in vastly different political contexts (e.g. China or America). However, some key lessons will apply to OECD countries, party to the UNFCCC Paris Agreement, on the feasibility of a deep reduction in emissions from the cement industry.

Table 2.1 Definitions of the areas of the Political Economy and examples of how they may apply

Area of Framework	Definition	Example of potential impact
Government policy objectives	Government targets, goals and objectives that relate to emissions control industrial strategy. This includes emissions targets, energy policy, climate policy and any policy or directive specifically related to either CCS or the cement industry.	Strong climate policy objectives signal a higher willingness to investment in carbon-abatement technology.
Political-institutional structure	Characteristics of the Swedish political system, including policy history, established political paradigms, party politics – and how these have influenced climate and energy-related decision-making. Also included is the institutional structure of decision-making and degree of federalism.	Established political paradigms may favour or discourage investment in new technology.

Economic factors	The cost of installing CCS on to a cement plant, as well as industry incentives and barriers to that cost. Also considered here are macro-economic trends including fuel sources, public finances and export earnings.	Uncertainty surrounding investment may increase weariness surrounding CCS. Economic recession generally will also discourage investment.
International considerations	Influences from international agreements surrounding climate change and the general conditions for the markets surrounding fossil energy, renewables and CCS technologies.	Pressure from and strong-adhesion to international agreements will make Sweden more likely to consider investment in carbon-abatement.
Public and political perception	CCS opinions given by ministers and politicians, the media and the public. Broadly speaking this is both considered at a national level debate, and at local level for individual projects. Also included are the opinions of relevant stakeholders including NGOs and the general public.	Strong opposition will make investment less likely.
Technical aspects	The feasibility of the technology to capture CO_2 as well as the likelihood of a viable infrastructure to store of use the CO_2.	Uncertainty around the technicalities will potentially raise costs and make investment less likely.

The economic feasibility question framework that has been developed based R2 and the accompanying two sub-research questions explained in Chapter 1. The economic feasibility of CCS for the cement industry is discussed by investigating the cost structure of the cement value chain and ascertaining whether or not there is a market for carbon-abated cement. This framework was developed following the conclusion of Rootzén et al. (2016) the cost of carbon-abatement in the cement sector could be managed by placing a larger proportion of the costs on the end-consumer. This naturally lends itself to the questions of whether or not the end-consumer would be willing to pay for carbon-abated cement. In other words, is there a market for carbon-abated cement? If there is a market for carbon-abated cement, that would increase the economic feasibility of introducing CCS in the cement industry.

The approach to address RQ3 is more open than the previous two. It has been designed this way to be informed by expert interviews as part of this research. Through theme comparison and analysis of interviews, important trends for CCS in Sweden were identified. As such, this research question is designed to be answered in a more open way, using data collected throughout the duration of the study.

The Political Economy and Economic Feasibility frameworks have been populated with data obtained from: an extensive review of scientific literature; analysis of reports by international research bodies such as the IPCC, the IEA and the GCCSI; and review of policy documents at the Swedish governmental and European level. In order to minimise bias from the author, this secondary data obtained has been triangulated with a series of semi-structured expert interviews. The secondary data was reviewed systematically in order to inform the interviews, and both the secondary data and interviews were used to derive conclusion from the analysis of both sets of data.

The Future Trends framework was initially populated and structured based on analysis of the semi-structured expert interviews conducted throughout the course of the research. The themes discussed were compared with each other, and cross-referenced with relevant literature to help avoid bias.

2.3 Research Methods

The research for this study was conducted through two main pathways. These were: a literature review and expert interviews. These two processes informed were conducted concurrently and informed each other throughout the collection of findings and analysis of data. For example, often literature suggested experts, or brought up a theme or topic that an expert could add perspective on. As well as this, experts often pointed towards pertinent literature they were familiar with or other experts which they thought could add value to the study. This relationship is displayed graphically in Figure 2.2. In this way, the research process was very dynamic, constantly evolving as new information was learnt, with the intention of investigating the full scale of the factors that are at play regarding CCS in the cement industry in Sweden.

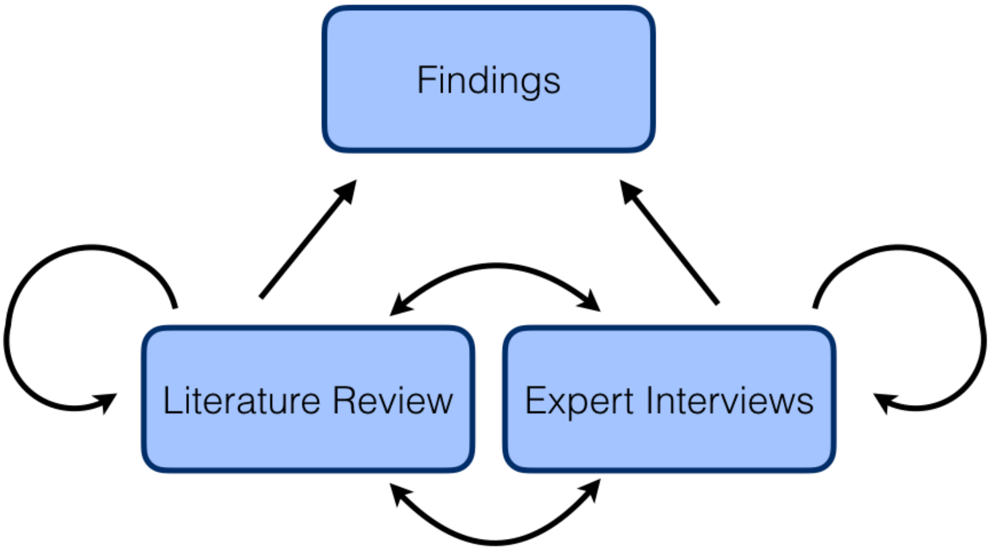

Figure 2.2 Research Methods

Source: Own source

2.3.1 Literature Review

The literature review for the sake of this thesis drew upon three main sources: academic literature, reports from research institutions and policy documents. The literature review for this study was comprehensive, and was completed until argumentation reached a degree of saturation. Articles relating to the political economy dimensions discussed for the cement industry and CCS were assessed. The political economy encompasses any different aspects so there is wide range of literature backgrounds included in this study including political science, transition management, business studies, environmental economics and geology.

The breadth of literature included in this study meant that argumentation saturation was difficult to achieve. However, the expert interviews provided an invaluable source for data triangulation. The interviews also helped to structure the literature review as it progressed, often pointing in the direction of valuable sources and reports relevant in their respective field of expertise. This included reports from separate research institutions and business reports. In methodological literature, these sources are described as grey literature. Grey literature includes reports and research conducted by institutions or researchers not within the traditional academic publishing distribution channels, which is often freely available online.

The benefits for the inclusion of grey literature in the review of a topic are discussed by Mahood et al. (2014). The main reasons for the inclusion of grey literature are that it contains a lot of information that has not yet been discussed in the academic discourse, so there is a whole wealth of data available that cannot be accessed in academic literature. Nowadays, grey literature is easily accessed online, whereas historically it was tough to find. In fact, there are even entire databases set up for the compilation of grey literature solely. Consulting grey literature means conclusions surrounding the topic at hand can be made from drawing upon a wider set of evidence.

The main challenge in the inclusion of grey literature is the systematic processes that must be applied in searching for appropriate sources. For example, why should one source be included over another? Another problem arises when searching is the sheer number of grey literature sources. It may not be possible based on time constraints in most studies to use all the appropriate grey literature. Another issue is the legitimacy of the evidence presented in the grey literature that is included. However, this is also the case for academic literature for issues that are more politically-charged, like the topic this study. In terms of grey literature, only reports from verified sources with reputable backgrounds have been used and the data obtained triangulated with other sources.

2.3.2 Expert Interviews

The data here has been triangulated with data from stakeholders from a wide range of backgrounds. This includes researchers, policy advisors, members of research bodies, industry representatives and policy experts. A list of these interviewees can be found in Table 2.2, and a list of example questions can be found in Appendix 1.

The interviews were semi-structured and exploratory in nature in order to maintain a degree of openness whilst allowing the focus to remain on key issues that each expert could address (Kvale, 1996, pp. 97). The interviews took place during June – August 2017, the time during which this study was conducted. Unfortunately, there were a limited number of experts that could be contacted due to this limited time frame and the fact that a lot of people take an extended vacation in Sweden during the summer. These interviews provided an account of the first-hand experiences of the actors, but may have been influenced by some of their vested interests e.g. political ambition, research funding etc. This bias was minimised by triangulation of data across the interviews and by only using this data to support evidence obtained during the collection of secondary data.

Expert interviews were used in this study. An expert, for the purpose of this study is an individual with a high degree of knowledge and experience surrounding the topic. This has resulted from their actions, responsibilities and obligations within the area of research. In this case, it is within the area of CCS, the cement industry or within the cement value chain. These experts are responsible for the planning, implementation or controlling of CCS technology within the cement industry in Sweden and as such have access to the decision-making processes and the people who make the decisions. Therefore, the findings of this study are particularly interesting because of the practical consequences of their expert knowledge for others (Littig, 2013).

The interviews themselves were semi-structured with the overall intention of the reconstruction of each expert's objective knowledge about CCS and/or the cement industry. However, there are some restrictions when gaining access to the experts in this case. This included the time restrictions of the experts, who tend to be very busy people. My position as a master student/junior researcher does not hold a lot of sway, so presumably there was some degree of reluctance or lack of urgency to respond. The experts themselves may have been reluctant to share certain areas of knowledge because of constraints within information in their organisation (Littig, 2013).

At the beginning of the process, the expert status of the interviewees was ascribed by the researcher. However, during the course of correspondence with interviewees, other experts were often recommended. This resulted in a somewhat iterative process whereby each expert contacted would often recommend another relevant to the field of study. This method ensures that you develop a list of interviewees who people involved in the field-of-study consider experts (Littig, 2013). However, this method does not eliminate bias because of the original ascription of by the researcher of what constitutes an expert. This is a major limitation of this method.

The interviews were transcribed and paraphrased. Then themes were compared and information that was relevant was discussed in this report. Interviews were cross-referenced with each other and literature, when possible, for accuracy and to achieve a degree of data saturation. The full list of experts for this study is listed in Table 2.2. When a specific point that was made by an interviewee is referenced in the text of the study, it will be referenced as "Interview X", where X corresponds to the appropriate number assigned each interviewee in Table 2.2.

Table 2.2 List of Expert Interviewees

Interviewee Name	**Role**	**Interview Date**	**Interview Method**	**Assigned Number**
Florian Kern	Co-Director of the Sussex Energy Group and Senior Lecturer at SPRU-Science Policy Research Unit.	25-05-2017	Skype	1
Tobias Persson	Analytiker och samordnare (analyst and coordinator) at Tillväxtanalys - Myndigheten för tillväxtpolitiska utvärderingar och analyser (Swedish Agency for Growth Policy Analysis).	13-07-2017	Phonc	2
Staffan Görtz	Former senior analyst and CCS head of communication at Vattenfall.	14-07-2017	Face-to-face	3
Tristan Stanley	Energy Analyst at International Energy Agency.	17-07-2017	Phone	4
Karolina Brick	Miljöchef (Head of Environment) at Riksbyggen.	10-07-2017	Email	5

Per Arne Nilsson	Senior consultant at Panaware AB.	16-08-2017	Phone	6
Laurin Wuennenberg	Associate at the International Institute for Sustainable Development	16-08-2017	Skype	7
Stefan Sandelin	Utvecklingschef (Head of Research & Development at Cementa AB	30-08-2017	Phone	8
Anders Lyngfelt	Professor, Department of Space, Earth and Environment, Energy Technology.	01-09-2017	Phone	9

2.4 Research Questions

Table 2.3 restates each research question and summarises the method through which it will be investigated.

Table 2.3 Research Questions

Research Question	**Research Method**
What are the political economy barriers and incentives to CCS implementation in the cement industry in Sweden?	Literature Analysis Content Analysis: Interviews with experts (researchers, policy advisors and member of the industry).
What is the economic feasibility of implementing CCS in the cement industry in Sweden? - What is the cost to the end consumer for implementing CCS across the value chain of cement production for public infrastructure? - Is there a market for carbon-abated cement in the public sector in Sweden?	Content Analysis: Interviews with experts (researchers, policy advisors and member of the industry). Literature Analysis
What are the trends for the future of CCS in the cement industry and how should this be addressed by the Swedish government?	Content Analysis: Analysis of policy documents and opinions and considerations from experts. Literature Analysis

3 Carbon Capture & Storage in Sweden for Cement Industry Decarbonisation

This section contains the findings from the literature review coupled with primary data taken from the expert interviews. Embedded within these findings is the analysis of the data including some of the important points for discussion in Chapter 5. This chapter is structured according to the political economy portion of the overall framework of this study, described in the Chapter 2.

