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Assessing the viability of Norwegian carbon capture and storage technology via application of a socio-technical framework

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Abstract

This thesis is concerned with Carbon Capture and Storage (CCS) technology and its viability for large scale deployment in Norway. Despite the significant role attributed to CCS in many climate mitigation scenarios, there is currently insufficient global uptake, with no European CCS facilities currently in operation outside of Norway. Norway is often referred to as a pioneer of CCS technology, thus viability in Norway can be seen as a crucial determinant in the context of wider global development. A socio-technical framework, designed specifically to assess CCS viability, is applied to the Norwegian context. This allows for the identification of key uncertainties which inhibit its technological development and diffusion. This paper should serve to contribute to the existing social science literature on CCS whilst also providing a useful overview to support decision making in Norway. Key findings are that uncertainty is diminished with regards to public acceptability, pathway variety and the safety of geological storage. However, it is still prevalent in other aspects, most notably that of economic and financial viability. The interdependent nature of the uncertainties makes resolution a complicated task. The paper concludes that, whilst further research is required, a targeted policy approach would seem to be the best method for diminishing the most prevalent uncertainties in order to bolster CCS viability.

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1. Introduction

Carbon capture and storage technology is seen by many as a crucial technology in meeting the challenge of preventing global climate change, as it has the potential to reduce the quantity of carbon dioxide (CO_2) that industrial processes release into the atmosphere. However, currently the pace of development is not sufficient in order for the technology to make a significant contribution to current mitigation targets. Whilst the technology itself is proven, widespread development and diffusion has thus far encountered numerous obstacles, leading to numerous setbacks, project cancellations and a lack of worldwide investment appetite. Due to its early developmental stage, there are many uncertainties that impede the ability for decision makers to make informed assessments, whilst simultaneously creating challenges for actors who support its use.

This thesis will seek apply a socio-technical framework, specifically designed to assess CCS viability, in order to make an interdisciplinary analysis of CCS viability in the case of Norway. Bellemare (2017) (as cited by Sovacool, Axsen, & Sorrell, 2018, p. 13) outlines that *"good papers do one of three things: ask a question that has not been asked before; ask a "Big Question" that affects the welfare of many people; or ask a question that has been asked before but can be answered in a better way".* The motivation for this thesis is to be ambitious and ask such a "big question", due to the welfare of many people at stake if we fail to address potentially the biggest threat in human history (Norton & Leaman, 2004), whilst CCS could make a huge contribution to successfully facing this threat. This thesis seeks to ask all three questions but, should it even address merely one with some degree of success, then hopefully some form of small contribution can be made.

1.1 Background: What is CCS technology and why do we need it?

According to the International Energy Agency (IEA), Carbon Capture and Storage (CCS) remains the only technology solution capable of delivering significant emissions reductions from the use of fossil fuels in power generation and industrial processes (IEA, 2016, p. 9). The Intergovernmental Panel on Climate Change (IPCC) presents four pathways to limit warming to 1.5 °C (P1, P2, P3 and P4 as detailed in Figure 1 below) with only one (pathway P1) achievable without negative emissions technologies and requiring a rapid increase in renewable uptake combined with reductions in global energy demand (the small amount of negative emissions in this scenario to be achieved by afforestation). The feasibility of scenario P1 is therefore certainly questionable, with little indications global energy demand is set to decrease. The IEA predicts energy demand to grow by more than 25% by 2040 (OECD/IEA, 2018).The overall deployment of CCS varies across 1.5°C-consistent pathways with cumulative CO_2 stored through 2050 ranging from zero up to 460 $GtCO_2$ (IPCC, 2018b, p. 9). According to the IEA 2°C scenario, CCS delivers 94 gigatonnes (Gt) of CO_2 emissions reductions in the period through 2050, which amounts to 12% of the cumulative emissions reductions required by the energy sector (IEA, 2016, p. 10). Therefore, CCS is seen by many to be a vital technology requiring widespread deployment if climate change targets are to be adhered to (Chu, 2009; Gibbins & Chalmers, 2008; MacDowell et al., 2018), whilst the current lack of large scale CCS projects threaten both 2030 targets and long term Paris ambitions (Peters et al., 2017).

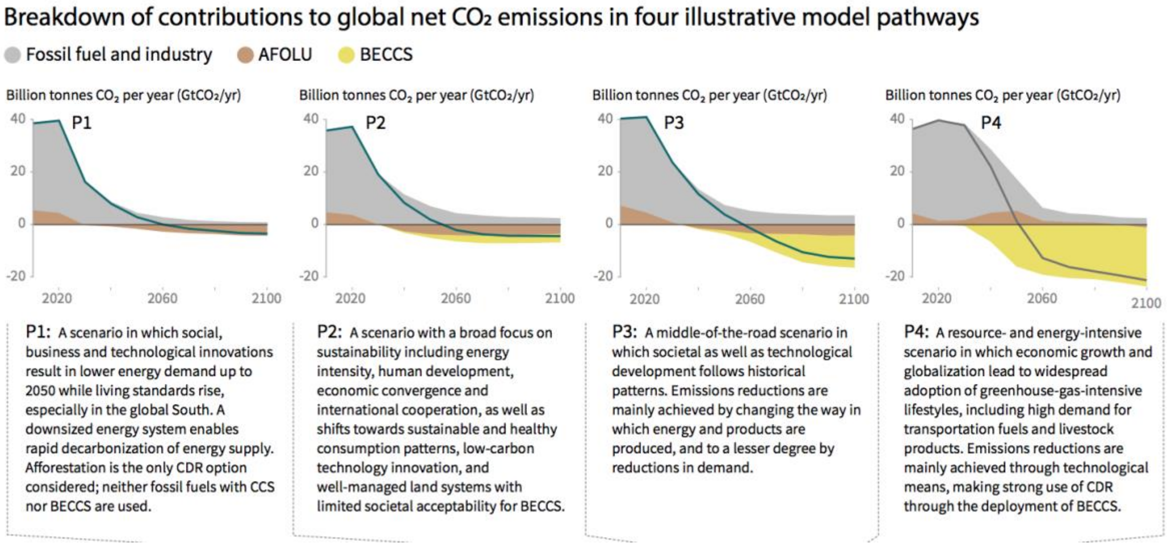

Figure 1[1]: Taken from (IPCC, 2018a) https://report.ipcc.ch/sr15/pdf/sr15_spm_fig3b.pdf

Mac Dowell, Fennell, Shah, and Maitland (2017, p. 244) state that CCS is *"expected to account for the mitigation of approximately 14-20% of total anthropogenic CO_2 emissions, in 2050 the industry will need to be larger by a factor of 2-4 in volume terms than the current global oil industry"*. If this expansion of scale proves even remotely accurate, then a dramatic global uptake of CCS technology is required. Indeed, a significant role for and recognition of

[1] AFOLU stands for agriculture, forestry and other land use, whilst BECCS stands for bio-energy with carbon capture and storage

CCS has been highlighted in several reports by the IEA and IPCC (Lipponen et al., 2017). CCS covers a diverse range of technologies and perhaps a broad portfolio is necessary to realise its long term potential (Rackley, 2017). The underlying principle is to abate the release of waste CO_2 resulting from combustion of fossil fuels (and other industrial processes) by capturing the emissions at source. There are three basic steps: capture of CO_2, transport to a suitable disposal site and long term storage (J. R. Meadowcroft & Langhelle, 2009).

The three main approaches to CO_2 capture are described by Rackley (2017, p. 23) as follows:

1) Pure or near-pure CO_2 stream from existing industrial process or by reengineering a process to generate steam (e.g., oxyfueling or chemical looping power-generation plant, pre-combustion fuel gasification)
2) Concentration of the discharge from an industrial process into pure or near-pure CO_2 stream (e.g., post-combustion separation from power plant or cement plant flue gases)
3) Direct air capture into a pure CO_2 stream or into a chemically stable end product (mineralisation of steel slag)

For this paper the viability of large-scale CCS facilities is the primary focus, therefore it is necessary to determine what precisely can be viewed as a large-scale facility to distinguish them from smaller projects. The GCCSI defines large-scale CCS facilities as those with an annual CO_2 capture capacity of 400,000 tonnes or more (Global CCS Institute, 2019). Therefore, this paper shall primarily focus on assessing viability for the development of facilities with a capture capacity equal to 400,00 tonnes of CO_2 or more.

The IEA describes CCS as slowly moving forward, stating that the number of large-scale CCS projects in operation has expanded to 15, with 6 more to come online in the next two years (IEA, 2016). However, this being a 2016 figure, we can then look at this in light of the latest project developments. The Global CCS Institute (GCCSI) lists 43 large scale projects. with 18 currently in commercial operation at present (16 of which are industrial) (Global CCS Institute, 2018a, p. 44). However, seeing as the IEA in their findings used data sourced from the GCCSI as of the end of August 2016, we can determine that out of the 6 to come online, only 3 look to have evidently come to fruition within the projected timescale. The IEA goes further to state that *"the current pace of CCS deployment is out of step with Paris ambitions and that the pace of CCS deployment has fallen short of initial expectations and is not* *consistent with a 2°C pathway, let alone one well below 2°C. The pipeline of new large-scale CCS projects is shrinking rather than growing, from 77 in 2010 to around 38 today, and no projects have progressed to construction since 2014. Even if all projects under consideration today were to proceed to operation, the entire CCS project portfolio would collectively capture less than one-sixth of the CO_2 capture requirements in the 2DS in 2025"* (IEA, 2016, p. 11).

Fossil fuels accounted for 81% of total energy demand in 2017, whilst overall global energy demand increased by 2.1% (IEA, 2018a, p. 2). As previously mentioned, in the IEA 2°C scenario, CCS delivers 94 gigatonnes (GT) of CO_2 emissions reductions to 2050 (IEA, 2016, p. 10). In 20 years of operation Sleipner, the first project to have permanent, dedicated CO_2 storage and monitoring, has captured and stored 17million tonnes (IEA, 2016, p. 9). Industrial CO_2 emissions also represent a significant proportion of total anthropogenic CO_2 emissions, thus CCS can prove a crucial technology for industrial processes with little alternatives for manufacture and CO_2 mitigation (Roddy, 2012). In its 5th Assessment Report the IPCC states that emissions from industry constituted 30% of total global greenhouse gas emissions in 2010 (Fischedick et al., 2014, p. 743). Industries such as cement, steel, refining and fertilisers entail substantial CO_2 emissions that are inherent to their operations and can otherwise not be abated without CCS (Roussanaly, 2019).

The question remains of how to gauge the progress of CCS. One example of how this is done is through a comparison of the amount of fossil fuels that can be consumed both with and without CCS. "*In modelled energy system transition pathways that limit global warming to less than 2 °C, scenarios without CCS result in 26% of fossil fuel reserves being consumed by 2050, against 37% being consumed when CCS is available"* (Budinis, Krevor, Dowell, Brandon, & Hawkes, 2018, p. 61). However, this provides no indication as to exactly how CCS technology will achieve such a reduction. The authors conclude that no CCS barriers are extensively technical, with cost being the most significant hurdle in the short-medium term, although long term it is cost effective when compared to other mitigation options (Budinis et al., 2018).

1.2 CCS: Norway's "moon landing"

First some context must be provided. Norway has a longstanding interest in CCS technology. The country is Europe's largest oil exporter and the world's third largest exporter of natural gas, whilst its petroleum sector is Norway's largest when measured in terms of government revenues, investments and export value (Ministry of Petroleum and Energy & the Norwegian Petroleum Directorate, 2019). Its domestic energy supply is predominantly hydropower, with a 92.7% share in electricity production as of March 2019 ("Electricity," 2019). With regards to CCS, Norway can viewed as a pioneer the technology (Lipponen et al., 2017). Herzog (2017) presents what are said to be the world's four pioneer CCS projects, with two out of the four being based in Norway (Sleipner and Snøhvit). It even been argued that Norway´s wider innovation system is specifically formed around CCS (Espen Moe, 2012).

Norway does not stand out as one of the strongest scorers according to the Global Carbon Capture and Storage Institutes Inherent Interest CCS indicator, with a score of 48 out of 100 as of 2018. The indicator gives an indication of potential interest countries may have in implementing policies that contribute to CCS deployment. For comparative purposes, the UK scores 70, Germany 88 whereas the USA, Russia and China all achieve scores of 100 (Global CCS Institute, 2018b). On the face of it then, Norway would seemingly have less motivation in comparison to its contemporaries, which can be explained by the indicator using an index that bases its findings upon global shares of fossil fuel production and consumption. Due to an abundance of hydropower in its domestic energy supply, Norway therefore has an almost emissions free power supply. With CCS often viewed as a means to mitigate CO_2 due to fossil fuel intensive power generation processes, the question could then be asked as to why Norway has a significant interest in CCS development.

The answer is lies in a combination of contributing motivational factors. Tjernshaugen and Langhelle (2009, pp. 98-99) outline four reasons for Norway's significant CCS interests: 1) Confliction of energy and climate policy targets due to a high environmental ambitions combined with a heavy economic dependence on the oil and gas industry, 2) CCS having been used as a solution to a political conflict over gas fired power plants, 3) Norwegian industry launching early and ambitious CCS initiatives and additionally 4) CCS having been promoted by environmental activists. Some would also suggest that, due to Norway being a large exporter of fossil fuels, it therefore has a special obligation to develop zero-emissions solutions (Skriung, 2013a, p. 10). CCS has also become a significant feature in Norway's approach to international climate policy, being a mitigation strategy that can also serve in preserving its national energy interests (Jo-Kristian Straete Røttereng, 2016; Jo-Kristian S. Røttereng, 2018).

The history of CCS technology in Norway has its origins as far back as 1986, when SINTEF Petroleum research proposed a combined CCS concept to the state-owned energy company Statoil[2]. Motivated by the CO_2 content of natural gas at the Sleipner West field (being too high for sale without treatment) in combination with the introduction of the Norwegian CO_2 tax, the CCS facility at Sleipner was conceived in 1990 and commenced operation from 1996 (Tjernshaugen & Langhelle, 2009, pp. 105-106). CCS has gained such prominence in Norway since its first conception that it was even hailed as Norway's equivalent of the "moon landing project" by former Prime Minister Jens Stoltenberg. He foresaw it to be the major Norwegian contribution to the world's climate problem. (Stoltenberg, 2007; Tjernshaugen & Langhelle, 2009, p. 116).

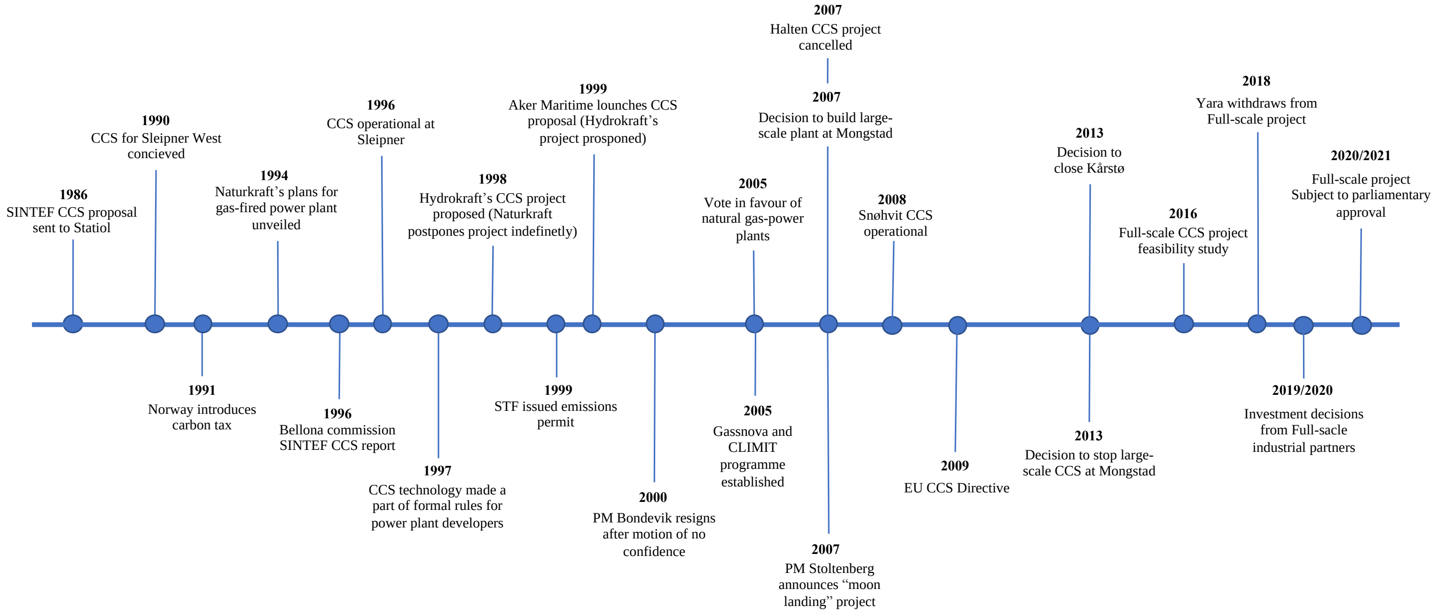

Figure 2: Timeline of Norwegian CCS development, own contribution. Sources of data: Tjernshaugen and Langhelle (2009), https://bellona.org/, https://www.gassnova.no/en, https://ccsnorway.com/, http://www.zeroco2.no, https://www.globalccsinstitute.com/

[2] Then fully state-owned. Statoil is the former name of Equinor ASA

Whilst Norway's reliance on the oil and gas sector provides motivation for domestic actors to develop CCS technology, in securing long-term economic interests in fossil fuels, there are also other applications that are suited towards CCS implementation aside from application for enhanced oil and gas recovery (EOR). Norway currently has an ambitious target to become carbon neutral by 2030 (*Innst. 407 S Innstilling til Stortinget fra energi- og miljøkomiteen*, 2015-2016; Kilpeläinen, Aalto, Toivanen, Lehtonen, & Holttinen, 2019) and CCS could be an option to help achieve this aim. Norwegian 2017 emissions to air indicate that oil and gas extraction accounted for 14.7 Mt CO_2 equivalents, whereas 12.1 Mt resulted from manufacturing industries/mining and only 1.9 Mt from energy supply (SSB, 2018). It is therefore evident that Norwegian industry contributes significantly towards overall CO_2 emissions domestically.

Industrial processes such as cement manufacture, iron and steel production, chemical ammonia as well as pulp and paper industries all have potential for application of CCS technology (Onarheim, Mathisen, & Arasto, 2015). Let us take cement manufacturing as an example. It is the world's second-largest industrial emitter of CO_2 and is the third-largest industrial energy consumer, with overall production estimated to account for roughly 7% of global CO_2 emissions (IEA, 2018b). In Norway, cement production accounts for around 2% of national emissions (Holmås et al., 2019), whilst the cement industry has few alternatives for reduction of CO_2 aside from CCS (Barker, Turner, Napier-Moore, Clark, & Davison, 2009; Mazzetti et al., 2014). Currently in development, the Norwegian Full-scale CCS project seeks to capture CO_2 from industrial processes, including cement and a waste-to-energy facility (although it is worth noting that the proposed Yara ammonia plant in Porsgrunn is no longer involved) (Rørvik & Ringrose, 2017). Waste incineration also has potential for CCS application and accounted for just under 2% of Norwegian CO_2 emissions in 2011 (Holmås et al., 2019, p. 7). Other industrial processes have more limited potential. Norway's CO_2 emissions from pulp and paper are not substantial, so it would seem the only real potential for CCS development here would be mainly for purposes of cross-border project collaboration as opposed to domestic application. For ammonia the production volumes are relatively small, thus limiting CCS potential, but there are opportunities nonetheless (Onarheim et al., 2015). It is also worth noting that aluminium CO_2 emissions are process related and thus, with most of the energy for this supplied by hydropower, there is little scope for CCS to assist in Norway's domestic emissions reductions (Onarheim et al., 2015).

Norway meeting its carbon neutrality target (which has been brought forward from 2050 to 2030) will require CCS to capture 3Mt of industry and 19 Mt of power sector emissions respectively, according to Mazzetti et al. (2014) when referring to the findings of the Lavutslippsutvalget (NOU, 2006). Whilst there is considerable potential for CCS to contribute to reducing CO_2 emissions from major industrial point sources in Norway, the actual feasibility of CCS application to industrial processes is somewhat more difficult to assess. This is due to substantially fewer studies having been undertaken for industrial CCS, lack of existing comparable projects and therefore limited access to the necessary site-specific data (NOU, 2006, p. 74). The findings of a 2006 special committee (NOU, 2006, p. 78) made suggestions to the Norwegian Ministry of Environment that it was realistic to realise a reduction of 6Mt CO_2 by 2050 from process industries, predominantly with application of CCS. The Nordic CCS roadmap, a collaborative research project between CCS research institutions in the five Nordic countries, outlines strategies for widespread implementation of CCS that could be realised through collaborative efforts (Mazzetti et al., 2014). Norway is envisaged as contributing in a number of ways; providing substantial storage capacity, helping to reduce costs of CCS by utilising CO_2 for EOR as well as through jointly helping to develop necessary CCS framework, thus providing a stronger position from which Nordic states can influence the EU. However, the most economically viable and cost effective scenario is seen to be “gas sweetening”, in removing high CO_2 content from natural gas before export (Mazzetti et al., 2014).

2. How to assess CCS viability in Norway

Having now established that there is a significant global need for large-scale CCS, and that it is essential that the technology is diffused rapidly in order to meet current climate targets, one could be forgiven for questioning as to why so few large-scale projects have been developed. It is evident that progress has been somewhat slower than is necessary, yet here is a technological solution that is proven to work and could also allow for continued use of fossil fuels with zero emissions. A solution that allows for a “business as usual” energy scenario, whilst providing the only current mitigation solution to many CO_2 intensive processes. Therefore, in light of such an urgent need for climate mitigation, it would seem prudent to believe that the problem must lie in within the viability of the technology itself.

Due to the potential value of CCS, the crucial contribution the technology can make towards climate mitigation and evidence of its prominence and suitability in Norway, this inevitably requires examination to establish as to what is in fact hindering further development. *"The question therefore is how to explain this uneven and slower-than-expected rollout of CCS, first, the slow progress, followed by a spurt of new projects and then a drying up of projects before lessons can be learned from the first projects?"* (Bui et al., 2018, p. 1138). Upon closer inspection it is soon apparent that there are common themes of uncertainty, evidenced not only by the literature, but also in wider discourse. Norway makes for an interesting case study, not only due to its complex energy and climate conflictions, but as a pioneer of CCS technology with extensive fossil fuel resources and a prominent position for CCS on the political agenda.

It is by no means a straightforward task to undertake such an assessment. There are numerous uncertainties, each with their own specific set of foundations, that occur due to a series of interrelated and yet diverse set of factors. Adequate assessment of these factors therefore requires a tool of analysis that allows for numerous considerations, engagement with a range of disciplines and a mixture of qualitative and quantitative approaches. With numerous and notable disagreements generating contrasting views within the literature, or highlighting many areas where data is insufficient as to make a conclusive inference, it is no wonder that such uncertainty exists. Yet urgency is paramount and decision makers are required to act, despite such uncertainties proving tremendously problematic in strategic planning. Thus, as daunting as the task may be, an attempt to examine CCS viability in assessing uncertainty is a vital one.

2.2 Why the need for a socio-technical framework?

Previously, CCS research was dominated by natural science and engineering perspectives, and only in more recent years has social science shed light on the need for observations surrounding politics and policy (Bäckstrand, Meadowcroft, & Oppenheimer, 2011). Technological change is largely driven by societal factors, which can often be neglected or missed entirely in purely narrow technical studies. This is not by any means intended to be dismissive of the valuable contribution such studies make towards our understanding of CCS systems, quite the contrary, but rather to merely highlight the need for supplementation in order to compensate for such deficiencies. Political uncertainty has been identified as one of the most dominant hinderances to stimulating action in the development and diffusion of sustainable energy technologies (Meijer, 2008; Meijer, Koppenjan, Pruyt, Negro, & Hekkert,

2010) and therefore understanding of CCS technology can be enhanced through perspectives that the field of social sciences can provide. Bäckstrand et al. (2011, p. 279) emphasise that a significant contribution can be made in expanding CCS research via engagement with a range of disciplines and through a broad scope of methodologies.

For example, the IPCC Special Report on Carbon Capture and Storage outlines five key drivers for the deployment of CCS. These are 1) the policy regime, 2) The reference case (baseline), as CO_2 concentrations are sensitive to the choice of the baseline scenario, 3) The nature, abundance and carbon intensity of the energy resources/fuels, 4) The introduction of flexible mechanisms such as emissions trading and 5) the rate of technological change (induced through learning or other mechanisms) (Metz, Davidson, Coninck, Loos, & Meyer, 2005, p. 351). Understanding these drivers entails numerous considerations and the assessment of many uncertainties as to determine the conditions that effect their influence on CCS technology. Industrial CCS applications are also much more difficult to assess in comparison to applications of CCS technology in the power sector, largely due to heterogeneity in the vast array of industrial processes (Farrell, 2018). Such complexity reinforces the need for an interdisciplinary tool that can assess the various elements and applications for CCS technology.

A portfolio of tools to enable transition management and define a common objective can help to overcome tensions between uncertain processes and the will to govern such a process (Frantzeskaki, Loorbach, & Meadowcroft, 2012). Here is whereby a socio-technical framework can be of assistance. The socio-technical framework is advantageous as; 1) it provides an interdisciplinary tool to assess the uncertainties of CCS innovation, 2) identifies important linkages between the uncertainties and finally 3) develops qualitative and quantitative indicators for assessment (Markusson, Kern, et al., 2012). The limitations for current CCS research, and suggestions to overcome these, are summarised below:

"There are significant limitations in current quantitative (and qualitative) data on CCS that lead to significant difficulties in identifying robust assumptions. One way to handle this is to develop multiple scenarios to illustrate the uncertainty. Another strategy is to make more use of qualitative methods for analysing CCS innovation processes. This latter approach could help to avoid some of the issues associated with CCS cost uncertainty and instead re-focus

attention on understanding critical aspects of innovation processes" (Markusson & Chalmers, 2013, p. 1409).

To assess the viability of carbon capture and storage technology within Norway, this thesis will seek to employ a socio-technical framework as developed by (Markusson, Kern, & Watson, 2011); Markusson, Kern, et al. (2012). This framework is an interdisciplinary tool to allow for the evaluation of the main uncertainties of CCS innovation by incorporating technical, economic, financial, political and social issues. The framework then proceeds to identify linkages between these uncertainties, and finally provides qualitative and quantitative indicators for assessing these uncertainties. This framework does not seek to make predictions for the future of CCS technology, but rather It seeks to help identify and guide the analysis of uncertain dimensions of CCS futures (Markusson, Kern, et al., 2012, p. 904). Many technologies that have previously emerged successful in the face of numerous uncertainties were faced with similar challenges to those confronting CCS at present (Rai, Victor, & Thurber, 2010). Chalmers et al. (2013) look at some historical case studies for examples of success stories in relation to specific uncertainties identified for CCS, such as the French nuclear programme from the 1950´s-1980´s. This is chosen to outline potential for development, despite technological diversity between components of the full chain and technological, with technological variety being reduced by policy (Chalmers et al., 2013, p. 7672).

2.2 The relationship between CCS and uncertainty

A common theme of uncertainty is apparent within the literature and, despite much debate as to exactly what is hindering CCS development (whether it be social-cultural, technical, economic, environmental or political feasibility), immediate decision making is required despite of this. A quick search of the 2005 IPCC Special Report on Carbon Capture and Storage reveals 134 instances whereby the word uncertainty is mentioned (Metz et al., 2005). Uncertainties can be said to naturally follow from new combinations of technological knowledge and application (Meijer, Hekkert, Faber, & Smits, 2006), whilst CCS is not exempt from such ambiguity. Although some may view CCS as a vital technology in a transition towards a zero-carbon future, others may disagree. Evaluating as to whether it can play a significant role in the transition to a low carbon economy serves to further emphasise the need for assessing the multiple uncertainties surrounding CCS technology (Markusson et al., 2011). Providing greater clarity through an examination of the uncertainties can help pave the way for considered CCS diffusion in order to enhance our understanding of what considerations are necessary.

Many prior cases evidence how accumulation of perceived uncertainties can lead to a decline in motivation and entrepreneurial efforts, a reason Meijer (2008) attributes to different uncertainties interacting and negatively reinforcing each other. Thus, a socio-technical framework that identifies such linkages can prove highly beneficial for actors in order to enhance strategic decision making. The purpose of thinking in advance about the future is to improve decision making in the present, and thus policy making surrounding technological and social changes require some degree of consideration for future trends in order for it to be sound. Higher levels of future uncertainty pose a challenge to strategic decision making and the capacity to make decisions that will prove beneficial in both the near and long term future (N. Hughes, Strachan, & Gross, 2013). Such a framework can help engage with technologically-driven uncertainty and allow for better management and regulation in emerging socio-technical settings (Laurie, Harmon, & Arzuaga, 2012). Engaging with a range of disciplines allows for a comparative study of CCS that can help with collective decision making and help bridge knowledge gaps (Bäckstrand et al., 2011).

Uncertainly is problematic in many respects. It is a problem for policy makers when drafting policy that deals with energy systems and climate mitigation, whilst is also problematic for business leaders when seeking to make informed investment decisions (Markusson et al., 2011). In dealing with uncertainty, a learning-by-doing process involving small-scale experiments is often a favoured approach as opposed to making definite choices (Kemp, Rotmans, & Loorbach, 2007, p. 323). The conundrum we encounter here is that time is of the essence, and large-scale CCS projects are now needed to make an impactful contribution to climate change mitigation. Uncertainties can prove a substantial barrier to technological developments. For example, the Norwegian case of full-scale CCS project at Mongstad was subject to repeated delays and overruns before being abandoned, with disagreements centering around the perceptions of uncertainties amongst the different actors involved (Markusson, Shackley, & Evar, 2012).

Understanding and evaluating uncertainty allows actors who advocate and push for CCS development to make informed decisions and direct their efforts in a more efficient, effective and pragmatic manner. The holistic and interdisciplinary nature of the framework is also advantageous in this regard. Fragmented frameworks can be counterproductive towards promotion of new technologies and narrow actors' vision due to the exclusion of key information. This framework tries to encompass a wide range of factors in measuring uncertainty in a cross-comparative manner to help overcome barriers to technological diffusion. The authors of the framework state that the *"assessment of the uncertainties of technological features needs to be socio-technical and co-evolutionary"* (Markusson, Kern, et al., 2012, p. 905).

