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Review of Measures to Enhance Cost-Efficiency in CCS Wells

Master's Thesis

Industrial Economics

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Preface

This thesis is written for the master's programme in Industrial Economics at the University of Stavanger in cooperation with Neptune Energy AS.

I would like to thank my supervisors in Neptune Energy, Gerhard Våland Sund and Brede Tøllefsen for their help, guidance and encouragement throughout the work on this thesis. Thank you for your availability, and for sharing your inputs and knowledge.

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Abstract

Carbon capture and storage is considered an essential method to mitigate climate change and global warming. In order to accelerate the deployment of CCS and make it more profitable, the costs associated with it must be reduced. The European Union has put a cap on the CO_2 market through the EU ETS allowance price, which means that the levelized costs per tonne of CO_2 captured and stored can't exceed this amount. The potential cost reduction by substituting expensive 25 Cr tubing with GRE lined carbon steel has been examined and was found to give a cost reduction of 0.4-0.6 % per tonne of CO_2 stored. Although this may seem like an insignificant reduction, the global scale of things will still make this significant. Furthermore, simplification and tailor-made equipment will also contribute to necessary revenue for this emerging industry.

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List of Abbreviations

IPCC: Intergovernmental Panel on Climate Change

IEA: International Energy Agency

CCUS: Carbon Capture, Utilization and Storage

CCS: Carbon Capture and Storage

DACCS: Direct Air Carbon Capture and Storage

BECCS: Bioenergy with Carbon Capture and Storage

Mtpa: Million tonnes per annum

E&P: Exploration and Production

R&D: Research and Development

LCOS: Levelized Cost of Storage

AI: Artificial Intelligence

DHSV: Downhole safety valve

1 Introduction

1.1 Global Warming and Climate Change Mitigation

Global warming is one of the biggest challenges the world is facing. According to the UNs Intergovernmental Panel on Climate Change anthropogenic greenhouse gas emissions have with high confidence already caused the global surface temperature to rise 1.1 °C above 1850-1900 in 2011-2020 (Intergovernmental Panel on Climate Change, 2023). If the global warming continues in the same rate as this it could have severe consequences, including more extreme weather, draught, rising sea levels and loss of species.

There have been multiple global measures taken in order to mitigate climate change. In 2015 the Paris Agreement was signed, which is an international treaty which has the primary aim of keeping the global average temperature from rising more than 2 °C above pre-industrial levels, and preferably limiting the temperature rise to 1.5 °C (United Nations Climate Change, n.d.). To achieve this goal the greenhouse gas emissions must be reduced significantly within the next decade. According to Rystad Energy, the global energy-related CO_2 emissions are now slightly less than 40 billion tonnes per year. Of this, Europe accounts for approximately 3.3 billion tonnes CO_2/year (Huseby, 2023).

There are 5 main methods to reduce anthropogenic CO_2 emissions (Kaarstad, 2008), (Ringrose, 2020, p. 6). These are illustrated in Figure 1-1 and include:

1) Switching from more carbon rich to less carbon rich energy sources
2) Using energy more efficiently
3) Using renewable energy sources
4) Using nuclear power
5) Capturing and storing CO_2 in geological formations