3.1 Government Policy Objectives

3.1.1 Previous Policy Objectives

The previous policy objectives of the Swedish government set out the targets and objectives that have been applied to environmental and energy policies, with an influence from climate change objectives. This has been broadly divided into Sweden's commitment under the European level Roadmap 2050, which the government has been working towards since the Roadmap 2050 was announced in July 2009. Since the current policy objectives have only recently been approved by the Swedish government, it is important to discuss the previous commitments to which it has been working in order to get a clearer understanding of the relevant environment and energy policy.

The Swedish government has a long history of innovative environmental policies. For example, when Sweden set up an environmental protection agency (Naturvårdsverket) in 1967 because of recognition of a limitation of the number of natural resources, it was the first country to do so. Internationally speaking, it hosted the first UN conference dealing with environmental issues in 1972. This landmark conference lead to the formation of the United Nations Environment Programme (UNEP). To this day, Sweden continue to aim to "create momentum" and "intensify negotiations" on international settings ("Sweden tackles climate change", 2017).

Until recently, Sweden's emissions reduction objectives were part of the EU's roadmap 2050. The aim was to have no net emissions from the country by 2050. This included: a 40% reduction on 1990 levels by 2020; and no vehicles using fossil fuels by 2030. The overall aim of Roadmap 2050 for the entirety of the EU was to cut emissions by a minimum of 80% on 1990 levels by 2050. The reason for targeting vehicle emissions like this is that Sweden's energy mix, comprising electricity and heat generation is largely from renewable sources, specifically hydro, nuclear and biomass. In fact, it is by far the highest in the EU-28 in 2014, with a share of renewables of 52.6% of final energy consumption coming from renewable sources. For context, the second highest share belonged to Finland and Latvia with 38.7% of final energy consumption coming from renewable sources (Eurostat, 2016). This means that to further reduce emissions from energy, there would be a considerable cost. Therefore, emissions reductions of the same magnitude will cost less through targeting other areas, such as transport and industry ("Sweden tackles climate change", 2017).

Another area for policy objectives is energy efficiency, where the government's goal was to make energy use 20% "more effective" by 2020, compared to a 2008 baseline. In 2005, the government offered tax reliefs to energy-intensive industries if they drew up plans to move towards more efficient energy use. In addition to this, municipalities have an "energy advisor" to advise households on best practices for energy efficiency including, but not limited to replacing windows, using low-energy lights and using the best heating systems available ("Sweden tackles climate change", 2017).

By and large, these policies were in line with the rest of the European Union. They tackled the "low-hanging fruit" of emissions reductions through transport and energy efficiency, given Sweden's relatively clean energy mix. These combined meant that for Sweden CCS was low on the political agenda. New, more proactive goals and objectives, with more financial support would be needed for CCS to take hold in the power and industrial sectors (Interview 3).

3.1.2 The Climate Act 2017

A new set of climate targets will be introduced into Swedish law on 1st January 2018. (Government Offices of Sweden, 2017). Initially, it is difficult to ascertain how this will affect the implementation of CCS in Sweden. However, there are aspects of the new Climate Act which point towards a more open discussion around CCS in the future, especially for industry (Interview 2) in political circles. There are also parts of the law which explicitly state an intention to view CCS as a viable solution to achieve deep emissions reductions in the industrial sector (Figure 3.1)

The framework for the policy consists of three main "pillars". These are the development of clear climate goals (Figure 3.1), the Climate Act policy and formation of the climate policy council. The government say that that the purpose of the framework is to develop a "clear and coherent climate policy". They also state that the framework has been agreed within the Cross-Party Committee on Environmental Objectives, with broad political support. The government also claims that the policy will "provide the long-term conditions for business and society to implement the transition needed to solve the challenge of climate change" (Government Offices of Sweden, 2017).

The Climate Act is the mechanism that ensures that the government's climate policy must be based on the new goals, making sure that work is carried out in order to achieve these goals. This new act will be enforceable from 1st January 2018. As part of this, reporting is central with a new requirement that the government present a progress report on achieving these goals every year as part of the Budget Bill. This is coupled with an action plan of pertinent actions, presented every four years, for how best to achieve the climate goals set (Government Offices of Sweden, 2017).

The policy has the main target of reducing Sweden's net greenhouse gas emissions to zero by 2045. After 2045, Sweden should work to achieve negative emissions through the creation of carbon sinks (natural and manmade) and through investment in carbon-reducing efforts globally. This could include investing in BECCS, for example. "Negative emissions" means efforts to reduce the amount of carbon in the atmosphere should be greater than all the carbon emissions produced by Sweden. In addition to this however, there is a sub-target that states that remaining emissions from activities in Sweden should be, at the very least, 85% lower than the greenhouse emissions in 1990 by 2045. These are accompanied by corresponding intermediary targets of 63% lower than 1990 levels by 2030 and 75% lower by 2040 (Ett klimatpolitiskt ramverk för Sverige, 2016).

The main emission sources targeted by the policy are those not covered by the European Union Emissions Trading Scheme (EU ETS). The EU ETS applies to emissions from industry,

Long-term climate goals:

- By the year 2045, Sweden will not have any net greenhouse gas emissions to the atmosphere, and then achieve negative emissions
- By 2045, emissions from operations in Swedish territory should be at least 85 percent lower than 1990 emissions
- In order to reach the target, carbon capture and storage of fossil origin, where reasonable alternatives are missing, are counted as a measure (CCS).
- Additional measures to achieve net zero emissions may be credited in accordance with internationally agreed rules.
- The target in 2045 requires increased ambitions in the EU Emissions Trading System.

Figure 3.1 Sweden's long-term climate goals

Source: (Ett klimatpolitiskt ramverk för Sverige, 2016)

electricity and district heating output, and flights departing from and arriving in the European Economic Area (EEA). Sources not covered by EUTS include “transport, machinery, small industrial and energy plants, housing and agriculture.” CO_2 from the production of cement is covered by the EU ETS as an energy-intensive industry with a considerable amount of CO_2 produced per tonne of cement manufactured. However, as part of this in certain sectors only plants above a certain size are included and can even be offset if the government introduces its own fiscal measures to cut emissions by the same amount (European Commission, 2016). However, due to the magnitude of cement plants in Sweden, all plants are covered by the EU ETS and must purchase carbon emission allowances from the European Union.

The third and final “pillar” of the new climate framework is the climate policy council which will provide the government with an independent assessment of the how the policies proposed by the government are compatible with the climate goals described above. This takes the form of deciding how the policies in relevant policy areas will affect the likelihood of achieving the desired goals by the government. This climate policy council is based on the Committee on Climate Change, based in the UK, which has been operating since 2008 (Interview 2). This committee is responsible for providing “independent advice to government on building a low-carbon economy and preparing for climate change” ("About the Committee on Climate Change", 2008). The Committee is made of experts from a wide variety of fields, including climate change, science, economics, behavioural science and business.

However, the Climate Change Act 2008 in the UK and the similar Swedish Climate Act differ in one major way. The British version has less ambitious targets than the Swedish i.e. 26% reduction of greenhouse gas emissions by 2020, and 80% reduction in greenhouse gas

Short-medium term goals for industry:

- A broad zero-emission strategy for the basic materials industry should be developed
- The target in 2045 requires increased ambitions in the EU Emissions Trading System.
- For the restructuring of the iron and steel industry, a focus should be on research and development and demonstration of new process technology is prioritized.
- The strategy work should include the prerequisites for introducing carbon dioxide separation technology
- Carbon capture and storage (CCS) in Sweden for parts of the basic materials industry's conversion into low-emission production and highlight the possibilities of applying CCS to biogenic emissions.
- The strategy work needs to be initiated with a preliminary study and followed by decisions on investments in major pilot plants by the middle of the 2020s.
- Proposals for a strategy for funding a preliminary study should be included in a forthcoming research proposal.
- The government should designate a responsible authority to provide resources for the work to drive and coordinate research and innovation efforts for a zero-emission strategy in the basic materials industry.

Figure 3.2 Short-medium term goals as part of the Climate Act

Source: (Ett klimatpolitiskt ramverk for Sverige, 2016)

emissions by 2050 compared to 1990 levels. On the other hand, the British law has legally-binding five-year carbon budgets that mean that emissions rise in one sector must be balanced by further reductions in another sector. There must also be a publically-available plan to produce these reductions. In contrast, the new Swedish Act has no legal enforceability mechanism (Interview 2). This means that the government cannot hold civil departments to account for not meeting their individual target of net-zero emissions by 2045.

Within the text of the new Climate Act, aside from the overall long-term goals, there are short-to-medium term goals for industry. These encompass the government's vision for what needs to happen in the coming decades in order to prepare Sweden's industrial sector to be able to make a transition to more sustainable production to keep in line with the new national targets. These are shown in Figure 3.2. By nature, short-medium term goals are more specific. Within these goals, there is a mention of broad zero-emission strategy indicating intention to move towards an industry with zero-emissions in Sweden. This includes a focus on new ways of producing iron and steel and, critically, a focus on developing the pre-requisites for CCS and storage in the basic materials industry.

Within the cement industry in Sweden, there is already evidence of developing the pre-requisites of CCS. Vattenfall and Cementa AB are currently piloting electrified cement production which will further increase the energy efficiency of cement production. Cementa AB CEO Jan Gånge says "'Electrification within the industry is an important element in the transition to sustainable urban development. We are now going to develop knowledge within the field in order to ascertain together with Vattenfall whether it is a potential future solution for cement production" (Vattenfall, 2017). The electrification of cement production will allow for easier integration of renewable energy. Crucially, however, it also allows for a smoother transition for incorporating carbon capture technologies into the production process (Interview 2). It is viewed as the next step in the transition towards incorporating CCS into the cement production process (Interview 8), because the gases produced in the kiln are largely pure CO2. This means CO2 does not have to be separated from other flue gases, and reduces the energy consumed in the plant by eliminating this step.

Another important aspect of these medium-term goals is the recognition of the economic potential of BECCS for a forest-nation like Sweden with a large forestry sector and a considerable dependence on biogenic fuel sources for heating and electricity. As a result, there is a large potential for BioEnergy with Carbon Capture and Storage (BECCS) (Interview 6) if the technology can be made commercially viable. The technology offers a form of carbon negative energy whereby CO_2 is absorbed by forests, which are then used to produce energy. Then, instead of emitting the normal CO_2 from this process it is captured and stored. This overall process, therefore, removes CO_2 from the atmosphere through natural processes before storing it permanently in geologic formations. This technology and process is included in the projected pathway for achieving the goals of the Paris Agreement through rapid decarbonisation by Rockström et al. (2017). However, achieving commercialisation of the process currently is very rare and tends to be linked to EOR or bioethanol production on relatively small scales (Sanchez et al., 2016). In the words of a group of industry experts, "BECCS could be used in Sweden to reduce total mitigation cost, by reallocating CO_2 emission budgets between different sectors and countries. In Sweden, CCS in industrial and energy processes with an increasing share of biomass could, therefore, be an opportunity to add value to biomass. Based on the installation of effective policies securing sufficient financial support and incentives, this could become a new industrial segment." (Nilsson, 2017)

Of course, it is too soon to successfully analyse the policy or to know how it will affect an industry in Sweden. However, it is clear that these brand-new policy objectives will affect the implementation of transitional carbon-neutral technologies in the cement industry in Sweden. At the very least, the wording of the new goals and objectives bring CCS from a place of political uncertainty and infeasibility to a more open and established debate for its potential to decarbonise the industrial sector in Sweden (Interview 2) although there are still significant obstacles to overcome. Moreover, the role for BECCS for Sweden to achieve negative emissions is being discussed in political circles, and this policy, at the very least, opens the door for political support of this technology.

3.2 Political-institutional structure

3.2.1 Innovation Paradigm

Internationally, Sweden takes pride in implementing policies to stimulate innovation. This is evidenced by their high ranking in the Global Cleantech Innovation Index. In 2015, they were ranked fourth among OECD countries in the amount of expenditure for R&D as compared to their GDP and in 2017 they were ranked third, behind Denmark and Finland in the Global Cleantech Innovation Index. This global index investigates entrepreneurial companies that are most likely to emerge with sustainable solutions in the next decade (WWF & Cleantech Group, 2017). Sweden promotes itself as a "pioneer country" in terms of reducing its greenhouse gas emissions. This reputation is evidenced by the country's high rate of innovation and its low

CO_2 emissions per capita - 4.6 metric tonnes in 2013, compared to 7.1 for the UK and 16.4 for the US ("CO_2 emissions (metric tons per capita) | Data", 2017).

Therefore, at least to an extent, there has been political pressure to develop a policy like the Climate Act. The policy has very ambitious goals, however, it is by no means the first of its kind. The political will for Sweden to be seen as a pioneer has played a role in the need to introduce this policy (Interview 2). Sweden's self-styled role as a pioneer in innovation in legislating to combat climate change will, therefore, have an effect on the decision whether to invest in CCS.