Some general theoretical concepts that have provided consideration for this paper will now be outlined. The thesis does not engage directly with all referred perspectives, but the following section should serve to help add context to the study and rationale for the objective.

2.3 Theoretical considerations

Persistent problems in society are said to require structural societal transformation (Van den Bosch & Taanman, 2006). The study of long-term transformative change has become increasingly relevant in recent years due to heightened awareness of the relationship between human systems, technological developments and environmental risks. Therefore transition management with regards to a long-term perspective for innovation strategy is vital (Grin, Rotmans, Schot, Geels, & Loorbach, 2010). Transitions can be defined as long-term radical shifts from one socio-technical system to another. They are co-evolutionary processes that require multiple changes involving multiple actors (Grin et al., 2010, pp. 11-12). Widespread deployment of CCS technology can be part of such a transition towards a sustainable future. Sustainability transitions are goal orientated, whilst not offering obvious user benefits with regards to price and performance in comparison to established technologies (Grin et al., 2010, p. 25). Hereby the difficulties present themselves in transitioning carbon emitting processes towards utilisation of CCS technology. The Multi-Level perspective is one systems based approach that is used to assist with understanding transitions and a tool for analysis (Geels, 2004). The Niche Management framework (Schot & Geels, 2008) is a another, whilst both view sustainable technologies as having disadvantages that require support to prevent rejection whilst in development (Raven, Kern, Verhees, & Smith, 2016).

Innovations literature is a limited but emergent area of research which looks towards the roles of actors and institutions (Markusson, Kern, et al., 2012). Schumpeter outlined the crucial role played by innovation in economic and social change, being a source within a given economic system that would disrupt any attained equilibrium (Fagerberg, 2007, p. 20). Lessons from institutional economics and innovation studies also outline how societies can lock-in to sub-optimal outcomes (J. Meadowcroft, 2009). Technological assessment literature has been a prominent field of study for the past four decades (Tran & Daim, 2008), but the focus has changed somewhat as recognition for co-evolution of technology and society has led to research into socio-technical systems (T. P. Hughes, 1986). Technological innovation system theory has resulted in a large literature designed to inform the policy process by identifying system weaknesses (Jacobsson & Bergek, 2011), whilst technology-specific policies can also be seen as necessary to meet the challenged posed by climate change (Jacobsson & Bergek, 2011). Thus, studies of technological development have evolved to recognise the need for the understanding of many heterogeneous aspects. The considerations for CCS viability therefore require such a wide and rounded approach.

2.4 Research questions

The overall aim for this thesis is to assess the viability of large-scale carbon capture and storage technology in Norway via use of a socio-technical framework. The research has been designed to be socially useful and improve fundamental understanding as advocated by (Sovacool et al., 2018), thereby a balance between ensuring this is problem-driven research as opposed to merely descriptive is attempted.

Exploring the following research questions will be necessary for achieving the overarching objective:

1. How can the framework be applied to assess CCS viability in Norway?
2. To what extent are these uncertainties prevalent?
3. How are these uncertainties inter-related?
4. What are the implications for overall Norwegian CCS viability?

3. Methodology and scope limitation

3.1 Research design

The study method for this thesis takes the form of a mixed methods approach. Studies using mixed methods are more difficult to execute (Yin, 2014, p. 67), however much of the research will incorporate and resemble case study methodology, using the guidance offered by Yin (2014). In this context, CCS viability shall be looked at in light of CCS projects within Norway and the context of overall Norwegian CCS viability. However, the scope of the framework, and its cross-dimensional requirements, results in the paper not taking a strict procedural approach. At times it may also bear some resemblance to a qualitative meta-analysis, on the basis that this seeks to synthesise existing findings into overall results in order to draw inferences (Miller, Fredericks, & Perino, 2008), however it is distinguishable in that it does not employ statistical methods for summarising the results. Different cases are looked at whereby they provide data useful for contextual analysis. Thus, they are used more as instrumental case examples, in that they facilitate understanding of the broader concept of viability, for use in a collective case study. A collective study being a joint study of a number of instrumental cases (Stake, 2005). Yin (2014) outlines that a larger study may call for case studies to be complementary as opposed to providing convergence. It is more a embedded study in this respect due to the sub-units involved in overall analysis (Blaikie, 2009).

Case studies help inquiries that investigate a contemporary phenomenon in depth and within a real-world context whereby the boundaries between the phenomenon and context are not clearly evident (Yin, 2014, pp. 16-17), in this thesis the case being that of CCS viability within the context of Norway. This type of method can help with technically distinctive situation in which there will be more variables of interest than data points, which is certainly of relevance considering the scope of the framework. Blaikie (2009, p. 39) states that the research design refers to the process that links research questions, empirical data and research conclusions, and the structure of the thesis follows this format. According to Yin (2014), case study inquiries rely on multiple sources of evidence, with data needing to converge in a triangular fashion. Here numerous uncertainties will be assessed, each with their own specific indicators, before turning to a brief consideration of the inter-linkages that connect them in order to reach our conclusion.

To summarise:

1) The project objective is to assess CCS viability in Norway.
2) The hypothesis is that uncertainty inhibits CCS viability.

3) The proposition is that the interlinkages connect the concepts of key uncertainties.
4) The theoretical framework is use of the socio-technical framework to assess CCS viability.

Case studies have limitations, in that the complexity is difficult to represent simply, they are easily dismissible, and they have difficulty to answer a large range of relevant research questions (Hodkinson & Hodkinson, 2001). These have all been considered, but nonetheless they provide a foundation for analytical generalisations of the phenomenon in question. Yin (2014, p. 3) emphasies that case study research is one of the most challenging social science endeavors, thus it is certainly not expected to be a perfect endeavor. The research questions were developed both as exploratory, prevalent questions but also due to the need to pursue "what" and "how" lines of inquiry (Yin, 2014). Thus, the need to assess uncertainty in relation to how it affects viability determined the choice of methodology. This process should therefore allow for a link between the research questions and findings, with the adaptive nature of the case study allowing for a mixed methodological approach and data whilst still confirming to structure and rigor of an overarching methodology. Hodkinson and Hodkinson (2001) state that case studies should be asked from a position of some understanding of the topic being investigated, thus the theoretical considerations discussed previously have been used as this foundation.

Theoretical propositions regarding a set of uncertainties has guided the guiding data collection and analysis, as suggested by Yin (2014). In trying to assess uncertainties to determine overall CCS viability in Norway, a case study therefore provides the most fitting and comprehensive method to cover the design, data collection and approach to analysis. A case study's strength comes from its ability to deal with a full variety of evidence and, with the variety of data and scope required by the framework, this methodology is therefore advantageous for the purposes of this thesis. This thesis is a more abductive study, as rather than concrete conclusions these will more be best assumptions of viability based upon the best understandings of the relative levels of uncertainty corresponding inter-linkages. The research approach shall be predominantly qualitative, due to the more diffuse and open nature of the study and being less precisely controlled. Quantitative data is used where available or fitting, but also whereby the overall approach is less defined. Markusson and Chalmers (2013) outline the need for more qualitative analysis for CCS innovation processes.

Reliability refers to consistency, which is difficult to achieve in an approach of this type of study. There is even suggestion that traditional views of relatability have no relevance in qualitative research, perhaps with the need for alternative interpretations of this and validity in pursing qualitative research (Stenbacka, 2001). Whilst steps have been taken to try and balance inconsistencies and to devote equal efforts to the extent to which each uncertainty is examined, the very hypothesis that these are inconsistent to the degree in which they are uncertain, will evidently generate inconsistent results. To account for this, a conscious awareness of the time dedicated towards each assessment in both research, data collection and analysis has sought to bring greater balance and consistency. The use of multiple sources of evidence assists with validity, as well as reliability enhanced via case study protocol. Replication logic is difficult due to the differing data collection and types in accordance with the indicators, but the same general approach and basis for assessment has been used. The text itself has also been written to try and strive for more balance in the data presentation, but of course data is more significant, accurate and available in certain aspects as opposed to others. Moss (1994) challenges the assumption that reliability is essential to sound assessment practice, in arguing that validity can exist without reliability, and that it is not always necessary depending on the context. The same foundational approach has been taken towards data collection and methodology, but inherently the different indicators entail different forms of examination and the end result is not evenly distributed between independent measures.

3.2 Evidence and data collection

Most of the data used is secondary data or tertiary data, whilst primary data has been generated in the form of the interviews. Documentation in the form of policy, reports, feasibility studies public documentation and media discourse surrounding the discussion have been used in conjunction with other data. These were used to corroborate and augment evidence. Whereby the indicators were suggestive of specific data requirements, the data collection was attempted as best fitting or alternate means if lacking. Reports and press releases directly from or commissioned by the Norwegian government and ministries or agencies such as Gassnova, The Research Council of Norway or CLIMIT. Reports from intergovernmental organisations such as the IEA, IPCC and GCCSI and also from Norwegian based NGOs such as ZERO, ENGO network and Bellona have been utilised. Documentation and reports from private organisations and consultancy groups such as Equnior and Mutliconsult where publicly available. Databases such as the GCCSI co2re database, MIT

CCS Project Database, ZEROCO2 CCS database, to name but a few, have also been sources for project data and quantiative information such as costs, project capacity and operational facilities. Documentation published regarding the CLIMIT programme has been used to gather data of R&D expenditure. Secondary and tertiary survey data has been collected from prior research for surveys of public acceptance.

3.3 Literature review

An extensive literature review was conducted as a foundation for this thesis, which was then refined and focused towards the main research questions that are the objective of this study. The research question should guide the literature review and collection of data and suggest the type of answers the study can give (Sovacool et al., 2018). The steps taken are broken down as follows:

1) A literature review encompassing worldwide CCS development was conducted as the first step towards the research. The purpose was to establish the state of CCS globally in order to gain a broad understanding of the technology and its developmental history. This also allowed for a general, but albeit somewhat ambiguous, overview of the interrelated fields of expertise and research that is applicable to CCS technology. Insight into required uptake for reconciliation with international climate targets also served as a basis for understanding its significance as a climate mitigation tool. Extensive reports by internationally recognised institutes such as the GCCSI, IEA and IPCC provided a solid basis for a generalised overview.

2) The next step entailed a literature review on the subsequent social science literature surrounding CCS technology. This was done via online scientific databases and through relevant literature with a specific focus on CCS. Many relevant areas such as papers from the fields of economics, environment, engineering and geology, to name but a few, were studied in order to understand the differing perspectives. This helped illuminate theoretical perspectives and potential avenues for further research. What soon became apparent was the lack of interdisciplinary research, as is noted by Choptiany, Pelot, and Sherren (2014, p. 445);*"To date, studies assessing CCS have been limited mostly to environmental, social, and economic fields in isolation from each other… Incompatibilities across CCS assessment methods have hindered the*

comparison of the results across these single-discipline studies and limited the possibility of drawing broader conclusions about CCS development."

3) Upon discussions with the thesis supervisor it was soon apparent that a holistic analysis of global CCS would be an incredibly ambitious undertaking. Therefore, the focus of Norway was chosen due to the following reasons: pragmatism for ease of data collection and resource access and Norway's oft cited position as a pioneer of CCS. This thus entailed an extensive literature review and database search for CCS research focused towards Norwegian developmental efforts. Key word searches were run in databases such as Web of Science, Scopus and Google scholar. Search strings included keywords and combinations of the following (in both English and Norwegian where distinguishable) such as: CCS, CCUS, Norway, Gassnova, projects, history, sequestration, carbon capture, viability, uncertainty, risk, barriers, obstacles, support, development, economics, cost, finance, storage, policy, politics, public acceptance/acceptability, industry, integration, full chain, law, liability, transport, CO_2, Sleipner, Mongstad, Snøhvit, Halten, Kårstø and full scale. This is by no means an exhaustive list but should provide some insight as to how this search was conducted. Upon selection of the framework, the search was then focused towards each of the key uncertainties and indicators as outlined (Markusson et al., 2011); Markusson, Kern, et al. (2012). The framework was selected due to its interdisciplinary and holistic focus as well as being a developed tool for quantitative and qualitative methods. The framework provided a good platform to build upon due to it having been drafted based upon a literature review of social science research on CCS as well as insights from innovation studies and expert interviews. Thus, this thesis can be said to replicate the approach that was employed for the framework design to a large extent.

3.4 Semi-structured interviews

3.4.1 Interview objectives

One of the main objectives for this thesis has been an examination of uncertainties that may pose as obstructions to large-scale CCS viability within Norway. Assessing CCS viability requires a broad understanding from various fields of expertise. Interviews conducted with key actors and experts within the field of CCS in Norway assisted in this task. The interviews have been used to help verify data collection and provide valuable insights as to the most prevalent uncertainties surrounding CCS development, whilst they also provided guidance for further investigation. Interviews are commonly found in case study research (Yin, 2014). As CCS viability is essentially determined by human decision making and uncertainty perception, they constitute useful evidence. This study used short case study interviews, normally of no more than one hour in duration. Tone of the interview, presentation, the asking of open ended questions and the choice to record the interviews were all considered as per the strategy considerations suggested by Harvey (2011). An open admission is that I have no prior experience of interviewing, thus with hindsight there are improvements that could have been made in questioning and technique. Probing further and directing respondents towards the research questions may have given more revealing data. One thing that has been recognized is the benefit that could have been derived by increasing the sample size although time considerations were also a constraint due to the large scope of this project.

3.4.2 Interview methodology

The interviewees were all selected due to their corresponding expertise, experience and knowledge of CCS in Norway. These fall into the category of elite or expert interviews, the terms often used interchangeably (Littig, 2009). Some requests for interviews were turned down due to potential interviewees feeling they did not have sufficient understanding of specific CCS systems, whilst some interview requests were met with no response. A total of five interviews were conducted, with the approach taken aimed at a smaller high-quality sample as opposed to conducting many of less practical relevance and low quality. This is not to say that more interviews would not have been preferable, but the difficulty of obtaining high quality interviews as well as the time constraints, have meant that limitations have had to be accepted. Awareness of the subjective nature of information in responses was also considered (Richards, 1996). For the purposes of this study however, which relies in part upon understanding of decision makers perceptions, this can also be uniquely used to an advantage. Whilst it is difficult to make general inferences from subjective responses, all the interviewees are currently or have been influential actors or part of the decision-making process, thus these may also be somewhat representative of how decision makers perceive uncertainty. These interviews served to further understanding, provide suggestions for further research and to gauge expert perspectives on uncertainties surrounding CCS development. Semi-structured interviews were chosen to allow for framework themes to be explored and so as to also best utilise the opportunity for learning based upon the respective expertise, whilst they are also suggested as the most suitable for the approach chosen (Richards, 1996). Yin (2014) suggests interviews should resemble guided conversations as opposed to structured queries. This also allowed them to discuss topics to which they have extensive knowledge, in order to gather the more valuable information.

A conscious decision was made to limit questioning to serve as a guide so as to not direct the interviewees into too specific responses or so as not to influence the results by alluding to or pressing for desired outcomes. Open ended questions were mostly employed, although for specific details it was necessary to add the occasional closed-ended question (Harvey, 2011). The interview guides were tailored to each respondent due to differing expertise and areas of specialist knowledge. There were also concurrent themes and similar lines of questioning in order to address the thesis objective. The framework was also presented to the interviewees towards the end of the interview, not at the beginning so as to not risk bias in response, in order to clarify the research aims and gauge their opinion on CCS uncertainties The interviews were then transcribed from recordings. Transcribing assisted in providing a different context once interviews were presented in a written format, whilst this also allowed for greater reflection of the content. The interviews were then coded into categories, these being categories of responses related to the uncertainties in question. Thus, the theoretical framework was then applied to the data for analysis. For example, responses that mentioned factors related to the economics or finance of CCS, such as costs, were categorized under the key uncertainty of economic and financial viability. Inevitably data is produced that is not in fitting with any of the uncertainty categories specifically, but in the wider context is inclusive of separate elements, which was then used as an indication of an inter-linkages and relationships.

4. Introducing the framework

The framework advocates a mixed methods approach, and this is employed in almost all of the uncertainty assessments. Systematic assessments of this nature, designed to enhance decision-making, require mixed methods in order to analyse different aspects for a holistic overview (Blaikie, 2009). Overall the approach can be mostly viewed as triangulation in concurrent use of both quantitative and qualitative data to draw conclusions, however the process may at times also reflect an embedded approach as one method of analysis may be chosen for an individual indicator that requires supplementation via alternative use in another.

Making generalisations from qualitative data can be challenging (Ritchie & Lewis, 2003), but the limited reliability of, and sometimes absent, quantitative data for CCS in many aspects means this is sometimes a necessity as opposed to a methodological preference. For example the absence of reliable cost data has resulted in many CCS studies having to rely almost solely on inferences from cost trends in other technologies (Markusson, Kern, et al., 2012). There is also little social science literature directly concerned with innovation and technological development on general CCS (Markusson & Chalmers, 2013), the field of which again narrows when considering that which is solely focused towards Norway. Thus for such a broad holistic analysis, limited to the scope of a master's thesis, this makes data collection challenging in many respects due to a small pool of research for which to draw guidance and secondary data, thereby some limitations and inconsistencies in the quality of the data have to be accepted. Whilst balance has been a consideration, even the number of indicators differs between uncertainties, thus the framework itself could be considered to lend itself to closer examination of certain aspects than opposed to others.

The assessment framework was designed by identifying key uncertainties regarding CCS development and deployment up until 2030. Insights from social science literature on CCS via a literature review, input from an interdisciplinary project group (geology, engineering, legal and financial expertise) and consultation with CCS stakeholders (Markusson et al., 2011, p. 5746). Thus, the authors were able to identify the uncertainties and suggest methods for assessment. The important uncertainties are listed as follows:

1) Variety of CCS pathways
2) Safe Storage
3) Scaling up and speed of development and deployment
4) Integration of CCS systems
5) Economic and financial viability
6) Policy, political and regulatory uncertainty
7) Public acceptance

Table 1 provides the indicators that can be used for assessment of the uncertainties. These were validated by the authors via literature and document reviews, stakeholder interviews and an inter-disciplinary research team. These interlinkages are important considerations, as any efforts to reduce a particular uncertainty can have consequential effects upon others, thus the complexity surrounding CCS means that they represent the interdependent and dynamic nature of the uncertainties (Markusson, Kern, et al., 2012, p. 911).

Table 1
Indicators and methods for assessing the uncertainties.

Key uncertainties	Indicators
1. 'Variety of pathways' The diversity of technological options represents an uncertainty for investors and policy makers. Early selection might accelerate development, but risks locking in weak technologies.	– Number of technology variants – Relative importance of variants for technology developers – Market share of technology variants – Extent of lock-in/dominance of particular technology variant
2 'Safe storage' There is uncertainty as to whether geological storage of CO_2 will prove safe over long time periods, as well as if and how the associated risks can be reliably assessed and managed.	– Availability of storage site data, including agreed robust estimates of their capacity – Nature of legal/regulatory framework to share risks/liabilities – Levels of public awareness/acceptance of risks
3. 'Scaling up and speed of development and deployment' There is uncertainty about whether and how fast CCS technologies can be scaled up and developed to maturity.	– Unit size, capacity and efficiency – Speed of unit scaling – Cumulative investment/installed capacity
4. 'Integration of CCS systems' It is unclear how CCS systems will be integrated. Integration is a technical challenge, as well as an issue of organisation and governance.	– Whether full chain integration has been achieved? – The allocation of responsibility for integration – Presence, role and importance of 'system integrator' firms/actors – Nature of development, including roles of key actors and the relative importance of 'bottom up'/emergent and 'top down'/directed development
5. 'Economic and financial viability' The future cost and financial risk of implementing CCS are very uncertain. The economic and financial uncertainty is heavily dependent on policy.	– Costs, including assessment of quality of cost data – Key financial risks and 'financeability' – Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 6)
6. 'Policy, political and regulatory uncertainty' CCS development is strongly influenced by uncertainties as to political support, as well as the choice and design of policies and regulations.	– Nature of legal/regulatory framework to share risks/liabilities – Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 5) – Role of other forms of policy support – Extent of political commitment/legitimacy
7. 'Public acceptance' Public acceptance may be crucial to CCS development, but is uncertain. Attitudes to CCS are shaped in social interaction.	– Levels of public awareness/acceptance of risks – Specific manifestation of public opposition (or support)

Table 1: Indicators and methods for assessing the uncertainties from Markusson, Kern, et al. (2012, p. 912)

In the following section the key uncertainties shall be presented in the order corresponding to that presented in Table 1 above. This should serve to explain the uncertainties as developed by Markusson, Kern, et al. (2012), with additional support from the wider CCS literature. The indicators for assessing the uncertainties can then be explained as to how they can be applied methodologically and interpreted for assessment of CCS viability in Norway. Thus, this section will present the indicators corresponding with some theoretical considerations and data sources where relevant.

4.1 Uncertainty 1: Variety of Pathways

With regards to uncertainty 1, variety of pathways, this is necessary to explore as competition amongst technology variants leaves uncertainty as to which technologies may win out long term. This leaves decisions about which technologies to back as well as the degree of political and economic support to provide (Markusson, Kern, et al., 2012, p. 907).

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Number of technology variants
- Relative importance of variants for technology developers
- Market share of technology variants
- Extent of lock in/dominance of particular technology variant

The number of variants, as well as their prominence, may be useful indicators to help with an assessment of this uncertainty. Although the number of variants would seem indicative of a quantitative approach, a more qualitative approach shall be employed, as a mere listing exercise would only clarify as to if there are many options or not. The more options available to investors and policy makers, perhaps the more likely they are to divert efforts towards alternatives or even, for want of a better analogy, practice a form of spread betting as it were. Focus, support and funding may all be diverted elsewhere or spread amongst variants. There is also evidence from the innovation systems tradition that significant value can be attributed to variety and experimentation at the early developmental stage (Markusson, Kern, et al., 2012, p. 907). It also leaves the question as to what the best application for CCS in Norway actually is and how this might be considered. The relative importance of variants for developers should also provide indication of which CCS technological applications are prioritised and incentivise development.

In the context of Norwegian CCS development, it will be worth consideration of these factors as CCS with the technology viewed as having hampered opportunities for renewables (Espen Moe, 2010). There are both positive and negative aspects associated with variety (Patel & Pavitt, 1997). On the one hand many options can divide resources and focus, perhaps generating conflict and stalling the emergence of the most optimal technology. In other words, variety can reduce economic performance by preventing the benefits of economies of scale. On the other hand, this can create a heathy and competitive market that ensures decision makers hands are not forced due to lack of alternatives and reduces the risk of lock-in to weaker technologies. The benefits from a process of learning from diversity (Menanteau, 2000). Prior projects and historical pathways surrounding CCS in Norway can provide evidence for which pathways are more prevalent or how uncertainty may have influenced the trajectory. Extent of lock-in/dominance for a particular variant will also be of significance. The authors refer to the possibility that policy may select a winner at an early stage, locking it in to a weaker variant and thus an inferior path dependency (Markusson, Kern, et al., 2012, p. 907). Markusson & Haszeldine describe lock-in as being *"caused by positive feedbacks among different elements of a socio-technical system, as well as resistance to the introduction of new technology from institutional interests."* (Markusson & Haszeldine, 2009, p. 4626).

Early selection could lock CCS into inferior technologies and leave actors stranded with uncompetitive assets (Markusson et al., 2011). Circumstances of increasing returns, or lower cost per unit, may determine a technological path that is neither most efficient nor predictable, however, it is worth noting that power generation technologies show eventual diminishing returns, or higher costs per unit (Arthur, 1983). Technology variants with a large market share are more likely to be more mature, more prominent and attract greater investment. Increased adoption brings accumulated experience and knowledge that makes technology more effective over time (Rosenberg, 1982) whilst the price reductions in solar photovoltaics, or Swanson´s law as it is now commonly referred to, showcases the effect a learning curve can have on costs (Swanson, 2006).

4.2 Uncertainty 2: Safe Storage

Storage risk has been a prominent feature in CCS research. Questions surrounding as to whether carbon dioxide may leak out of storage sites, thus posing a local risk to human health and the environment, as well as on a global scale via re-entering the atmosphere and jeopardising climate change goals (Markusson, Kern, et al., 2012, p. 907). Many state that concerns over leakage and the long-term effects of geological storage are also yet to be fully resolved (Johansson, Patwardhan, Nakićenović, & Gomez-Echeverri, 2012; Queirós et al., 2014; Widdicombe, Blackford, & Spicer, 2013), and such concerns are highly disputed (Boyd et al., 2013; Ha-Duong & Loisel, 2009; Juanes, Hager, & Herzog, 2012; van der Zwaan & Gerlagh, 2009). The IEA seems in little doubt however, heralding Sleipner as a *"major technology milestone that confirms the feasibility of safe, permanent storage of* CO_2 *in deep saline formations"* (IEA, 2016, p. 13). Questions remain as to long-term viability of storage sites (Thomas & Benson, 2015). Knowledge over the environmental costs of potential damage and potential response caused by leakage is also seemingly a grey area which would benefit from further clarity (Lee & Choi, 2018), such as potential harmful effects on marine ecosystems (Rastelli et al., 2016) and vegetation (Al-Traboulsi et al., 2012).

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Availability of storage site data, including agreed robust estimates of their capacity
- Nature of legal/regulatory framework to share risk/liabilities
- Levels of public awareness/acceptance of risks

Here we can look at these indicators as to what the data shows with regards to Norway. In addition, it would be prudent to also look towards current data related to risk. Whilst it may be somewhat of a rough assessment, establishing a least a generalised picture of the likelihood of CO_2 leakage in current and potential CCS projects is beneficial in this regard. Storage site data and capacity estimates should provide some quantitative measures for analysis, whilst qualitative examination via document analysis and review of research based on public acceptance and legal/regulatory frameworks will also be employed to give a robust overview.

The nature of legal/regulatory frameworks for sharing risks/liabilities can also be used for indication. Strong regulation that is favourable to CCS implementation whilst balancing liability can also help pave the way for development due to helping enhance the attractiveness to both investors and decision makers. Firms may be reluctant to absorb all liability for risk, whilst the state will want regulation to help ensure sufficient safeguards against complacency and negligence. Stable regulation that is unlikely to see major alterations also helps to provide a better platform for investment decisions regarding project feasibility. There is also arguably a need for regulation that can overcome cross-border activity and harmonise aspects of the CCS value chain (R. J. Heffron et al., 2018).

The lens in which this is perceived is also crucial for determining acceptability. One could view this through the lens of economics and climatics as to whether it is based on acceptable levels of CO_2 leakage to still make CCS a viable climate mitigation tool (van der Zwaan & Smekens, 2009) and an economically viable mitigation option (van der Zwaan & Gerlagh, 2009), through the lens of political and sociological aspects such as transportation (Kjärstad, Skagestad, Eldrup, & Johnsson, 2016) and health risks (Fogarty & McCally, 2010) or additionally engineering and legal aspects for regulation and monitoring (Stenhouse, Gale, & Zhou, 2009).

Public perceptions regarding risk and safety are also factors to take into consideration. Concerns amongst the public can lead to backlash and even rejection of new technologies (Gupta, Fischer, & Frewer, 2012). There is some evidence to suggest that Norwegians are less adverse to opposing CCS on grounds of storage concerns in comparison with other countries (EASAC, 2013; Karimi & Toikka, 2018). If decision makers are uncertain about public reaction to CCS projects, then they may be hesitant to proceed and lend support to projects that could place its implementation in jeopardy or damage the reputation of CCS technology.

4.3 Uncertainty 3: Scaling up and speed of development and deployment

Questions can also be asked as to how quickly CCS technology can be scaled up and developed, as well as retrofitting to projects with suitability for CCS implementation. Implementation and the number of projects required varies dependent upon application and capacity, as well as the efficiency and longevity of selected projects. Due to the ever-decreasing window of opportunity for meeting climate targets, speed is a necessary consideration. The lifespan of current and potential CCS projects is also a consideration for both investment decisions and policy implementation. The pace of CCS development may also influence development amongst other climate mitigation technologies or fossil fuel dependent industries and energy production.

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Unit size, capacity and efficiency
- Speed of unit scaling
- Cumulative investment/installed capacity

Unit size, capacity and efficiency can give indications of current maturity as well as set a benchmark for comparative progress when contrasted with a prior snapshot of previous project capacity. Developments outside of Norway also have a bearing upon this overarching uncertainty of scaling and speed due to learning and spill-over effects, as well as historical analogues providing a reference for technological pathway trajectories. The efficiency of CCS projects can also indicate technological maturity to assess development and scaling possibilities. Changes in unit size, capacity and efficiency can all indicate progression (or even perhaps regression) for technological development. Thus, we can look at current capacity of existing CCS projects in Norway, potential capacity of those proposed/in development and what bearing existing projects have had on wider CCS development domestically.

The uncertainty surrounding the speed of CCS development can also prove a barrier towards wider diffusion of the technology. There is something to be said for the benefits derived from a learning by doing process with regards to new technologies, which can be in the form of cost reductions (Söderholm & Sundqvist, 2007), spillover effects (Irwin & Klenow, 1994) or earlier deployment. The industry as a whole can learn lessons from project implementation. In this regard, developers may be reluctant to be the first mover or may be more inclined to withhold investment until a period in time at which they are more likely to benefit. There is also the question of the environmental value of CCS for Norwegian policymakers, in that the argument could be made that Norway has significantly lower domestic emissions than many of the other countries currently investing in CCS technology, thus has less developmental responsibility. Of course, this can also be determined by the choice of lens and as to whether one looks to emissions on a per capita basis or in a direct comparative perspective.

Cumulative investment/installed capacity is yet another indicator to assist with assessment, however, due to the limited portfolio of CCS projects and difficulties in obtaining investment data from private actors, this indicator will not be examined in isolation. Whereas this would certainly add value to this study, public investment is explored under uncertainty 6 and some of the established cost data outlined under uncertainty 5. Making any suggested estimation of cumulative investment whilst being unable to verify this would be misinformative. The greater the capacity of accumulated CCS, the more entrenched the technology can become, whilst attracting greater support as its feasibility is recognised and as uncertainties reveal themselves, with barriers being gradually diminished or overcome entirely. The lack of data due to a limited number of projects is perhaps indicative in itself of uncertainty, due to many project proposals and feasibility assessments often reliant on accumulated knowledge for guidance and projections.