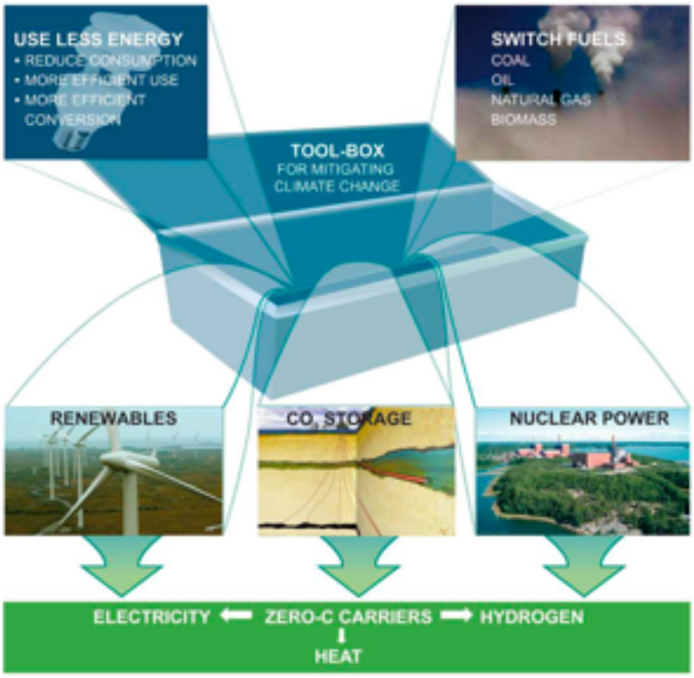

Figure 1-1: Toolbox for mitigating climate change (Kaarstad, 2008)

All the above-mentioned methods are important steps to achieve climate change mitigation, however, this master's thesis will focus on carbon capture and storage (CCS).

1.2 Value of CCS in the Context of Reaching Climate Goals

Carbon capture, utilization and storage is considered an essential climate change mitigation technology by the IPCC, IEA, and multiple other international specialist bodies (Global CCS Institute, 2017). In order to reach the goals of the Paris Agreement, the IEA has estimated that the CCS industry must be responsible for 14 % of the world's cumulative emission reductions, and for this to happen, the amount of CO_2 captured will have to be increased from 40 Mtpa today, to over 5,600 Mtpa by 2050 (Global CCS Institute, 2017, 2021). Climate change mitigation strategies that do not include CCS are likely to face challenges in achieving the 2 °C target. Even if they succeed, the associated cost is estimated to be approximately 140 % higher than it would have been with the implementation of carbon capture, utilization and storage (Global CCS Institute, 2017; Ringrose, 2020, p. v).

Most of the global emissions are not relevant for CCS, as their emission sources have other methods to reduce their carbon footprint. Coal power plants can e.g., be substituted by renewable energy sources like solar power or wind power, and fuel powered vehicles can be replaced by electrical ones. However, about 300 million tonnes of CO_2 emissions each year come from hard-to-abate sectors where CCS have a strong value proposition (Huseby, 2023). These industries are hard to decarbonize using other mitigation methods due to their industrial processes and high temperature requirements (Global CCS Institute, 2020b). Examples of these industries are cement factories, iron- and steelworks and chemical plants. The cement industry alone contributes to about 5% of the global emissions (Bjerge & Brevik, 2014). A visual representation of global, European and hard-to-abate carbon emissions can be seen in Figure 1-2.