3.2.2 Consensus Building

The political system in Sweden also has an effect on how policies are developed and implemented. Policies are by and large developed based on cross-party consensus and minority government legislation. This history of minority governments and formation of coalitions (Figure 3.3) has made a difference to Sweden's historic energy and environment policy. For example, the current government is made up of the Social Democrats and the Green Party and

History of Swedish elections:

2014: A minority left-of-centre coalition takes over after the Alliance.

2010: The ruling centre-right Alliance beats the left-of-centre coalition, but fails to gain an outright majority.

2006: The non-socialist parties form a four-party coalition government called the Alliance.

2002 and 1998: The Social Democrats remain in office after both elections, but in order to implement their policies are forced to form a parliamentary alliance with the Left Party and the Green Party.

1994: The Social Democrats form a new minority government. Starting from this year, general elections are held every four years instead of three.

1991: A non-socialist minority government of the Moderates, Liberals, the Centre Party and Christian Democrats is formed.

1988 and 1985: The Social Democrats remain in power after both elections.

1982: The non-socialist parties lose their majority and a Social Democratic minority government is formed.

1979: The non-socialist parties retain their parliamentary majority, and a new three-party government is formed. In the spring of 1981, the Moderate Party leaves the Government.

1976: The Social Democrats are defeated by a coalition consisting of the Centre

Figure 3.3 History of Swedish elections

Source: ("The Swedish system of government", 2016) within the government, the Green Party has the portfolio for both environmental and energy policy. Within each coalition government, individual parties take portfolios for their flagship policies. Even in the previous government, within the more right-of-centre “Alliance”, the party responsible for the environment ministry was the Centre Party with a strong interest in preserving rural and agriculture-supporting policies.

In terms of policies, the new Climate Act was the result of discussions within the Cross-Party Committee on Environmental Objectives (Government Offices of Sweden, 2017). Any policy that is developed with a cross-party consensus such as this may contain a number of compromises. Greenpeace (2016) argue that this is the case for this policy, they say that there are a number of political compromises even when there is a good scientific basis for a common consensus. They argue that policy does not go far enough and that if all countries adopted similar strategies, we would still exceed the carbon budget proposed by the IPCC (2012), leading to a “global climate disaster.”

However, politically, the development of the new Climate Act has been heralded as progress (Interview 2) because it was approved by all parties, with the exemption of the Swedish Democrats. This consensus is vitally important for large infrastructure projects like CCS and other big investments so it has a stable investment behind it. This means that confidence and investment will not change subject to a change in government. This continuity of support is important to de-risk investment in large investment projects like CCS going forward (Interview 2). In other words, a strong paradigm of consensus building is important for the advancement and dispersion of CCS technologies.

3.2.3 Federalism

There are four levels of government with influence over decisions affecting different areas of society. The first is at the European level, in which Sweden has been a member of the European Union since 1995. The next is at the national level, where the government submits policy proposals to the Swedish Parliament and implements policies which are approved. The government is responsible for decisions surrounding budget allocations, bilateral and multilateral agreements, representation in the EU, taking decisions in some administrative areas that are not covered by other levels of government and controls and directs the decisions and actions of the executive branch ("The Swedish system of government", 2016).

The subsequent level is the regional level of government, where Sweden is divided into 20 counties. Each county has a council which coordinates tasks that cannot be simply handled at a local level and requires the coordination of different local municipalities. This includes, for example, healthcare where a hospital in one municipality can provide healthcare to multiple neighbouring municipalities ("The Swedish system of government", 2016).

Locally, Sweden is divided into 290 different municipalities. In each of these municipalities, locals elect an assembly responsible for a wide range of services including local transport infrastructure, water, schools, welfare, childcare, social care and housing. They are able to levy taxes to charge for the services that they offer and have a large degree of autonomy with regard to the provision of these services, that is outside of the basic services which they are legally obliged to provide ("The Swedish system of government", 2016).

At the national level, the current government is a minority government formed by the coalition of the Social Democratic Party and the Green Party. The Social Democratic Party have traditionally been a linchpin of modern Swedish politics but over the last 30-40 years, successive governments have alternated between the Social Democrats and parties from centre-right "Alliance" including the Moderate Party, the Liberal Party, the Centre Party and the Christian Democrats ("The Swedish system of government", 2016).

The degree of federalism and the responsibility of decision-making is important when building large infrastructure projects. The sharing of information, costs and responsibilities between each governmental level will ensure that a project has the best chance of moving forward. If members of local or regional government do not approve or see the need the infrastructure project, in this case, CCS, they could delay the project or cancel it altogether.

3.3 International considerations

3.3.1 The Paris Agreement

International climate agreements greatly impact a government's willingness to legislate in order to reduce the amount of emissions that the particular country generates. The UNFCCC agreements signed in Copenhagen in 2009 and Paris in 2015 represent a political willingness to address the issue of global warming. Sweden is party to both these agreements and is seen as a leader in terms of fulfilling its commitment(s) to them (Carbon Market Watch, 2017). However, one of the main caveats of these environmental agreements is that there is no legally enforceable mechanism to make sure particular countries meet their agreed targets.

Following the Paris Agreement in December 2015, policymakers and industries have been left to develop effective strategies for climate change mitigation. The Paris Agreement aims to limit global warming to 2°C but make the necessary changes to aim for only 1.5°C of warming based on pre-industrial levels Limiting present and projected emissions so that they only cause a global rise in temperature of 1.5°C is an ambitious target; very few global forecasts see it being reached without large-scale deployment of CCS technology (Roettereng, 2016). It has been suggested that a more effective climate regime, including deals such as that struck in Paris, should encourage strategies and overall aims that already have some traction at the national level. The pledge-and-review system under the Paris agreement will go some way to evaluate the mitigation measures that each party has sought to implement. Each party to the agreement will have to legitimise its own pledge to the agreement.

In the realm of international climate agreements, the Paris Agreement has been heralded as the most successful attempt at a global, legally binding political measure to mitigate the emission of CO_2 and other greenhouse gases into the atmosphere. As of December 2016, 194 parties have signed the agreement and 133 had already ratified it. The signing of the agreement opened in April 2016 and saw unprecedented and swift levels of signing by government around the world.

Given that the targets of the Paris Agreement are ambitious, Roettereng (2016) states that it is important to highlight CCS as a potential key investment area for policymakers that could help them in meeting their nation's pledges whilst investing in technology that is already technologically feasible. CCS, in its current state, is a long way from meeting the projected 13% possible overall contribution to CO_2 reductions (IEA, 2016). If this potential is to be realised, the GCCSI say that CCS technologies must become a focal point of climate mitigations policies and actions executed by industries and governments (Global Carbon Capture and Storage Institute, 2016). However, the agreement does provide some optimism for CCS-interested parties. The role of investment into environmentally friendly technologies looks promising, including regarding CCS. According to the GCCSI, policy decisions should continue to focus on the potential that the technology represents (Global Carbon Capture and Storage Institute, 2016).

As part of the Paris Agreement, nations submitted Intended Nationally Determined Contributions (INDCs), which they are accountable to once they are revised into Nationally Determined Contributions (NDCs) and help favour the formation of "predictable national climate and energy policies." Commitments to policies such as this are usually welcomed by industries because it gives them a predictable future to plan for. It also gives confidence to investors to engage with the development of long-term, carbon-reducing technologies that otherwise would be too risky to invest a lot of upfront capital in, including CCS. However, the IEA (2015) has warned in their report "Energy and Climate Change, World Energy Outlook, Special Briefing for COP21" that the initial submitted INDCs "…*fall short of the major course correction required to achieve the agreed climate goal*" (pp. 4). It could be argued that this "shortfall" of INDCs and the lack of CCS legislation in the Paris agreement highlights the need for the introduction of CCS in order to bring into force NDCs.

It is clear, therefore, that whilst CCS implementation has faced many setbacks it has not left the international climate change mitigation debate yet. This is due to the unique potential the technology represents to decarbonise large parts of our infrastructure and eventually achieve negative carbon emissions through BECCS.

3.3.2 International Markets and globalisation

Cement is a global product and is a prime example of a homogenous product in terms of quality. This means that there is no difference in quality between cement produced all over the world. However, it cannot be transported over large distances cheaply so the cement is largely produced in close proximity to where it is used. The difficulty of transporting cement is a limiting factor for the globalisation of cement. This means that individual cement companies do not have to worry about a loss of competitiveness to cheaper markets.

One of the main issues discussed in the literature is the concept of carbon leakage. Carbon leakage is defined "as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries" (IPCC Fourth Assessment Report: Climate Change, 2007). This is a concern for governments legislating to reduce carbon emissions because by manufacturing abroad, you will reduce greenhouse gas emissions in your own country, but there will be no net benefit to the reduction of CO_2. In a lot of cases, it could cause a rise in global CO_2 emissions because of asymmetric regulation where the new country-of-origin has less strict emissions standards.

Cement, despite a high transportation cost, can logistically be transported very easily. The cement industry, therefore, is concerned about globalisation and competitiveness from producers in other parts of Europe, China and even parts of the developing world (Interview 8). It is important, therefore, in order to keep the Swedish cement industry competitive that it is able to innovate and produce low-carbon cement, as well as keep the costs of the cement competitive.

3.4 Economic Factors

3.4.1 The Cement Industry

Cement is part of a strong Swedish base industry. Within manufacturing, different industries are affected heterogeneously by the introduction of more intense or strict climate targets. The degree to which an industry is affected by a change in climate targets will be a function of how energy-intensive its processes are and ultimately how much emissions that it produces. Another factor that has influence when considering the effect that the introduction of climate target will have on an industry is the industry's adaptability. The adaptability of a business to a change in regulation is complex but largely revolves around the nature of the primary product and the regulation of the market in which it operates.

For the manufacturing of base materials, such as cement, switching to a system where there is a lower amount of carbon emissions is particularly difficult. Often in these industries, in order to reduce carbon emissions significantly, there has to be a large amount of reconstruction of the core processes involved. This could be through an end-of-pipe solution, e.g. CCS, or through a dynamically different process that produces fewer emissions, incorporating the principles of cleaner production.

It is difficult to argue, with any degree of certainty, the cost of introducing any long-term climate policy, such as decarbonising the cement industry. However, within the base industry in Sweden (steel, cement, aluminium) it is useful to discuss the likely effects of the cost increase per unit of product. A rise in the cost of carbon means that the cost of product will increase, compounded an increase in energy costs for production. Åhmen et al. (2013) compare the estimated carbon cost in the future to the current market price for some of the base industries in Sweden in order to see how they might compare.

For steel, there are 2 tonnes of CO_2 produced per tonne of steel. This is sold for around 600 EUR per tonne. A carbon cost of 100 EUR per tonne of CO_2 corresponds to around 30% of that sales value in today's market (Åhmen et al., 2013). For aluminium, there is a direct emission of 0.5 tonnes of CO_2 per tonne of aluminium produced. This sells for between 1800 EUR and 2000 EUR. This is around 2-3% of the sales value in 2013. Cement clinker produces around 0.8 tonnes of CO_2 per tonne of cement clinker and is sold at 110 EUR per tonne. At a carbon cost of 100 EUR per tonne, this is around 90% of the sales value in 2013. There is clearly a large difference between the adaptability of base materials to changes in the price of the emissions of CO_2. The largest sensitivity was found to be for cement clinker by Åhmen et al. (2013).

Moreover, the basic materials are also known of their long investment periods, typically decades in advance. For example, a cement kiln is expected to last for at least 20 years. This makes it particularly bad at adapting to changes in relative prices for energy and emissions. Moreover, the energy cost of producing cement is particularly high as a percentage of the overall price of cement by weight. A rise in energy costs will have a particularly strong effect on the production of cement (Tillväxtanalys, 2016).

3.4.2 Carbon Capture and Storage

Installing CCS requires a large amount of capital to make the plants in which they are fitted as efficient and safe as possible. The extra equipment required for implementation of CCS technologies for these plants raises the overall energy demand of the plant itself and so the energy efficiency of the plant decreases. More fuel is combusted for the plant to produce the same amount of energy. Tan et al. (2009) however show that there are plenty of opportunities to produce the energy needed to power the CCS retrofit with renewable, even carbon-neutral energy. There is also the capacity using new technologies to upgrade other parts of existing plants so that they become more carbon neutral.

The economic feasibility of large scale implementation of CCS has been a significant barrier to CCS. Anderson & Newell (2003) calculated the then cost of using CCS as between $200 and $250 per tonne of carbon captured and stored, although this price is variable depending on the cost of the fuel among other variables and assumptions. However, as pointed out by the UK

CCS Cost Reduction Taskforce (2013), costs for CCS will decline following technology maturity after it has been implemented on a larger scale. In this way, investment in technologies such as CCS should be seen as a reinforcing loop of investment and growth.