4.4 Uncertainty 4: Integration of CCS systems

Uncertainty can hamper governance and the integration/diffusion of new technologies. In the context of CCS this entails integrating various competencies, components, processes and operations into working CCS systems. Integration is normally understood as retrofitting the system to complement existing technologies and processes, such as to a power plant or industrial facility (Bielicki, 2009), but here it will also be used to describe diffusion of the technology in more general terms. For purposes of this thesis, integration will be viewed as coupling CO_2 capture, storage and transportation technologies into an overall working system. Enhanced integration can reduce costs and improve efficiency whilst integration between the host plant, transportation, storage facility and other elements can enhance the business case and reduce uncertainty for both private and public actors (*CCS System Integration Workshop*, 2012). The complexity of governance is compounded by the inherent complexity of the activities involved. The IEA has previously stated that the *"largest challenge for CCS deployment is the integration of component technologies into large-scale demonstration projects"* (IEA, 2013, p. 5).

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Whether full chain integration has been achieved?
- The allocation of responsibility for integration
- Presence, role and importance of "system integrator" firms/actors
- Nature of development, including roles of key actors and relative importance of top down/directed vs bottom up/emergent development

Integration of CCS systems is complex due to incorporation of the technology into a larger chain of interconnected systems and larger networks. CCS integration is likely to be a much more straightforward process whereby existing infrastructure, expertise and industry is positively disposed towards CCS implementation. In accordance with transitions literature, socio-technical regimes are comprised of social groups such as scientists, users, policy makers and special interest groups. The rules of socio-technical regimes account for the stability and lock-in of socio-technical systems (Grin et al., 2010, p. 20). Collaboration is required, as well as effective organisation and governance. Coordination at both the system level and component levels may differ, and factors such as market orientation, centralisation, fragmentation and participation may also affect coordination models (Markusson et al., 2011, p. 5747).

Achieving full chain integration indicates that many obstacles are likely to have been overcome. As systems develop, mutually supportive sets of inter-related elements develop in tandem whilst in socio-technical systems, other elements such as business models or safety regulations are also incorporated (Markusson & Haszeldine, 2009, p. 4626). If existing technological systems are resistant to change and re-alignment, then new technologies may suffer as a result and struggle to develop regardless of performance capabilities. The further advanced and synchronised the CCS chain, the increased likelihood that effective cooperation, competencies and technical aspects are developed. On the contrary, without full chain integration the probability of viability diminishes due to negative impacts upon factors such as learning and costs amongst others.

The allocation of responsibility for integration is another suggested indicator. This can give an indication as to whether a prominent and significant actor, best suited towards CCS integration and implementation, is given corresponding responsibility. A look towards which actors have a prominent role in CCS systems integration, as well as who is responsible for management and what this responsibility entails, should assist with such an assessment. Whilst the framework does not distinguish between a key actor and a system integrator actor, the chosen distinction for purposes of this thesis is that key actors may be those with the ability to influence CCS development trajectories as opposed to system integrators having the ability to directly participate in integration itself. For example, politicians are key actors, but it is Gassnova who is tasked with responsibility for integration. Norwegian CCS cases can help outline as to exactly how integration has previously been managed, the prominence of the actors involved, as well as highlight the particular obstacles and uncertainties that have been encountered previously. Looking at coordination and governance, as well as heterogeneity of actors, can all provide aspects for use in the assessment. The prospective Full-scale project also provides indications for how integration is currently being planned in Norway. Seeing how CCS has been largely utilised in complementing existing infrastructure and recovery operations, such as with the Snøhvit CCS project or TCM Mongstad, will also shed light on this uncertainty.

The presence, role and importance of "system integrator" firms/actors are another gauge suitable for assessment. Technological development and integration require novel resource combinations and actors. As outlined by Cantù, Corsaro, and Snehota (2012), this is in part due to actors having control over resources, but also due to the required combination of resources being scattered and controlled by different actors. Resource combinations are therefore needed for complex solutions. The final indicator regarding integration of CCS systems is that of the nature of development, including the roles of key actors and relative importance of bottom-up emergent and top-down directed development. Top-down management mechanisms have increasingly been questioned with regards to their effectiveness in generating sustainable solutions (Grin et al., 2010).

4.5 Uncertainty 5: Economic and financial viability

Economic and financial viability is a crucial determinate for decision makers when assessing CCS project feasibility. The economic considerations of CCS are important in impacting the subsequent diffusion of the technology (Lohwasser & Madlener, 2012). Economic viability is related to a cost-benefit outlook but, even in instances where this is positive, its financial viability may be less when considering investment in other options. They are not mutually exclusive. Willingness to invest must be present and therefore uncertainty that clouds such decision making is a hinderance for CCS deployment, as companies will be reluctant to invest if the economic risks are too great (de Coninck et al., 2009). Enhancing economic and financial viability should therefore be an important consideration for policymakers. Irlam (2017, p. 2) states that the reporting of CCS funding implicitly presumes poor value for money, even though analysis repeatedly finds that the deployment of CCS would actually avoid significant costs in achieving emission reduction targets. Helle and Koefoed (2018) see cost as the main barrier for CCS deployment.

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Costs, including assessment of quality of cost data
- Key financial risks and ´financeability`
- Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 6)

The fact that there is very limited commercial CCS makes it very difficult to obtain data and make sound cost estimates, and indeed, it has been suggested that due to such uncertainty it is merely speculative and counterproductive to do so (Nauclér, Campbell, & Ruijs, 2008). There are also differences in how major decision makers make cost estimations for CCS technology (E. S. Rubin, 2012). Markusson and Chalmers (2013) list some key problems with the need for immediate cost assessments in light of weak and substantiated data. These are: 1) limited number of sources contributing to limited supply of data due to CCS being at an early stage,

2) multiple cost metrics and different approaches, combined with scarcity of data, making comparative assessments difficult, 3) different measures for estimating the same costs and what costs to include limits comparability, 4) good data being hard to access to due corporate confidentiality, 5) comparability being constrained by variation across time and space, and finally 6) lack of estimates regarding the uncertainty in the data itself. Thus, they advocate for more qualitative analyses to support such assessments. Ideally a full life-cycle cost that accounts for social, environmental, economic and political benefits is optimal to maximise its socioeconomic utility (Karayannis, Charalampides, & Lakioti, 2014). Irlam (2017, p. 7) cites Gorgon, Sleipner and Snøhvit, as suggesting that carefully targeted penalties or licencing conditions relating to emissions can contribute to overcoming the cost of CCS as opposed to large public subsidies, believing the perception of high cost stemming from estimates for the power sector and inappropriate comparison to renewables (Irlam, 2017, p. 10). A major issue is that CCS is not seemingly high on the list of investment priorities (Fridahl, 2017). Overall financial risk and financeability is compounded by such difficulties and uncertainties.

Valuation of carbon is also an important incentive for emissions reductions. Weak carbon pricing has been criticised as threatening CCS deployment in the EU (Renner, 2014), whilst a ack of carbon pricing has been cited as reason for a lack of acceleration in CCS implementation globally (Celia, 2017). Policy options include, but are not limited to, carbon taxes, emissions trading, tax credits and feed-in schemes (fixed fee to compensate for the high costs compared to conventional alternatives) and minimum standards (requirement for CCS on future installations) (Budinis et al., 2018). The logic is that a carbon price would incentivise operators and investors to implement CCS or otherwise face paying for emitted CO_2. In addition, with a high enough CO_2 price, it can become more profitable to run a plant with CCS than a plant without. A price on carbon can help avoid investment uncertainties and policy inconsistencies (Budinis et al., 2018). Markusson, Kern, et al. (2012) state that they foresee carbon pricing as an important element for CCS viability, but that it has thus far been too low and volatile to justify CCS investment. A look towards pricing mechanisms such as the EU Emissions Trading Scheme (ETS) and Norwegian carbon tax will provide useful context for analysis and as to what implications this has for uncertainty,

4.6 Uncertainty 6: Policy, political and regulatory uncertainty

Many view lack of adequate policy to be a fundamental obstacle that has hindered the development CCS (Bäckstrand et al., 2011; Global CCS Institute, 2018a; IEA, 2016; Lipponen et al., 2017). Lipponen et al. (2017) describe support for CCS as inconsistent and tumultuous, thus concluding that CCS will not advance without significant public investment and required support policies. The policy and political issues surrounding CCS are likely to have major role determining the road ahead (J. R. Meadowcroft & Langhelle, 2009).

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- the nature of legal/regulatory framework to share risks/liabilities
- Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 5)
- Role of other forms of policy support
- Extent of political commitment/legitimacy

Political support is one of the key determinants in facilitating CCS development. The International Energy Agency (IEA) describes CCS as proven technology, attributing its slow deployment as being explicitly due to a lack of policy support (IEA, 2016, p. 13). The Global CCS institute (GCCSI) also states that it is policy confidence that is needed to sustain investment (Global CCS Institute, 2018a). CCS is now of key focus and subject to increasing recognition in international climate policy and mitigation strategies (Bäckstrand et al., 2011). The significant potential and substantial contribution of CCS in meeting climate mitigation targets cannot be understated (R. S. Haszeldine, Flude, Johnson, & Scott, 2018; Mac Dowell et al., 2017). However, many do not see parallels between its increased recognition as a necessary climate mitigation tool and such representation being reflected in political and policy support (Lipponen et al., 2017). CCS, as with other technologies that are related to energy and climate change, has inevitably become entangled in political and policy arguments of great complexity and convoluted in their framing (J. R. Meadowcroft & Langhelle, 2009).

CCS deployment is said to be lagging behind expectations due to institutional inertia and poor temporal fit (Karimi, 2017). Integrated policy architecture, with multiple policy phases and economic instruments, is therefore necessary to support development and facilitate full-scale deployment (Krahé, Heidug, Ward, & Smale, 2013). Directing policy at identifiable weaknesses, whilst developing a coherent and long-term policy strategy, can enhance and accelerate CCS deployment and implementation (van Alphen, Hekkert, & Turkenburg, 2009). Watson, Kern, and Markusson (2014) state that CCS deployment is shaped by policy due to both its climate policy rationale and reasoning there would be little commercial interest without strong policy drivers. Other lessons they state can be learned from prior efforts is that the choice of policy instruments and market structure are also likely to be influential, whilst too much flexibility in policy making can result in increased uncertainty.

The strength of the legal/regulatory framework to deal with risks and liabilities are important indicators. If there is insufficient clarity within the framework to deal with liability, or if the framework places a burden upon developers which increases investment risk or complexity, this can inhibit CCS development (Haan-Kamminga, Roggenkamp, & Woerdman, 2010; Reins, 2018). Clarity is a fundamental principle for legislation, as ambiguity or vagueness can jeopardise the legal and political function of the law (Wagner & Cacciaguidi-Fahy, 2008). Here we can look to analyse findings from within the research surrounding frameworks that are designed to regulate CCS risk and liability within Norway, whilst also looking at comparative development and the strength of such frameworks in contrast to other nations who also harbour strong CCS interests.

With regards to economic and financial support government R&D expenditure will be a useful indicator for analysis, with a case to be made that perhaps high R&D expenditure is indicative of wider support to see CCS development realised (Tjernshaugen, 2008). It is, however, worth bearing in mind that some would suggest subsidies alone are perhaps not the most cost effective methods in meeting mitigation targets and only play a limited role in promoting R&D for non-carbon technologies (Duan, Fan, & Zhu, 2013). Political will is hard to quantify, however economic and financial support is perhaps one of the clearest indications. Strong political commitment helps to cement CCS on the state agenda, whilst providing influential supporters of CCS a platform. It imbues investors and operations with greater confidence that political will is unlikely to dissipate in the near future. Whilst R&D investments do not guarantee innovation (Mytelka & Smith, 2002), they can certainly help incentivise investment and ensure that the financial risk in developing CCS technology is more evenly distributed as opposed to solely on the operator. Espen Moe (2012) states that amongst high-income countries, when looked at in relation to GDP, Norway has substantially the highest funding for CCS.

Exploring Norwegian R&D expenditure and finance for CCS can give us a quantitative data for which to assess political commitment, which is can be analysed through qualitative methods. Hereby this should provide an insight into these two aforementioned indicators in combination with what we have explored in uncertainty 5 with regards to carbon taxes and other forms of policy support. The extent of political commitment/legitimacy provides yet another indicator for evaluation. There is evidence to suggest CCS has benefited from greater political support in Norway than in other countries (Tjernshaugen, 2008) and exploring this will be a useful method for uncertainty assessment. It should also help give us a means by which we can view trends to show as to whether this is growing or diminishing. Policy network structure is also significant in strengthening political commitment, as well as relations with state actors and strategically important players, as is evidenced by Norwegian CCS development (H. E. Normann, 2017).

Assessing uncertainty surrounding these political and policy factors can be a crucial determinant for CCS viability as the future deployment will depend on explicit political and policy choices (Markusson et al., 2011). Policy making is very seldom straightforward, and any policy enacted with the purpose of promoting CCS can have multifaceted and unintended consequences, thus it must be carefully considered (Watson et al., 2014). Yet again it can be emphasised as to the benefits of unclouding and assessing uncertainty, in that it can assist policymakers in making better informed decisions. These benefits are then transferred to the private sector by providing stability and a platform for technological development whist simultaneously inspiring confidence amongst operators and investors.

4.7 Uncertainty 7: Public acceptance

Public acceptance is recognised as an important factor for successful diffusion of new technologies (Huijts, Molin, & Steg, 2012; Schweizer-Ries, 2008; Wüstenhagen, Wolsink, & Bürer, 2007). Indeed, societal controversies have also led to public backlash and rejection in the past (Gupta et al., 2012). Whilst some would disagree or seek to downplay its significance, there are many historical examples where negative public perceptions have resulted in rejection or stalled adoption of technologies. For example Germany, a country with long standing anti-nuclear sentiment, began phasing out its nuclear power plants in the wake of the accident at the Fukushima Daiichi Nuclear Power Station (Glaser, 2012). Whilst it is arguable as to the degree of influence public acceptance has upon technology diffusion, it is certainly not to be dismissed. Public acceptance is seen by many as one of the main challenges CCS must overcome in order to direct favourable political attitudes in the future (Wennersten, Sun, & Li, 2015).

Indicators as per table 1. (Markusson, Kern, et al., 2012):

- Levels of public awareness/acceptance of risks
- Specific manifestation of public opposition (or support)

In light of this, uncertainty over public acceptability can have negative consequences on technological development for numerous reasons. Negative perceptions of a technology may make policy makers reluctant to support its development due to public backlash and could also make companies more reluctant to invest should it jeopardise feasibility or negatively impact upon their public image. Knowledge that the public is accepting of CCS technology, whilst also having confidence that public understanding is sufficient so as to lessen the likelihood that there will be a negative backlash with wider deployment, thus makes development a more attractive option.

There has previously been much research orientated towards informing the public about CCS, whereas information is only one element of the vast array of factors that influences perceptions of CCS (Vercelli et al., 2013). Ensuring the objectivity of content presented is also a consideration in this regard and the sources used for presentation to participants. A question of interest, but beyond the scope of this thesis, would be to view not only public awareness of CCS but also to establish where the public has derived its information with regards to those individuals having already heard of CCS technology. Vercelli et al. (2013, p. 2) summarises findings for framing effects within the literature, emphasising that framing is evident of influencing public views on the technology alongside audience characteristics. It is a useful exercise to bear in mind and acknowledge the extent to which these results can truly represent a consensus view and how they may be subject to change in light of heightened awareness.

Public engagement with CCS is significant for numerous reasons. From reasons of democratic governance in considering public views to improving the quality of decision making by embracing diverse knowledge and fostering trust in experts and developers (Whitmarsh et al., 2019). Awareness of social perceptions can bring additional dimensions to planning and implementation of CCS technologies (Aursland & Jordal, 2018). Few studies actually provide a definition for what is meant by the term acceptance, however this can be attributed to its self-explanatory use in everyday language (Schumann, 2015, p. 222). Schumann (2015, p. 223) defines public acceptance of CCS as *"passive or active approval of the development, the large-scale demonstration or the implementation of CCS technologies, which is reflected in the attitudes and behaviour of individual or complex social actors, and which can be measured at a certain point in time".*

Measuring public acceptance is not necessarily straightforward, especially as it is hard to encapsulate knowledge and views of entire populations in small scale samples. CCS is also a relatively technical and "remote" subject for many (Metz et al., 2005). CCS technology is also not widely deployed, and in many cases not well understood, thus it can be hard to foresee quite how the public will react to scaling up or projects that may be in close proximity to communities previously unexposed to CCS technology and storage. An examination of the literature on public acceptance of CCS technology, particularly research focused on public acceptability in Norway, should help give an indication of the levels of acceptance and risks. We can also look towards public reactions towards existing and future CCS projects, and thus see just as to how public opposition to CCS manifests itself in Norway.

4.8 Inter-linkages between uncertainties

None of the uncertainties exist in isolation. The relationships between the uncertainties are numerous, dynamic and interdependent. An overall alteration in one key uncertainty will affect overall CCS viability and requires consideration outside of itself, for such alterations will have ramifications that can transmit between the separate aspects. Such relationships can be better understood via the identification of inter-linkages, which help identify interactions, trade-offs and potential reverberations through the overall construct. 11 are presented by Markusson, Kern, et al. (2012) as having been identified via their analysis, however undoubtedly many more exist and could be considered. It also prudent to mention that case specific interlinkages may occur, whilst they are likely to multiply under greater scrutiny and could be further broken apart should a method analysis choose to do so. Therein it is not possible within the scope of this thesis to make holistic assessments of all the key uncertainties and inter-linkages additionally. Therefore, the first major step in assessing CCS viability shall be taken, in assessment of key uncertainties. This provides the basis for suggested further research, which is more thorough identification and examination of inter-linkages based upon uncertainty assessment. What is possible is to acknowledge the uncertainties and provide brief considerations for what they entail and how they could be considered in light of this research. An assessment of CCS viability would also be wholly inadequate without some form of consideration for these so, whilst a conclusion shall be reached based upon the findings, it is certainly not suggested to be conclusive. Further research into assessing these linter-linkages is the most evident area to bolster the overarching objective.

5. Assessing key CCS uncertainties in Norway:

In this section the empirical findings will be presented in accordance to the framework, whilst any deviations from this will be made clear. Before continuing it is also prudent to mention that, where the framework is more ambiguous as to what examination of the indicators precisely entails, the best effort has been made to interpret this in a manner fitting the overall assessment of the uncertainty in question whilst accounting for availability and clarity of data.

5.1 Uncertainty 1: Variety of pathways

Uncertainty as to which technology will prevail, and as to when exactly this will occur, proves problematic for actor’s decision making. Examination of this uncertainty in Norway can provide indications of current pathway selection and potential barriers towards diffusion of CCS technology.

5.1.1 Number of technology variants

Here a brief insight will be given into technological variants available to decision makers, which is assumed to focus on technological variants for CCS application and not technological variants in the wider context of zero emissions technologies. Providing a comprehensive list of all variants is not the objective here, as this would be a rather futile task for purposes of assessment. We need know if the options are numerous or not, as opposed to an exact number. There are a number of diverse technological options for CCS application in Norway within each component of the CCS chain. Post-combustion capture (using amines or ammonia), pre-combustion capture or oxy-fuel combustion are considered the main three groups for CO_2 capture that are considered mature with regards to full-scale implementation.

There are also possibilities for chemical looping combustion, solid oxide fuel cells and hydrogen membrane reactors. The Norwegian Institute for Energy Technology (IFE) has been involved in the Zero Emission Gas Power Project (ZEG), looking at combined power and hydrogen with carbon capture (Berge et al., ´n.d.´, p. 23).

There is then the choice as to whether to develop CCS for application with the power generation industry or for industrial processes. For example, within industry a multitude of options are presented such as cement, iron and steel, ammonia, pulp, oil and gas processing as well as bio CCS (BECCS) and carbon capture and utilisation (CCUS). To take one case illustration, Yara produces over 200,000 tonnes of CO_2 for use in the food-grade industry from ammonia (Berge et al., ´n.d.´, p. 26). CO_2 can also be used for enhanced oil recovery (EOR), beverage carbonation, wine making, food processing and packaging as well as pharmaceutical processes to list but a few examples. How best to transport the CO_2 also comes into question, such as via ship or pipeline, and as where best to store CO_2 with regards to the options available. This is certainly not an exhaustive list by any means, yet it helps to illustrate the variety and complexity of CCS options for actors, as well as highlighting the vast potential of the technology. This diversity can thus fuel uncertainty for investors and policy makers as to which options to support, develop and as to the scale of the portfolio and number of variants to explore. There can be a risk of locking into a technology option that eventually may prove redundant in terms of efficiency, cost and performance.

5.1.2 Relative importance of technology variants for technology developers

Norwegian large-scale CCS projects have until now been developed for application with natural gas. Statoil was already removing CO_2 from the natural gas at Sleipner due to its high CO_2 content of up to 9.5%, which requires reductions to 2.5% due to commercial specifications (R. Andrew Chadwick & Noy, 2015, p. 306). At Snøhvit, gas contains up to 8% CO_2 and is then treated for conversion into LNG, with the CO_2 captured in this process then compressed into a liquid state and transported back to the injection site ("Snøhvit," ´n.d.´). This “gas sweetening” is currently the most cost effective application for CCS in Norway (Mazzetti et al., 2014). Thus, the importance of pre-combustion capture for CCS for developers on the Norwegian Continental Shelf is evident, not least for commercial purposes in light of the domestic tax on emissions. The Norwegian oil and gas industry is very focused towards making production more sustainable whilst this rhetoric is also heavily prevalent in

Norway's wider climate policy (Ihlen, 2009; Jo-Kristian S. Røttereng, 2018). CCS can be seen as a way to balance two seemingly contradictory agendas of national energy interests and CO_2 mitigation (Jo-Kristian S. Røttereng, 2014), therefore it is not so surprising that this is the first development for large-scale CCS in Norway. With regards to power generation, and in light of Norway´s domestic energy supply being almost completely renewable, there would seemingly be less importance placed upon post-combustion capture.

The now abandoned proposals for full-scale CCS at Halten, Kårstø and Mongstad sites would have all been for post-combustion application to gas-fired power plants. These proposals came in the wake of a 2005 parliamentary vote in favour of investment in natural gas infrastructure and a decision that the retrofitting of the Kårstø power plant would be undertaken with public funding (H. E. Normann, 2017). The Halten project could be viewed in the context of differing social and private valuations for CCS development, thus public actors may place greater importance on technology variants with a high social value in contrast to the private interest often placing greater value towards profitability (Torvanger, 2007). With all three projects there were numerous uncertainties, but there is a common link between all three cancelled projects, in that all were post-combustion for gas-fired power generation. This may therefore indicate that the relative importance of this particular CCS application may have been less important for the developers involved, as opposed to its importance for the political goals of the Norwegian State (Gassnova being the state established developer to represent the public interest). The push for CCS in application with gas-fired power was more conceived as a political compromise but resulted in little incentive for industrial actors to develop the technology and bear costs (Tjernshaugen & Langhelle, 2009).

Pre-combustion may itself be more attractive to private actors in Norway for economic reasons. One of the informants outlined that traditionally the focus has been on post combustion at the user site, which has never really succeeded. The reason is probably due to this being a very complex solution, which requires the user to invest large amounts of money into capture plants on top of what is potentially a stranded asset. Thus, whilst fully supporting the Full-scale project, Equinor sees pre-combustion CCS as an easier concept to commercialise, as it is more feasible and simpler (interview with Eikaas, 2019). The upcoming Full-scale project is again another attempt at post-combustion, with support from private actors including Equinor but, being another state driven project, this is perhaps indicative of post-combustion to be a more favorable technology for the government's objectives than for those of private actors at present.

One could postulate that, if international climate commitments were to become more constraining in the future, this could result in a greater drive for CCS development from both public and private actors in order to secure the value of petroleum resources so that untapped fossil fuel reserves are not left as stranded assets. Therefore, the relative importance of CCS technology for future EOR, refining and post-combustion may be of heightened concern for developers in Norway even if such activities do take place within Norwegian borders. Developing the technology domestically in order to help diffusion for cross-border projects and for mitigation of CO_2 emissions downstream may also incentivise development and heighten the importance of CCS options. Yet this can generate uncertainty, as investing in a capital-intensive technology in order to safeguard against future unknowns and potential constraints is a technological and financial risk. According to Røkke (2012) there are four perspectives that contribute to CCS reasoning in Norway: The power perspective (domestic power generation), the industrial perspective (developing technology that can be exported), the "do good" perspective (moral obligation) and the "licence to operate" perspective (securing the value of petroleum resources).

5.1.3 Market share of technology variants

As previously mentioned, with so few operational projects, it seems of little use to try and map the market share of CCS technology options in Norway. The two currently operational large-scale facilities of Sleipner and Snøhvit are both for application with gas sweetening, as has been discussed, so within the context of large-scale CCS facilities they currently occupy the entire market. The other way in which this could be interpreted is in terms of competition between other green technology variants. CCS is often talked about in terms of competing for market share with other green technologies. However, such comparisons are not so straightforward in Norway. Increased renewable capacity would not make any meaningful contribution to domestic CO_2 abatement due to Norway's energy mix being almost solely reliant on hydropower. With regards to negative emissions technologies, it has already been outlined that there are currently no alternatives to many industrial processes aside from CCS technology (Barker et al., 2009; Mazzetti et al., 2014). In this regard it is more worthy noting the relevance of this for consideration as opposed to having any meaningful data to present.

Thus, whilst CCS could be seen as competing for R&D funding or prominence on the technological agenda, it is hard to make comparisons or view it as competing directly for market share as a mitigation option for domestic emissions (but this is not to suggest that it is impossible to do so). Notably, none of the respondents felt that CCS would obstruct renewable developments when asked.

5.1.4 Extent of lock-in/dominance of particular technology development

A lack of knowledge and uncertainty regarding other principal mitigation options have been identified as a potential barrier for CCS (Curry et al., 2005), but it would seem Norway has already identified CCS as its primary focus in this regard and thus this uncertainty is not regarded as prevalent. There is also a great deal of literature that discusses the potential for CCS to compete with other power generation technologies, particularly regards to investment (Espen Moe, 2012; Rohlfs & Madlener, 2013; Jennie C. Stephens & Jiusto, 2010; Torvanger & Meadowcroft, 2011). Again, with CCS for gas fired powerplants now seemingly on the backburner for the time being, it seems the prospects for CCS to compete directly with renewables in the context of power generation is somewhat less of a concern in Norway. Questions could be asked as to whether CCS absorbs R&D investment that could be directed towards development of renewable technologies (Espen Moe, 2012). However, as Norway has a domestic energy mix supply that is almost exclusively based upon hydropower, with regards to mitigation strategies renewables have limited scope for making significant contributions to domestic CO_2 reductions. With regards to industrial emissions however, this makes CCS for industrial application an important mitigation tool due to there being no other present alternatives for many industrial processes.

Markusson, Kern, et al. (2012) outline that technological selection can happen through market competition, expert consensus or policy selection. In the Norwegian context it seems that a combination of all three factors have led to the pathway that has been pursued to date. The carbon tax introduced by the Norwegian government, along with the commercial opportunities to implement CCS, contributed to realisation of the Sleipner and Snøhvit full-scale CCS projects. The need to remove CO_2 from gas before export, as well as the existing infrastructure for both injection and storage of CO_2, helped CCS proposals come to fruition. Experts have lobbied and advocated for its introduction, whilst CCS seems a committed policy option and selected pathway in light of political cohesion (Tjernshaugen & Langhelle, 2009), the extent of which should prove evident in the examination of political commitment with regards to uncertainty 6. For the time being at least, CCS seems to be somewhat locked-in with regards to this political cohesion as well as significant expenditure and resources having been devoted to development thus far. Its development trajectory is certainly more advanced than any other comparable negative emissions technology in Norway and it fits the conflicting objectives of Norwegian climate policy at both the domestic and international level (Jo-Kristian Straete Røttereng, 2016). Despite this, the lack of large-scale commercial projects and early developmental stage would suggest that it is not fully locked-in as of yet.

The abundance of CO_2 storage capacity (outlined under uncertainty 2), economic dependence on petroleum activity, accumulated developmental experience and existing CCS ready infrastructure would all serve as indications that CCS is a selected technological pathway. The only question marks surrounding the extent of lock-in would be with regards to developmental trajectories also being resultant of cumulative development, with the only existing large-scale developments being in the form of pre-combustion CCS linked to gas purification. Demonstrations of particular technology variants are often taken as representing CCS as a whole (Russell, Markusson, & Scott, 2012) but they may entail very different practicalities or emerge over separate developmental trajectories. Once operative, the Norwegian Full-scale CCS project should give a clearer picture of the trajectory of industrial CCS in Norway on the back of prior CCS developments and research. This would serve as evidence that, whilst Norway may have selected a CCS developmental pathway, there is technological diversity at least within the general field of CCS applications and processes.

5.1.5 Uncertainty 1: Assessment summary

CCS has clearly been chosen as a technological option, but the variety of applications within CCS technology itself still leaves questions as to which are best suited for mitigation options. Gas sweetening has the most logical and cost-effective option but, with 90% of greenhouse gas emissions occurring downstream when the fuel is combusted (Gavenas, Rosendahl, & Skjerpen, 2015), this is not necessarily the most effective from the perspective of portfolio mitigation options. CCS application for gas-fired power plants has been subjected to cancellations and is no longer of focus, which could be indicative of uncertainties arising from pathway variety within the CCS portfolio itself. CCs with gas-fired power was also very much a top-down push approach, thus this highlights difficulties when there are little market generated incentives to motivate industrial actors. CCS is also often viewed as being in direct competition with renewables, however in consideration of the potential reductions for Norway's own domestic emissions, the choice is relatively straightforward. At present, most industrial process CO_2 emissions reductions can only be achieved with CCS. Selection of CCS as a pathway is thus resultant of a number of factors and, whilst there is little uncertainty in the selection of CCS as a mitigation technology as a whole, there may be more uncertainties in terms of differing CCS application pathways. The technology appears a dominant mitigation technology at present, which provides a great deal of clarity to public and private actors, but it is not clear from the assessment as to whether it can be considered fully "locked-in" as of yet.