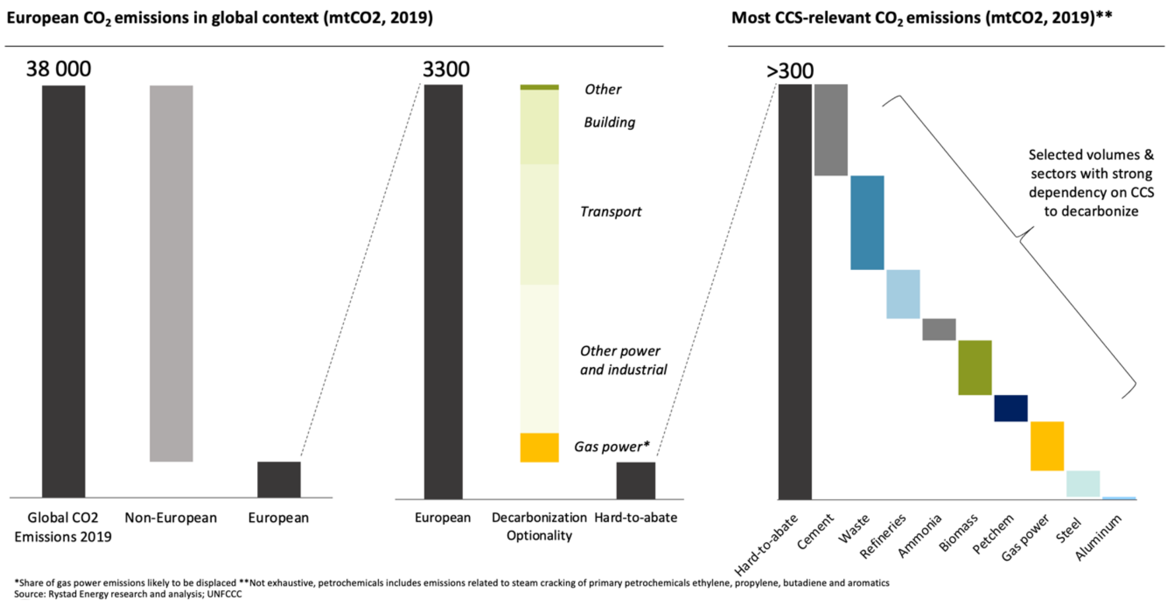

Figure 1-2: Representation of global, European and hard-to-abate CO_2 emissions (Huseby, 2023)

CCS technology can also have the potential to enable negative emissions either by capturing CO_2 directly from the atmosphere (DACCS), or from the combustion of bioenergy (BECCS). Other important applications for CCS includes decarbonization of electrical power plants and facilitating the production of synthetic hydrogen fuels (Global CCS Institute, 2020a).

1.3 Research question

- What measures can be taken to enhance the cost-efficiency of CCS wells in terms of technology maturation?
    - Explore how economic principles, technological advancements, legal framework and effective project management practices can contribute to the cost efficiency of CCS wells in a small scale and in a global scale.

2 Theoretical Background

2.1 Carbon Capture, Utilization and Storage (CCUS)

Carbon capture, utilization and storage is a climate change mitigation technology where CO_2 is captured from various emission sources and then transported either for utilization or geological storage. Figure 2-1 shows different technologies and methods used in different phases of carbon, capture and storage. A short introduction to each phase is given in in the sections below.