3.4.3 Carbon Pricing and the EU ETS

Rootzén et al. (2016) highlight that under the current price of emission for the EU ETS, there is little incentive for private investment in production processes to lower the amount of CO_2 produced in carbon intensive industries, including cement manufacturing. To overcome economic barriers to CCS implementation, the cost of emitting CO_2 must be raised considerably so that it is comparable to the cost of CCS. The technology will only likely continue as pilot projects with small-scale investment as a result (Wennersten et al., 2014).

CCS is costly to implement in any circumstance without a sufficiently high carbon price. This means the cost of emitting CO_2 is much lower than the cost of implementing the technology. Financial support is required for industry to invest in the technology unless the cost of emitting carbon is significantly raised. In Sweden, this would mean reform of the EU ETS. However, whilst Sweden is an active member of the EU a reform of this policy to produce a higher cost of emitting CO_2 requires approval from the European Council and Parliament.

3.4.4 Business Competitiveness

Traditionally, firms do not like the implementation of environmental regulations on them by the state. This is because it may reduce the competitiveness of the firms because they will have to invest in order to comply with environmental regulation. However, this claim was disputed by Porter et al. (1995) who claimed that environmental regulation will not reduce firms' competitiveness uniformly. In fact, they claim, that regulations that are well-designed can trigger innovation to offset the costs of complying. This has been deemed the Porter hypothesis and although it's well established, many empirical and theoretical studies have found fault with the hypothesis. However, according to Yatsuki (2014,) the theory can still have some very important implications when designing successful environmental regulations.

According to Yatsuki (2014), there are six ways in which the theory can help create successful environmental regulation. These are listed in Figure 3.4.

1. Regulations signal to companies that resource inefficiencies and potential technological improvements are likely.
2. Regulation focused on information gathering can achieve major benefits by raising corporate awareness.
3. Regulation reduces the uncertainty that investments made to address the environment will be valuable.
4. Regulation creates pressure that motivates innovation and progress.
5. Regulation levels the transitional playing field (not picking a favourite etc.)
6. Regulation is needed in the case of complete offset, because innovation cannot always completely offset the cost of compliance, especially in the short term before learning can reduce the cost of innovation-based solutions.

Figure 3.4 Ways in which environmental regulation can benefit a business

Source: Yatsuki (2014)

If the Swedish government were to attempt to regulate the Swedish cement sector or a higher carbon price was introduced from the EU, the competitiveness of the Swedish cement could be reduced. It is therefore important that the government and industry together consider applying regulation befitting of Yatsuki's (2014) six ways in which Porter's hypothesis can help regulate the cement industry but still keep it competitive.

3.4.5 Business Opportunities

Carbon capture and utilisation (CCU) has provided a commercial-scale application for the implementation of carbon capture technology in some places around the world. In contrast to CCS, where the carbon is sequestered in the long-term, CCU makes use of the extracted CO_2. The most widespread and developed example for CCU is in Enhanced Oil Recovery (EOR), where CO_2 is injected at sustained high pressure into oil reservoirs to improve oil displacement, making it possible to retrieve a larger amount of oil from the reservoirs. This is the largest industrial use of CO_2 in the world is for EOR, where there is 70Mt used annually (IEA, 2016). EOR inexplicitly links the price of oil with the viability of carbon capture in power stations because the economic feasibility of installing carbon capture would depend heavily on the price of the extracted oil. EOR is a well-established technology which has been commercial for many years. The first EOR project was applied in Scurry County Texas in 1972 (Hill et al., 2013). In 2013, there were 152 EOR projects using CO_2 worldwide. Two-thirds of these currently use naturally-derived CO_2 (IEA, 2016), however, there are cases where projects use industrially-derived CO_2. Given time and the correct infrastructure, this could be replaced with CO_2 derived from industrial and power operations. This could provide a site for permanent CO_2 storage, if proper monitoring and site selection is carried out.

A study published for Enterprise Scotland confirmed that in the North Sea, a CO_2 EOR project would be profitable, however there are still significant barriers to the realisation of the project including the cost of an offshore EOR installation, as most EOR projects are onshore. There is also a lack of availability of cheap CO_2 for a project like this which requires large amounts of it (Element Energy Limited, 2013). It is clear therefore, that there could be a profitable case for storing and transporting CO_2 for use in the North Sea and overcome the financial gap for businesses, including the cement industry in Sweden, to install CCS technology on their operations.

As well as EOR, there are other potential uses for CO_2. These include urea yield boosting, carbonated drinks, water treatment and pharmaceutical processes. However, despite there being many uses for CO_2, the amount required is relatively low in terms of the amount of CO_2 that needs to be removed from the atmosphere under most future climate scenarios that limit warming to 2°C. For example, in the drinks industry around 8Mt CO_2 is used each year for carbonated drinks – just 0.5% of 1.6Gt CO_2 that needs to be captured and stored by 2030 under the IEA 2DS (IEA, 2016).

There are some emerging technologies for CO_2 utilisation. Mineral carbonation is an emerging technology whereby CO_2 is reacted with metal oxides, producing the metal carbonates and a solid by-product. The process is analogous to the natural process of chemical weathering, where silica-containing minerals form carbonate compounds when reacting weak carbonic acid in rainwater (IPCC, 2005). The resulting products are naturally occurring, stable solid minerals perfect for long-term geologic storage. Another emerging technology is the use of CO_2 for concrete curing. Curing concrete makes sure it's suitably strong by controlling the moisture content in which the concrete sets. Using CO_2 to this means that concrete absorbs the CO_2, and becomes a sink of CO_2. These technologies, however, do not represent a large portion of the market and their ability to reduce carbon in the atmosphere is therefore limited (IEA, 2016).

3.5 Public and political perception

Political opinion is a decisive factor in considering the political feasibility of decision-makers financially supporting the implementation of a new technology in industrial or energy systems. Whilst there are many voices that could influence a politicians' decisions surrounding support of technologies such as CCS this section covers the three main areas which inform politicians views.

3.5.1 NGO stances

Many environmental advocacy groups are diametrically opposed to the idea of CCS as a solution to help contribute to the reduction of carbon emissions globally. According to Greenpeace: "Despite years of vociferous backing from the International Energy Agency, the Intergovernmental Panel on Climate Change and a host of major world leaders, CCS continues to move forward at only a snail's pace" (Scott, 2016) In a statement on their website they say that CCS is "costly, risky distraction" ("Carbon capture and storage a costly, risky distraction", 2016). The organisation associate carbon capture and storage with the extension of dirty industry provided by the fossil fuel industry. Moreover, they cite the withdrawal of funding of CCS projects such as the FutureGen project in the US and the Mongstad project in Norway as evidence that "CCS does not work" ("Carbon capture and storage a costly, risky distraction", 2016).

However, there are other environmental advocacy groups that think differently. One such group is Bellona, an independent organisation that helps to advocate for sustainable environmental solutions. The group recognise the failures of CCS till this point whilst, on the other hand, acknowledging the potential the technology still represents in order to meet the 2°C of the Paris Agreement (Digges, 2016). They recognise that the "storyline" surrounding has been developed wrongly, saying that CCS is primarily useful for abating coal emissions. From their perspective, the most potential for CCS lies in industry. This is because there are now alternatives to coal power, such as renewables. Changing this storyline and mending the rifts between different stakeholders within the CCS debate is vital in order for the technology to progress further (Digges, 2016).

3.5.2 Public opinion

According to Wennersten et al. (2014), the biggest barrier for society, with regards to CCS, is related to the storage of CO_2, which has received very low acceptance levels from the public. The low level of public acceptance has led to a lack of certainty and action in political spheres regarding large-scale storage of CO_2 (Wennersten et al., 2014). This has been compounded by the fact that CCS remains an unknown technology for a lot of important stakeholders. Overcoming this barrier through full, transparent communication about the costs, safety and how it relates to other climate change mitigation options (e.g. renewables) is needed to successfully implement large-scale applications of CCS technology (Wennersten et al., 2014).

3.5.3 Politician Knowledge

Chaudhry et al. (2013) discuss in their research the views and knowledge of policymakers with regards to CCS. Their research highlighted the variation of depth and breadth of knowledge regarding climate mitigation technologies for policymakers. The research also showed that although there was a wide-ranging international dialogue surrounding CCS, more times than not, understanding of CCS is limited to, and often shaped by the local political context of that particular policymaker (Chaudhry et al., 2013). For example, if locally there is the potential to store CO_2 or the economy relies heavily on a carbon-intensive industry.

3.6 Technical Aspects

Technical considerations can be divided into two main areas of concern. The first of these is CO_2 capture from the power-generating or industrial process in questions. The second is dealing with the captured CO_2 whether that be transporting it, storing it, utilising it in another process or any combination of those three. Therefore, the technical infrastructure required to produce a carbon-abated product is significantly larger. The exact scale of the required infrastructure is dependent on the underlying production process and the location of the plant to which CCS is to be applied.

3.6.1 Carbon Capture

For the cement industry, carbon capture technology is being applied successfully in a Norcem Cement plant in Brevik, Norway. This was plant was originally set up with a number of aims. The first was to examine the possibility of utilising excess energy from cement production to capture CO_2. Secondly, as this was one of the first CO_2 capture projects applied to the cement manufacture, the project aimed to report on the individual challenges for applying CCS in the cement industry and assess to what extent varying CO_2 capture technologies can be applied in cement plants. The project started in May 2013 and was due to run for 3.5 years until November 2016. It has since received new funding as a result of the Norwegian government's commitment to support CCS (Ambrose, 2017).

The costs of implementing a capture project based on oxy-fuel technology for carbon capture are the subject of a study published by the European Cement Research Academy (2016). This study analyses the costs of installing carbon capture technology and relevant capture infrastructure on a "brownfield" site. This means that there would be a new oxy-fuel clinker production line, but in an existing site environment, making use of useful sections of existing infrastructure already on the site. This could include the raw mill, clinker handling equipment, fuel, power and auxiliaries supply and the waste-management/disposal facilities. New equipment, according to the plan, would be: an air separation or oxygen tank; a kiln; a precalciner; a preheater; a clinker cooler including gas mixer; a heat exchanger; a bag filter; and a recirculation duct. These pieces of new equipment, according to the study will cost 16.1M€. Charges for installation (civil steel works, erection), engineering, procurement, construction (EPC), fees and contingencies were added to the total equipment costs meaning the total cost for the plant would be 38M€, if that were to be added to the operational cost of the plant for the duration of their proposed study (European Cement Research Academy, 2016).

3.6.2 Carbon Transport and Storage

The transport of CO_2 has been happening since the 1970s when the first EOR operations were initiated in the US. Storage of CO_2 has been happening since 1996 in the Sleipner project in the Norwegian North Sea. It is clear therefore that the assertion that the major barriers to the implementation of CCS are largely economic and political in nature by the IEA (2016) holds some weight.

Baltic Sea

The Bastor2 project sought to raise awareness about the potential for CO_2 storage as part of the CCS value chain in Baltic Sea. Under the South-Eastern parts of the Baltic Sea, there is the theoretical regional capacity to store $16GtCO_2$ in the Dalders Monocline, a Cambrian era sandstone aquifer (Nilsson, 2014). The location of the Dalders Monocline is shown in Figure

3.5. A monocline describes a dipping layer of bedrock in an otherwise flat or more gently-dipping strata. However, "theoretical" capacity describes the lowest confidence levels used by experts to describe opportunities for carbon storage. It is therefore important for continued evaluation of Baltic Sea storage opportunities happens in order to fully understand the capacity of Baltic Sea geology to store CO_2 produced by Sweden (Nilsson, 2014). There are two problems that had been brought up as barriers to storage in this formation. The first is the long-term CO_2 migration in the bedrock, resulting in potential carbon leakage in outcrops. The second is pore pressure build-up, as a result of CO_2 injection in the bedrock, which could damage the integrity of the bedrock indefinitely. This, however, is somewhat dependent on the on the mechanical properties of, and in-situ stresses on, the rock.

The report, however, found that better reservoir qualities in the Dalders Monocline, that is better permeability and porosity for CO_2 storage, was identified offshore and onshore in Latvia and Kaliningrad. An additional study by Yang et al. (2015) agreed that in the Cambrian Monocline there was a significant capacity to store CO_2, however the dominant constraint affecting the storage capacity of the Cambrian Monocline is pressure build-up as a result of the injection rate of CO_2. The capacity of the Cambrian Monocline to hold CO_2 is significantly reduced, with Yang et al. (2015) estimating a capacity of 100MtCO_2 over a 50-year storage period. They add to this by saying that CO_2 leakage is unlikely in the northern part of the formation (the exposed outcrop), and containment can be ensured through the interaction of water in the sandstone aquifer with the injected CO_2 in a process known as residual and dissolution CO_2 trapping. However, this information has been obtained through dynamic modelling techniques and requires more field data in order to improve the accuracy of the models (Yang et al., 2015).