5.2 Uncertainty 2: Safe Storage

Safe storage of CO_2 is key to reducing uncertainty for CCS viability. In 2005 the IPCC described the number of CCS projects too limited to serve as a basis for conclusions about the physical leakage rates and associated uncertainties (Metz et al., 2005, p. 48). However, it is worth bearing in mind that there were only three commercial CCS projects as of mid-2005. Despite an increase to 18 large-scale commercial projects in operation today however, (Global CCS Institute, 2019) the number of projects is still rather limited globally. With Sleipner and Snøhvit being two of these, as well as the Full-scale CCS project being in advanced development and Norway's extensive mapping of the Norwegian Continental Shelf, it would appear Norway is better placed than many to begin to draw conclusions (Halland, 2019b). Uncertainty is still evidently present however, and thus frameworks for risk and liability are necessary contingencies.

5.2.1 Availability of storage site data, including agreed rough estimates of their capacity

Capacity estimations can vary. Robust estimates based upon sufficient data are therefore necessary to decrease uncertainty surrounding storage, both with regards to capacity and long term safe storage. Elenius et al. (2018) advocate cross-disciplinary collaboration in conjunction with some form of uncertainty analysis in the face of sparse data, and this helps outline just how paramount the parameters surrounding uncertainty are in storage estimations. Zweigel et al. (2018, p. 1) state that "*capacity estimates for CO_2 storage sites are more uncertain than for hydrocarbon fields; this is related to integrity uncertainty*". Whilst it is difficult to give robust estimates of storage site capacity, the level of activity and timespan for accumulated data should provide some confidence that the data for Norway is more concrete as opposed to other estimates that can be purely speculative. Much of the North Sea has been geologically mapped due to petroleum exploration (Anthonsen et al., 2013), whilst Norway has already significant experience with offshore storage.

Bui et al. (2018) states that research surrounding storage is progressing rapidly. Rørvik et al. (2013) state that safe storage is the most important factor in CCS feasibility but use the example of the Norwegian Johansen Storage Complex Study to outline challenges such as data availability, size and qualification. There is also uncertainty about when oil and gas fields will be depleted and become available for CO_2 storage (Metz et al., 2005, p. 221). In the Norwegian context, it seems conflicts with active petroleum exploration have also pushed CCS projects into unexplored areas, with projects encountering problems with limitations of data availability (such as low well density or lack of seismic data) that make identifying storage somewhat challenging (Rørvik, Eggen, Carpenter, & Christensen, 2018). There is also a minimum 4-10 year process from site identification until saline formations are mature enough to qualify for CO_2 storage (IEA, 2013, p. 17; Tangen, Lindeberg, Nøttvedt, & Eggen, 2014), thus this time delay is a consideration for the speed of CCS projects, whilst there is also a need to speed up this process (Rørvik et al., 2018).

Norway is seen as having significant experience with regards to storage of CO_2 offshore. After 20 years of operation, Sleipner has stored 17 million tonnes of CO_2 (IEA, 2016), whilst treatment at Snøhvit has seen 0.7 million tonnes annually injected and stored since 2008 (Halland, 2019b). Offshore storage capacity is significant in Norway and has already been successfully demonstrated, however it is seemingly more expensive and more complicated than onshore storage (Shogenova et al., 2014). (Norwegian Petroleum Directorate, 2019b). Also the capacity for onshore storage is limited in many areas in Norway, which makes offshore storage the only real alternative (Anthonsen et al., 2013; Haugen et al., 2013). The Nordic region was previously said to contain 59% of mapped storage capacity in Europe, and 86% of all offshore capacity (Anthonsen et al., 2013, p. 5081). Of note is that Michael et al. (2010), in reviewing projects that store CO_2 in saline aquifers[3], state that the reservoir properties of Sleipner and Snøhvit are unrepresentatively good on a global scale, thus perhaps

[3] Geological formations considered as having greatest storage potential (Sengul, 2006)

indicating the strength of Norwegian storage capabilities. Therefore Norway´s storage capacity has the added benefit of being an attractive option to enable cross-border collaboration, particularly in light of limited public support for onshore storage elsewhere in Europe. With this in mind Norway can strengthen the business case for storage and help facilitate wider European development (Tangen et al., 2014).

The Norwegian CO_2 Storage Atlas provides an overview for long-term storage sites in estimating storage capacity and efficiency. The atlas is based on data from seismic, exploration and production wells in combination with production data, and the NPD has access to all data from the NCS (Halland et al., 2014). The data is derived from 40 years of petroleum activity and from the Sleipner and Snøhvit CCS projects. This should therefore provide for a rather robust and agreeable estimate for decision makers. According to the atlas there is potential to store more carbon dioxide on the Norwegian Continental Shelf which, according to the NPD, is *"equivalent to the current level of Norwegian CO_2 emissions, for 1000 years"* (Norwegian Petroleum Directorate, 2019a). It is stated that the Norwegian Sea alone may be able to store 5.5 gigatonnes of CO_2, 100 times that of Norway's 2018 combined CO_2 emissions according to the NPD, with the larger Norwegian area of the North Sea able to store around 70 gigatonnes. One of the respondents, a co-author of the atlas, outlined the strength of the Norwegian data:

"There are very few countries that have access to data like this. And that was extremely valuable. We know all the dry drilled wells, and when it was a dry drill, we know there's no oil and gas and evaluate that we now can use that for a storage" (interview with Halland, 2019a).

However only 1.1 Gt of the North Sea and 0.02 Gt of the Barents Sea respectively is currently determined as suitable for long-term storage when based upon maturity for effective and safe storage (Halland et al., 2014, p. 148). The Norwegian Sea having 0.17Gt based on this measure (Halland et al., 2014, p. 51). The preliminarily estimates do not necessarily guarantee that all estimated storage will be deemed safe and effective. In the Norwegian Sea for example, capacity of 5.5Gt is determined based upon size and quality, whereas the figure of 0.17Gt arises from *"sites that have been mapped and evaluated in terms of regulatory and technical criteria to ensure safe and effective storage"* (Halland et al., 2014, p. 18). Although the prospective capacity would seem substantial and encouraging, this could be indicative of some uncertainty as to exactly how much of the estimated capacity will prove safe and effective. For the prospective Full-scale project, a well will be drilled late in 2019 to confirm the properties of the storage reservoir, as a well is needed for absolute verification for storage due to the limitations of seismic testing (interview with Halland, 2019a).

5.2.2 Nature of legal/regulatory framework to share risks/liabilities

Keating, Middleton, Viswanathan, Stauffer, and Pawar (2011) specifically look towards storage uncertainty as a driver for CCS infrastructure. Uncertain parameters they specify in subsequent modelling are both geological (such as permeability, porosity) and economic (including costs for drilling, distribution, piping and maintenance). They find that cost and capacity uncertainty of reservoirs has a significant impact on CCS infrastructure, with pursuit of lowest costs having an impact of spatial deployment. They also find that costs between two solutions capturing the same amount of CO_2 can vary by 100% or more. It is worth bearing in mind that CCS uncertainty is not merely problematic for decision making but can also determine strategy and deployment in the pursuit of optimal solutions. In Norway the use of existing oil and gas infrastructure helps with cost-reduction and experience with development and extensive mapping helps with capacity uncertainties. This has also helped build confidence over safety concerns due to existing projects having developed monitoring and pressure management techniques (Philip Ringrose, 2016).

There are also problematic uncertainties with regards to liabilities, presenting risks that operators may not be willing to undertake. According to Weber (2018, p. 158), the biggest legal impediment to CCS projects appears to be that the potential liability is uncertain. For example, liability for damage caused by storage and CO_2 leakage may encounter uncertainty with regards to time limits for civil claims or administrative liabilities, and as to powers of public authorities to enforce requirements upon operators in such circumstances (Havercroft, 2018). The CCS Directive lacks of clarification over the type of liability and culpability over CCS project lifetime (Weber, 2018). This is therefore left to common law, and thus there is a lack of developed case law legislation domestically which, in turn, results in investment and operational decisions regarding risk being left to theoretical and speculative suppositions. Nykvist (2013, p. 685) cites storage as being one of the most problematic and underdeveloped issues surrounding CCS and attributes this to the lack of regulation and prevalence of uncertainties surrounding liability.

The directive assumes that Member States will be motivated to participate in CO_2 capture and storage, and thus there are questions as to whether this, in combination with the EU framework, will be enough to facilitate large scale CCS deployment (Haan-Kamminga et al., 2010, p. 241). Weber (2018) is also critical, outlining that the European legal framework is not perceived as having provided sufficient certainty to operators regarding potential liability. This is with regards to liability surrounding both temporal and financial terms, and thus it will require resolution of omissions and lack of specificity in the directive at Member State level.

"The directive allows transfer of responsibility for the storage site from the operator to the competent authority…whilst transfer of site responsibility releases the operator from monitoring and corrective obligations, as well as from any liabilities under the EU ETS and the environmental liability directive. However, the CCS directive refers to a number of situations where costs incurred by the competent authority are eligible to be reimbursed by the operator, notably in the cases of wilful deceit, negligence, lack of due diligence or the provision of deficient data" (Chiavari, 2010, pp. 165-166).

Whilst one can see the logic behind such legislation in trying to provide a degree of flexibility yet also a framework for a degree of clarity, it could perhaps be seen as too ambiguous and as imposing too great a degree of risk and potential liability. Such uncertainty could also negatively impact cost-benefit analysis, particularly if a worst-case scenario approach is the chosen constraint. On the other hand, the state can also be exposed to an operators insolvency or deficiencies in meeting obligations. Havercroft (2018, p. 320) cites the approach of the Canadian model in the state of Alberta or the Australian model in the State of Victoria, whereby operators would make financial contributions throughout a projects operational phase as a more sensible approach, as opposed to merely at the point of transfer of responsibility to the state. The lack of uncertainty and need to determine liability on an individual member state basis could also pose difficulties and reluctance amongst operators in projects requiring cross-border CCS operations. Norway has however introduced regulation to specifically cover CO_2 storage. Norwegian petroleum law already covers aspects of hydrocarbon field developments, and this is supplemented by domestic storage regulation (Ministry of Petroleum and Energy, 2014) and the EU directive.

There are new international standards to support the commercial deployment of CCS with more to come. Ombudstvedt and Jarøy (2018) outline that such standards may be one of the last items needed to deploy CCS technologies at a commercial scale, with standardisation helping to bridge gaps. The International Standards Organization (ISO) TC 265 project has working groups on capture, transportation, storage and quantification/verification (International Organization for Standardization, ´n.d.). Its goal is to *"prepare International Standards for the design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CCS"* (Ombudstvedt, 2019b). These standards will bring clarification if adopted by Norway and other states. Currently Article 18 of the EU CCS Directive provides for transfer of liability to the state after a monitoring period of 20 years, but uncertainty arises from the need to satisfactory show CO_2 to be permanently contained, thus standardised methods for monitoring and measurement can be seen to *"help unlock the uncertainty and unpredictability around the transfer of liability post closure" (Ombudstvedt & Jarøy, 2018, p. 5)*.

The Norwegian Full-scale CCS project has resulted in Equinor augmenting its governing documentation to address CO_2 storage issues. This is the first project covered by recent Norwegian regulation for CO_2 storage, thus the project is expected to be a learning-by-doing process for how the company can meet requirements and update its documentation if necessary (Zweigel et al., 2018). Thus, there is not only a need for sufficient legal and regulatory frameworks, but also industry procedures. Companies with a track record in CCS development do not necessarily have sufficient procedural guidelines and documents in place. This may be resultant of the small fraction CCS tends to contribute towards the overall company portfolio (Zweigel et al., 2018, p. 3). Learning by doing can be viewed as a vital part of an evolutionary regulatory process.

5.2.3 Levels of public awareness/acceptance of risks

Finally, with regards to levels of public awareness and acceptance of risks, it would seem that this is less of a barrier to CCS development in Norway than in other comparable cases. Safe storage of CO_2 is seen as being key to public acceptability of CCS (Davis, Landrø, & Wilson, 2019). Public acceptance for offshore CO_2 storage is regarded as higher than for onshore (Davis & Landrø, 2019, p. 88; Haug & Stigson, 2016; Pietzner et al., 2010; Schumann, 2015), and this may be a reason for Norwegian projects such as Sleipner seemingly being readily accepted (Hammond & Shackley, 2010). The risk towards jeopardising human health are also minimised when compared to onshore (Metz et al., 2005). Eiken (2019) outlines that the

Sleipner project, with regards to the monitoring process producing 4D seismic images, has been an influential driver for public and political acceptance of the storage process. The data from the Sleipner project has also improved data and research, with over 300 scientific papers as a direct result. As one of the respondents outlined, leakage is a very low risk if procedures are followed properly (interview with Halland, 2019a).

Evidence suggests that there has been no subsequent leakage from Sleipner in 20 years of monitoring and storage, with CO_2 being safely stored thus far (Arts, Chadwick, & Eiken, 2005; R. A. Chadwick, Williams, & Noy, 2017; Furre, Eiken, Alnes, Vevatne, & Kiær, 2017), and that whilst the probability of leakage is very low, more data is required to be certain (Karstens, Ahmed, Berndt, & Class, 2017). One consideration could also be to consider what is an acceptable level of leakage, although of course complete prevention should be the objective. Sleipner and Snøhvit storage sites are projected to CO_2 for at least 1000 years (Bellwald et al., 2018). Perhaps the reason for negative public perceptions of CO_2 storage elsewhere in Europe, and need for clear information, is as follows:

"I think it's very interesting going into this because people are never concerned about oil and gas leakage. But the moment you start talking about putting CO_2 into the ground, it's a big concern of leakage. The reason why people are concerned is that they don't understand the whole trapping mechanism, and I don't expect people to understand it, but if people had understood how oil and gas are captured in the ground at this moment and this is not leaking up it would be a start." (interview with Rørvik, 2019)

Storage site verification also goes beyond mere technical feasibility, for example a storage site evaluation study in 2016 found the Utsira site to have insufiicent capacity due to well-leakage risk but additionally limited area for storage licencing, whilst Heimdal was found feasible but not cost effective (PS Ringrose et al., 2017). It would therefore seem promising based on evidence thus far that the risk of leakage is remote, and this should serve to strengthen confidence in Norwegian competencies for offshore storage. It is worth noting that Norway lacks sufficient representative data on CCS perceptions (Pietzner et al., 2011), however there has seemingly been little public opposition to Norwegian CCS projects (Nordic Council of Ministers, 2007).

5.2.4 Uncertainty 2: Assessment summary

Norway has significant experience in CO_2 storage and related activities, as well as vast offshore storage capacity. The extensive data for Norwegian capacity estimates also appears rather concrete due to 40 years of cumulative petroleum activity, exploration and geological mapping. The Norwegian Storage Atlas has access to all data on the NCS and thus provides a comprehensive and robust data set for decision making. Operational CCS projects have also provided experience in offshore reservoir management, research and monitoring with no evidence of leakage. The locality of storage capacity, being offshore, also helps to alleviate public concerns and minimises risks to human health. Existing projects have generated no apparent opposition to storage and have been used as an opportunity to bolster public confidence, suggesting perhaps scaling may provide further opportunities to display competence and increase acceptability.

Uncertainty can therefore be said to be highly diminished, but it is not completely eradicated. Norway does have existing regulations and has supplemented these, but there may still be liability uncertainties over the long-term. The EU Directive still leaves some uncertainty surrounding site verification monitoring and liability transfer. Should international standards be implemented and adopted, this could help diminish uncertainty not only within Norway, but also help with cross-border projects and thus facilitate wider deployment of CCS technology. There are still some uncertainties to be resolved over site integrity and qualification, whilst regulation and industry procedures are still part of an evolutionary learning process. The vast capacity estimates mean that, even if some of these sites were deemed unsuitable, there should be plenty of storage options remaining.

5.3 Uncertainty 3: Scaling up and speed of development and deployment

Scaling can mean both the extent and rate of growth for both units and industries (Wilson, 2009). For widescale deployment of CCS technology, supply chain capacity also needs to be sufficient to support deployment. A key question for decision makers is how to best facilitate such rapid up-scaling, whether it be through a regulatory approach or perhaps via market-based incentives. An argument can be made that the current limitations surrounding the number and scale of existing CCS projects, both domestically and globally, may hamper diffusion and incentives to invest for both private and public actors.

Chalmers et al. (2013) explore this uncertainty via the comparable cases of combined cycle gas turbine (CCGT) power plants in the UK and flue gas desulphurisation technology (FDG) in the US. These technologies were both successfully scaled up. CCGT due to long-term R&D investment taking the technology from the first plant to a competitive power sector technology within 30 years, then subsequently a variety of factors such as cheap gas, stronger environmental regulations and the technological developments. Competition between manufacturers also resulted in lower costs. In the case of US FDG the roll-out of the technology expanded five times over within 30 years, which was driven by a variety of policy approaches such as performance standards and emissions trading (Chalmers et al., 2013, p. 7673). These cases indicate that there is perhaps not a "one-size-fits-all" approach to scaling, but a combination of factors that can result in rapid diffusion. The case of the French Nuclear scale up is worth bearing in mind however, in that complexity and uncertainties might be larger than assumed, thus it is possible for costs to increase with accumulated experience (Grubler, 2010). It is not therefore a given that cost per unit will decrease with increased scaling, although large systems do often benefit from economies of scale (Roddy, 2012). Policy is seen as a tool to help facilitate CCS solutions, both within Norway and Europe, to help reduce the cost of CCS and provide learning benefits (Holmås et al., 2019).

5.3.1 Unit size, capacity and efficiency

Herzog (2011) emphasises the need for growing CCS from megaton level to gigaton level to help combat global climate change and outlines that Norway had two out of only four near megaton-scale CCS projects worldwide at the time of publication, Sleipner and Snøhvit, both able capture around a combined 1.7 Mt CO_2 annually, or 1 Mtpa and 0.7 Mtpa respectively (Global CCS Institute, 2019). There are currently 11 projects globally at present with capture rates at over 1 Mtpa according to the GCCSI co2re database (Global CCS Institute, 2019). The Full-scale CCS project is projected to capture around 0.8 Mtpa by 2023/2024, 400,000 tonnes from both the Norcem and Klemetsrud plants (Gassnova, 2018a). This will therefore bring Norway's total capture capacity up to 2.5 Mtpa from large-scale CCS facilities, whilst the smaller scale TCM Mongstad test facility captures between 0.02-0.10 Mtpa (Global CCS Institute, 2019).

This would indicate Norway is a significant contributor to worldwide CCS development and current capacity. In Europe there is no other CCS plant currently in operation outside of

Norway (Holmås et al., 2019). With CCS at Sleipner operational in 1996 and subsequently the only operational project since being Snøhvit in 2008, one potential criticism could be that the change in size and capacity of large-scale Norwegian CCS projects has not progressed in accordance with the diminishment of several uncertainties. Thus, we can return to precisely which uncertainties are proving a barrier to CCS implementation later in our discussion. Large-scale CCS at Mongstad was originally conceived with the intention to scale up to capture of 2 Mtpa (Shackley & Evar, 2012) and this failure can be viewed as having been a major setback. However, this also provided opportunities for learning whilst the trade-off for the full-scale CCS project, focusing on industrial CCS as opposed to familiar application with gas, may be a smaller scaling step for greater learning benefit. Therefore, increased capacity alone is not necessarily an adequate measure of developmental speed, as the benefits of the learning process and application may outweigh pure CO_2 reduction capacity in the long term.

The Halten CCS project was initiated by Shell and Statoil and conceived to capture 2.25 Mtpa from a gas-fired power plant from 2011, with CO_2 to be injected at both Draugen and Heidrun storage sites in the Norwegian sea (Torvanger, 2007). The projected cost was around 8-10 billion NOK, with roughly half going towards both the construction of the plant and CCS infrastructure. However, feasibility studies raised doubts over CO_2 assisted EOR, whilst poor projections over the power plants profitability, combined with the high levels of envisaged public finance required, resulted in the project being subsequently cancelled in 2007 (MIT, ´n.d.´). Prior to its cancellation Torvanger (2007) argued that there was a need for public support for the project due to spillovers in learning that could be gained and thus the social value potentially outweighing the private value, whilst also outlining that there is likely to be underinvestment in technologies by private companies due to different measures of valuation. Halten would have been the world's largest project for using CO_2 in EOR offshore (Ministry of Petroleum and Energy, ´n.d).

Kårstø would also have enhanced Norway's CCS portfolio, having had a proposed capture capacity of just over 1Mtpa. However many uncertainties such as health, learning benefits, economic costs, low regularity and overall climate benefit over the plant life cycle were viewed as unresolved or potentially negative in an analysis by Osmundsen and Emhjellen (2010), therefore the value of this is questionable. The authors also projected that Kårstrø would capture closer to 50% of the proposed 1.05 Mtpa. This being due to gas-fired plants only operating for half of the time compared with the study conducted by the Norwegian

Resources and Energy Directorate, which calculated the capture rate based on over 8,000 hours of uptime, which the authors describe as “completely unrealistic” (Osmundsen & Emhjellen, 2010, p. 6). The irregular operation of the gas-fired power plant since it was commissioned would appear to validate their logic (ZERO, ´n.d´-b).

5.3.2 Speed of unit scaling

Building up capacity in supply chains is needed in order to facilitate the scaling of key technologies (Markusson, Kern, et al., 2012). With the Full-scale CCS project, a number of different private actors, with differing competencies, are involved. The project is a collaboration between actors and the state, represented by the Ministry of Petroleum and Energy along with Gassnova (Holmås et al., 2019). A learning process, utilising and developing the skills of numerous Norwegian operators, is underway. Successful development of full chain CCS could therefore have numerous benefits towards reducing uncertainties in a number of different aspects. To accelerate large scale deployment, projects need to be chosen that integrate all parts of the chain, in readiness for commercial operation (Michael et al., 2010). The Full-scale project is also projected to have surplus capacity that will be open to other projects, thus providing opportunity for increased CCS capacity and scaling (Gassnova, 2019b). Equinors participation in the project will help to establish an infrastructure whereby it will be possible to collect CO_2 at any port, thereby granting the ability to offer to take and store CO_2 from any customer with access to a port. Additionally, there are a lot of companies who want to capture CO_2 but have no options for transportation and storage (interview with Eikaas, 2019). This could provide tremendous opportunities for scaling across wider Europe, and the success of the project could be crucial for wider viability:

“In Norway we’ve had at least two of those rounds before with Kårstø and Mongstad being cancelled, and now if we have a third round and another full-scale demonstration project is cancelled, I think we will struggle not just getting CCS to work in Norway but also in Europe. All of Europe is looking to Norway for leadership and inspiration and experience, and if Norway is not able to make it, and not deploy a full-scale demonstration project, why should any of the others?” (interview with Ombudstvedt, 2019a)

The results of a study by Størset et al. (2019), conducted to look at potential economic gains based on CCS R&D, in line with IEA and IPCC scenarios, show numerous benefits. The results show that value creation from large scale CCS deployment substantially outweighs investments into research. Seven innovation cases that cover the whole value chain were selected that show various quantitive and qualitative examples of value creation. There are several assumptions that the examples were based upon, however. As well as cost reductions, there are qualitative effects across the cases such as improved storage safety and spill-over effects, societal and environmental benefits, increased public acceptability, transferable commercial methods, reduced uncertainties, reduced energy needs and competence building (Størset et al., 2019). Gassnova lists four categories of valuable outcomes that can be realised through the Full-scale CCS project: 1) demonstration effect, 2) cost reduction effect, 3) business development effect and 4) the CO_2 emissions reduction effect, whilst also envisaging it to lower risks and subsequently bring down costs that other projects outside of Norway.

There is also the need to recognise that most industrial facilities have not been designed with CCS in mind and therefore there are obstacles towards retrofitting the technology (Nykvist, 2013; Roddy, 2012). Much of the focus and research has been geared towards CCS application for the power sector as opposed to implementation with industrial processes, thus work is not as advanced and costs are more uncertain (Kuramochi, Ramírez, Turkenburg, & Faaij, 2012; Roddy, 2012; Roussanaly, 2019). Indeed, one of the first studies on the techno-economic performance of CO_2 capture from large scale industrial processes was in 1995 (Farla, Hendriks, & Blok, 1995), just a year before the Sleipner project began successful capture and storage operation in Norway. Kuramochi et al. (2012) compile a brief overview of the literature on CCS in the industry and summarise that chemical absorption CO_2 capture has been heavily investigated due to lack of alternatives, despite it being considered less economical than other applications. They also outline that the article *"is one of the first to assess CO_2 capture options for various industrial processes in detail and in a comprehensive way"* (Kuramochi et al., 2012, p. 109). This would indicate there are still many uncertainties towards scaling up the technology for application in these process industries and the lack of worldwide cumulative investment and installed capacity would therefore mean Norway is left to bear the burden for costs of learning with the Full-scale CCS project.

Ho, Allinson, and Wiley (2011) assess CO_2 capture for three Australian industrial emission sources: iron and steel, oil refineries and cement manufacturing. They conclude iron and steel may be suited towards early deployment of CCS technology due to moderate cost and economies of scale, but that both cement manufacture and oil refineries require technological improvements or financial incentives. Whilst this study is not of course focused on Norway, its findings are worth consideration for Norwegian industrial CCS outlook. Additionally, carbon price increases are viewed as crucial for CCS timeline implementation. With the Full-scale CCS project receiving financial support from the Norwegian government for the exploration well on the NCS, it would seem that the necessary incentive has been put in place in order to reduce cost uncertainty for the storage operators (Gassnova, 2018a; Ministry of Petroleum and Energy, 2019a). With this project including the world's first cement plant with full-scale CCS, a significant step towards fulfilment of a large-scale industrial CCS development and full-chain implementation is close to being realised (Rørvik & Ringrose, 2017).

Nykvist (2013), in drawing quantitative conclusions based on another study that employs CCS Technology Innovation Systems theory, finds that even if CCS is pursed, there are four challenges that are found to be 10 times greater than often acknowledged: *"(i) a tenfold up-scaling in size (MW) from pilot plants to that of commercial demonstration, (ii) a tenfold increase in number of large scale demonstration plants actually being constructed, (iii) a tenfold increase in available annual funding over the coming 40 years and, (iv) a tenfold increase in the price put on carbon dioxide emissions."* (Nykvist, 2013, p. 683). This study comprised an overview of projects both in the US and Europe, however it would appear Norway would fare better should the same perspective be applied to a single country case study. Some of the barriers highlighted for scaling include storage being one of the most problematic and least developed areas, being subsequently due to lack of regulation and uncertainties around liability. However, as we have seen in our examination of uncertainty 2, Norway is much more advanced in this regard.

Resistance from local governments and communities is said to be a barrier, however, as will be discussed in uncertainties 6 and 7, there is political cohesion and higher indications of public acceptability in Norway. Offshore storage is again seen as difficult due to the need for pipelines and complex permits, but then again, Norway exhibits evidence of having existing infrastructure, advanced expertise and substantial storage capacity. The upcoming full-scale CCS project seeks to transport CO_2 via ships and Norway already has experience in this. Difficulties are also viewed in the need for CCS to be retrofitted to coal power plants, however Norway only has one coal power plant located in Longyearbyen on the Svalbard archipelago (Tønseth, 2017). With these considerations, it should be safe to say that scaling is unlikely to be so challenging in Norway, although accurate assessments of the prospective size of the challenge are still difficult.

5.3.3 Uncertainty 3: Assessment summary

Norway is evidently a significant contributor to worldwide CCS development and currently operational global capacity. There have been significant setbacks however to scaling attempts, with numerous underestimated uncertainties still of prevalence that have emerged as barriers to subsequently abandoned projects. A question thus emerges as to whether costly projects justify increased public expenditure due to learning benefits and subsequent value creation potentially outweighing the significant investment costs. The Full-scale CCS project could prove a significant milestone due to full-chain optimisation, the collaboration of numerous actors and prospective learning benefits in tandem with surplus capacity that may allow for accelerated future deployment. However, the investment decision is still pending. Measuring uncertainty is therefore challenging in this regard, as deployment is still at an early stage, and this challenge is perhaps itself indicative of the uncertainty still present. Additionally, there is still much uncertainty over the scaling of industrial CCS as much of the prior focus has been on application towards power generation, thus technological improvements may be required to overcome the difficulties in retrofitting the technology. Norway benefits from diminished uncertainties in other key areas, such as acceptability and storage, which should go some way towards facilitating more rapid deployment. The prospective Full-scale project will likely illuminate uncertainties and provide clearer indications of their effects on viability based upon the extent of its success.

5.4 Uncertainty 4: Integration of CCS systems

"The subject of Carbon Capture and Storage (CCS) for power stations running on coal or natural gas is both important and prominent. The application of CCS to other industries which have large carbon dioxide (CO_2) emissions is equally important but much less prominent." (Roddy, 2012, p. 459). This is particularly notable in the history surrounding CCS in Norway. The power sector became a source of political controversy in the 1990s due to plans to build natural gas fired power plants into a largely renewable energy mix (Tjernshaugen & Langhelle, 2009). With Norway's substantial interest in offshore oil and gas, as well as existing expertise with EOR, it is therefore understandable that CCS to help and

reduce emissions in this sector would be the first port of call. Combined with promotion of the technology by influential actors from existing research projects (Tjernshaugen & Langhelle, 2009), it explains integrational focus into natural gas projects. The Full-scale CCS project therefore represents an ambitious departure towards industrial CCS application and indicates Norway's desire to broaden its CCS portfolio. There have also been project failures towards the realisation of full-scale CCS facilities, such as in the cases of Mongstad and Kårstrø, which highlight that integration in Norway has met with emergent uncertainties and has not necessarily been straightforward. These failures have also provided opportunities for learning, as uncertainties are better understood and steps can be taken to mitigate them. Uncertainties around integration present numerous challenges. Greater clarity around coordination, planning, experimentation and supply chains can all strengthen possibilities and opportunities for diffusion of CCS technology.

5.4.1 Whether full-chain integration has been achieved?

Full-chain integration can be an indication that CCS systems have been well embedded and that the elements of the chain allow for effective operation. Bringing all elements of the CCS chain together in unison is no simple task, and each element entails its own set of challenges and considerations. One of the informants indicated the complexity of the CCS value chain as a reason for a lack of implementation, with an advantage being when the use of existing assets and infrastructure can be utilised (interview with Eikaas, 2019). As outlined by Tjernshaugen and Langhelle (2009, p. 120); *"there is an assumption that CCS represents a technology, where the reality is that the method requires assembling and integrating different technological components from different established industries"*.