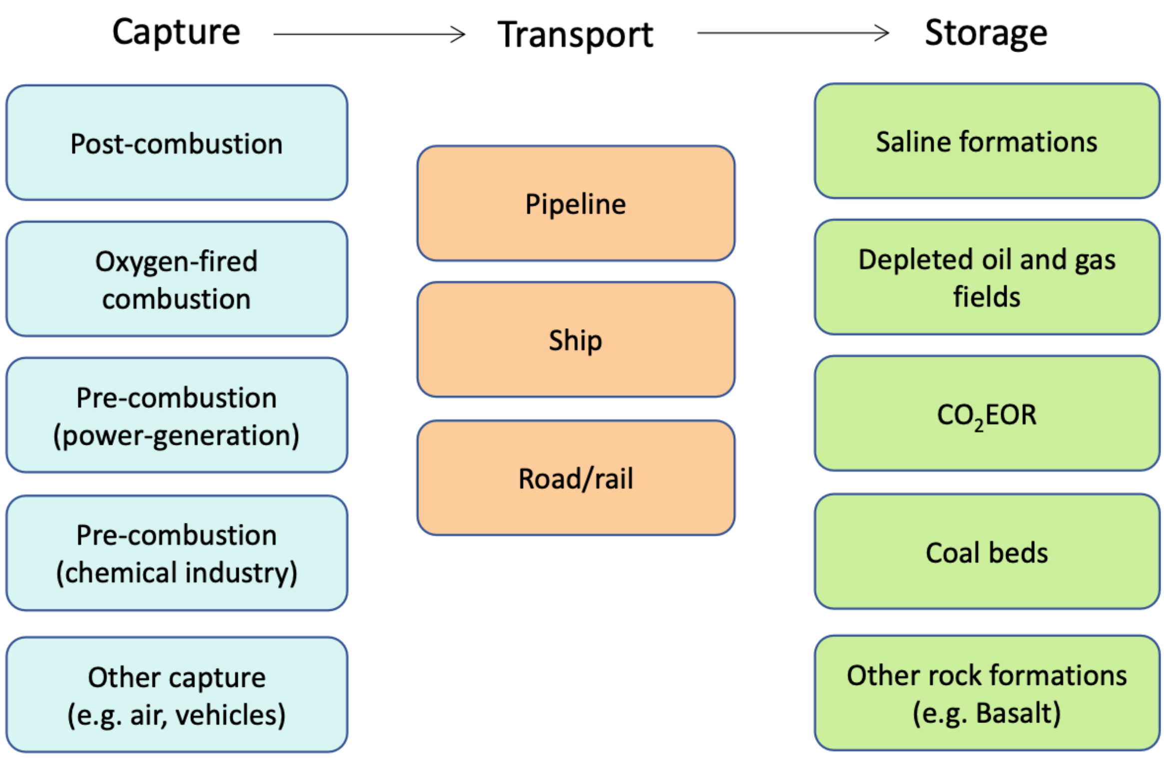

Figure 2-1: The phases and different technologies of CCS (Ringrose, 2020, p. 8)

2.1.1 CO_2 Capture

CO_2 capture involves collecting carbon dioxide from different emission sources. The CO_2 can be removed pre-combustion from gas blends that have a large fraction of it, or it can be removed post-combustion in flue-gas. Oxygen-fired combustion is another technology used when capturing carbon. Here, nitrogen is removed from the air before combustion in order to produce a stream that has a high concentration of carbon dioxide and water vapour, making it easier to separate the CO_2 (Ringrose, 2020, pp. 7-8). It is also possible to capture CO_2 directly from mobile sources or the atmosphere, but the volumes captured this way are currently minor as it is very expensive and energy-demanding (Ringrose, 2020, p. 7). Direct air capture is considered a negative emissions technology as it reduces the concentration of CO_2 in the atmosphere.

There are different physio-chemical processes that are used for separating CO_2 from gas blends. These processes include solvent-based methods that utilizes absorbent liquids, sorbent-based techniques that use solid particles, cryogenic methods where different condensation temperatures are used, and membrane-based approaches using solid-state chemical barriers (Ringrose, 2020, pp. 7-8).

2.1.2 CO_2 Transportation

After the CO_2 has been captured at the source, it needs to be moved to either a utilization point or a storage facility. CO_2 can be transported by pipeline, ship or road/rail. The choice between the different methods is usually dependent on factors like cost, volume of CO_2 to be transported, distance between capture point and storage site, and infrastructure available. Pipeline is often preferred when there are large amounts of CO_2 being transported shorter distances, whereas ship is preferred with longer distances and smaller amounts of CO_2. Transport by road or train is used in a lesser extent as it is less efficient and more expensive than the other methods. It is typically used for smaller-scale projects, or to transport CO2 from multiple small industrial sources to a central storage facility.

It is important that the transport of CO_2 from industrial plants to storage sites happen in a safe, effective and economical manner. Carbon dioxide is usually transported in a supercritical or liquid state at pressures ranging from >5 to >10 MPa in order to avoid two-phase flow (Cole et al., 2011). It can also be transported in a gaseous phase, but this takes up larger volumes than a liquid or supercritical state does and is thus less efficient (Blunt, 2010).

2.1.3 CO_2 Utilization

Captured CO_2 can be utilized in different products and services. It can either be used directly without any form of alteration, or it can be altered chemically. The primary utilization areas today are in enhanced oil recovery and production of fertilizers, while smaller utilization areas are within making of fuel, chemicals and building materials. (IEA, 2021a). Currently, most of the captured CO_2 are stored and only a small part is intended for utilization. This is a reason why CCUS is often just referred to as CCS. There is however an increasing trend of industrial utilization of CO_2, see Figure 2-2 (Rystad Energy, 2023).