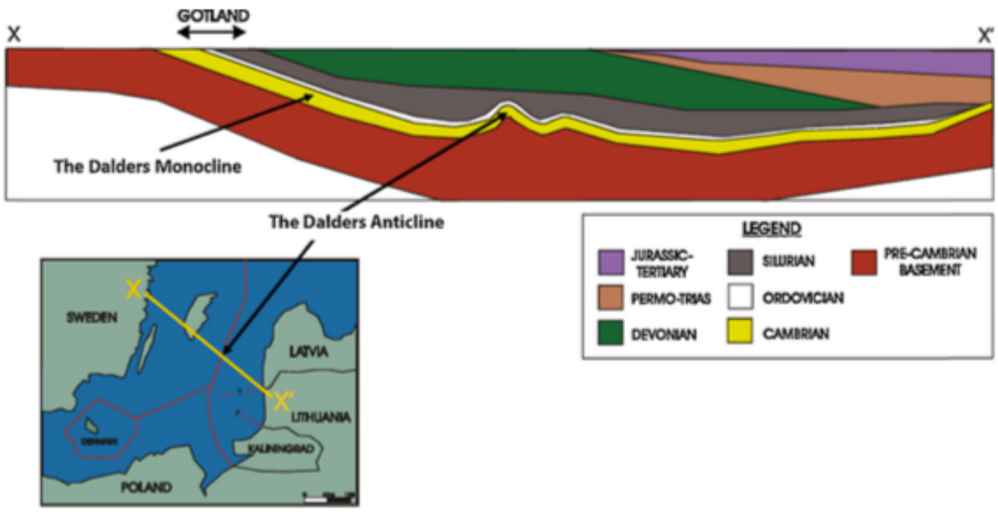

Figure 3.5 Cross-section and position of the Dalders Monocline

Source: Yang et al. (2015)

A significant barrier to the development of Baltic Sea CO_2 storage is the regional cooperation it would take for countries surrounding the Baltic Sea. This would be a large political endeavour and could be very costly (Interview 2). However, if the Baltic States were to be involved the share of the cost of a common storage and transport infrastructure would be reduced significantly for any one country. If Sweden were to pilot CO_2 injection in the Dalders Monocline, the accompanying necessary legal framework would be very costly. There may be some loopholes however. For example, Cementa AB has a large production facility on Gotland, where theoretically it would be very easy to begin testing onshore carbon storage using captured CO_2 from the cement kiln here. This would avoid some legal barriers imposed by Directive (2009/31/EC), the EU CCS Directive, for transboundary CO_2 storage and would help to gain field data for storage in the Dalders Monocline (Nilsson, 2014).

North Sea

It is well documented that the is large potential to store CO_2 in the Norwegian continental shelf, with several saline aquifers and many dry-drilled structures proving the suitability of the underlying bedrock. Additionally, there have has been 20 years of CO_2 storage from the Sleipner Vest Field of the Utsira formation and 9 years of CO_2 in the Snøhvit Field in the Barents Sea (Halland et al., 2013). The total capacity to hold CO_2 for the Norwegian continental shelf was estimated by Halland et al. (2013) to be 48 $GtCO_2$ in aquifers and 24$GtCO_2$ in the established hydrocarbon fields after they have been abandoned. Most of the suitable aquifers are found in areas where there is good seismic coverage, due to the exploration of North Sea for its oil and gas reserves.

The Norwegian government has already committed to investing in the infrastructure of transport and storage, with the role for carbon capture being helped by research and development but ultimately left to the responsibility of the respective industry actors to upgrade their facilities accordingly (Ambrose, 2017). The government's role in the funding includes ships for transporting CO_2, subsea pipelines and storage options. They have put aside 1.4bn EUR in the 2016 budget as an estimate for setting up the system, with an annual running cost of 100m EUR. Having a collective research body to decide where this finance encourages knowledge sharing and builds momentum towards improving the feasibility of CCS (Ambrose, 2017).

4 The Economic Feasibility of Implementing CCS in the supply chain

The purpose of this chapter is to present the value chain of cement and concrete for a typical product in Nordic countries, in particular Sweden. Then, through analysing megatrends and taking into consideration important stakeholder opinions, it will be suggested whether or not a market for carbon-abated cement exists. Rootzén et al. (2016) found that the overall cost of introducing CCS into cement production, if it were passed through to the end-consumer, would mean a rise of cost for an average residential building of only 1-2%.

4.1 Cement Value Chain

The cement-to-final-product chain is relatively simple but there are considerable cost transformations along the way. For example, for an end-consumer, the relative cost of cement used for the concrete is very small as compared to the overall project. The main material flows and key actors in the Swedish cement sector are displayed in Figure 4.1.

Final end-use		Share of total concrete production (%)
Civil engineering		40
Non-residential buildings		37
Residential buildings		23

Figure 4.1Final use of concrete as a percentage of total production

Source: Andersson et al. (2013)

The value chain for cement, that is from limestone and other raw materials to a final product (e.g. concrete) involves many transformational steps, involving a wide range of actors. However, there are relatively few cement producers, one major one in each country, which are usually owned by much larger multinational companies, e.g. Cementa is owned by Heidelberg cement. Similarly, within the construction sector in Sweden, there are a number of large firms which own a number of subsidiaries accounting for a large portion of the construction market in Sweden.

Concrete may be produced in plants for pre-cast concrete products or on-site, where it will be used or moulded for construction. The main ingredients of concrete are cement, aggregates and water. Andersson et al. (2013) divide the end-consumers of concrete and cement in to three parts. These are civil engineering, non-residential buildings and residential buildings. The transformations in the cement and concrete industry can be divided in to three main stages. These are: from limestone to cement clinker; from cement to concrete; and, finally, from concrete to final construction.

4.1.1 Limestone to Cement

The unit selling price of cement, that is price/tonne, works as a function of the average total production cost, transportation to a cement terminal and the amount of operating profit. The cost to consider for the cement industry is the carbon cost, considering that the carbonintensiveness of the cement production. These costs can fluctuate over time and not in any way static due to varying local conditions and fluctuating costs of materials and energy.

Rootzén et al. (2016) discuss the average total production cost of an average Nordic cement plant. They find this to be €58.40 per tonne of cement. They then consider the production costs for three different scenarios of updating the kiln system in the cement production. One using state-of-the-art technology and another two applying carbon capture and storage technologies. For the new state-of-the-art kiln the average operating cost will rise to €60 per tonne. For installing a post-combustion carbon capture solution, the cost per tonne of cement produced will rise to €100 per tonne. On the other hand, installing full oxy-combustion carbon capture would raise the price to $85 per tonne of cement produced (Rootzén et al., 2016).

The carbon price for cement manufacture depends on the price of purchasing emissions allowances and the costs of transporting and storing any captured CO_2. In the case of Sweden, purchasing emission allowances is a part of the EU ETS, from which credits are purchased to emit the amount of CO_2 that the business activity produces. The cost of transporting and storing CO_2 will depend largely on the proximity to a suitable storage site, the mode of transport (e.g. pipeline or shipping) and the possibility for developing a shared CO_2 network with other carbon-intensive industries.

4.1.2 Cement to Concrete

For concrete, the main costs in the industry are from the materials and the transportation. However, there may be certain variable input costs and delivery prices in different regions (Syverson, 2008). The price of concrete can be calculated as a function of the raw materials (cement, water, aggregates), the price is costs for the manufacturing of the concrete, the delivery costs and any additional profit.

4.1.3 Concrete to Construction

The overall construction cost for a residential building includes four elements: structural costs; material costs; building construction cost; and total production cost. Concrete can make up any percentage of these and is variable dependent on the overall design and architecture of the structure or building in question.

4.1.4 Compliance cost for carbon-abated cement

This section describes how each part of the value chain would therefore absorb the cost of a tougher carbon regime, in this case introducing CCS into cement production.

Compliance cost for cement production

It is obvious therefore, that the combined effects of internal abatement cost and the cost of buying emissions allowances will have a significant impact on the break-even costs of cement and therefore the eventual market price. Analysis by Rootzén et al. (2016) reveals that under current projected prices for emissions under the EU ETS up to the year 2030 i.e. €10-40 per tonne of CO_2, the price of emitting carbon will not be high enough to incentivise companies to increase their internal abatement cost by applying CCS technologies. That is to say that, the introduction of CCS will not be profitable for these companies unless the cost for emitting CO_2 becomes significantly higher. This analysis includes a projected cost for transporting and storing CO_2 where CCS is applied, although as already discussed, this cost is dependent on a number of factors.

Compliance cost for concrete manufacturing

The manufacturing cost for concrete of installing CCS for the production of cement is significant. The analysis by Rootzén et al. (2016) reveals that the increase in cost is likely to completely cover the assumed profit margin suggested by the concrete industry. This is around €15 per metre cubed of concrete produced. This assumption is based on the traditional amount of cement in the concrete (10-15% of the total by volume) however if there is increasing use of fly ash and other calcareous materials in concrete, that lower the necessary amount of cement in concrete. In this case, the overall cost of CCS to concrete producers would depend on the cost of the alternative materials.

Compliance cost for construction projects

For construction companies, the overall cost of the concrete used depends on the cement content of the concrete used, the price of alternative binders to cement found in certain types of concrete and the how much concrete is present in the structure e.g. for a residential building, whether or not the frame is concrete or wood. The analysis by Rootzén et al. (2016) reveals that the overall cost of the concrete would increase for the individual constructors sizeably. However, the cost of concrete represents a very small portion of the overall construction cost that the overall cost of the project would not be appreciable. The analysis reveals that even when the modelled increase of the cost of cement is 100%, the overall increase of the construction cost of the project in question is limited to 1%.

4.2 Is there a market for carbon-abated cement?

The analysis by Rootzén et al. (2016) revealed that even though every construction project is unique and there are different conditions across different markets, passing on the compliance cost of installing CCS as a CO_2 mitigation measure in the cement industry would only cause a small increase to the end-consumer of the cement. However, this is of course dependent on the amount of cement as a proportion of the final project, which would differ greatly for example from a residential building to concrete bridge.

4.2.1 Megatrends

Whilst it is difficult to find literature about a potential future market for carbon-abated cement, it is clear there is an increasing demand for greener building materials. A report by the independent industry group Freedonia (2013) predicted that the demand for green building materials in the US would, on average, increase by 11% annually between 2013 and 2017. This represents a growth from 51.8bn USD in 2013 to 86.6bn USD in 2017. In Europe, the situation is similar with European projects like BREEAM (Building Research Establishment Environmental Assessment Method) which certify green buildings and promote the use of more sustainable building materials at the European Level, at the Swedish level being implemented by the Swedish Green Building Council.

These green building systems are defined as a tool that helps the construction industry to evaluate, enhance and promote a building's or project's sustainability (Nguyen et al., 2011). The main mechanisms through which they do this are information analysis, valuation and comparisons. This is with the overall aim to: improve the building's operational performance; reduce its environmental impact; quantify the effect the building has on the environment; and provide objectivity to evaluate the building's development (Nguyen et al., 2011).

4.2.2 Market Views

During the interview process, interviewees from Cementa AB and Riksbyggen confirmed the companies were both operating under the premise that there is a market for carbon-abated cement (Interviews 5 & 8). The market for sustainable products in Sweden will drive demand for products that have a lower environmental impact. Building companies, such as Riksbyggen, see having more sustainable buildings and projects in their portfolios as a competitive advantage over rivals and recognise the market for sustainable construction materials as opening.

Cementa AB also recognise being able to offer climate-neutral, carbon-abated cement will offer a competitive advantage (Interview 8) and keep them relevant in a competitive global market. This is evidenced by their vision for carbon-neutrality, as part of Heidelberg Cement, by 2030. Cementa AB are already piloting the prerequisites introducing CCS, through the testing of electrifying cement production. This will not only increase the energy efficiency of the process of producing cement and allow of the incorporation of renewable energy products, but it also means that the gases produced from the kiln will be a much purer CO_2 stream and therefore much easier to capture for transport and storage.

The abatement curve for the cement sector produced by McKinsey (2009) (Figure 4.2) shows that CCS new build and CCS retrofit are the final stage of producing carbon negative cement. In Europe, the cement industry has taken major steps towards clinker substitution with calcareous materials, using alternative fuels and increasing energy efficiency. However, the incorporation of CCS remains the only way by which the cement industry can achieve carbon-neutrality.