Jakobsen et al. (2017) assess nine CCS chain alternatives related to the Norcem Brevik cement plant, with different choices of capture technologies, transport type and storage all offering differing cost-cutting potentials. If all these elements can be successfully integrated into a working large-scale facility, then the prospects for successful CO_2 mitigation are positive. There is also a need to optimise the chain from capture to transport and CO_2 injection and ensure that sufficient infrastructure and expertise is in place (Roddy, 2012). Prior projects having successfully achieved full-chain integration would also go some way as to indicate uncertainties having been diminished for subsequent CCS projects whilst also signifying the likelihood of increased learning benefits and developed technical competency.

The only operational large-scale projects, Sleipner and Snøhvit, are full chain with regards to they deal with all separate elements of capture, transportation and storage. However, all this is done on-site thus making it a rather more simplistic task than the prospective Full-scale project, which will capture CO_2 at the point source but then transport via ship to the storage sites on the Norwegian Continental Shelf. Figure 3 below represents an example of a full CCS chain to provide a visualisation.

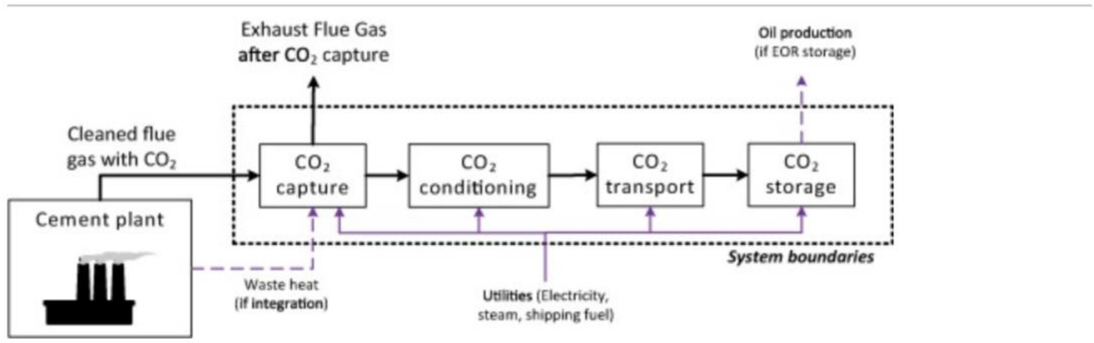

Figure 3: Block structure and system boundaries of the considered CCS chains from cement. Taken from (Jakobsen et al., 2017, p. 525).

Norway's preparedness for full-chain integration appears promising. Storage capabilities are already well developed, sites have been identified, capacity is evidently no barrier for the project and those involved in the project with the transportation and storage elements already have experience with CO_2 transportation, injection and storage. Norway has had significant learning opportunities with regards to CCS project organisation and management, as well as governance and private/public collaboration. The project has also undergone numerous studies, planning and feasibility checks and, on the evidence, the prospects of the full-scale CCS project being realised in the coming years looks to be highly promising. A fully integrated value chain is seen as a criterion of high importance for a commercial scale project (Sivertsen et al., 2012).

In the Norwegian Full-scale project, CO_2 will be captured at two possible capture sites; Fortum Olso Varme´s waste-to-energy facility and Norcem´s cement factory in Brevik. Yara´s ammonia factory at Porsgrunn had also been proposed (Rørvik & Ringrose, 2017) but is no longer involved in the project. One of the respondents outlined that the reason for Yara´s withdrawal was that it deemed it not industrially sensible to continue (interview with Rørvik, 2019). There were also findings that Yara`s project had a smaller learning potential in terms of optimization and upscaling, in addition to uncertainties concerning the plant (Ministy of Petroleum and Energy, 2018). Many actors, such as Equinor Aker Solutions, Shell and Total, are involved in the project (Duckett, 2018), and thus through public-private partnerships Norway hopes to demonstrate a framework that will prove attractive for both industry and government. Equnior is also optimistic this may help realise other CCS projects across Europe and be the start of the world's first cross-border CCS network (Equinor, 2019). The Preem refinery, one of the largest CO_2 emitters in Sweden, is also considering connecting to the Norwegian Full-scale project. Storage of CO_2 captured in Sweden would be shipped to Norway for storage on the NCS (SINTEF, 2018). The shift in approach to this development could be evident of a major learning step from prior projects:

"Both the country and Equinor were thinking of developing the whole supply chain themselves. I think that's the positive thing, that both the government and Equnior has shifted the approach and understand that they have to develop a supply chain and encourage competition. Which I think was one of the main barriers in the beginning" (interview with Kalesi, 2019)

5.4.2 Allocation and responsibility for integration

Allocation and responsibility for integration is also an important indicator. The more actors involved in a project, the more vital it is to ensure cohesion, coordination and utilisation of different competencies and expertise. The Norwegian CCS innovation system has been described as "*a network of actors interacting under a particular institutional infrastructure and involved in the development, diffusion, and utilisation of CCS technology in Norway"* Carlsson and Stankiewicz (1991) as cited by (van Alphen, van Ruijven, Kasa, Hekkert, & Turkenburg, 2009, p. 44). There are both merits and drawbacks to incorporating more actors into a CCS chain. On the one hand, this can utilise specialist knowledge, resources and expertise orientated towards specific responsibilities as well as provide avenues for potential support and greater unity. Drawbacks can include increased complexity, cooperative/cohesion difficulties, fragmented structure and difficulties for project management/coordination. Actors may also be more exposed to risk should another fail to uphold their obligations. The learning process is also likely to be beneficial as numerous actors have the opportunity to develop skills, experience and competencies towards CCS project implementation and development. The Norwegian Full-scale CCS project has been specifically designed as a learning opportunity and with the intent to further develop competencies and infrastructure. It is also a demonstration project to outline that CCS can be implemented technically, regulatory and commercially that is intended to allow further business development for future projects (Gassnova, 2019a). Fortum Olso Varme`s participation at one stage looked in jeopardy as it was deemed to have greater implementation risks related to the length of the pipeline, public perception of having emissions of amines close to a city and, notably, concern over the project management experience in the organisation (Ministy of Petroleum and Energy, 2018).

The innovation system surrounding CCS can be seen to have developed in accordance to increased prominence of CCS on the political agenda and through the learning process with prior project development. Norway has altered the framework for full-scale CCS as a result of prior projects that did not come to fruition (Gassnova, 2019c). Institutional support is evident in substantial R&D funding, political discourse and the establishment of Gassnova SF. Gassnova SF has key responsibilities for CCS integration in Norway. A state enterprise, it was established in 2005 to specifically lead CCS technological development and advises the government and manages its interests (Gheorghe & Muresan, 2011). It contributes to CCS research through the CLIMIT programme and grants financial support for development and demonstration. It also operates TCM Mongstad alongside Equinor, Shell and Total whilst managing and coordinating work on the Norwegian Full-scale CCS project. Thus, with regards to allocation and responsibility of integration, Gassnova plays a leading role in Norway and is a prominent “system integrator” actor. With regards to the Full-scale project it is responsible for optimisation of the entire management chain. This means there is a clearer picture for actors and developers, as well as for the government, as to how CCS will be integrated and as to how it will be managed and governed.

Equinor, Shell and Total form the Northern Lights consortium to handle transportation and storage. All of these actors have prior experience and knowledge with CCS in Norway via prior collaboration on TCM Mongstand whilst Equinor and Total are also partners in the Sleipner and Snøhvit projects. The roles of these key actors, already having developed competencies with regards to transportation, injection of CO_2 and safe storage, should again prove indicative of efforts to reduce uncertainty in the project. Many steps involving planning studies and evaluations have already been undertaken. A feasibility study in July 2016, concept studies for CO_2 capture in 2017, approval by the Norwegian Parliament of funding in 2018 for subsequent advanced planning studies for both Norcem and FOV. A concept study for storage has also been completed and an advanced planning study is also underway regarding this, whilst consultancies Atikins and Olso Economics have also conducted reports into quality assurance (Gassnova, 2018b). Thus, actors are clearly taking steps to reduce risks and uncertainties, whilst the presence and participation of key CCS “system integrator” actors with responsibilities for areas in which they have existing expertise should also help reduce uncertainties. In an evaluation and ranking processes for Norwegian CCS, commissioned by Gassnova, project partners competence and capacity was considered of high importance but as a criterion that receives low emphasis in the reviewed projects (Sivertsen et al., 2012). The website for the Full-scale project states that dividing the chain is a lesson that has been learnt from prior CCS projects and thus this ensures partners will not bear risks related to areas outside of their own responsibilities (Gassnova, 2019c). Ownership of CO_2 throughout the chain is outlined in the feasibility study for full-scale CCS in Norway. Capture players are deemed to have ownership of CO_2 until shipping, whilst the state outlines that if the storage operator organises transportation, then responsibility is transferred at this point. At offloading, ownership will then be transferred to the storage operator (Gassnova & Gassco, 2016, p. 52).

5.4.3 Presence, role and importance of “system integrator” firms/actors

The presence, role and importance of system integrator actors has evidently proven crucial for Norway’s efforts to integrate CCS thus far. Actors have also been afforded the opportunity to develop CCS specific competencies whilst utilising existing experience with related operations such as storage, transportation, injection and monitoring. This makes their continued project participation and input crucial for CCS integration. S. Haszeldine and Ghaleigh (2018, p. 21) state one lesson from Snøhvit is that a competent operator is vital for initial learnings whilst one experienced in deep subsurface problems adds greatly to resilience and remedial choices. One informant outlined the need for a set of actors who can bring divided industries together, which is a goal of the Full-scale project (interview with Eikaas, 2019).

However, cohesion is important. The Mongstad case provides an interesting example of the difficulties of public driven management and discontinuity that can arise in the face of uncertainties. Differing assessments amongst actors over the scale of uncertainties led to numerous project delays and eventual abandonment of Full-scale CCS (Shackley & Evar, 2012). The State Auditor and a parliamentary committee concluded that the project was mismanaged, whilst participants defended it on the basis that important technological advances had been made (Haarstad & Rusten, 2016). Bellona responded negatively to the Mongstad delays, with Erlend Fjøsna believing Statoil had created unnecessary uncertainty about an issue that both researchers and suppliers deemed manageable (Kristiansen & Digges, 2010). However, a 2008 TCM impact assessment outlined that there were a number of uncertainties remaining, whilst Statoil and Gassnova outlined that revised cost estimates and delays due to knowledge gaps, particularly with regards to health concerns surrounding amine degradation (Shackley & Evar, 2012, p. 177). Statoil has been described as having a precautionary approach that introduced more uncertainty into the TCM project, resulting in higher costs and longer construction timeframe (Markusson, Shackley, et al., 2012, p. 183).

What is clear from the case of Mongstad is that, whilst uncertainties themselves may prove barriers to integration, actors perceived exposure to risk is also an obstacle, whether this be financial, safety, feasibility or otherwise, There is evidently potential for differences in the perceptions of benefits and uncertainties to prove problematic. Shackley and Evar (2012) question as to whether greater recognition regarding scientific uncertainty could have informed planning at an earlier stage, which outlines the importance of uncertainty assessment for CCS viability. Such a case may illustrate that there are even uncertainties with regards to assessing outcomes. Thus, clarity over system integration and governance would seem fundamental to a project’s success. Experimentation can pose exposure to risk in regard to actors reputational standing, thus uncertainty with regards risk is not limited to pure financial considerations. Innovation is inherently uncertain (Jalonen, 2012), so it is not an easy balance to be struck with public/private collaborations. This is particularly prevalent with risk, whereby some actors may be subject to differential pressures and accountability as well as potential discontinuities over expectations and desired outcomes. Commitment to the business case is an important factor to ensure the risk of partners withdrawing at a later-stage is minimalised (Sivertsen et al., 2012).

Gassnova, as the state established organisation to facilitate CCS development, is a key actor. Gassnova has the ability to grant funding through the CLIMIT research programme, heading its secretariat (Gassnova, 2013), which provides it with the tools to help incentivise development of CCS in prospective projects whereas, if solely left to the market, may fail to incentivise private developers without public funding. Gassnova also manages the government’s stake at the TCM. Criteria for owners governance processes related to CCS are viewed as: 1) ensuring formal communication of owners requirements and decisions, 2) providing a sound basis for decisions and 3) proposals for pursuit or discontinuation of a project, as well as alternative solutions (Sivertsen et al., 2012, p. 6). Equinor is also an experienced and key actor with regards to CCS integration in Norway, and indeed wider Europe, being the main developer and operator of both the Sleipner and Snøhvit CCS projects. These two projects are the only CCS projects currently in operation in Europe and the only ones in the offshore industry (Norwegian Petroleum Directorate, 2019a). Equinor has also had some degree of involvement with every proposed full-scale CCS project in Norway, including the cancelled Kårstø, Mongstad and Haten projects and the prospective Full-scale project. It also has substantial resources as the largest operator in Norway.

Karimi et al. (2012) divide CCS stakeholders into four different categories, as per the table below. Whilst the categorisations of some actors could be discussed and debated, it nonetheless provides a useful snapshot. It is worth bearing in mind this is data from 2012, thus there are some notable omissions and changes that could be applied in the present context. Norcem and Fortum Oslo Varme seem soon to be two major technology uses, whilst Yara still may yet become involved, and another example is Vår Energi now contributing to CCS research (Vår energi, 2019). Also notable is that Naturkarft looks less likely to be an influential CCS stakeholder after the shift in focus away from CCS in conjunction with gas-fired power. Those under the category of technology users are those who have a direct interest in CCS application and could be considered those who either are, or have potential, to be integrating actors.

Policy makers	Technology producers	Technology users	Others
UNFCCC	IN	Exxonmobil	NORAD
EU	SINTEF	BP	Nord Pool
EU ETS	TCM	Total	PointCarbon
IEA	BIGCSS	Statoil	ECON
CSLF	CIPR	ConnocoPhillips	DNV
Norwegian government	FNI	Sasol	ZERO
NVE	NIVA	Shell	NU
OD	IFE	Statkraft	WWF
PSA	IRIS	Vattenfall	Greenpeace
Petoro	CICERO	NorskHydro	E3G
IEEN	UiB	Naturkraft	Enova
Norwegian Res. Council	UiO	RWE	
	NTNU	DONG	
	UNIS	Gassco	
	NGI	GDF-SUEZ	
	NGU	Aker Solutions	
	Bellona	Gassnova	

Table 2: Subdivision of the basic Norwegian stakeholders into four basic categories. Taken from Karimi et al. (2012, p. 25)

5.4.4 Nature of development, including roles of key actors and relative importance of bottom up/emergent and top down/directed development

The Full-scale CCS project could be viewed somewhat as a combination of bottom-up and top-down development. Whilst Gassnova, representing the public interest, has overall responsibility for optimisation, private actors also have to manage their own elements of the supply chain. A steering group made up of members from Gassnova and the Ministry of Energy and Petroleum will oversee the project. This could be described as somewhat technocratic management and seems indicative of more central innovation planning as opposed to via market experimentation. Haarstad and Rusten (2016) use the case study of Mongstad to outline that interactions between the policy-making arena and industrial sector is challenging as they operate according to different logics. Torvanger (2007) presented the case for increased public support for the (since cancelled) Halten CCS project in order to make up the shortfall for insufficient profitability for private investors, which also serves to highlight private/public disconnects in CCS development. In the feasibility study for the upcoming Full-scale project, the goal for the framework is an emphasis on State and industry interests to coincide as much as possible, whilst the report outlines that the States need for control and management of the project will depend on the extent of these incentives coinciding. The planned approach from the State will be the equal for both capture and storage, but that adaptions for storage will be needed (Gassnova & Gassco, 2016, p. 54). Quite what these adaptions may entail is not made clear however.

CO_2 mitigation is in the public interest and therefore the Governments motivations for CCS development are clear. Private operators are likely to want to see returns on investment, whether in the form of profits or due to value added in developmental or corporate responsibility benefits. The dilemma is that large Norwegian private operators are those with the sufficient expertise and resources needed to realise CCS, thus they need incentives to contribute if they assess return on investment negatively. Norway’s approach, in trying to balance these interests, is an evolving process but it would be unlikely to succeed in its CCS ambitions without harmonisation. With substantial public funding, the state is obviously going to want to minimise risk and secure a return on its investment with regards to CCS diffusion, learning benefits and CO_2 mitigation. It is therefore logical that some form of top-down development is used to direct development. Still, the approach is one of encouraging collaboration as opposed to forcing developers' hands as it were. Until more stringent economic market incentives make CCS investments more bankable investments, then such an approach seems appropriate. Gassnova is designed as a facilitator and thus can help bridge the gap between public and private interests that, whilst sharing a common objective, may lead to actors harbouring differing perceptions of risk, benefits and uncertainties.

There also is the question of the best approach innovation and technological integration. For example, in light of the failure to realise full-scale CCS at Mongstad, Markusson, Shackley, et al. (2012, p. 183) advocate a neo-incrementalist approach, small-scale trial and error, that they as having been shown to be more successful in developing new technologies in the face of significant uncertainty. They perceive an end-goal orientated approach, that relies heavily on upfront analysis, a dubious approach in light of CCS being an emergent technology. It can be said that there is no ideal model for innovation policy, as innovation activities require different approaches (Tödtling & Trippl, 2005). Haarstad and Rusten (2016) state that the CCS project at Mongstad emphasises that "big push" policies in the energy sector should consider the particularities of industrial dynamics and regional conditions. They also emphasise that government-policy making should consider policy mechanisms on appropriateness and effectiveness as opposed to being shaped by internal logics. According to Nykvist (2013), reducing CO_2 emissions with CCS is a political challenge, not a technological one. However, climate mitigation is also inherently goal-driven in light of mitigation targets and an ever-decreasing window for abatement, so it is difficult to see how an approach other than one that is goal orientated and top-down would work unless the market were to provide the right incentives. The outcome of the Norwegian Full-scale CCS project should eventually determine as to whether lessons have been learnt and as to whether the right balance has been struck. Sleipner could be viewed as indicative of bottom-up firm orientated innovation, but this was also motivated by policy designed to incite CO_2 abatement, whilst cancelled Norwegian CCS projects are perhaps indicative that the state is a necessary driver. The continued commitment to realising a full-scale CCS project and the role of Gassnova would appear to be pivotal factors for the instigation of the prospective Norwegian Full-scale project.

5.4.5 Uncertainty 4: Assessment summary

Uncertainty undoubtedly remains with regards to CCS systems integration in Norway, but this has been substantially reduced. The Norwegian CCS infrastructure seems well prepared for full-chain integration having developed strong capabilities, as well providing ample learning opportunities for developers provided by prior projects, both successful and unsuccessful. There now appears to be a clear project management structure that involves key actors and utilises their specific competencies. The substantial level of planning and due diligence for the upcoming Full-scale project is indicative of attempts to minimise risk and rectify past failings. Dividing the CCS chain ensures risks can be isolated to ensure other partners will be not be affected should an individual element experience difficulty. Additionally, Norway has important system integrator actors, whose continued participation would seem crucial for future integrational success. On the other hand, it is not only the uncertainties in themselves, but also perceptions of risk and level of exposure that may prove problematic. Cohesion and unity are therefore crucial, whilst commitment to the business case is important. Effective governance and project management reduces uncertainty, although there is no ideal universal model for innovation. However, prior public vs private conflicts of interest and differences in valuations have arisen. A concrete assessment is again challenging, but indications would be that this uncertainty is gradually diminishing with accumulated learning.

5.5 Uncertainty 5: Economic and financial viability

Economic and financial viability is a key determinate to the potential and appeal of CCS technology. There are a multitude of various considerations and factors that one could consider and to do so extensively is beyond the scope of this paper. However, many of the prime considerations will be presented here to assess what level of uncertainty for CCS viability in Norway remains and what steps have been taken to reduce this. Economic viability alone is also not sufficient in isolation of other uncertainties: "*Actual implementation of CCS, as for other mitigation options, is likely to be lower than economic potential due to factors such as environmental impacts, risks of leakage and the lack of a clear legal framework or public acceptance"* (Metz et al., 2005, p. 12)

5.5.1 Costs, including assessment of quality of cost data

Uncertainties surrounding costs of CCS abound, which in turn contributes to uncertainty surrounding overall viability. Fitting systems with CCS technology entails additional costs which von Stechow, Watson, and Praetorius (2011) outline as follows: *"i) the installation of capture equipment, (ii) additional fuel cost required for the capture process, (iii) the installation of a transport system (e.g., pipeline network), and (iv) the storage of CO_2, including the cost of injection, monitoring, liability, and post-closure stewardship"* (von Stechow et al., 2011, p. 347). For example, CCS is estimated to increase costs for waste-to-energy plants by 17% (Chandel, Kwok, Jackson, & Pratson, 2012 via ; Lausselet et al., 2017). Indeed, all of these cost aspects entail some degree of uncertainty with CCS still lacking many large-scale projects that would provide more concrete long-term indications. The more definitive the data for estimation, the lesser the uncertainty in decision making. Learning and experience curves are often assumed to indicate lower costs with scaling up of technologies and reduce economic and financial uncertainties (Markusson, Kern, et al., 2012) but the lack of data from large-scale CCS projects means such assumptions are speculative. Power generation CCS costs also entail very different considerations than that of CCS from industry (Roussanaly, 2019). There are also a number of problems with CCS cost data as discussed in the introduction of the framework (Markusson & Chalmers, 2013). These problems make it difficult to assess cost data in Norway, with difficulties of access, differing methodologies, time variations and differing metrics and therefore this assessment is subject to certain limitations.

Crucially, the cost of emitting CO_2 is lower than the cost of implementing CCS, and thus subsidies and government support have been necessary for the Norwegian Full-scale CCS project. Industry partners will also receive subsidies of that can amount to 100% of the costs for capture, transport and storage. Risk has been reduced with the actors negotiating separate agreements with the state, thus uncertainty over one another's competencies should be somewhat alleviated (Gassnova, 2019c). The estimated cost (investment cost plus 5 year operations cost) for full-chain CCS with both Norcem and Fortum Oslo Varme is within the range of 15,3 to 20 billion NOK, or 9,3 billion (Norcem) to 13,8 billion (FOV) for a full-chain with one capture plant. (*Kvalitetssikring (KS2) av demonstrasjon av fullskala fangst, transport og lagring av CO2. Tilleggsvurdering fase 2*, 2018). In the feasibility study for the Full-scale CCS project, it is worth noting that there was no uncertainity analysis of costs at full-chain level, but are based on expectations of costs from each of the individual industrial partners and the states expected follow up costs (Gassnova & Gassco, 2016, p. 43).

Steps to eliminate uncertainty over economic and financial liability of the project have been taken as evidenced in the quality assurance report prepared for the Ministry of Petroleum and Energy and Ministry of Finance. Differential costs uncertainty is acknowledged, with a mandate that evaluation as to whether uncertainty in cost estimates can be compared and as to whether the alternatives have different risks (*Kvalitetssikring (KS2) av demonstrasjon av fullskala fangst, transport og lagring av CO2. Rapport fase 1 og 2*, 2019, p. 26). According to the report, industry actors have themselves operated with a narrow range of cost uncertainty. The authors of the KS2 report suggest that the cost uncertainties associated with large, complex projects such as the proposed full-scale projects in Norway should be higher. In other words, the report suggests that the industry actors underestimate cost uncertainties. (*Kvalitetssikring (KS2) av demonstrasjon av fullskala fangst, transport og lagring av CO2. Rapport fase 1 og 2*, 2019, p. 29). Fortum Olso Varme was said to have cost estimates considerably higher than Norcem or Yara, which had led to the government previously considering as to whether to offer funding for further studies. However, after proving new information, a new external quality assessment process was announced. Via Front End Engineering and Design studies, uncertainties and risks for the project are projected to be reduced, whilst cost estimates *"will reach a higher level of certaint*y" (Ministy of Petroleum and Energy, 2018). The study will provide a detailed review for an investment decision that will be ready at the end of August 2019.

It is worth bearing in mind that cost considerations vary based on CCS application and that these may compromise optimisation in terms of maximizing environmental and technological efficiency. For example, process gas from aluminium production has a low CO_2 concentration of roughly 1% and is thus generally deemed insufficient for economically viable CO_2 capture, thus Mathisen et al. (2014) run simulations to suggest CO_2 concentration of 4% is recommended. They also find that a capture rate of 55% as opposed to 85% is optimal with regards to both investment and operational costs, which suggests pure cost considerations are not necessarily sufficient to induce optimal capture efficiency. A technical-economic optimum may advocate partial CO_2 capture, even though technically capture rates of above 90% are relatively straightforward (Skagestad et al., 2018). The same logic may apply for full-scale CCS. In their analysis of the Norcem Brevik cement plant Jakobsen et al. (2017) indicate that full-scale CCS may not be the most suitable due to the significant capture costs, regardless of whole chain benefits from economies of scale. There is also a need to find the optimal relation between fixed operating costs (e.g. investment) and variable operating costs (F. Normann, Garðarsdóttir, Skagestad, Mathisen, & Johnsson, 2017).

Norwegian CCS project proposals have already experienced issues with costs proving a barrier to deployment. Full scale CCS proposals for both the Mongstad and Kårstø sites were cancelled for reasons largely attributed towards underestimations of costs amongst others (Dag Erlend Henriksen & Ombudstvedt, 2017; Karimi et al., 2012; MIT, ´n.d.´). This was despite expenditure of 1.9 billion NOK on planning for full-scale CCS on both projects between 2007-12 (Riksrevisjonen, 2013 via Normann 2017). Seeing as these were halted after substaintial funding and a lengthy planning process, it would appear that the projects enountered more uncertainties than orginially envisaged. Osmundsen and Emhjellen (2010) conducted a commerical analysis of the Kårstø CCS project, conculding that it would be a *"very unprofitable climate measure with poor cost efficiency. It would require more than USD 1.7 billion in subsidies, or in excess of USD 133 million per year"* (Osmundsen & Emhjellen, 2010, p. 7818). A feasibility study also revealed that there were risks in investing due to unknown future demand, which was uncertain after 2020 (Gassnova SF & Gassco, 2010, p. 9).

A report by the office of the Auditor General of Norway expressed concern with Mongstad as having operating costs that were too risky and not proportionate with regards to the return on investment regarding CO_2 handling (Riksrevisjonen, 2013, p. 117). A driver of full-scale CCS at Mongstad for private actors had been the prospect of CCS costs being fully covered by the authorities (Kaarstad, ´n.d´). The contract negotiated with the government stipulated that public funds would be used for planning and construction, but with a cost overrun gurantee to be beared by Statoil. According to a report by the ENGO Network on CCS, the estimate was thus set higher by Statoil and, with the prospect of cancellation of the full-scale factility, the report made recommendations including a renegotiation and competative tender process (Skriung, 2013b, p. 11). Offical cost estimates for the full-scale facility suggested an investment outlay of 20-25 billion NOK, whilst the planning process costs were no less than 3.2 billion NOK for caputre and 1.6 billion NOK for transport and storage according to the ENGRO Network report (Skriung, 2013b, pp. 10-12). The report also drew comparisons with other worldwide projects, stating that "*For the project to be a facility that paves the way for CCS, the costs must be reduced to the level of CCS implementation elsewhere, like the*

Boundary dam project in Canada, which is building a full–scale CCS project at a cost of about CA$0.6 billion"[4] (Skriung, 2013b, p. 10).

Whilst early estiamtes in 2006 suggested costs amounting to 1,2 billion NOK for the TCM (aside from the 25 billion NOK for the full-scale facility), changes to estimates in 2008 riased this to 2 billion NOK. In addition, planing and preperation costs towards full scale cature were estimated to reach 1,5 billion NOK. The 2009 government budget suggested to more than double funding from 0.92 to 1.882 billion NOK, however this was later reduced back 0.9 billion NOK. The total cost estimate increased further to 5.2 billion NOK in 2009 and 6.452 billion NOK in 2011 (Shackley & Evar, 2012). Thus cost uncertainties proved very problematic in the Mongstad project, both for the TCM and subsequently cancelled full-scale facility. Uncertainty in other aspects also can have negative impacts upon costs, such as scientific uncertainty in the case of Mongstad leading to project delays and subsequently higher economic costs (Haarstad & Rusten, 2016; Markusson, Shackley, et al., 2012). The Halten CCS project was also cancelled after the project was shown not to be cost effective, desptire no apparent barriers towards technical feasiblilty (MIT, ´n.d.´; Torvanger, 2007).

5.5.2 Key financial risks and "financeability"

It has been suggested that CCS projects rank lowest amongst prospective projects on the Norwegian Continental Shelf with regards to willingness on behalf of private companies: *"From all the projects we analyze, the CCS project ranks lowest on project profitability, measured by net present value and internal rate of return. When capital or other input factors are scarce, oil companies apply net present value indexes to rank projects. The CCS project also struggle in comparison with petroleum projects on such rankings, both due to higher capital commitments and lower net present value. In projects with perceived high political risk, oil companies prefer a short pay-back time for projects. We find that the CCS- project has a much longer pay-back time than the petroleum projects"* (Emhjellen & Osmundsen, 2013, p. 10). One of the respondents outlined that, with small domestic emissions, it is difficult to generate a CCS economy in Norway (interview with Halland, 2019a). Herzog (2017) outlines that Sleipner and Snøhvit have had common financial drivers: the cost of

[4] Boundary Dam has cost significantly more, however. According to Zero it is a $1.24 billion demonstration project, with $0.6 billion for CCS and the rest for modernizing the plant (ZERO, ´n.d´-a).

adding CCS being s small percentage of overall costs, the projects still being profitable despite absorption of the costs and that the projects align with a broader business strategy.

"A private actor's main purpose would be to make money. They're not implementing CCS only to save the world. They are doing that because they have to basically, they have obligations through the framework, and they have some pressure from the politicians and also the social responsibility they have as a major company. But they would not implement CCS if it's more financially viable not to do it, and if they can get away with not implementing it. If they find a cheaper way of cutting their emissions, they will of course do that." (interview with Ombudstvedt, 2019a)

With regards to process industries, the question of whether the burden lies upon the producer or user is also relevant. Operators may seek to recuperate the costs of CCS implementation by raising the price of products, thus willingness to pay becomes a consideration. With regards to Norwegian CCS projects, the outlook looks somewhat positive with the ramifications of the Full-scale CCS project. Jakobsen et al. (2017, p. 534) find that capture would increase the cost of cement production at the Norcem plant by 70% excluding transport and storage, which they state would impact the competitiveness of the cement produced. Thus, they see public financial support as necessary to overcome this additional cost. However, Holmås et al. (2019, p. 7) find that, even if cement prices rise by 100% once CCS is fitted in Norway, this would only result in a 1% increase in the cost for new buildings and 3-6% for concrete based road projects. There may be a willingness to pay for an incremental cost increase if the product is produced with zero emissions, as arguably such an incremental increase could be seen as good value for such an environmentally friendly product. One would suspect that the developers also recognise the value of a carbon neutral product, thus other externalities are worthy considerations in economic analysis. This could therefore increase the finaciability of such projects with this added value, although there is insufficient data to make concrete conclusions at present.