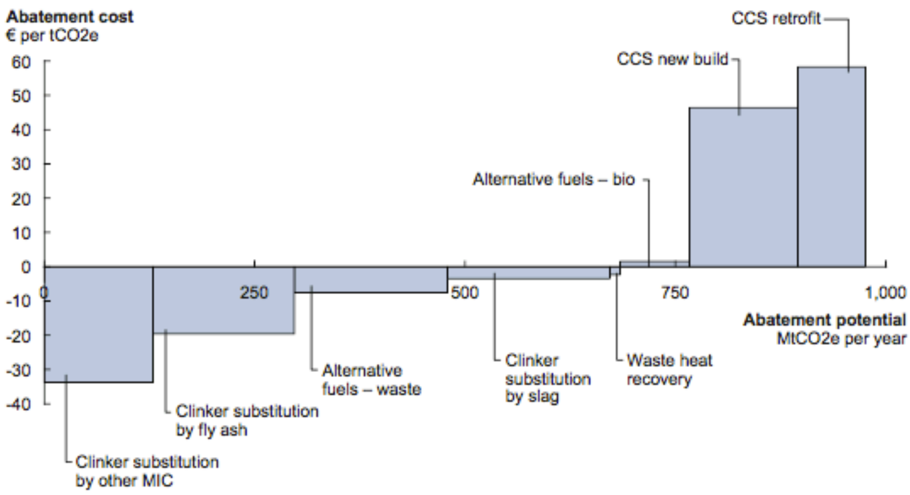

Figure 4.2 Global CO_2 abatement cost curve for the cement sector

Source: McKinsey (2009)

5 Discussion

5.1 Methodology

For a study of this nature, there are seemingly limitless sources of information in which to ground and base arguments. It is assumed that there could be better sources of information for some of the evidence that has been cited in this paper. It can also be assumed that there is evidence available that is contrary to some of the evidence presented in this report. However, in a report of this nature, where the topic of research is often a politically-contested topic of debate, it is difficult to ascertain whether there is bias in literature and during the process of the interviews. However, every effort was made to triangulate data with multiple sources, so it is assumed that bias has been minimised in this report.

During the course of the study period, experts in the relevant field were difficult to contact. This was the result of two main issues. The first of these is that the position of an expert is difficult to reach for a junior researcher, even in Sweden. Often, they will not have the time or see the necessity of taking part in a study of this nature. The second of these is that during the Swedish summertime (June-August) most people take an extended vacation and are difficult to contact. More interviews from relevant experts would have provided more knowledge and opinion surrounding the topics discussed. Moreover, the interviewing of experts is a skill and it takes time to train in order to achieve the perfect style for interviews of people of a high-calibre. Therefore, it assumed that the researcher's style could have been better in order retrieve more information from the interviewees. Conducting more interviews and being able to retrieve better data from the interviews would have helped to further eliminate possible bias in this research, as well as adding more perspectives on the arguments discussed. This would serve to improve the usefulness and legitimacy of the results of this study.

The results of this study provide an overview of the current debate surrounding CCS in Sweden and in the cement industry. This includes relevant opinions from experts as well as an overview of the some of the main debates surrounding the relevant options. The data collected was accurate at the time of data collection and may not apply in periods long after the study was completed. In this sense, it is a snapshot of fast-moving and politically-charged debate, both nationally and internationally.

The rationale behind this research was to explore the relevant factors for a proposed implementation of CCS for the decarbonisation of the cement industry in Sweden. It aimed to answer the research questions provided in an inductive way. This means answers to the research questions should not be seen as conclusive, but they do provide evidence to support or oppose an argument. More research is required to conclusively answer each research question. For example, a wider range of backgrounds for the interviews conducted would have helped further legitimise the results of RQ1. Quantitative. econometric analysis, perhaps using a case study, would have further helped legitimise the conclusions made surrounding RQ2. The aim of RQ3 was to provide a snapshot of the current debate surrounding CCS topics and worked alongside focussing on the other two parts of the conceptual framework. More legitimacy could have been brought to this research questions through extra time spent on the study, more interviews and consultation of policymakers in Sweden.

The concurrent and interdependent research methods described in Chapter 2 worked to allow the research to remain open and fluid. It also allowed for literature analysis to inform interviews and interviews to further inform literature analysis. However, there were some caveats and some areas where there was room for improvement, which could be employed should this research or similar research be conducted again. A longer period of research before the beginning of the project would have allowed for more informed interviews. In such a method, there is also no clear endpoint. The researcher can move in circles, collecting information to support and against an argument, before finding anything conclusive. There came a point when the decision was made that enough data and opinions have been collected to give an overview of the debate as required by the research questions. There was limited scope to improve this particular method, however, perhaps performing more structured interviews with groups of similar experts would have provided more conclusive results to the research questions.

The results obtained could be applied to a limited number of cases outside of CCS for the cement industry in Sweden. They are relevant as a case study to those engaged with CCS technology diffusion. They are relevant to other base material industries as an example of ways to approach decarbonisation. In developing countries where climate targets are not as ambitious, this approach may be not all that applicable. The main audience for this research is industry and policymakers in Sweden, although the results are also interesting for other similarly developed economies with ambitious climate targets. Cement is produced in many developed countries around the world and this study is a good starting point for discussing the possibility to decarbonise the cement industry.

5.2 Important trends in the CCS debate

This section of the discussion will describe the topics that came up during the course of the study that are relevant for policymakers in Sweden.

5.2.1 "A lack of political will..."

During interview 1-4, 6 & 9, a lack of political will to invest and/or promote CCS was discussed. This lack of political will cannot be put down to any one factor for CCS, however, there are a number of points to consider for the lack of political will to invest in CCS based on literature review and expert interviews.

Cost of investing in CCS

CCS is a costly investment, whether it be to develop new plants or retrofit old plants with additional technology. Then, there is the cost of developing infrastructure for the transport of CO_2 to a suitable storage site. Then, there is the cost of assessing a suitable storage site and monitoring the storage site as well as the cost of the storage itself.

Sharing the risk

It is clear, therefore, that given the scale of carbon transport and storage, that a common infrastructure is the best way to minimise cost. However, coordinating different actors, investors and firms in order to achieve a common transport and infrastructure is an intervention that some policymakers may not be willing to take. The fact that public money may have been used to subsidise or even pay fully for the cost of the infrastructure further compounds the uncertainty of policymakers with regard to the cost of CCS.

Existing alternatives

For the power sector, especially in Europe, the success of policy measures for the dispersion of renewable energy and increased energy efficiency has meant that there have been better more appealing options for policymakers to reduce CO_2 emissions, as opposed to investing in CCS. This is another likely component of the lack of political will to invest in CCS technologies. The appeal of renewable technology is somewhat more universal. For example, solar PV where you can put a solar panel on your roof and feel like you're doing something for the environment. Power is generated, the government pay you subsidies - you have feed-in tariffs. It has a nice storyline, everybody gets something from it. CCS does not have a comparable storyline, is more complicated and less tangible for policymakers and the general public.

Previous CCS failures

The lack of political will surrounding CCS also stems partly from the high-profile failures of some projects around the world. Notable cases of CCS failures include the American FutureGen project and the cancellation of the 1bn GBP CCS competition from the UK government. The high-profile failures of these projects have led to the development of a perceived negative connotation surrounding CCS, especially among NGOs and certain parts of the press. Politicians, therefore, are even more reluctant to invest in CCS or support a CCS project for fear of public backlash.

Norwegian government's position

Despite the political uncertainty surrounding CCS and lack of support at the global level, Norway is pushing ahead with developing CCS technologies. In the Norwegian budget statement on 6^{th} October 2016, the government announced 1314M NOK (146M EUR) of public funds to be spent on CCS in 2017 including 360M NOK to for further studies on full-scale demonstration plants for the capture of CO_2 ("Norwegian state budget confirms 1.3 billion kroner investment in CCS including support for full scale CCS", 2016). The aim of these studies is to further optimise the technical solutions, reduce risks involved and develop a better estimate of the cost of implementation of the technologies. Moreover, the government proposals show that an additional 360M NOK is to be allocated to developing full chain project development of the CCS value chain in Norway ("Norwegian state budget confirms 1.3 billion kroner investment in CCS including support for full scale CCS", 2016). The full value chain for CCS, under the Norwegian government's proposal, includes having the capacity for capture, transport and storage all in Norway. This includes gas-carrying ships for transport, deep-sea pipelines and the development of a storage facility off the coast of Norway. This is estimated to cost 1.4bn EUR, with an estimated operating cost of 100M EUR to operate every year (Ambrose, 2017).

As part of this strategy, industry partners including Norcem AS (cement), Yara Norge AS (chemicals) and Klemetsrudanlegget AS (a waste-to-energy plant in Oslo), will pay for upgrading their plants to trap CO_2 (Ambrose, 2017). However, the state will take on the risk and considerable cost of developing the transport and storage infrastructure. It is clear therefore that Norway believes that CCS still offers a lot of potential, and through pushing ahead with the technology they hope to be able to create a new section of industry in Norway to store carbon emissions. It should also be noted that the Norwegian government's interest in CCS aims to form a coherent policy direction for an economy that is reliant on fossil fuel exports with an effective climate change policy (Roettereng, 2014).

5.2.2 CCS for Industry vs CCS for Power vs BECCS

The storyline surrounding CCS has been somewhat demonised, largely because of its association with the extension of the fossil fuel industry. Whilst there remains a large potential for CCS in the power-generating sector, especially with regards to the projected use of coal over the coming decades, the case can still not be easily made in Europe with the rise of renewable and nuclear energy. However, CCS in Europe still remains the most developed technology with the potential to decarbonise the industrial sector. Moreover, BECCS remains the most developed technology through which it is possible to achieve negative emissions.

CCS for Power

Globally, CCS for the power sector is vital in the best low-cost transformation of the power sector. The IEA (2016) state that without CCS, the transformation of the power sector to carbon neutral will cost at least 3.5 trillion UDS more, than in the 2DS scenario where 12% of total global energy would be produced in coal plants fitted with CCS. In a 2DS scenario with no CCS, renewables would need to be deployed at a rate that is 4 times as fast as the deployment observed in the past decade. In addition, nearly all coal-fired power generation would need to be immediately ceased, creating a significant amount of stranded assets. In other words, whilst limiting warming to 2ºC is possible without CCS, investing in CCS opportunities as soon as possible lowers the overall cost considerably (IEA, 2016).

CCS for Industry

CCS remains the most developed technology that allows for deep emissions reductions in many carbon-intensive industries, including cement. In fact, for many, it remains the only way to achieve carbon neutrality realistically within the next few decades. The three major sectors in which emissions can be reduced. These are chemical & petrochemical, iron & steel and cement. In the IEA 2DS scenario, CCS accounts for 29GtCO_2 of emissions reductions with the remaining 113GtCO_2 emissions reduction achieved through other improvements. However, this is not uniform across the industrial sector. Figure 5.1 shows that the amount of emissions reductions that can be achieved without CCS is only half of the overall reductions for cement needed under the 2DS scenario. CCS for cement, therefore, is crucial in order to achieve deep emissions reductions. (IEA, 2016).

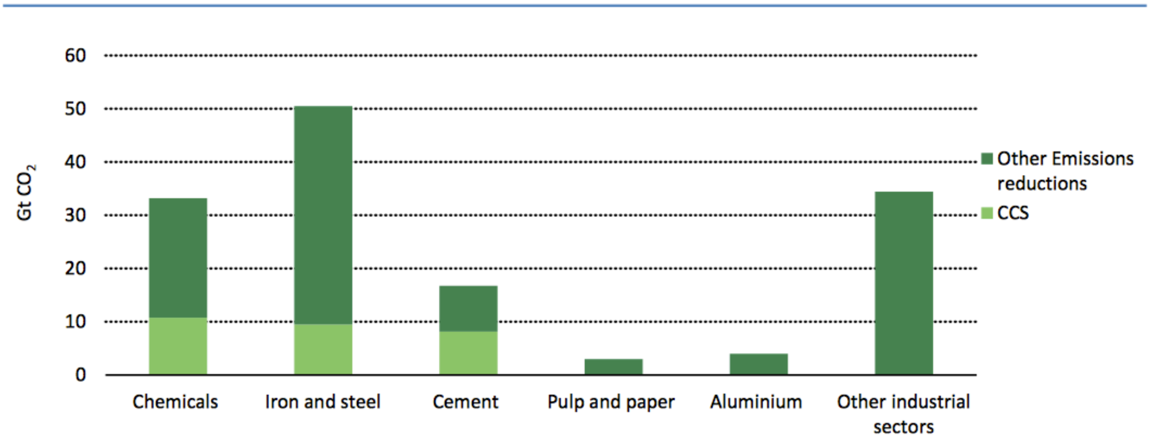

Figure 5.1 Potential emissions reductions through CCS and non-CCS pathways by sector

Source: IEA (2016)

BioEnergy with Carbon Capture & Storage

Following the Paris Agreement, there has been much more debate surrounding the topic of negative emissions, with BECCS the most advanced of the negative emissions technologies. In fact, the world's first BECCS plant operated by Archer Daniels Midland Company, called the Illinois Basin Decatur Project, came online in April 2017. The project will capture 1 MtCO_2 annually from the bioethanol plant. As part of the Climate Act introduced in 2017, BECCS has come to the forefront of the debate in Sweden as a way to help Sweden achieve CO_2 neutrality by 2045 and have negative emissions afterward. However, there has not been concrete policy measures to ensure that the technology can be commercialised to the scale it needs to be in Sweden in order to help achieve the goal of zero-emissions. For new technologies and infrastructure projects, policy planning should be long-term if the goals are to be achieved (Lyngfelt et al., 2017). Especially this should include a policy measure for the storage of carbon. However, Sweden is uniquely positioned to introduce BECCS because of its large biomass sector.

5.2.3 Developing transportation and storage infrastructure

One of the most important policy recommendations made by the IEA (2016) for the de-risking of future investment for industrial actors, is the taking-on of responsibility for transport and storage infrastructure needed for CCS. The development of suitable storage sites for CO_2 is a very important part of the implementation of large-scale CCS in a country. For government, this means disaggregating the CCS value chain and promoting a more storage driven approach through the implementation of appropriate policy frameworks. For example, the storage of CO_2 could be an interesting investment for firms who already have experience working with the Earth's subsurface e.g. gas companies, geothermal heating providers.

5.2.4 Remaining competitive in a low-margin sector

As has already been alluded to, the cement industry is somewhat unique in terms of the profit margins and cost structure of the overall value chain. Notoriously, grey Portland cement has a very low profit margin. If the cost of production were to increase, either through installing CCS in the production process or through the introduction of a tougher carbon regime whereby the cost of emitting CO_2 becomes significantly higher, this could eliminate any profit made by the cement industry altogether. However, it is clear from the data presented in Chapter 4 of this thesis that the unique value chain for cement, especially the large price transformations from cement to concrete and from concrete to construction, mean that an increase in cost of cement can be absorbed into the value chain with relative ease, compared to other carbon-intensive products.

It was made clear in the interviews that the industry does believe there is a market for carbon-abated cement. However, there were varying opinions on how "sustainable cement" could be qualified. For example, some interviewees believed that CCS was too expensive to be considered for sustainable cement and there were more affordable innovations that showed greater promise for sustainable public procurement of cement including…. Others believed that there was no sustainable cement without CCS.

What could be useful for both of these areas is the development or introduction of an ecolabel for the cement industry. This would be a way of signalling to consumers that the cement that they are using is in fact sustainable. By creating an eco-label that is third-party certified, it also helps to homogenise a standard for "sustainable cement."

5.2.5 Marginal abatement cost curve

The marginal abatement cost curve for CO_2 measures the cost of reducing one more unit of CO_2. This provides decision-makers with the most cost-effective way to reduce overall CO_2 emissions. The most famous of these curves is one produced by McKinsey (2009), shown in Figure 5.2. Although this is an old curve, with most recent curves available, it serves to show the position of CCS, which remains largely unchanged. The abatement potential of CCS remains the largest for any one given technology, however, it remains the most expensive. However, recent years have seen the uptake of many of the innovations shown in Figure 5.2. This is with the notable exception of CCS technologies.

As CO_2 emissions continue to reduce in developed countries, it is without the massive potential for CO_2 abatement that is possible with CCS technology. If it becomes possible economically and politically feasible, which this thesis argues that it is, for CCS to be implemented then it will help provide a large value of CO_2 reduction from power-generating and industrial processes. If Sweden is to reach carbon neutrality and achieve negative emissions thereafter, investment in CCS should be a part of the action plan, even if it is costly.

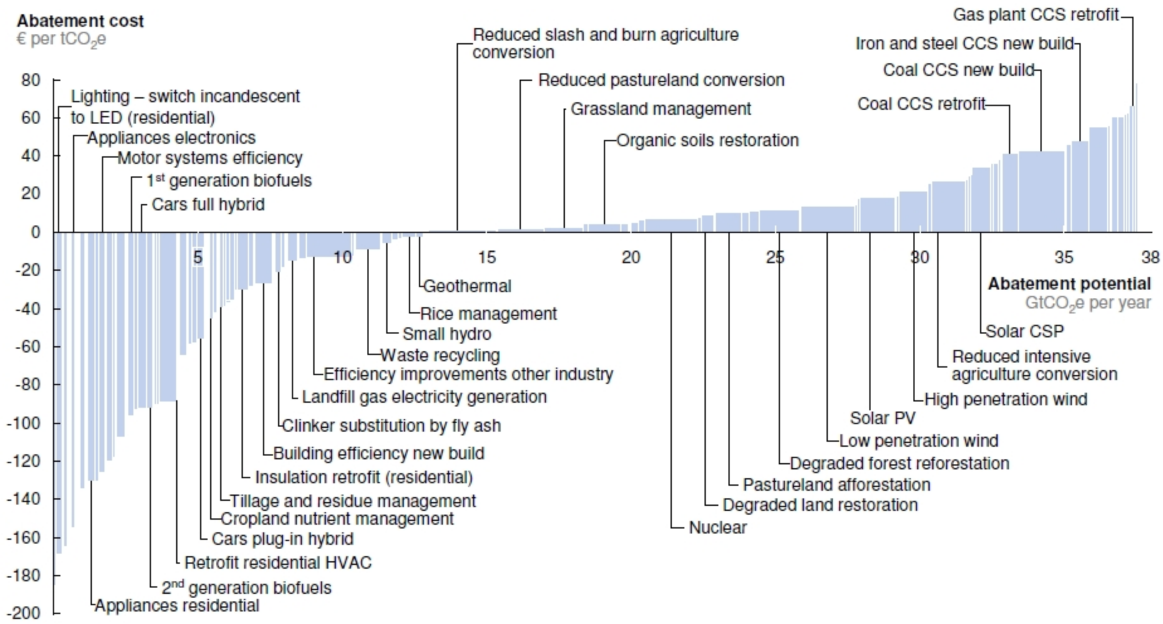

Figure 5.2 The Classic CO_2 Marginal Abatement Cost Curve from McKinsey

Source: McKinsey (2009)

For the cement industry in particular, the most advanced technology, indeed the sole technology, to achieve zero emissions in the cement industry is CCS. This has been compounded by the fact that the value chain of the cement industry is unique, with extremely lows margins and huge price transformations through the supply chain. This means the cost of CCS or carbon abatement in general could be managed with relative ease. The next step in moving through options in the CO_2 abatement curve is beginning to develop the options for CCS. CCS for cement could be a good first step for the Swedish government.

5.2.6 North Sea vs Baltic Sea for storage

The Swedish Geological Survey has collected a large amount of data from the Swedish territory to test the availability of storage-ready bedrock. Moreover, through the acquisition of geological base data from other Baltic Sea countries, areas of the Baltic Sea have been noted as possible storage sites for large quantities of CO_2. However, it has also been noted that there is lot more political and legal uncertainty surrounding storage in the Baltic Sea because the suitable storage bedrock crosses into the different countries surrounding the Baltic Sea.

The Norwegian site, in comparison, already has the legal and political sovereignty of the bedrock resource settled. In addition, the expertise of the established Norwegian hydrocarbon industry means that the North Sea is already well established. Under this model, it is clear Swedish companies would pay Norwegian countries to store carbon in the North Sea. Initially, this may make economic sense, however, in the long-term it would be significantly cheaper to use Sweden's own natural resources to store carbon. Whilst there are no exact estimates for this, it is comparable to the UK case in which a full report, including the cost of the full infrastructure needed for carbon storage was calculated at 1.6bn GBP (1.75bn EUR) or a cost of 12.22GBP per tonne of carbon stored. The amount of carbon that Sweden would have to store is significantly lower than in the UK, because of the low CO_2 emissions per capita already. However, the alternative is to pay into the Norwegian scheme, at a cost presumably dependent on the amount of CO_2 to be stored.

Given that Norway has already made significant progress towards the full CCS value chain, and the urgency with which capture technologies should be deployed under climate models, a wise course of action for the Swedish government to take would be to cooperate with Norway initially. Then it is important to work towards developing their own infrastructure for carbon storage. What is clearer however is that a government role will be the difference if Sweden is to be able to store its own carbon, utilising its own natural assets or if will have to rely on Norway for the storage of its carbon going forward.

5.2.7 Public Procurement

One of the most innovative areas of current research for sustainability in the cement industry is the role that Green Public Procurement (GPP) could play in stimulating the growth of sustainable cement. In the EU, public procurement is worth 14% of the EU's total GDP ("Public Procurement and Innovation for Low-Carbon Infrastructure", 2017). Moreover, public procurement for infrastructure project makes up around 22% of the total construction sector's output, with continued growth expected in the coming decades in most construction areas. Public procurement, in this light, has the potential to play a significant role in the decarbonisation of the construction sector, especially in the carbon-intensive cement sector. This means it can help create markets or pioneer markets for more sustainable cement and concrete, as well as the whole construction sector ("Public Procurement and Innovation for Low-Carbon Infrastructure", 2017). For Sweden, this would require developing GPP practices for the construction of infrastructure projects – something which should be a clear objective for policy coherence with the 2045 zero-emissions target.

One of the ways in which the cement industry and government could signal their intention to move towards production and purchasing of more sustainable cement is the introduction of an eco-label. An eco-label would help standardise a definition of sustainable cement and encourage green innovation in a not-so-green industry. It would also help intermediary construction companies and concrete producers to legitimise buying more sustainable cement which will be considerably more expensive.

However, there are two major caveats to the consideration of an eco-label for cement. One of the questions surrounding GPP is what constitutes "green" cement, with there being a wide range of opinions in the literature surrounding the definition of green or sustainable cement and this is just regarding the amount of carbon emissions produced during the production of the cement. Cement production is also associated with a much wider range of environmental impacts. Another is the structure of the cement industry itself. Sweden's public procurement is based on the EU legislation which prohibits bias based on nationality – with all companies bidding for a contract must be treated equally on a European Level. However, the case for cement is somewhat different with one dominant actor, Heidelberg Cement, accounting for 80% of the overall market. An eco-label therefore is hard to develop, and be adhered to because there are no significant competitors offering cement of a similar quality with a lower climate/environmental impact. Moreover, there does not appear to be significant interest from other producers of cement, so an eco-label would likely see no uptake and would not incentivise innovation or steer the market towards more sustainable alternatives.

6 Concluding Remarks

6.1 Conclusions

What are the political economy barriers and incentives to CCS implementation in the cement industry in Sweden?

It is clear from the analysis presented in this study that there has been a political paradigm-shift surrounding the feasibility of the introduction of CCS. It seemed to many that the idea of CCS had been buried by the unprecedented rise in renewable energy and the failures of CCS projects around the world. However, the debate has once again opened up, driven by: Sweden's ambitious new climate targets; keeping within the warming budget of 2ºC as indicated in the Paris Agreement; and the new storyline surrounding CCS in Europe away from power-generation toward industrial decarbonisation and BECCS.

At present, CCS (September 2017) remains too expensive for individual companies to risk investing in by themselves. However, carbon-intensive industries continue to invest heavily in the research and development of ways to decarbonise their operations. This is being driven by the interest of an ever-increasing green market and political pressure to achieve carbon-neutrality. For the cement industry, the CCS pathway remains the only technologically-mature way to achieve full decarbonisation. Moreover, to remain competitive in an increasingly global market the industry see it as imperative that carbon-neutral cement becomes a reality. For other actors, this increasing globalisation of the industry is also of concern because of the asymmetrical emissions standards around the world, leading to carbon leakage.

Technically, capture technologies are currently available and mature enough to invest and implement with a large degree of certainty. The cost of these technologies is relatively more feasible for companies when compared to the cost of the full value chain including transportation and storage of CO_2. Storage options in Sweden are technically feasible but remain legally and politically uncertain due to the rights of other countries surrounding the Baltic Sea. However, the Norwegian government's push to implement the full CCS value chain means that storage options should be available for Swedish industry within the next 10-20 years.