The price of CO_2 emissions can be a crucial determinant in CCS investment decisions (Holmås et al., 2019). The market value of CO_2 emissions needs to be of a sufficient level to incentivise mitigation and is seemingly insufficient under the EU ETS (von Stechow et al., 2011). The lack of a CO_2 price to make CCS commercially interesting was highlighted by one of the respondents to be the main barrier and source of risk (interview with Kalesi, 2019). The

EU ETS is described as not sufficient to trigger rapid CCS diffusion. Indeed, one of the informants outlined the need to close the cost gap, as current projects will cost far more than the current ETS price (interview with Eikaas, 2019). However, state support and instruments in Norway are seen as giving potential to promoting markets for low-carbon solutions and making CCS attractive in Norway (Holmås et al., 2019, p. 6). Thus, Norway has gone some way towards rectifying this market failure. There are a number of financing methods, both technology push and market pull, that can be used to incentivise projects as well as regulatory and business drivers (Herzog, 2017). Subsidies can help with capital costs and expenditure, but still leave uncertainty regarding project lifecycle costs (von Stechow et al., 2011). What has been suggested is that market internalisation combined with increased R&D funding and robust CO_2 taxation policies is needed in Norway (Karimi et al., 2012). The outcome of the Full-scale project is likely to be large determinate of future uncertainty in this regard. One of the informants outlined that, after its completion, the Norwegian state expect private actors to find business models without further state contribution for closing cost gaps (interview with Eikaas, 2019). Another outlined that the government has to enable the business and market starting, with perhaps a similar regime as has been applied to the offshore industry to encourage industries to step up (interview with Ombudstvedt, 2019a)

5.5.3 Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 6)

The EU ETS, launched in 2005, is a cap and trade scheme and the world's largest emissions trading system. It is designed to incentivise greenhouse gas reductions via the establishment of a carbon price. Cap and trade approaches have been criticised for not giving sufficient incentives to investors of new technologies. The return on investment is still often negative, despite high carbon prices, due to the high capital costs involved (Groenenberg & de Coninck, 2008). The EU-ETS is said to have a limited impact on CO_2 abatement technology, due to the low carbon price and future carbon market uncertainty (Mo & Zhu, 2014). Low carbon pricing and price fluctuation adds to uncertainty and serves to hinder CCS development, as does uncertainty over future EU policy. Löfgren, Wråke, Hagberg, and Roth (2014) are critical of the impact of the EU ETS, stating that in Sweden it has had no significant effect on firms' decisions to invest in CO_2 mitigating technologies. They question as to whether it should be reformed, or as to whether other policy instruments should take an increasing role. Kemp and Pontoglio (2011) concur in the EU ETS having had no evidential impact of innovation. Knopf et al. (2014) argue that it is likely political factors and regulatory uncertainty may have played a key role in prior EU ETS carbon price decline, and that specific policy instruments related to innovation and technology diffusion should be used to supplement the scheme. Groenenberg and de Coninck (2008) are critical of the EU ETS due to its limited time horizon and short-trading periods. They recommend complimentary polices at EU and Member State level to account for its deficiencies and provide greater incentive for CCS.

Norway has had a carbon tax implemented since 1991, which applies to emissions from oil and gas production. Statoils decision to test CCS, the Sleipner Project, was credited in part due to the carbon tax (Banet, 2017; Price & McLean, 2014), the carbon tax having also incentivised the Snøhvit project in addition (Jennie C Stephens, 2006; Zapantis, Townsend, & Rassool, 2019, p. 11). The rationale is well summarised as follows:

"If we ventilated it at Sleipner, we would have to pay the CO_2 tax offshore, which is about 50 euro a ton. It's been 50 euro for the past 25 years. So it's a commercial decision. Once you have captured it should you release it and pay the tax or should you inject it and take the cost of injecting it, but then you don't have to pay the tax. That's a pure commercial decision. And for Sleipner that is a positive case. Of course, we also like to store it for environmental reasons, that's an addition argument, but the financial incentive itself is sufficient. It demonstrates that the high CO_2 tax works" (interview with Eikaas, 2019).

The level of carbon tax versus the cost of injection swayed the decision to store CO_2 as, according to the GCCSI, the tax penalty for CO_2 was US$50/tCO2 at the time, whereas the cost of injection and storage was US$17/t$CO_2$ (Zapantis et al., 2019, p. 11). Statoil has avoided paying tax on an estimated 1 million tonnes of injected CO_2 per annum, which is reputedly cost effective (Global CCS Institute, Baker & McKenzie, WorleyParsons, & Electric Power Research Institutue, 2009, p. 39).

Norway almost doubled the tax rate for offshore oil and gas production from 210 NOK to 410 NOK per ton of CO_2 in 2013 (Price & McLean, 2014), or 0.96 NOK/Sm3. The 2018 general rate is around 500 NOK per tonne of CO_2 (Finansdepartementet, 2018). The 2019 state budget increases the CO_2 tax again from 1,06 to 1,08 NOK/Sm3 (Samuelsen, 2018). The level of tax also adjusts depending on the different CO_2 levels of the fuel content (heavy oil, light oil and natural gas). All participants in a production licence are jointly held responsible for payment (Banet, 2017). The tax is applicable to burning of petroleum, discharge of natural gas into the air and discharge to air of CO_2 separated from petroleum. Therefore if CO_2 is captured or re-used it is not subject to the tax, and for the same reason is not subject to the obligations of the EU ETS (Banet, 2017). These two regulatory instruments, the CO_2 and the ETS, are therefore applied in Norwegian regulation of the offshore petroleum industry.

Norway joining the EU ETS in 2008 means that those required to surrender allowances under the scheme are exempt from paying the tax with regards to some sectors or products. Sectors that are at risk of leakage can receive up to all their allowances at no charge, but the petroleum sector is not allocated free allowances under the EU ETS and must purchase these from the market. In 2016, the cost of an allowance for emitting one tonne of CO_2 was around 45-55 NOK. (Banet, 2017, p. 32). If emissions are subject at the same time to a CO_2 tax and an emission quota obligation, they are in principle subject to double regulation. However, taxation of the petroleum industry has been lessened to account for the price of carbon emission allowances under the EU ETS (Global CCS Institute et al., 2009, p. 38). This is to avoid double counting of emissions; thus, a reduced tax rate is applied to keep the carbon price at a reasonable level. The 2012 Kilmameldingen allows for CO_2 tax adjustment if the price allowances in the EU ETS were to increase, however the methodology for how the overall carbon price and CO_2 tax rate are calculated remains vague (Banet, 2017). Banet (2017, pp. 35-36) suggests that perhaps the series of adjustments necessary to deal with the overlap raises questions of climate regulation effectiveness, whilst advocating the Norwegian approach due to the low level of EU allowances. It is argued the Norwegian government corrects two market failures, 1) social costs of emissions from petroleum activities and 2) the failure of the ETS market.

Duan et al. (2013) find that the implementation of a carbon tax helps to promote CCS development. It would seem this is evident in the Norwegian case from the origins of the projects at Snøhvit and Sleipner. The carbon tax makes investment more economically viable and thus can be seen to reduce uncertainty with regards to expectations over future emissions pricing in long-term decision making. With the EU ETS seemingly not providing the desired incentives for investment in CO_2 abatement technologies, Norway's policy makers seem to have had some success domestically in reducing uncertainty in strategic decision making. Currently the rules do not recognise negative emissions, and thus no economic incentives exist in this regard. This issue has been highlighted as a potential issue for Norcem and particularly Klemetsrud should Norway choose to opt in waste facilities to the EU ETS (Gassnova & Gassco, 2016, p. 53).

A stable carbon price, as opposed to a more flexible scheme, allows for considered long-term investment decisions. Uncertain future costs and revenues can be off-putting for investors, but the government's commitment to the carbon tax, evident in incremental increases since its implementation, helps to provide a degree of clarity. If the tax continues to increase the rate on CO_2, then CCS projects should become increasingly attractive. Carbon price volatility can be seen to discourage investment (Mo, Schleich, & Fan, 2018). Fuss, Szolgayova, Obersteiner, and Gusti (2008) distinguish two types of uncertainty with regards to the commitment of government to a climate policy regime: market driven price volatility around a mean price and bifurcating price trajectories mimicking uncertainty about changing policy regimes. They find that a producer, facing uncertainty around future CO_2 pricing, invests into carbon-saving technology earlier than if the price path was known beforehand. This would seem at first hand to contradict the need for a stable carbon price path. The reasoning is that "imperfect information", in simulating stochastic price paths, will also generate CO_2 prices high enough to warrant earlier investment. Knowledge that CO_2 prices will not decrease drives investors to act sooner and thus the authors see fluctuations as beneficial for early investment in this regard (Fuss et al., 2008, p. 716). If prices are known, then investors may only implement CCS at the specific period in which it becomes worthwhile to do so, thus delaying investment in such cases. They also find that policy uncertainty induces the producer to wait until the government makes further commitment, thus the learning about government commitment becomes more valuable than investing into mitigation technologies (a real options effect). Thus, viewing policy uncertainty as more harmful than market uncertainty. A government with a consistent commitment to carbon reductions and CCS development, bi-lateral and cross-party support for objectives and cohesive long-term strategy should therefore provide a greater degree of clarity and incentives for investment in CCS technology as opposed to one that gives fewer indications to strong policy commitments.

Another Norwegian government mechanism that also incentivises petroleum exploration is the reimbursement system for exploration costs, introduced in 2005, the details of which can be found on the governments webpage Ministry of Petroleum and Energy (´n.d.´). If this were also applicable to CCS activities it would reduce uncertainty for developers with regards to the costs of establishing storage site viability:

"Well, it's a bit strange the whole funding of wells in Norway, because if you call this a exploration well for petroleum, then the company would get 78% back. But when you have an exploration well for CO_2, you don't have this tax-refund mechanism" (interview with Rørvik, 2019).

5.5.4 Uncertainty 5: Assessment summary

The lack of large-scale projects and thus availability of data adds to uncertainty. Fitting CCS entails additional costs and the Norwegian development history indicates that actors may have underestimated cost uncertainties, a concern that has been raised with regards to the prospective Full-scale project. Economic considerations can vary based upon CCS application, whilst a pure cost-based approach my not result in optimal environmental and technological efficiency. Issues with cost have evidently proven a major barrier to CCS deployment in Norway, particularly underestimations, and the Full-scale project awaits investment approval.

Other uncertainties can also have negative implications for costs, as evident in the case of Mongstad. Absence of profitability negatively impacts willingness to invest, with CCS projects a low priority for Norwegian private companies. The price of CO_2 is also a key determinant, with the EU ETS having evident shortcomings. Norway's domestic carbon tax has helped incentivise investment but still requires increases to further reduce uncertainties related to the costs of CCS. Public subsidies and finance can also help mitigate uncertainties and increase viability, but evidently there are limitations. Several project cancellations attributed largely to an absence of economic viability, despite heavy public financing, are evident that public financial support is not sufficient in isolation. Uncertainty related to economic and financial viability seems to be one of the most significant barriers to CCS development in Norway. Policy uncertainty is heavily linked to economic uncertainty, but policy seems the best tool via which the most prevalent uncertainty can be rectified.

5.6 Uncertainty 6: Policy, political and regulatory uncertainty

The GCCSI states the policy environment must achieve four things: 1) A clear aligned purpose with CCS investment, 2) be clear and unambiguous, 3) give predictability for investors regarding future policy and 4) provide stability for investors against political risk (Global CCS Institute, 2018a, p. 33). Watson et al. (2014) are critical of flexibility in policy making generating uncertainty.

"One of the main conclusions of the State Auditor was that the complexity of the development of CCS at Mongstad had been underestimated when the original agreement with Statoil was made, and that this later limited the state's opportunities for managing the project. What we are trying to show is that underlying these financial and organizational problems there are more fundamental disconnections between policy-making arenas and industrial actors. " (Haarstad & Rusten, 2016, p. 348)

These disconnections, as outlined above, can also have a significant impact on the effectiveness of the policy making process. CCS development thus requires a well-managed policy network to align actors towards cohesive strategies. The policy network for CCS in Norway has been strengthened through the compromise reached via CCS deployment at gas-fired plants, evidenced in the resultant spending of 1,9 billion NOK on the planning of full-scale CCS at Kårstø and Mongstad, and approx. 5 billion NOK on a technology test centre for CCS at Mongstad between 2007-2012 (H. E. Normann, 2017, pp. 86-87). H. E. Normann (2017) also illustrates how CCS is evident of a cohesive policy network conditioned on long-term state interest. Thus, the strength of the policy network for CCS in Norway also reduces uncertainty, with CCS advocates having privileged access to the policy process and strengthening policy protection for the technology. The GCCSI policy indicator assesses nine policy measures to derive an assessment of each nations policy strenght with respect to deployment of CCS. As per Figure 4 below, we can see Norway is by far the best performer when it comes to the CCS policy indicator score:

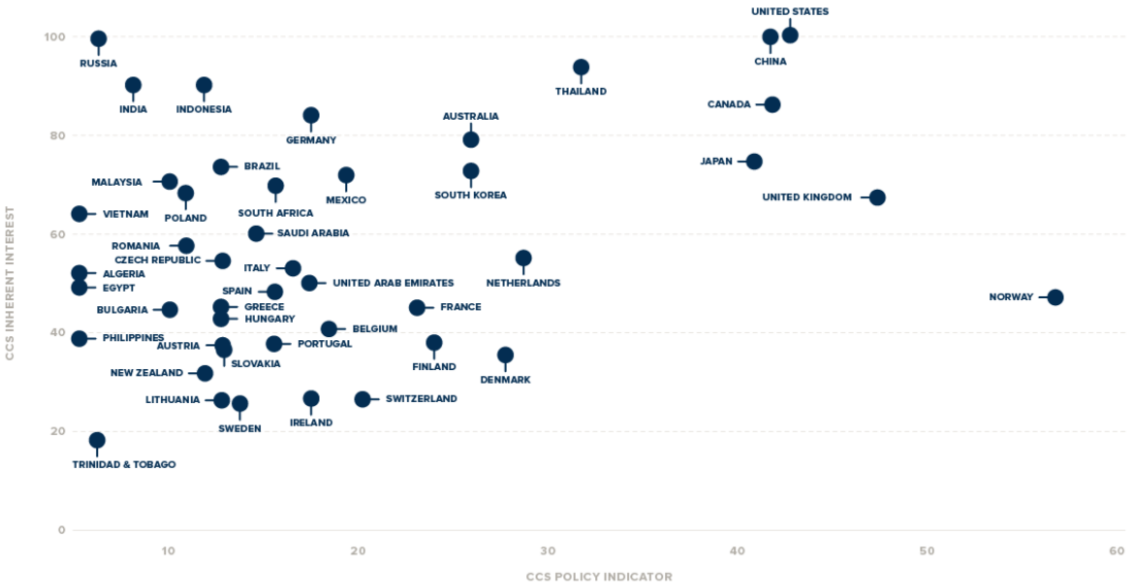

Figure 4: Comparing 2018 CCS Policy Indicator results and the 2018 Inherent Interest Scores for key countries Taken from: (Global CCS Institute, 2018a, p. 34)[5]

Norway has increased its score from 40 in 2015 to 56 in 2018, whilst the GCCSI recognises Norway's long history of government policies designed to support CCS (Zapantis, Consoli, & Havercroft, 2018, p. 8). Again, this would support any argument of Norway, at least comparatively, having a strong policy framework for CCS. The uncertainty around CCS development should therefore be somewhat reduced and inspire greater confidence for Norwegian CCS development. Suffice to say that, if one perceives Norway as having deficiencies in its CCS policy, then these deficiencies are likely to be exemplified elsewhere.

5.6.1 Nature of legal/regulatory framework to share risks/liabilities

Legal uncertainties are not merely limited to issues surrounding storage, as was mostly discussed under uncertainty 2. Reins (2018) also places emphasis on the legal/regulatory uncertainty in asking as to whether the Carbon Capture and Storage Directive stifled the technology within Europe. The 2009 CCS directive (Union, 2009) is the world's first dedicated piece of CCS legislation (Chiavari, 2010). It makes amendments to prior directives in order to create incentives for fast rollout of CCS technology. The EU Directive, despite providing a legal framework the development, leaves many barriers and uncertainties that require resolution in order to provide companies with proper incentives to invest in CCS (Haan-Kamminga et al., 2010). The uncertainties in the implementation of the CCS Directive

[5] For matters of clarity, the Inherent Interest Indicator is a relative determination of a nation's economic dependence on fossil fuels.

and the regulatory issues encountered at Member State level are listed by Haan-Kamminga et al. (2010, pp. 244-248). These are as follows:

1. Capture of CO_2: The directive does not provide for mandatory CCS, but a legal basis for CCS as a mitigation option under the ETS. Proposals for mandatory CCS on new installations might be problematic if emission caps based on the Directive on integrated pollution prevention and control (IPPC) clash with CCS in the ETS system.
2. Transport of CO_2: Transportation is subject to little international regulation and the directive does not provide uniform standards, thus creating legal uncertainty.
3. Storage of CO_2: Responsibility for management, maintenance and safety for potential sites yet to have a CCS licensee needs to be addressed. The United Nations Convention on the Law of the Sea also prohibits installations being left abandoned, but these may be suitable for CCS at a later stage. Liability issues also arise.
4. Third party access: The Directive obligates Member States to guarantee access to pipeline and storage facilities for potential users. However, Member States may decide to apply a stricter regime hampering cross-border collaboration.
5. Closure/Long-term Stewardship: The competent authority will take on responsibility 20 years post-closure. This transfer happens once it is satisfied that CO_2 is permanently contained, and a payment has been made from the operator, thus there can be uncertainty surrounding the requirements. Liability uncertainties exist regarding damage post-closure, whilst point emitters may seek to make use of storage facilities in other territories should the liability framework be more favourable elsewhere.

It is argued that the CCS Directive was adopted too early, with regulatory intervention at a premature stage challenging because of insufficient and conflicting data about the impact of the technology as well as societal and environmental uncertainties (Reins, 2018, pp. 44-45). This is what is referred to as the Collingridge dilemma (Collingridge, 1980). The intention to facilitate rapid roll-out of CCS through the creation of financial incentives is deemed a failure by Reins (2018, p. 57) as, due to low carbon prices and other complications, it did not provide sufficient incentives for investors.

So, what of these uncertainties in relation to CCS in Norway? Norway is not a member of the EU, but has implemented the directive due to its membership of the European Economic Area

(R. Heffron et al., 2017, p. 13). Hallenstvedt (2008) states *"As the Norwegian rules were not written with CCS in mind, they do not solve all the legal questions adequately. There is a need for further legislation, for example concerning responsibility for leakages, clarification of the permit system and usage of the territorial sea for CCS not part of petroleum activities"*. CCS activities in Norway are largely subject to legislation that is generally applicable to industry activities and, due to CCS bearing many similarities with existing petroleum activities, much of this legislation is of relevance ("Norwegian CCS legislation," ´n.d.´). Whilst there is a degree of uncertainty that remains with regards to a lack of clarity in the CCS Directive and fragmented domestic framework, Dag Erlend. Henriksen and de Besche (2012) outline that, as the regime already applies to Norwegian industrial activities on a general basis, its structure and features should be well-known for experienced investors. They do not view the regulatory regime as a barrier towards CCS projects. As one respondent outlined:

"We do have a regulatory framework so, even thought there might be some uncertainty on how to use that framework, and what kind of flexibilities you have and what kind of leverage you have and the way to do things your way, there are uncertainties, but they're not show stoppers." (Ombudstvedt, 2019a)

Irene Rummelhoff, Equinor's executive vice president for New Energy Solutions, stated that *"the next big tasks are developing technology, regulations and general commercial conditions that may stimulate an extensive roll-out of CCS"* (Equinor, 2017). Legal frameworks around CCS can be seen as continuously evolving (Marston & Moore, 2008), whilst if the regime is too inflexible this may also generate barriers to diffusion or augment other uncertainties unintentionally. For example, too restrictive regulations may make storage unfeasible if provisions are excessive in the extent to which preventative leakage measures and safeguards must be implemented, monitored and controlled, or if penalties are disproportionate so as to make the investment unattractive despite minimal risks. Common law can also be understood as an attempt to achieve economic efficiency and must be subject to changes and development for it to remain efficient (P. H. Rubin, 1977).

Transportation is a key consideration in full-scale CCS development. The CCS Directive focuses on pipelines connecting major point emitters and storage, and thus other forms of transportation are notability omitted (R. Heffron et al., 2017, p. 13). With the North Sea viewed as a key area for CO_2 storage, transportation by ship is of increasing relevance. The

CCS Directive does not specifically address the issue of transboundary transportation, thus again requiring statutory frameworks at Member State level (R. J. Heffron et al., 2018). This also adds to uncertainty regarding liability for CO_2 lost during transport. According to (R. Heffron et al., 2017, p. 5), Norway joins the Netherlands and UK in having the fewest legal hurdles to overcome for realisation of cross-border CO_2 projects as illustrated by table 3 below.

Legal Issues	**Germany**	**Belgium**	**Netherlands**	**UK**	**Norway**
	German Backbone	**CAR Pipeline**		**UK-Norway EOR**	
			Rotterdam Nucleus		
International Legal Issues					
International Participation	☑	☑	☑	☑	☑
London Protocol	☒	☒	☑	☑	☑
National Legal Issues					
National Law & Policy	☑	☒	☑	☑	☑
Law & Economics	☒	☑	☑	☑	☑
Liability Issues	☒	☑	☑	☒	☒
Local Legal Issues					
Planning law and Permitting Issues	☑	☒	☑	☑	☑
Other Issues	☑	☑	☑	☑	☑

Note: Key: ☑ = good legal environment; ☒ = problems in legal environment

Table 3; Legal assessment overview of CO_2 transport scenarios. Taken from R. Heffron et al. (2017, p. 5)

R. Heffron et al. (2017) believe that international agreements will take some time, as evidenced by the UK Norway Framework Agreement for transboundary hydrocarbon reservoirs and infrastructure taking 3 years to be agreed. Norway's CCS policy is deemed somewhat clearer than that of the UK for example: *"Norway has CCS legislation in place for* CO_2 *transport pipelines and other CCS-related infrastructure. Approval must be obtained under the Petroleum Act for storage of* CO_2 *from petroleum activities (including EHR). It should also be noted that Norway has indicated an interest in international CCS collaboration"* (R. Heffron et al., 2017, p. 14). The GCCSI also assesses national legal and regulatory frameworks in 55 countries yet does not rank Norway as amongst Band A countries with highly advanced CCS-specific regimes: *"Critically, the sluggish pace of legal and regulatory development continues among nations included in Bands B and C…for these countries there has again been little or no observed improvement to their regimes in the past 12 months"* (Global CCS Institute, 2018a, p. 39). The GCCSI outlines that several uncertainties surrounding the technology remain within international agreements and require resolution (Global CCS Institute, 2018a, p. 40). Figure 5 below shows the global overview of the CCS regime strength as determined by the GCCSI.

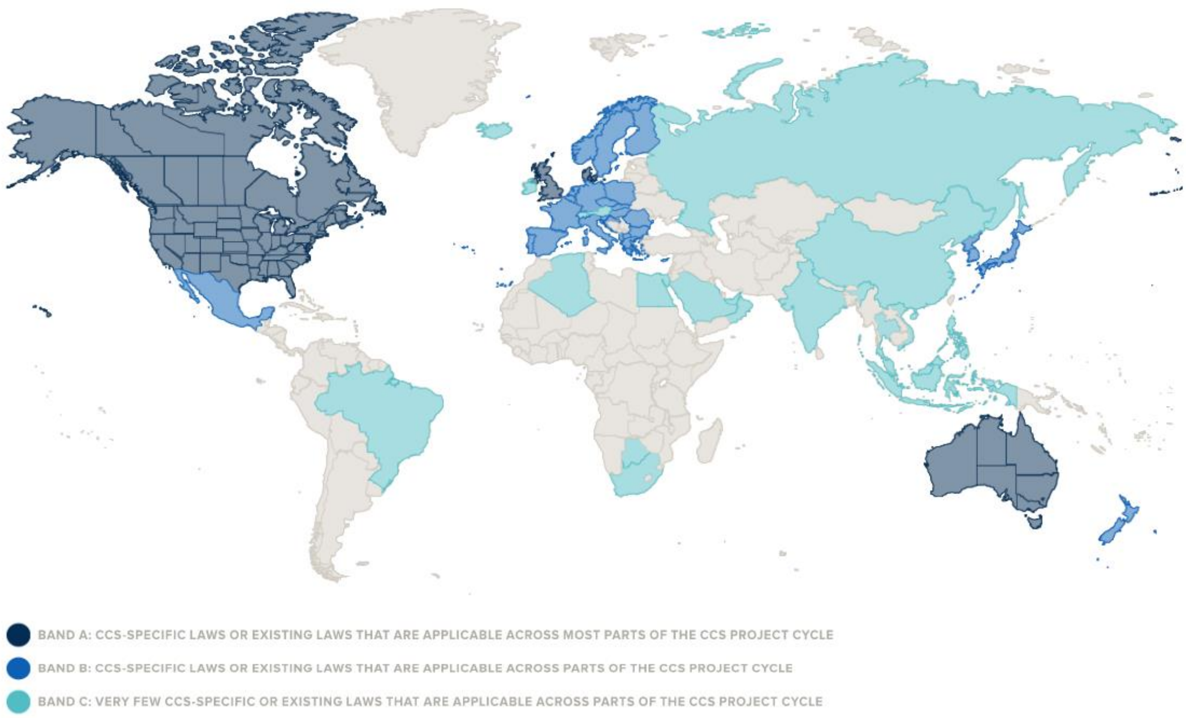

Figure 5: Global perspective of CCS-specific law and regulation 2018. Taken from Global CCS Institute (2018a, p. 39)

5.6.2 Role of subsidies, other forms of economic/financial support, and other sources of finance (shared with uncertainty 5)

In uncertainty 5 examination of the EU ETS and carbon price in relation to CCS uncertainty was assessed. Suffice to say these are also indicators for policy uncertainty. To avoid repetition we will now focus our attention towards subsidies and economic/finance support. Here the focus will be predominantly upon state funding, which can also be used for a quantitative measure of political commitment. Martinsen (2010) uses Norway to illustrate that governments should assume the high costs of early development via technology subsidies, advocating that a target national subsidy for nascent technologies (whilst having only a marginal influence on Norwegian CO_2 emissions) can have a significant contribution to early deployment.

Tjernshaugen (2008) uses research, development and demonstration (RD&D) budgets to measure political commitment to CCS, thus this can be used as an indicator in both displaying economic and financial support as well as the extent of political commitment in Norway. The RD&D budgets in the study are then divided by GDP. The results show Norway as having the most extreme values, with CCS RD&D relative to GDP several times higher than any other country (Tjernshaugen, 2008, p. 12). This study used 2005 RD&D budgets, and thus in 2005 CCS RD&D amounted to 152.4 million NOK (Tjernshaugen, 2008, p. 6). In 2010 CCS was RD&D funding accounted for over 30% of Norwegian clean energy RD&D (E. Moe, 2016), thus seemingly a substantial portion of energy solutions funding is allocated towards CCS. Since this study, only one large scale Norwegian CCS facility has been realised in the form of the Snøhvit CCS project, and thus an updated measure of Norway's political commitment in the form of direct RD&D contributions may provide indications of two aspects: 1) whether Norway still has a strong political commitment to CCS and 2) if a lack of CCS funding that is contributing to uncertainty.

The Norwegian CLIMIT programme for RD&D of CCS has been active since 2005 (Slagtern et al., 2018). It is a cooperative programme between the Research Council of Norway, who administer R&D and Gassnova, who administer pilot and demonstration projects. As of 2018 CLIMIT has supported 500 projects, whilst the Norwegian Government has invested more than €870 million in RD&D of CCS. The other instruments for development are the centres for Environment-friendly Energy Research (CEER), the ECCSEL platform[6] and the TCM which has received almost €600 million in investment (Slagtern et al., 2018, p. 2). R&D within CEER focuses on CCS deployment in industry and European CO_2 storage in the North Sea (Slagtern et al., 2018, p. 3). Of interest is that Slagtern et al. (2018, p. 4) state that *"due to lack of business models and commercial initiatives, investment from industry has been scarce, and an increasing part of the CLIMIT R&D portfolio has the last years been researcher projects with no financial support from industry…however a shift took place in 2017, when almost 60% of the funding for new projects was competence projects in industry or innovation projects for industry"*. This we can see in the graph below, as well as funding distributions for both CLIMIT and CEER.

[6] A pan-European research infrastructure, the centre in Trondheim is funded by the research council of Norway

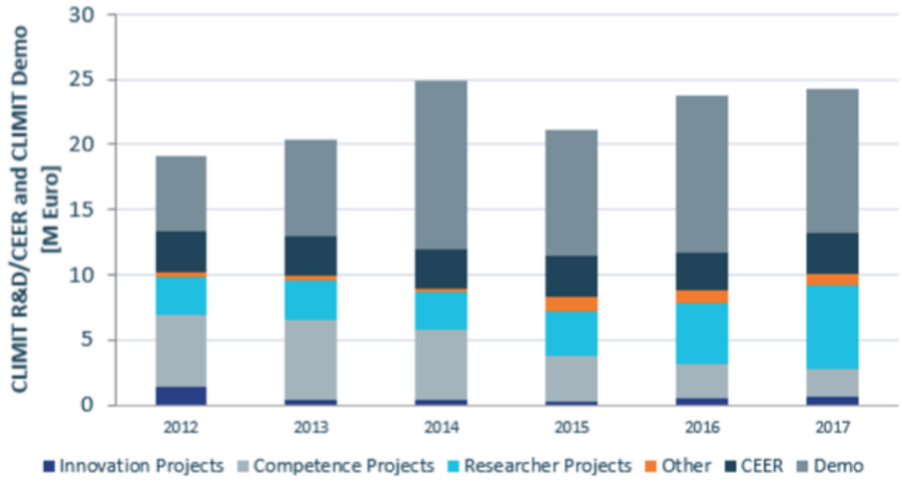

Figure 6. Public RD&D funding for CCS in Norway. Taken from (Slagtern et al., 2018, p. 4)[7]

The 2016 budget proposed 255 million NOK to invest in new technology for CO_2 handling, with 230 million allocated to the CLIMIT research program and 25 million to the Technology Center Mongstad (TCM). A 30 million increase from 2015, as well as 80 million NOK granted for studies to explore possible sites for a full-scale demonstration plant (energidepartementet, 2015). Altogether, according to CLIMITS yearly review, 38 new projects received grants of 254 million NOK. At the end of 2016, the CLIMIT R&D programme had 68 active projects with a combined support budget of NOK 478 million NOK, whereas CLIMIT Demo had 107 active projects with a combined support budget of 632 million[8] (CLIMIT, 2016, p. 22).