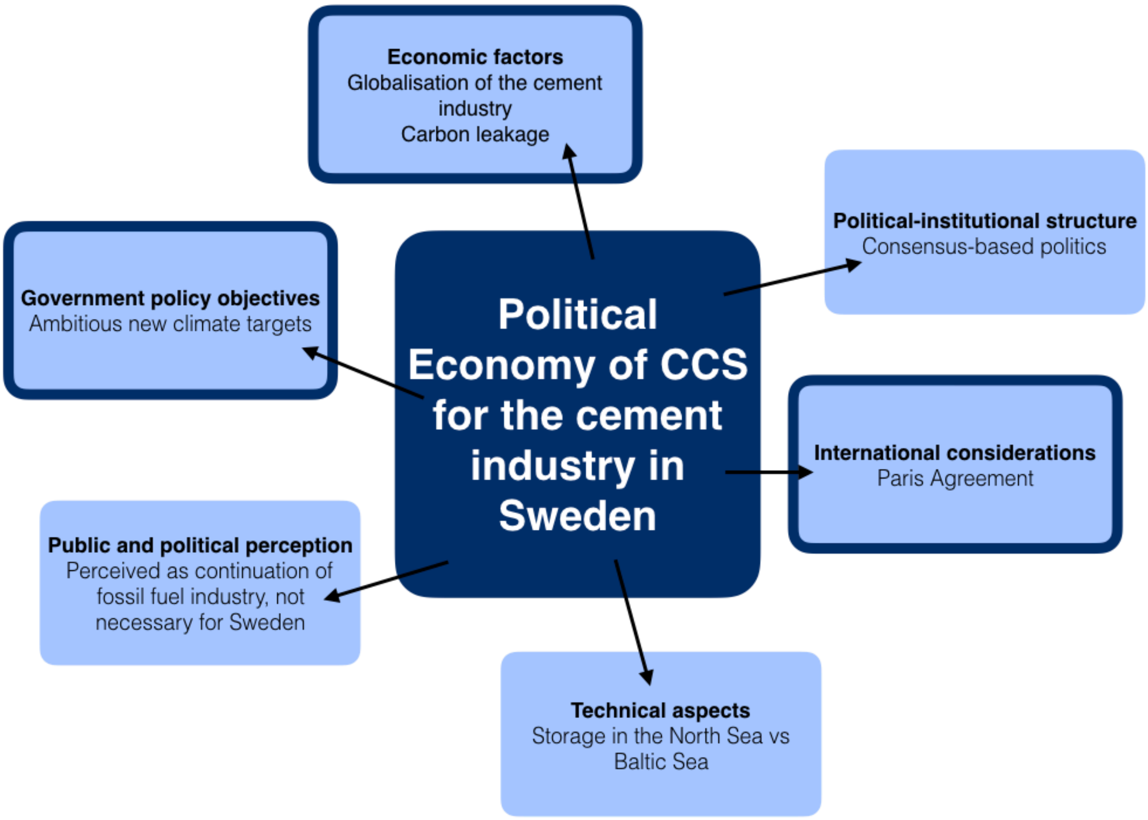

Figure 6.1 Illustration of important points for RQ1

What is the economic feasibility of implementing CCS in the cement industry in Sweden?

The value chain of cement is unique, even among the value chains of other heavy industry like iron & steel or chemical production. This is evidenced by the small profit margin of the product and the changes in cost share between easy transformational stage i.e. from cement to concrete to construction. This means that the proportion of the cost of cement in relation to the overall cost at that stage in the value chain. Analysis by Rootzén et al. (2015) found that this meant that a considerable proportion of the costs could be directed towards the end-consumer of the cement without drastically changing the cost structure of the value chain.

The cement industry in Sweden faces two major threats to their business in the coming decades. These are: globalisation i.e. the continued rise in the production of cement in China, India and Africa; and the need for decarbonisation as a result of political and scientific pressure. In light of these two pressures, developing a pathway for cement with a low climate impact lies at the top of research and development agendas. Moreover, the most technologically mature pathway to produce carbon-abated cement is through the application of CCS. The quality of cement must remain high because of its use in infrastructure and CCS, as an end-of-pipe solution, allows for the production of cement to remain similar to what is currently produced with drastic changes in the production process.

Cementa AB and Riksbyggen are both working under the premise that there is a developing market for carbon-abated cement. Analysis of megatrends, including perceived "sustainable consumption" in Sweden, suggests that this is also the case. Therefore, given the cost structure of the cement value chain, the need to diversify and innovate for the cement industry and a perceived market for carbon-abated cement, there is clearly strong merit in an argument that CCS implementation is economically feasible for the cement industry in Sweden.

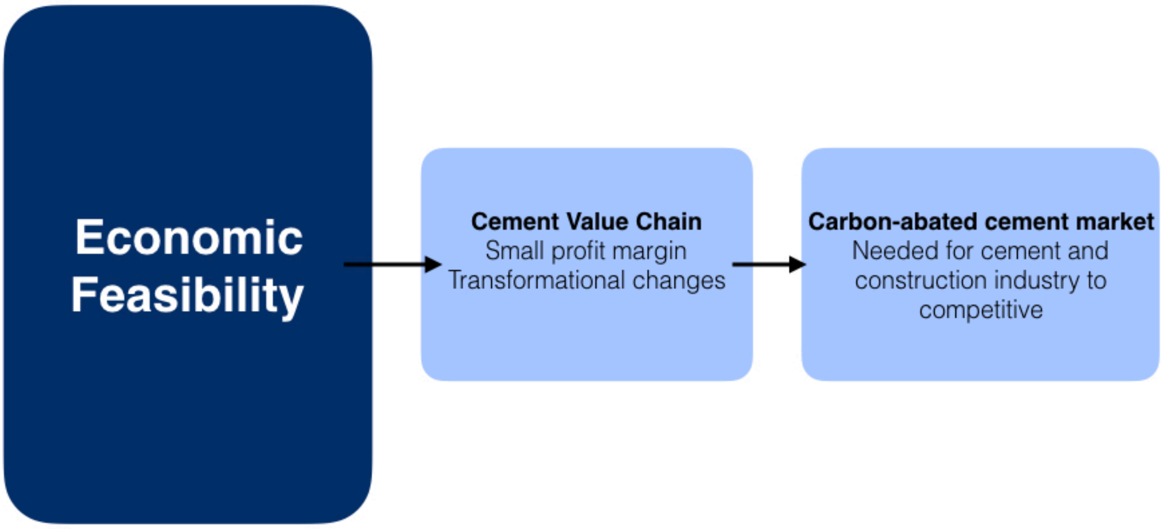

Figure 6.2 Figure 6.1 Illustration of important points for RQ2

What are the trends for the future of CCS in the cement industry and how should this be addressed by the Swedish government?

There has been a change in the European discussion around CCS, largely as result of the renewed pressure for policy measures to reduce CO_2 emissions as a result of the Paris Agreement. For a scenario where global warming is limited to 2ºC, the widespread implementation of CCS is necessary (IEA, 2016). The political debate must become more informed and more open surrounding CCS – there are already signs of this happening in Sweden as a result of the new Climate Act entering law on 1st January 2018.

Having established that CCS is necessary, the leverage points where there are no substitutes for emissions reductions should be targeted by decision-makers first. This study finds that the cement industry would be a great first leverage point. Possible others include BECCS, where there is great potential to reduce Sweden's emissions.

The IEA (2016) recommend that, in order to encourage the dispersion of CCS technologies, government's take regulatory and financial responsibility for developing the transport and storage networks necessary for the implementation of the full value chain of CCS. This is a strategy which the Norwegian government has already implemented, planning to have the full value chain operational by 2022. There are two main options for carbon storage in Sweden. These are offshore storage in saline aquifers in the Baltic Sea or the saline aquifers and depleted hydrocarbon fields of the North Sea. The North Sea storage is already established and is run by the Norwegian government, so even without the direct involvement of the Swedish government, this programme will go ahead. However, if Sweden were to take an active role in developing carbon storage infrastructure in the Baltic Sea, it could be a lucrative opportunity to commercialise a carbon storage network for the Baltic Sea countries.

The Swedish government could also play a role in developing a market for more sustainable cement through the implementation of more strict procurement practices. This would help de-risk the investment in carbon capture infrastructure for companies and help improve green policy alignment for the government.

The common thread between all these trends is the need for an active government role in both a regulatory and financial sense. CCS will play a role in future climate mitigation efforts if global warming is to be limited to 2°C. There are even some opportunities to make it an economic and technological asset. The extent to which this asset can be exploited depends almost entirely on a good government strategy to address the barriers to CCS presented in this thesis and capitalise on the easy leverage points.

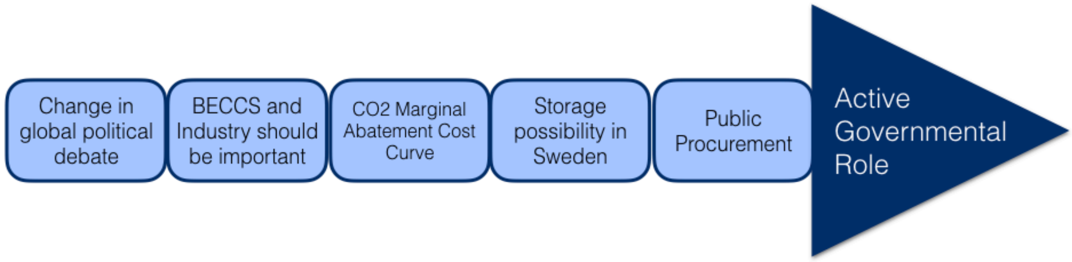

Figure 6.3 Figure 6.1 Illustration of important points for RQ3

6.2 Policy implications and areas for future research

For a study of this nature is hard to make conclusive policy recommendations. This is because of the wide scope and exploratory, inductive rationale of this research. However, there are some key areas for future research that the policymakers could be actively involved in order to capitalise on the potential of CCS technologies for the abatement of carbon emissions that have been discussed throughout the course of this study.

CCS in the cement industry

CCS is the only option for the full decarbonisation of the cement industry. From the results of this study, it is clear the government could support this transition in a number of ways, which would be in line with their commitment to achieving carbon-neutrality by 2045. Further research directions for the best way to for the Swedish government to engage with CCS is needed. The areas highlighted in this report are:

- The possibility of direct subsidy investment with Cementa AB, given that they make up around 80% of the cement market in Sweden. Questions that have arisen from this research include how will this affect other actors in the cement market? Will this receive public support? Is it economically feasible?
- Setting procurement standards that limit the amount of carbon emissions per unit of cement used in public infrastructure projects. Questions that have arisen from this research include: is this enough to incentivise the cement industry to invest in CCS? Will it create enough certainty to overcome the "financial gap"?

BECCS for negative emissions

BECCS is the currently the most mature commercial technology with the potential to offer negative carbon emissions. The ability to create negative emissions is vital in order to achieve a fully carbon-neutral society. This has been recognised in the new Climate Act by the Swedish government. There are some industries in which full decarbonisation will not be possible. Moreover, Sweden's large biomass and forestry sector intensify the potential for the easy implementation of BECCS. Further research in this area should include: how to make BECCS fully commercial, what sectors are best suited for the incorporating of BECCS and how big a contribution to carbon-abatement can BECCS offer.

Plans for developing storage infrastructure

In order to maximise the uptake of CCS, this study has found argumentation that a government should take on the fiscal and regulatory responsibility of developing transport and storage infrastructure in order to reduce the financial and administrative burden on industrial actors. This report has presented two clear options for decision-makers for the storage of carbon. These are:

- Developing storage infrastructure in the Baltic Sea, where evidence suggests there is significant capacity in the saline aquifers. This would be costly in the short-term and would require significant political discourse between the nations surrounding the Baltic Sea. However, in the long-term, it could a major economic asset given the carbon emissions of the countries surrounding the Baltic Sea.
- Working the government of Norway to transport and store carbon in the depleted oil fields and saline aquifers of the North Sea. Norway has a costed plan to implement the full value chain for CCS and has enough theoretical capacity to store carbon emissions from all over Europe in the future.

Future research into this should concentrate on costing these two scenarios. In particular, field studies of the feasibility of storage in the Baltic Sea should be implemented in Gotland. For the Norwegian case, bilateral talks about costings and responsibilities would help provide an accurate costing of following this pathway for carbon storage.

6.3 Reflections

This research, therefore, is useful for policymakers and industry actors to gain an overview of the current debate surrounding CCS and the decarbonisation of the Swedish cement industry. It has provided clear areas for future research that will be important for producing evidence for a specific course of action for the Swedish government. It also brings together information and perspectives from a wide-variety of actors, providing a holistic case study of transition management in a complex carbon-intensive industry.

For policymakers, the CCS debate is beginning to intensify once again, with a renewed sense of purpose. If the climate targets specified in the Paris Agreement are to be met, the international community must learn from the mistakes made previously with CCS and begin to act soon. The cement industry for Sweden provides the perfect place to start introducing the technology and will help Sweden achieve carbon-neutrality.

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Appendix

The interviews for this study were open, in order to maximise the amount of data that could be collected from each expert. The aim of the interview process was to use the data to triangulate findings from literature and to discover new perspectives on the debate surrounding CCS. This is reflected in the list of sample questions that follows.

Sample Interview Questions

How do you think the new Climate Law will change the position of CCS in Sweden?

Do you think that it has opened up a debate to the point where people are considering CCS seriously?

Do you think party politics, for example, one party implementing a policy, then it being changed or repealed by another party, has had an effect on the development of Swedish environmental policy?

Do you think the Climate Act has been affected by political consensus, like stated in the Greenpeace response, and has been watered-down?

Has Sweden's role as a "pioneer" country been a pressure to push legislation through?

What do you think of the concept of a transport and storage network for CO_2, whether that be in Sweden, or Scandinavian network or Europe-wide network? How likely is that? Is it something that could happen?

For which sectors does CCS hold the largest potential?

Do you think the market is pushing for carbon neutrality?

Do you think there would be a market from the construction sector for carbon abated cement?

What do you think are the main barriers to the large-scale implementation of CCS?

If a government then has recognised CCS for cement as a viable option, what would be the next steps for implementing policy to support that uptake?

How do you think the CCS debate is evolving and changing at the minute?