In 2017 new projects received 221 million NOK from the CLIMIT programme, thus a slight decrease from 2016. This brought total support for CLIMIT R&D up to 483 million NOK for 69 active projects, whilst CLIMIT Demo had 103 active projects (a decrease of 4) and total allocated support of 564 million NOK (down from 632). The Research council of Norway also coordinates the European initiative Act for accelerating CCCS technologies. In 2017 eight new projects were started, seven of which have Norwegian partners, receiving 96 million NOK in support. This funding comes from CLIMIT R&D (38 million NOK), CLIMIT Demo (28 million NOK) and the European Commission (32 million NOK) (*CLIMIT Summary*, 2017, p. 22). Act funding therefore also has helped to increase overall support. The tables below both help to outline recent trends in CLIMIT RD&D expenditure.

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[7] The figures include funding from CLIMIT R&D research projects, competence projects for industry, innovation projects in industry, CEER and CLIMIT Demo

[8] Note that combined support budgets are support that has been budgeted to projects over several years.

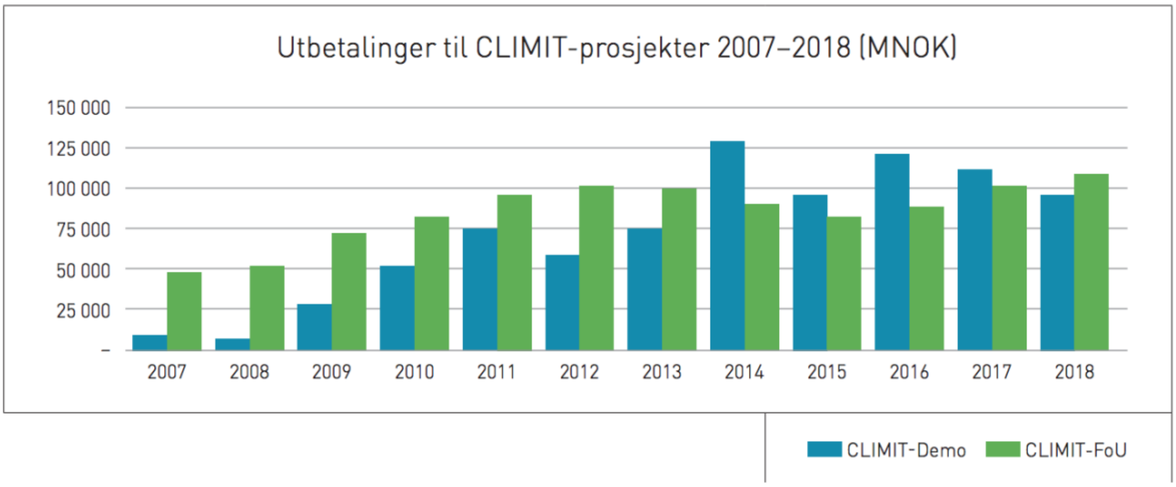

Figure 7: “Payments to CLIMIT projects 2007-2018” taken from (*CLIMIT oppsummert*, 2018, p. 27).

The 2018 budget proposed cuts to 509 million NOK, down from 1.3 billion in 2015 and 2.2 billion in 2016 respectively (Tveit, 2016; ZERO, 2017). In response to the proposed cuts, Bellonas Sirin Engen remarked “*we find it difficult to see that CO_2 management is one of the Government's five priority areas for climate policy"* (Tveit, 2016). ZERO stated that these cuts, as well as delays for the realisation of the full-scale CCS project, would create uncertainty amongst actors over the government’s intention (ZERO, 2017). Despite the proposed cuts, in 2018 new projects received 201.5 million NOK in support from CLIMIT. CLIMIT Demo has a total of 102 active projects (a decrease of 1 from the year prior) with a total allocated support of 473 million NOK (a decrease of 91 million NOK), whereas CLIMIT R&D had 64 active projects (a decrease of 5) and total allocated support of 490 million NOK (an increase of 7 million NOK). It is also worth noting that the report stipulates the reason for the low amount of 57 million NOK for new projects is that ACT projects are granted in 2017 and 2019, but not 2018 (*CLIMIT oppsummert*, 2018, p. 26).

According to the GCCSI the Norwegian government allocated 280 million NOK to advance CCS deployment in 2018 (Global CCS Institute, 2018a, p. 35) via funding to support Front End Engineering and Design (FEED) studies for the two developers involved in the Full-scale CCS project (Zapantis et al., 2018, p. 11). Financial support for CCS appears to be increasing. The national budget for 2019 proposes 670 million NOK for work on CCS, an increase of 160 million NOK compared to the prior year (Ministry of Petroleum and Energy, 2019b). The government has also recently announced plans, pending Parliament`s consent, to fund 75% of the costs for an exploration well for CO_2 storage on the Norwegian Continental Shelf, which will bear un upward limit of 345 million NOK on the total estimated cost of 535 million NOK (Ministry of Petroleum and Energy, 2019a). The grant for TCM Mongstad is increased by 13 million NOK to 208 million NOK, whilst the Norwegian CCS Demonstration project is proposed to receive 175 million (Stokset, 2018). One respondent outlined that uncertainty arises in the manner in which funds are granted. This being due to funding being announced annually in the state budget, as opposed to reserving a set amount of money to guarantee project development through to operation, such as establishing a fund so that private actors can be sure of investment (interview with Ombudstvedt, 2019a)

What is therefore evident is substantial financial support for CCS in Norway. Tjernshaugen (2008) already found extreme values from 2005 figures, and investment has increased dramatically since then, despite some fluctuations. It also indicates resolve to see CCS realised in spite of slow development and high-profile project cancellations. However, the amount of public funding previously awarded with little result may also be seen as a failure and evident of the high risk in funding CCS. If the funding is still not deemed enough to incentivise CCS investment in Norway it would most likely indicate the strength of current uncertainties.

5.6.3 Role of other forms of policy support

Bui et al. (2018, p. 1134) see the key commercial risks that require public support as being (i) cross chain default risk, (ii) post decommissioning CO_2 storage risk, (iii) CO_2 storage performance risks, (iv) decommissioning cost and financial securities related to the CO_2 storage permit, and finally (v) insurance market limitations for CO_2 T&S operations. They state that the introduction of commercial models that entail a transfer of risks iii–v categories to the public sector a way to remove the key barriers that have thus far prevented the private sector from investing in CCS, improve financeability and consequently reduce the risk premium added to the cost of capital funding. Management of the risks for technical and integration across the full CCS chain is difficult for the private sector without proven models for commercialisation (Bui et al., 2018).

Norwegian State aid rules prohibit covering more than the costs related to CCS (Gassnova & Gassco, 2016, p. 54). A summary of the feasibility studies for full-scale CCS in Norway outlines that, for the framework conditions and incentive structure, the starting point of the

State is a split cost and risk between the state and industry partners (Gassnova & Gassco, 2016, p. 54). The regulations in the Greenhouse Gas Emissions Trading Act are the only regulations for the entire chain and, whilst they do not cover transportation other than pipeline transport, according to the report this may be subject to change (Gassnova & Gassco, 2016, p. 55). Thus, most aspects of the chain are pursuant to existing regulations specific to the established practice, with shipping pursuant to maritime regulations and storage to the Petroleum Safety Authority regulations and Pollution Control Act amongst others (Gassnova & Gassco, 2016, pp. 55-57). Awareness that the regulations may need to be adapted has been recognised, thus indicating a flexible learning approach.

Transportation is a key consideration in full-scale CCS development. The CCS directive focuses mainly on pipeline transportation, however with the North Sea viewed as a key area for CO_2 storage, transportation by ship is of increasing relevance. The CCS Directive does not specifically address the issue of transboundary transportation, thus again requiring statutory frameworks at Member State level (R. J. Heffron et al., 2018). This also adds to uncertainty regarding liability for CO_2 lost during transport and risk assessments for cross-border activities. Norway of course is not a member of the EU, but has implemented the directive due to its membership of the European Economic Area (R. Heffron et al., 2017, p. 13). Therefore Norway has implemented similar requirements, whilst all transportation arrangements must be approved by the Ministry who can also make alterations (Roggenkamp, 2018, p. 255). Transboundary movement of CO_2 is prohibited under Article 6 of the London Protocol (" London Protocol," 2012). Norway has proposed an amendment to the protocol to allow export in certain circumstances, but it will require broader ratification for cohesive cooperation (Dixon, Garrett, & Kleverlaan, 2014) and requires the agreement of 29 member states before it enters into force (Dag Erlend Henriksen & Ombudstvedt, 2017, p. 7445). This is seen as a major barrier to cross-border projects. Uncertainty is not so prevalent in projects based solely within Norwegian borders but, to facilitate development in Europe and to exploit Norway's substantial storage potential for CO_2, the framework needs to be developed.

5.6.4 Extent of political commitment/legitimacy

CCS has frequently been at the top of the national political agenda in Norway (Tjernshaugen & Langhelle, 2009), with Norway having developed an extensive CCS policy backed by strong political support (Ishii & Langhelle, 2011; Lipponen et al., 2017). Political support for CCS in Norway, which is comparatively higher than in many other countries, can be seen in the context of the following summarisation: *“By political support I mean three things: A central place for CCS on the national climate policy agenda, strong statements of commitment to a CCS strategy by political leaders, and finally policy measures to foster technology development and commercial applications”* (Tjernshaugen, 2011, p. 228). Indeed, Prime Minister Kjell Magne Bondevik resigned in 2000 due to losing a motion of no confidence over the question on whether to allow gas-fired power stations without CCS (Tjernshaugen & Langhelle, 2009)**.** Lipponen et al. (2017, p. 7591) make suggestions on how long-term political support for CCS implementation can be fostered. These include consistent bipartisan or multi-party support, a national strategy for climate mitigation (with a clear role for CCS), support from proactive environmental NGO´s and finally global leadership to act as a catalyst for CCS policy commitments. They emphasise that Norway is evident of consistent multi-party support and highlight Bellona as having a positive impact on promoting policies supportive to CCS. Such consistency, as evident in the Norwegian CCS story, ensures a stable landscape for operators and investors. Multi-party support can give confidence that even changes of government are unlikely to see withdrawals of support for funding and projects. Budinis et al. (2018) outline that major oil and gas companies have previously asked for clear, stable and long-term policy frameworks.

CCS has in fact been described as a political glue and a win-win-win solution in the context of the Norwegian approach (Tjernshaugen & Langhelle, 2009). This is due to it being viewed as a technology that solved political difficulties related to Norway’s heavily fossil fuel based economy and climate policy, helping to unify political parties and coalitions via compromise to the country’s climate policy dilemma (Tjernshaugen & Langhelle, 2009, p. 111). *“As an affluent small state seeking to harmonise petroleum exports with ambitious normative commitments, Norway makes a valuable setting for learning how certain types of mitigation measures may help bridge a states otherwise conflicting energy interests and climate obligations”* (Jo-Kristian S. Røttereng, 2018, p. 216). Realisation of CCS technology would allow Norway to justify continued extraction and exportation of fossil fuels whilst upholding commitments to international climate agreements.

Political drivers can help give legitimacy and impetus to technological development. “*The private sector is very unlikely to deliver fully integrated CCS infrastructure and projects without increased public sector support and clear government policy that supports CCS.”* (Bui et al., 2018, p. 1137). Policy development can also be seen in relation to levels of awareness and public perceptions of CCS, with Norway having well-developed policy correlating with higher public acceptability (Haug & Stigson, 2016). The political connotations of CCS are particularly prevalent in the context of Norway's domestic political discourse and international climate policy (J. R. Meadowcroft & Langhelle, 2009; Jo-Kristian S. Røttereng, 2014; Jo-Kristian Straete Røttereng, 2016). Evidence of this can be viewed in the light of the technology test centre and carbon capture storage project at Mongstad being the centrepiece of the Stoltenberg governments climate strategy (Haarstad & Rusten, 2016). However, as one respondent pointed out, willingness alone is not enough:

"In Norway we see enough political willingness to act, my question mark would be, is political willingness enough? Is the Norwegian government actually listening to the industry's needs, and is the Norwegian framework providing enough incentives and clarity for CCS?" (interview with Kalesi, 2019)

CCS also appeals as a fit-and-conform strategy in this regard, requiring little changes to the current energy system. With Norway's economy being heavily reliant on oil and gas exports, and the total government net cash flow estimated to rise to 286 billion NOK in 2019 (Ministry of Petroleum and Energy & the Norwegian Petroleum Directorate, 2019), CCS can be a less disruptive climate mitigation strategy likely to find common support despite the various diverging domestic agendas. Norway's reliance on oil and gas is therefore unlikely to see drastic curtailment in the near future, thus reducing uncertainty surrounding potential longevity of CCS projects and support amongst national actors. It is a solution that would enable continued fossil fuel extraction and ensure a market for Norwegian exports.

5.6.5 Uncertainty 6: Assessment Summary

The CCS policy strength of Norway provides a great deal of clarity to decision makers. Norway is by far the best policy performer according to the GCCSI. Norway also has a strong policy network that helps to reduce uncertainty. This network is not only bolstered by influential actors working to strengthen CCS protection, but also benefits from political cohesion surrounding CCS technology. The legal framework is still evolving and, whilst not specifically written for CCS, the regime already applies to general industrial activities which induces confidence in being extensive, familiar and highly developed. Whilst the EU CCS Directive leaves many barriers and uncertainties, Norway's strong domestic legalisation helps compensate. The remaining uncertainty seems largely to emanate due to a lack of specifically tailored CCS legislation. However, lessons from the early adoption of the EU Directive may indicate that this approach is beneficial over the long-term as opposed to adopting legislation early without an adequate learning process. There is awareness that regulation will need to be adapted, although uncertainty remains over cross-border projects due to inconsistent legislation across wider Europe.

RD&D expenditure can provide a useful (albeit imperfect) quantitative measure for political commitment. Public financial support can thus be shown to be consistent and indicative of unflinching political resolve to develop large-scale CCS, having increased dramatically over the years despite high profile setbacks and lack of uptake. Commitment is also demonstrated via multi-party support and the regularity at which CCS has emerged at the top of the political agenda. Substantial public expenditure and strong policy has still struggled to incentivise CCS which, judging by the oft mentioned cost ineffectiveness of subsequently cancelled projects discussed in the assessment of uncertainty 5, would yet again be indicative of uncertainties surrounding economic and financial viability proving a major hurdle to development. Based upon the evidence, policy seems one of the lesser problematic and prevalent of the key uncertainties, however a major obstacle is Norwegian policy's failure to overcome economic and financial uncertainty with its current approach.

5.7 Uncertainty 7: Public acceptance

Public acceptance is considered to be recognised as an important factor for successful diffusion of new technologies (Devine-Wright, 2007; Huijts et al., 2012; Wüstenhagen et al., 2007). Indeed, societal controversies have also led to public backlash and rejection in the past (Gupta et al., 2012). Whilst some would disagree or seek to downplay its significance, there are many historical examples where negative public perceptions have resulted in rejection or stalled adoption of technologies. For example Germany, a country with long standing anti-nuclear sentiment, began phasing out its nuclear power plants in the wake of the accident at the Fukushima Daiichi Nuclear Power Station (Glaser, 2012). Whilst it is arguable as to the degree of influence public acceptance has upon technology diffusion, it is certainly not to be dismissed. Public acceptance is seen by many as one of the main challenges CCS must overcome in order to direct favourable political attitudes in the future (Wennersten et al., 2015). There are a number of recurrent themes with regards to public concerns surrounding

CCS that are apparent in the literature. So, if the existing literature stresses that public acceptance is one of the main challenges facing CCS, what of public acceptance in Norway?

5.7.1 Levels of public awareness/acceptance of risks

Pietzner et al. (2011) cite Norway as an example of a country that lacks representative results with regards to public perception and awareness of CCS. Their research was conducted via surveys conducted in six European countries, with a random sample of each survey consisting of over a thousand respondents, to provide a data set of more than 6100 available interviews. The objective was to gauge CCS awareness and perceptions, whilst an experiment was conducted to investigate whether different information content affected public perceptions of CCS. The findings were that respondents in Norway expressed the highest level of awareness of CCS, with 62.6% having heard a little or quite a bit about the technologies. Also, that older age groups indicated a lower level of awareness in contrast to younger respondents (Pietzner et al., 2011, p. 6302). Still, with 37.4% of those surveyed in Norway having never heard of CCS, it can be seen as a good indication that there is still a large proportion of the population who are unaware of the technology.

Country	**Never heard about CCS**	**Heard a little bit**	**Heard quite a bit**
Germany (N=1017)	61.9	28.3	9.7
Greece (N=1000)	76.5	18.7	4.8
The Netherlands (N=1109)	50.0	44.5	5.5
Norway (N=1000)	37.4	45.2	17.4
Romania (N=1002)	75.7	21.4	2.9
UK (N= 1040)	61.9	31.8	6.3
Total	60.4	31.9	7.7

Table 4: Percentages of self-reported awareness of CCS specified per country. Taken from Pietzner et al. (2011, p. 6302).

The researchers also found the results of the experiment to confirm the assumption that initial perceptions of those with little knowledge about CCS can be strongly influenced by new information (Pietzner et al., 2011, p. 6304). Relating back to criticism of surveys predominantly capturing pseudo opinions, we can therefore take some degree of reassurance against drastic future opinion shifts based upon lack of information in the Norwegian context. This is due to a significant proportion of those surveyed at least having some awareness of CCS technology.

Another more recent study also showed higher public awareness of CCS amongst Norwegian participants, in comparison to other nations that were selected due to their differing stages of CCS development. Questions of support for energy sources, attitudes to CCS, CCS risk and benefit perceptions and a range of psychological constructs and demographic measures were asked (Whitmarsh et al., 2019, p. 3). Interestingly, despite Norway having the highest levels of awareness, the UK showed higher levels of support for CCS (Whitmarsh et al., 2019, p. 5). Norwegians were found to express significantly higher support for CCS when it is framed in "business as usual" scenario (as opposed to with carbon dioxide utilisation (CDU) or lifestyle change) (Whitmarsh et al., 2019, p. 6). Thus, it would seem CCS framed as a "technological fix" solution to climate change has greatest appeal in Norway based upon these results.

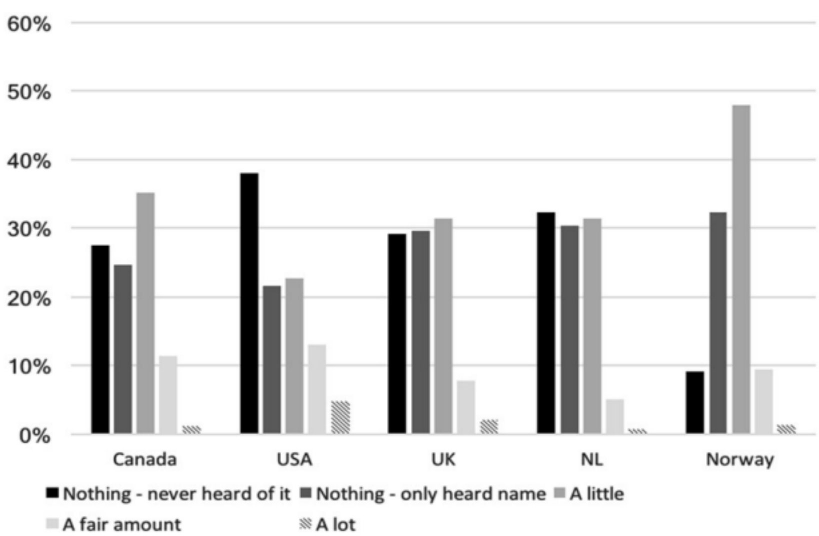

Figure 8: Public awareness of CCS by country. Taken from Whitmarsh et al. (2019, p. 3)

Suffice to say that awareness of CCS technology is seemingly higher in Norway than in many other nations who also hold at least some degree of CCS interest. This is not necessarily surprising due to the significant contribution of oil and gas exports upon the wider Norwegian economy, the proportion of the population with ties to the energy industry as well as the prominence given to CCS in the form Norwegian policy, R&D expenditure and discourse surrounding climate mitigation methods (Espen Moe, 2012; Jo-Kristian S. Røttereng, 2014; Tjernshaugen & Langhelle, 2009).. But awareness of CCS is not implicitly indicative of support for the technology, and indeed, there could be circumstances where opposition grows with heightened awareness of potential negative consequences. For example, the German public have been found to have knowledge of CCS, whilst acceptance of CO_2 storage remains low (Dütschke, Schumann, & Pietzner, 2015).

With regards to risk, research has shown that concerns over storage and risk perception results in the public being more adverse to CCS storage when in close proximity to their communities (Braun, 2017; Krause, Carley, Warren, Rupp, & Graham, 2014). An assessment of CCS in the Nordic region found that possibilities to store CO_2 offshore was a clear advantage based upon public perceptions (Haug & Stigson, 2016). Although there is limited evidence, many sources speculate that offshore storage of CO_2 helps to alleviate public concerns in comparison to onshore storage (Davis & Landrø, 2019; Hammond & Shackley, 2010, p. 32; Lofstedt, 2015, p. 686). As discussed in examination of uncertainties surrounding safe storage, there seems to have been little opposition to offshore storage in Norway (Nordic Council of Ministers, 2007), whereas onshore storage has resulted in public protests in cases such as Germany (North Frisia and Eastern Brandeberg) (Dütschke et al., 2015) and the Netherlands (Barendrecht) (Brunsting, Best-Waldhober, Feenstra, & Mikunda, 2011). With early CCS developments in Norway and focus of future projects being focused towards development of offshore CO_2 sequestration, this may also be a contributing factor towards higher levels of public acceptance amongst the Norwegian public. Projects that would bring carbon storage in closer proximity to communities, particularly onshore, could therefore have a negative impact upon public perceptions. This concern seems to be reflected in the governments considerations, as a summary of the Full-scale project outlines that there is a risk with Fortum Olso Varme`s project over public perception of having amine emissions close to a city (Ministy of Petroleum and Energy, 2018).

Surveys of public opinion are of course subject to various limitations. One of the criticisms levelled at traditional surveys regarding public opinions of CCS is that they predominantly assess pseudo opinions, which are of low utility due to their unstable and inconsistent nature (Daamen et al., 2011). Suffice to say, the more information an individual is provided with regarding CCS technology, the higher the quality of the opinion and thus the better they can be used to predict and explain future levels of CCS acceptance (Daamen et al., 2011, p. 6183). The various factors that influence public perceptions of CCS, such as individual, geographical and informational are varied and heavily contextualised (Whitmarsh et al., 2019). Thus, causation between public opinion and technological development is not easily measurable, but it is a useful indication of how likely the landscape may shift from under developers' feet if public opinion were to sway heavily towards support or opposition towards particular technologies, which in turn may alter the inclination of policy makers in particular.

Effective communication can also help reduce uncertainty and increase public acceptability. Gassnova initiated the Beyond Acronyms project, that sought to understand the challenges of language in facilitating CCS communication. There is suggestion that CCS is too technical in its phraseology and that this can create a barrier for people in understanding CCS (Bryhn, Brønn, & Håndlykken, 2018). Norway has also hosted CCS "safaris" to help with engagement and communication (Doyle, 2018; Gassnova, 2018c). Communication strategies may go some way to reducing uncertainty, both via engagement with the public and through feedback loops. There is suggestion that low public acceptability in one country may affect others, thus this may be something for Norwegian actors to bear in mind (Ashworth, Boughen, Mayhew, & Millar, 2010).

5.7.2 Specific manifestation of public opposition (or support)

There is also logic in suggesting that perhaps political party preference may have some bearing on attitudes towards new technologies. This can also be seen as indicative of the ideological framing of the wider issue of climate change and efforts to mitigate (McCright, Dunlap, & Marquart-Pyatt, 2016; Zia & Todd, 2010). Karlstrøm and Ryghaug (2014) present the results of two sets of survey data (Table 5 below) that highlights the significance of political preferences, whilst also finding that these have a greater bearing upon attitudes to renewable energy in Norway than geographical factors.

	Onshore wind	Offshore wind	Hydro	Bio	Gas with CCS	Gas w/o CCS
Constant	4.405	4.611	4.497	3.907	2.766	2.560
Age	–.07*	–.10**	.05	.00	.26**	.04
Gender	–.00	.01	–.19**	.11**	–.15**	.05
Income	–.01	–.02	–.03	–.04	–.01	.11**
Education	–.07*	–.04	.05	–.00	–.02	–.10**
Labour Party	.01	.08	.01	.03	.12**	–.05
Progress Party[a]	–.02	.01	.02	–.02	.04	.06
Conservative Party	.11**	.13**	.07	–.01	.12**	.04
Christian Democrat Party	.02	.03	.03	–.01	–.02	–.08*
Centre Party	.02	.07	–.06	–.01	.04	–.02
Socialist Left Party	.02	.08*	–.01	.06	.04	–.13**
Liberal Party[b]	.05	.06	–.01	.03	.07*	–.11**
R-squared	.02	.02	.06	.02	.13	.07
N	1017	1007	1011	969	910	904

Table 5: Regression results for energy technologies. Taken from Karlstrøm and Ryghaug (2014, p. 660)

With regards to CCS technology, gas plants without CCS scored unfavourably amongst environmentally orientated voters on the left and centre, however many right voters were more strongly in favour of this option than the alternative fitted with CCS (the authors suggest this could be due to the cheaper costs involved). With CCS policy having been adopted by Norway's major political parties and having had relatively stable political support (Lipponen et al., 2017; Jo-Kristian Straete Røttereng, 2016), this should also go some way to explaining high levels for CCS acceptability. Cross-party support, dialog among a broad array of actors and influential environmental groups such as the Bellona Foundation and ZERO can thus also help to explain public acceptability for CCS technology in Norway (Tjernshaugen, 2011; Tjernshaugen & Langhelle, 2009).

Haug and Stigson (2016) find that interviewees from the Porsgrunn municipality display positive attitudes towards CCS activities, with these seen as providing opportunities for the local community. Positive attitudes arise due to socioeconomic factors and community history and identity. The municipality views jobs related to CCS as helping to legitimise and maintain industry in the region, thus preventing depopulation and perhaps promoting new industrial activity. Inhabitants are also adjusted to industrial activity that has been a vital part of the community and, as a consequence, the environmental challenges related to this. Promoting the community as an environmental and technological leader, as well as experience with shipping of more dangerous products, also makes Porsgrunn well suited to CCS. Yara and Norcem capture activities have not generated major concerns (Haug & Stigson, 2016, p. 320). The authors state that *"Porsgrunn municipality's positive view on CCS to a great extent mirrors what has been deemed key to acceptance in the literature on CCS, i.e. managing risks, creating benefits and taking the local community's history, identity and future plans into consideration."* (Haug & Stigson, 2016, p. 322)

A recent study also looked at the Norcem cement plant in Brevik as a case study of communication and social perceptions towards CCS. The study argues that the position of Norcem is a positive one in this regard, due in part to it being an important and well liked company in the Breivik community, but also due to Norcem having a considerate approach in building trust with the local community (Aursland & Jordal, 2018). The study also notes that this communication has also been limited due to uncertainty as to whether full-scale CO_2 capture would be realised.

We can therefore see that, at least in the context of the Norcem project, public perception seems to be positive. Local involvement could therefore be seen as helping to reduce uncertainty in this regard, perhaps increasing the viability of projects due to positive perceptions built up via various communication channels. Support for technologies can be heavily influenced by the form and medium through which information is communicated (Hobman & Ashworth, 2013). It would seem safe to assume that decision makers would also be more positively inclined towards lending support to projects that receive high levels of support amongst the local community, although this is not a specific finding of the study.

There may also be incentives amongst decision makers in the strategic planning of projects if they help stimulate local employment, support established businesses whom have a positive identity in the local community and achieve environmental policy aims. It has also been suggested that R&D activities have had a vast impact on both political and public acceptability (van Alphen, van Ruijven, et al., 2009). Norway's significant investment in R&D would perhaps therefore contribute to respective political and public acceptability.

Governments may also be reluctant to support CCS technology if public acceptance is lacking (Karayannis et al., 2014). Public acceptability in Norway is likely to reduce uncertainty in the eyes of decision makers and provide them with greater confidence to support CCS technology both via policy and economic instruments. CCS actually proved the solution towards public opposition towards gas-fired power in the early 90´s (Tjernshaugen & Langhelle, 2009). Political parties, environmental NGOs and even the media showed support and helped embed CCS in Norwegian society (Klimek, 2014). A study by Klimek (2014) into Norwegian discourse strongly suggests that there is no organised opposition to CCS and that Norwegian newspapers are positively supportive of the technology. In the research undertaken for this paper, little evidence of any notable present Norwegian opposition to CCS has been found.
It seems that a substantial majority of ENGOS, industry and political parties share confidence in CCS (Jo-Kristian S. Røttereng, 2018, p. 481). This is well outlined by one of the informants:

"I think we are in a very special situation in Norway, because I think nearly all the environmental groups like Belona and ZERO are very eager to get CCS going. And very active, doing a lot of work and communication and a lot of work in the EU system."
(interview with Halland, 2019a)

5.7.3 Uncertainty 7: Assessment summary

In summary there does not seem to be any evidence of present uncertainty forming a barrier to CCS viability in Norway with regards to public acceptability. Norway displays some of the highest levels for CCS awareness according to the research, with no evidence of any notable opposition to CCS technology. The limitation to the findings however is that Norway still lacks representative results and, whilst awareness can be said to be comparatively high, this is not necessarily indicative of support. For example, the German public also have (albeit lower) awareness of CCS technology, but there has been a significant public backlash against CCS developments. On the other hand, this could also be interpreted as an indication that acceptability is high in Norway, as higher levels of awareness have not manifested into public opposition. Offshore CO_2 storage capabilities are also a significant advantage for Norway, with storage proximity seemingly a key area of concern and is a significant reason for such backlash elsewhere in Europe. Political party preferences can also be shown to influence attitudes towards new technologies, with research indicative that this is more significant than geographical factors in the Norwegian case. With CCS development supported by major political parties, whilst experiencing stable and unified support at present, this can also be viewed as indicative of high acceptability.

6. Inter-linkages between uncertainties

Now that assessments of each of the key uncertainties in relation to Norwegian CCS viability have been undertaken, the next step is consideration of the interlinkages between these. As outlined by the frameworks authors, any assessment of overall CCS maturity must not only add up assessments of each aspect, but recognise their inter-related nature and assess what a future change in an individual uncertainty may entail in its impact upon the others (Markusson, Kern, et al., 2012). A visual representation of these as shown in figure 9 below:

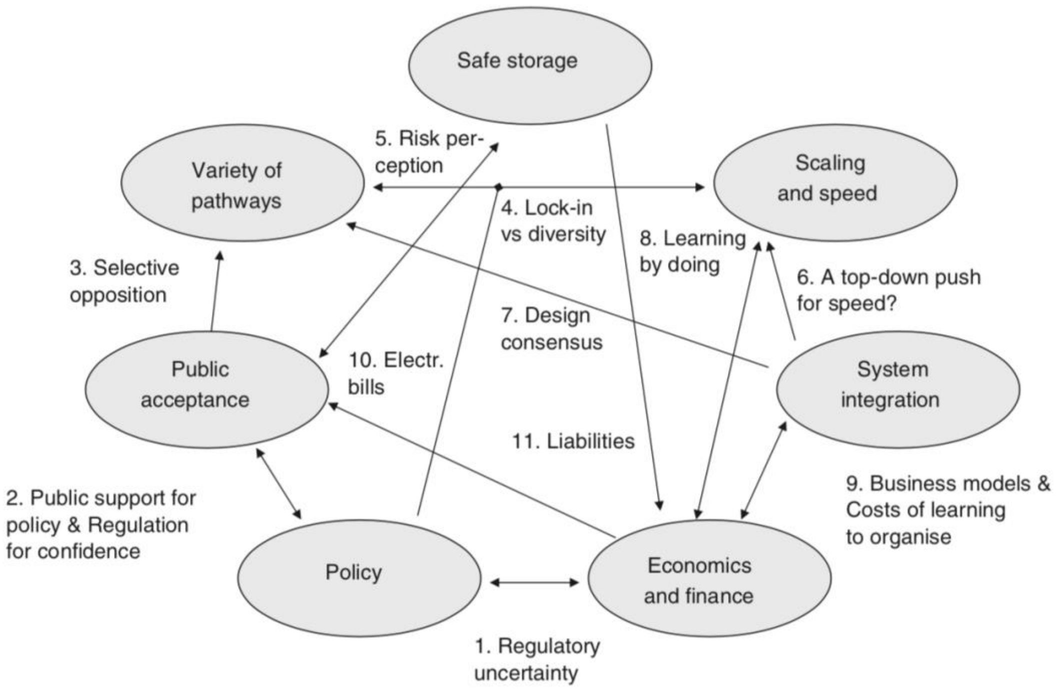

Figure 9: Inter-linkages between uncertainties. Taken from (Markusson, Kern, et al., 2012, p. 912)

These examinations shall mainly be based upon the data that has been presented thus far. This section will also form the premise for the discussion of an overall assessment of CCS maturity, as these examinations inherently entail interpretations regarding the significance of the findings and the insights these provide. It should also be mentioned that examination of these inter-linkages is subject to recognised limitations, as they are too numerous and complex for this paper to provide comprehensive dynamic assessments. It was the original intention to investigate these more thoroughly, but this has been scaled back. An in-depth analysis of these interlinkages is a sizeable task and could quite easily justify a separate paper devoted solely to their assessment, whilst even merely one would provide enough consideration for a paper devoted solely to its assessment. Thus, each shall be acknowledged but addressed very briefly to avoid unwarranted speculation and provide a contextual bridge to the conclusion. The assessment of overall CCS viability in Norway is therefore not conclusive. The findings also suggest there are more than those outlined in figure 9, many of which could be uncovered upon further examination. This would be a recommendation for further research or a more extensive study in building upon the findings presented by this paper. None of the uncertainties exist in complete isolation of another, with greater uncertainty in one aspect having some form of ramification no matter how remote. Some interlinkages are more prevalent than others, such as those outlined by Markusson, Kern, et al. (2012) and discussed below. The following are therefore examples of how interlinkages interact and not conclusive assessments.

6.1 Regulatory uncertainty

The framework presents this as an interaction between the key uncertainties of economics and finance and policy (5 and 6). This is certainly prudent, and perhaps most crucial, due to the significance of economic and financial viability. However, both these uncertainties can be said to impact all key uncertainties to some degree, as well as being interdependent of one another. To take one example of this interlinkage, the significance of the domestic carbon tax in Norway has been outlined in the findings, a major incentive behind the Sleipner project. The problematic pricing under the EU ETS also outlines the importance of carbon pricing in incentivising CCS development and its current deficiencies. The findings suggest that Norwegian policy measures have failed to sufficiently diminish uncertainty surrounding the economic and financial viability of CCS, the insufficient carbon price combining with a price trajectory that has not enticed developers to invest early. Norway’s clear policy and cohesive political support has afforded policy makers the opportunity to implement a domestic carbon tax, which has gone some way towards reducing uncertainty, but the inter-linkage represents the limitations to which this can overcome prevalent economic and financial uncertainty. For want of a better analogy, it can perhaps be easiest to visualize as a seesaw, with the inter-linkage representing the board. If uncertainty is particularly heavy at one end, the load needs to be lightened in order to achieve balance. Any effect on the weight at one end inevitably entails effect at the other.

6.2 Public support for policy and regulation for confidence

A strong regulatory regime is seen as one that can give confidence to stakeholders and generate public support, whilst public acceptance is necessary for political support. It seems reasonable to therefore conclude, based on assessments on uncertainties 6 and 7, that there is a noticeable correlation between strong CCS policy and high public acceptance in Norway. The interlinkage is strengthened at both ends, in the same manner to which a piece of string is pulled to tension. A number of factors evidenced by the findings show this, such as cohesive political support not limiting acceptability via political orientation, favourable discourse manifested in media and public communication, a variety of influential actors having lobbied for CCS early on, offshore allaying public concern and R&D activities establishing a support base and aligning actors. The interplay between public support and regulation and policy serves to embolden both factors simultaneously whilst giving decision makers the reassurance and confidence needed to further support for CCS. With little apparent prevalent uncertainty surrounding public support for the technology in Norway, this should serve to reduce uncertainty for decision makers and illustrates how diminishment of one uncertainty can serve to diminish uncertainty in another. Research is also indicative of awareness being comparatively higher in Norway than its contemporaries, but with few CCS projects currently in operation some degree of caution should still be advised in order to ensure developments do not result in an adverse public reaction. Germany outlines the difficulties in the interdependent nature of this relationship, with conflicts translating over into the federal states influencing the policy process, thus having successfully made implementations to regulations so that they have the opportunity to prevent storage projects (Fischer, 2015).

6.3 Selective opposition

The interlinkage between pathway variety (1) and public acceptance (7) can be seen in the context of opposition to certain technology variants, which can reduce the viability of technological options. This interlinkage is less problematic in the context of Norway, for we have already outlined how there is comparatively high acceptability and knowledge about CCS technology, no prominent opposition to the technology from domestic interest groups and an offshore storage focus that helps to alleviate public concerns. This provides Norwegian decision makers with a privileged opportunity to pursue a variety of technology options for

CCS that may even increase their standing amongst groups who support its development. Of note is that selective opposition to gas-fired power plants actually emboldened pathway selection of CCS as a solution to satisfy all parties, so selective opposition to other technological choices can be seen as having actually strengthened the case for CCS in Norway. The pursuit of this option has seemingly strengthened the regime around CCS, thus increased political support looks to have translated into increased public support, abetted by influential actors and stakeholders (Klimek, 2014). For comparison, an illustrative example can again be seen in Germany due to onshore storage concerns, the so-called NIMBY effect, which may also have generated animosity to the very technology itself and generated a stigma around CCS technology (Fischer, 2015). Public rejection of the technology therefore limits the technological options for decision makers in Germany, regardless of application.

6.4 Lock-in vs diversity

This interlinkage is seen as a connection between uncertainties 1, 3 and 6, in that quick-up scaling can lead to lock-in of inferior technological solutions, whilst on the other hand diversity in pursuit of numerous pathways can spread resources too thinly (Markusson, Kern, et al., 2012). Choices over policy and regulation undoubtedly have a large bearing in determination of the outcome. Technological systems are not wholly resistant to change, but are difficult to transition once entrenched (Markusson & Haszeldine, 2009). Whilst CCS has been said to be lagging behind due to institutional inertia (Karimi, 2017), this does not seem to be the case in Norway, quite the contrary in fact. Norway has dedicated substantial R&D resources to CCS and arguably has an innovation system formed around the technology (Espen Moe, 2012). The findings suggest Norway is arguably not solely at risk of “locking-in” to a specific technological solution. However, it is locked in to a petroleum-based economy. Consequently, should this so called “political-glue” as Tjernshaugen and Langhelle (2009) call it, begin lose its adhesiveness and fail to win out, the remaining available pathways will be severely limited without wholescale structural change. CCS could be seen as resultant of a carbon lock-in pathway. Tjernshaugen and Langhelle (2009, p. 121) view Norway’s consensus mentality as obscuring trade-offs between different CCS policy priorities and more general energy technologies. Prior political push for CCS technology in combination with gas-fired power has failed to result in immediate increased scaling but may have resulted in the industrial alternatives for CCS application being pursued at present. Exploring other mitigation options entails very different connotations for Norway however, as

CCS is presently the only solution that can reduce domestic industrial emissions from certain process industries whilst many other green technological options, such as renewables, would not have any significant impact on domestic emissions resulting from power generation due to Norway's current energy mix. Domestic politics therefore largely defines pathway variety, with direct ramifications for scaling and speed.

6.5 Risk perception

This is largely attributed to perceptions of storage risk as an interaction between uncertainties 2 and 7. Suffice to say, there appears to be little to no evidence of public concerns surrounding storage risks in Norway. All prior and current project proposals are with a view towards offshore storage of CO2 and therefore, combined with no notable opposition towards CCS in Norway, this linkage looks to have strong foundations due to little present uncertainty in either facet. Perceptions could be subject to alterations as CCS developments start to present themselves as more tangible to the general public, however high-profile incidents related to petroleum activity, such as that of the Bravo blowout or Alexander L. Kielland platform accident (Kalsaas, 2013), have not thus far deterred offshore activity on grounds of public acceptability. Thus, the value added by CCS projects may come to be determinant of the risk perceptions surrounding storage in the public sphere, but extensive experience with petroleum activity may also be indicative that the public is somewhat tolerant when it comes to risks related to offshore activities. Risk concerns are perhaps also alleviated due to CCS retaining the support of influential actors who play an important role in communication and fostering trust. Risk governance in the petroleum industry has subsequently been strengthened via responses leading to increased confidence, so there is also perhaps reason to suggest the same process may be applied to subsequent CO_2 storage activities in Norway (Lindøe, 2016).

6.6 A top-down push for speed

A inter-linkage between uncertainties 3 and 4, this interaction is viewed by Markusson, Kern, et al. (2012) to be of importance due to differing governance models being determinate of the speed of deployment and subsequent scaling. A top-down approach perhaps accelerating CCS activity but also increasing the likelihood of technological shortcomings. A balance between integration and speed, particularly in light of the immediacy of climate targets and the ever-diminishing window of opportunity, can be a difficult reconciliation. Herzog (2017, pp. 5697-

5699) lists numerous lessons to be learnt from a review of two decades of CCS demonstration projects, with many seemingly reflected in the history of Norwegian CCS development. Amongst these are; that there are strong links between successful projects and the oil and gas industry, access to markets has to move beyond EOR, regulatory drivers are critical for creating CCS markets, business drivers play a major role, overreliance on subsidies is risky, gasification power-based projects have a poor record and that setting arbitrary time limits on projects has generally led to failure. The failures of top-down driven large-scale gas power with CCS at Halten, Kårstø and Mongstad, contrasted with the success of more bottom-up incentivised natural gas processing in the cases of Sleipner and Snøhvit, would seem to indicate that many of these lessons ring true.

6.7 Design consensus

The inter-linkage between uncertainties 1 and 4 is due to the potential for heavier top-down organisation of the CCS community to result in stronger consensus over design choices, in turn then leading to reduced technological variety (Markusson, Kern, et al., 2012). It is safe to say based on the evidence that there is certainly consensus over CCS as technological pathway in Norway, but as to what degree this can be accredited to top-down organisation is more difficult to conclude. The Norwegian CCS community can certainly be said to be in alignment over support for the technology whilst the government, in establishing the state innovation company Gassnova and Climit R&D fund, also emboldened more specialised and technical focus towards CCS technology (Tjernshaugen & Langhelle, 2009, p. 115). However, due to CCS being first introduced to the Norwegian context by engineers in petroleum research (Tjernshaugen & Langhelle, 2009, pp. 104-105), it could also be viewed as having origins from top-down organisation of the Norwegian petroleum industry. In the long run, should continued efforts on CCS technology prove costly in not providing sufficient learning benefits or economies of scale, this may make continued pathway selection more uncertain for both investors and policy makers. Thus, with changes in either uncertainty 1: pathway variety, in the form of more favourable emerging alternatives, or uncertainty 4: integration of CCS systems, in facing substantial difficulties, this would inherently impact the other and potentially challenge the consensus view for CCS as a “best fit” technological solution.

6.8 Learning by doing

Learning trajectories are often envisaged as reducing capital and operational costs with cumulative production, research, development and demonstration (Kobos, Erickson, & Drennen, 2006). Typically, we would expect diminishing uncertainties surrounding scaling and speed to therefore also positively impact economic and financial aspects. For example, it has already been mentioned that cost reductions and business learning effects are some of the key benefits envisioned by Gassnova in the upcoming Full-scale project. On the other hand, the aforementioned case of French nuclear serves as a reminder that it is possible for costs to increase with accumulated experience, particularly if uncertainties are larger than assumed (Grubler, 2010). Cases of negative learning benefits often prove to be the exception as opposed to the rule, but such cases are indicative that without considered strategy or diminishment of other interacting uncertainties, benefits cannot be taken for granted. This interlinkage is therefore not exclusively one between uncertainties 3 and 5, it is more nuanced, with policy and organisational approaches evidently determinate for the selected developmental approach.

Perhaps so-called learning by searching is also an interlinkage that is omitted from those suggested, whilst necessary due to the findings of Norway’s substantial RD&D expenditure. Learning by doing incorporates effects of cumulative capacity, whereas consideration for learning by searching can incorporates cumulative RD&D in the learning function. Learning can depreciate over time, with RD&D increasingly unlikely to influence cost reductions towards technological optimisation, whilst both learning and depreciation rates may differ both between and within industries. Thus a two factor experience curve is shown to give a more robust approach to capital cost projections (Kobos et al., 2006). This is just but one example, but it is illustrative of the fact that the relationships outlined by the interlinkages are not simply black and white.

6.9 Business models & costs of learning to organise

Varied business models for handling financial risks can be seen as having a better fit with different approaches to CCS integration (Markusson, Kern, et al., 2012, p. 913). Business models can be viewed as an interlinkage between uncertainties 4 and 5, but the severity of all uncertainties should have some influence on the eventual business model selected in a thorough analysis. It is almost impossible to eradicate financial risk completely, but selection of the right business model can certainty help to minimise exposure. Business models must also consider what value can be obtained for the developer. We have seen this inter-linkage evident in the case of Yara`s withdrawal from the Full-scale project, where the business model deemed the learning benefits not sufficient for participation. Sleipner is a contrasting example. Although the projects profitability was evidently attractive, the business model was selected not solely due to this but due to a combination of factors: the need to lower the CO_2 content before export, use of existing infrastructure, considerations of the carbon tax as well as the opportunity to expand the overall business strategy. Thus, a multitude of factors combine in business model selection, which will consider multiple uncertainties.

6.10 Cost of abatement

This interlinkage is referred to as electricity bills by Markusson, Kern, et al. (2012, p. 912 figure 1), an interaction between uncertainties 5 and 7, but CCS in Norway has cost implications for consumers outside of power generation. For example, CCS as applied to pre-combustion for petroleum exports should not have a direct cost implication for domestic electricity bills, whilst CCS for application in industrial processes may be reflected in the price of the product charged to consumers. Amendment of this interlinkage to being termed as the cost of abatement is therefore a more appropriate heading for interlinkage assessment in the Norwegian CCS context. The considerations for this inter-linkage have already been touched upon in section 5.5.2 with the Norcem project. The extra costs entailed with CCS application may be transferred onto consumers by producers, or hypothetically could be subsidised through public investment borne by the taxpayer themselves. Greater confidence in public acceptability for CCS, as well as numerous socioeconomic factors, will indicate whether consumers will be willing to pay for added abatement costs. Public resolve could be tested via perceived mismanagement of public funds at a high cost to the taxpayer if more projects are cancelled despite substantial public finance. The perceived value placed by the public on CCS utility may also affect willingness to pay as well as the general health of the economy or influence of social capital (Jones, Malesios, & Botetzagias, 2009).

6.11 Liabilities vs future costs of CCS

Here the framework presents interlinkage 11 under the heading liabilities, showing interaction between the key uncertainties of safe storage and economics, but in the description it is referred to as the uncertainty regarding future costs of CCS for policy makers in decision making for climate change mitigation options (Markusson, Kern, et al., 2012). Therefore, this has been interpreted as referring to the overall costs of storing CO_2 with CCS as a climate mitigation option and subsequent value of CCS as an abatement tool. Thus, liability for climate change may be weighed against the cost of mitigation portfolio options. Policy makers may employ a strategy orientated towards utilisation of the cost-effective mitigation strategies, or in extreme cases, disregard mitigation efforts entirely should such mitigation costs be deemed as too high when weighed against the valuation of the environment.

Whilst cost uncertainties may lead to dilemmas for policy makers, the findings show that Norway appears firmly committed to CCS development. A number of reasons that have been explored come into play, including; its fit within Norway's constrained climate politics, utilisation of existing infrastructure, relative maturity of the technology, political cohesion, large storage capacity and strong actor consensus. CCS is also a preferable pathway to Norway in allowing for continued petroleum activity and securing the value of reserves. Norway's selection of CCS has been described as a non-cost effective solution to an approach chosen primarily for cost effectiveness reasons (Espen Moe, 2012, p. 26) and thus, if this proves the case over the long term, Norwegian policy makers may start to reconsider. Indeed, the view of its cost effectiveness is dependent upon the unit of comparison. As one of the informants outlined, the basis of comparison has to be with other carbon neutral solutions, which would establish the technology as cost effective (interview with Eikaas, 2019).

7. Conclusions

CCS can make a significant contribution towards meeting both national and international climate targets in the reduction of carbon emissions. With little indication that energy demand is set to diminish in the near future combined with the lack of alternatives for many high emitting industrial processes, accelerating large-scale deployment of CCS technology may be a mitigation necessity as opposed to a preference. Viability of the technology in Norway, with the country's position as a pioneer of CCS development, can be said to have significant implications for worldwide development and deployment. Here a summarisation of the findings will follow in the context of the research questions, before closing with final remarks.

7.1 How can the framework be applied to assess CCS viability in Norway?

In light of this, the purpose of this thesis has been to assess the viability of CCS technology in Norway. This has been achieved via the application of a socio-technical framework as designed by Markusson, Kern, et al. (2012). The first step has been to interpret the framework for application in assessment within the context of Norway. Key uncertainties have been assessed, using the frameworks suggested indicators for measurement and data collection, in order to provide summarised evaluations for each aspect. These suffice for a generalised assessment of CCS viability via consideration of which uncertainties are the most prevalent and present the greatest constraints. The more diminished the uncertainty, the greater strength afforded to overall viability. The interlinkages are then outlined and briefly considered, but these are so numerous and dynamic that this is a limited assessment, therefore further research would be a useful addition for more definitive measurement of overall viability. Generalisations are still possible, and certainty can make a valuable contribution to the currently limited social science research on CCS technology.

7.2 To what extent are these uncertainties prevalent?

Pathway variety, safe storage and public acceptability are found to be the least prevalent of the key uncertainties. The evidence is somewhat clearer with assessment more easily measurable in these aspects, and this clarity alone is undoubtedly indicative of diminished uncertainty. The more difficult and elusive generating data and drawing correlations proves, the more uncertainty is likely to be present. Of course, this is not a basis for conclusion in isolation, thus examining each indicator in turn and applying a qualitative assessment provides for more definitive analysis. Scaling and speed is perhaps the most difficult of the key uncertainties to assess, but this is in part to the limited time dimensions of early CCS development that are inherently linked to this factor. Merely two currently operational projects in Norway are also indicative of uncertainty, however, the maturity of the technology counteracts this to some extent. Whilst a definitive conclusion proves elusive with regards to this uncertainty, it also does not appear to have been as prominent nor as problematic as economic and financial viability thus far, although the two cane be seen as closely interrelated. Uncertainty regarding integration of CCS systems is found to be diminishing with increased learning, but a more detailed comparative technological assessment would allow for a more concrete picture.

Economic and financial viability seems the most prevalent, with numerous indications of its severity evident within the assessment. This is also evidenced by all of the informants having outlined obstacles related to economic and financial viability when asked as to what they considered to be the major barriers to CCS development. Policy, political and regulatory measures provide substantial clarity in many respects. However, the inter-linkage to economic and financial viability, combined with policy failure to address the uncertainty in this relationship sufficiently, results in this being a prominent aspect with important ramifications for viability as a whole. Clarity in one aspect can also embolden aspects related to other key uncertainties via interlinkages. For example, with safe storage generating little uncertainty in Norway, it can then strengthen public acceptance in turn via the inter-linkage of risk perception. Thus, whereby interlinkages interact, efforts to address threats to viability can be targeted to where uncertainty is most prevalent. These uncertainties may therefore change based upon alterations within themselves or via developments in other key aspects. Thus, this dynamism may generate alterations in overall uncertainty levels should elements in socio-technical aspects of CCS be subject to change.

7.3 How are these uncertainties inter-related?

The inter-linkages display the interdependent nature of the uncertainties. Assessment of all inter-linkages as presented in the framework, as well as those that could be exposed with a more detailed examination, is beyond the scope of this paper. The findings evidence this interconnectivity, as well as the potential transferal of uncertainty from one facet to another. Interactions and trade-offs outline the dynamic nature of socio-technical systems and the difficulties in governance. Transition management emphasises that decision making in conditions of uncertainty requires the inclusion of a multitude of microconcerns at the decentralised level (Kemp & Rotmans, 2005, p. 54), thus the interlinkages help to contextualise these. In certain aspects uncertainties can be hard to distinguish from one another, such as the mutual indicator of subsidies/economic and financial support. It is clear that decision makers need to consider a whole range of potential adverse consequences and complications, and hereby the socio-technical framework can provide a valuable tool. The interlinkages between uncertainties require consideration in order for strategies to be effective.

7.4 What are the implications for overall Norwegian CCS viability?

The findings suggest that pathway variety, safe storage and public acceptability seem to be of little impediment to CCS viability in Norway. With regards to pathway variety, CCS seems the prevalent technological choice, receiving substantial investment whilst no alternative exists for CO_2 reductions from many industrial processes. For storage, Norway has ample capacity and data is rather comprehensive, whilst the monitoring of operational CO_2 storage actives has not presented cause for concern thus far. Public acceptability can be said to provide confidence to decision makers due to a combination of factors including; the locality of offshore storage sites, no evidence of significant opposition to CCS and the Norwegian public being well adjusted to similar industrial activities. All of these aforementioned factors contribute towards diminished uncertainty and strengthen overall CCS viability, but steps can still be taken to further diminish what little uncertainty remains.

Policy, political and regulatory uncertainty does not negatively affect viability when measured by most of the suggested indications. Norway is a comparatively strong policy performer with a robust policy network, cohesive political commitment, an established regulatory framework and substantial support for CCS via public funding. However, it is evident that policy drivers have still not provided adequate incentives for CCS development in Norway, the main barrier being the failure to adequately address economic and financial uncertainties. Thus, whilst policy strengthens viability in many respects, the inter-linkage with economic and financial viability also provides a prevalent weakness that affects viability across the sphere of the socio-technical framework. The domestic carbon tax has not resulted in any developments aside from Sleipner and Snøhvit, both of which seemingly required little additional incentive due to the need to purify the gas. It is not merely domestic policy that affects viability either. Norway has taken steps via domestic legislation to reduce the uncertainty generated by EU ETS and CCS Directive, whilst a proposed amendment to the London protocol awaits ratification, but the uncertainty generated upon viability in Europe as a whole also limits the viability of CCS deployment elsewhere from which Norway could derive learning benefits.

More indications of uncertainty are found in the other key aspects. Integrational uncertainty in Norway has been substantially reduced, with prior projects having provided significant opportunities for learning and governance restructure. Uncertainty in this aspect seems largely to generate from contrasting public and private objectives, valuations and conflicts of interest. The success of the prospective Full-scale project will provide clearer indications as to whether such conflict has been adequately resolved. Scaling and speed is perhaps the most difficult of the key uncertainties to assess. Prior attempts at scaling have suffered notable setbacks, such as in the cases of Karstrø and Mongstad, whilst the lack of operational large-scale projects is indicative of the early developmental stage of the technology. Thus, a lack of comparative cases makes the prospective speed of development hard to ascertain whilst providing limited beneficial spill-over effects. This lack of data is perhaps itself indicative of uncertainty in itself however, as uncertainty remains as to whether and how fast CCS can be developed to maturity. Viability is therefore negatively impacted in this manner, however if the prospective Full-scale project is realised then this would certainly diminish scaling and integrational uncertainties significantly.

Economic and financial viability would seem to have many negative consequences for overall viability. The lack of sufficient data is evidently problematic, with economic uncertainties clearly having proven themselves to be significant barriers with regards to prior CCS developments in Norway. Cost uncertainties and the absence of profitability limit the ability of public financing being able to incentivise development. Additionally, the price of CO_2 is evidently insufficient at present, despite the domestic carbon tax going someway to rectifying the failure of the EU ETS. With the difficulties experienced in the lack of commercial opportunity for private developers in the market, a higher carbon price seems the most direct method to achieve accelerated large-scale deployment. This uncertainty has evidently proven a major obstacle to the viability of several subsequently cancelled projects and has also proven a major cause of concern for the viability of the prospective Full-scale project.

7.5 Final remarks

Innovation is inherently uncertain (Lazonick & Mazzucato, 2013, p. 1), therefore it is an impossible task to completely eradicate all identifiable uncertainties. Time is also a constraining factor, due to the need for rapid large-scale worldwide CCS deployment in order to meet climate targets. With this in mind, efforts to reduce uncertainties should be focused as to where these are most prevalent, or as to where there are simple and efficient solutions. Some degree of uncertainty will always be present, therefore decision makers have to decide as to what levels are acceptable, yet do not pose as significant barriers to development. Early identification and recognition of uncertainty is therefore of crucial importance for project development and long-term strategic planning. Resolution can be a challenging and time-consuming process and ironically can only serve to generate more uncertainty if not carefully considered. Overall CCS viability is difficult to conclude without deeper examination of the inter-linkages, and therefore further research is required. Suffice to say it seems that policy is the most appropriate tool by which CCS viability can be strengthened, as the domestic carbon tax has had an evidential impact. Uncertainty surrounding economic and financial viability is a major barrier, but not the only impediment. Norwegian CCS viability could be greatly bolstered should the prospective Full-scale project prove successful, whilst it could open up new pathways for CCS application. The learning and spill-over benefits may have a significant impact for CCS development not only within Norway, but with regards to the global challenge of mitigating worldwide CO_2 emissions. Viability seems healthy in a comparative perspective, but it is still precarious at this early developmental stage. CCS fits Norway as a win-win-win solution (Tjernshaugen & Langhelle, 2009, p. 120), but failure to develop CCS could result in substantial environmental and economic losses, of which future generations will bear most of the consequences.

8. List of interviewees

The following 5 people were interviewed for this thesis project. 3 of the interviews were conducted in person, with two being conducted remotely via conference call.

- Eikaas, Steinar, Head of Low Carbon Solutions, Equinor, Stavanger, 3 May
- Halland, Eva, Project Manager, FORCE, and Geologist, Norwegian Petroleum Directorate, Stavanger, 20 May
- Kalesi, Poppy, Former Senior Consultant Innovation and former EU Regulatory Affairs Advisor, Statoil, Former Programme Manager, Carbon Capture and Storage, Coal and Oil Unit and Policy Analyst, Strategic Energy Technologies, European Commission, Stavanger, 13 May
- Ombudstvedt, Ingvild, Owner/lawyer, IOM Law; Chair, Norwegian CCUS Association; and Chair BASRECCS, Stavanger (remote call), 9 June
- Rørvik, Kari-Lise, Senior Adviser, Gassnova SF, Stavanger (remote call), 21 May

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Appendix: Interview guide[9]

- Can you tell me a little about your role and your experience with CCS technology?
- What would you consider to be the main obstacles/barriers towards large-scale CCS deployment?
- In your experience, do private and public actors perceive CCS development differently?
- Are there any ways in which you feel CCS development could be better facilitated?
- Do you feel CCS is experiencing sufficient uptake in order to sufficiently meet the requisites of current climate targets, both at a domestic and global level?
- How can development be accelerated in your view?
- Is public acceptability for storage high or is there a lack of informed understanding?
- Are current levels of government support and RD&D expenditure sufficient to incentivise developers of CCS technology?
- Full-scale CCS was cancelled with regards to TCM Mongstad in 2013. Could you clarify as to the exact reasons for this?
- The Johansen Storage Complex outlines challenges such as data availability, size and qualification that makes identifying storage somewhat challenging. Is there still much uncertainty surrounding storage capacity in Norway?

[9] This is just a general template of some general questions but, as outlined in the methods, specific questions were tailored to the individual's area of expertise or experience. The last question is one such example. Not all questions were asked if unnecessary due to the detail or elaboration in responses.