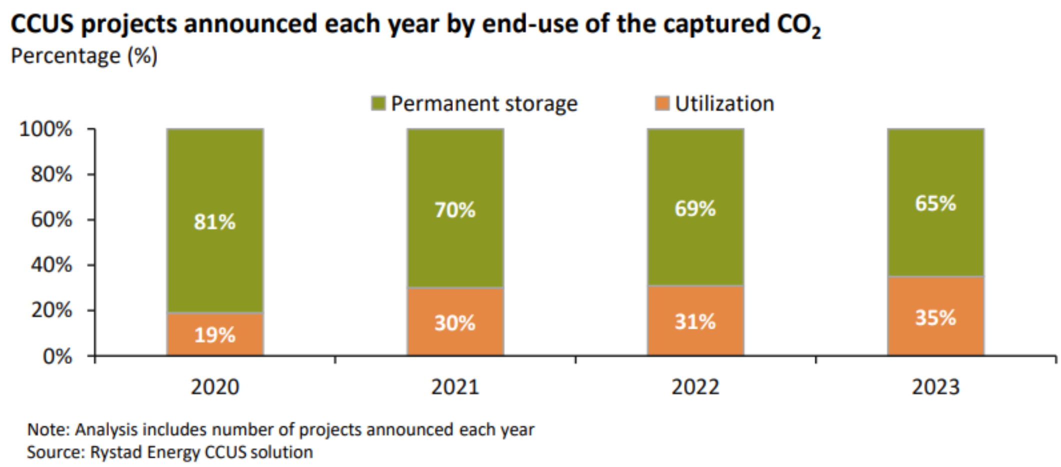

Figure 2-2: Overview of the intended end-use of the captured CO_2

2.1.4 CO_2 Storage

CO_2 is isolated from the atmosphere by injection in geological formations. The rock formations utilized to store the CO_2 are porous reservoirs that have an overlying cap rock that keeps the CO_2 from escaping or leaking. Thorough geological investigations must be done to make sure the storage site is suitable, and that CO_2 injection wells can be drilled without major difficulties. Capacity, injectivity and integrity are key elements to consider when finding a potential storage site (Cooper, 2009; Haigh, 2009). The capacity is determined by examining the formation size and the rock porosity. The reservoir must be large enough to store the anticipated volume of CO_2 to be injected throughout the project's life cycle. The injectivity depends on the permeability of the formation and the design of the injection wells. For effective storage and injectivity it is important that the permeability near the wellbore is high so the CO_2 can spread and migrate through the formation (Cooper, 2009). To ensure that the injected CO_2 will remain in the storage site long term the reservoir needs to have a seal that keeps it from leaking to other formations or the atmosphere. Each potential leakage path should be examined to make sure the storage site has a high integrity (Haigh, 2009).

As seen in Figure 2-1 there are five main categories of storage possibilities:

1. *Deep saline aquifers*: One of the formation types that are the most common and have the largest capacities are deep saline aquifers. They are porous and permeable formations that contain water with a high concentration of dissolved salts.

2. *Depleted oil and gas reservoirs:* Reservoirs that have previously been used for oil and gas production and are no longer economically viable can be reused for storing CO_2. Advantages of using abandoned oil and gas fields is that there is already data and information available about the reservoir, as well as there is already industrial infrastructure in place.

3. *CO_2-EOR:* In some reservoirs CO_2 injection is used to enhance oil recovery by increasing the pressure and facilitating the displacement of oil towards the producing well. The CO_2 either stays in the formation or gets produced and then reinjected.

4. *Coal beds:* Coal seams that are considered unmineable are possible options for CO2 storage.

5. *Other rock formations:* Other rock formations such as basalt and shale can serve as potential storage sites.

Although there are many different types of storage formations, saline aquifers and depleted oil and gas reservoirs are considered the most optimal as they have the largest capacities (Metz et al., 2005)

2.2 Policies and Regulatory Frameworks for CCS

There have been various policies implemented and measures taken by governments and organizations the last couple of decades to facilitate and regulate the deployment of CCS. The measures can generally be divided into three different categories: climate-based regulations, regulations that are designed to support CCS and regulations of CCS activities (IEA, 2016).

2.2.1 Climate-Based Regulations

Climate-based regulations are in principle designed to reduce emission of greenhouse gases and mitigate climate change, but it can also indirectly contribute to investment in CCS. One example of this is the implementation of emission fees. In 1991, the Norwegian government introduced an emission tax for CO_2, which was an influential factor in the initiation of the Sleipner and Snøhvit CCS deployment (IEA, 2016).

2.2.2 Regulations to Support CCS

Financial support from governments is important for incentivizing the implementation of CCS (IEA, 2016). While investments by private sector companies are driven by the expectation of financial returns, governments can often have other reasons for their investment decisions. If a governmental investment fails to deliver financial returns, it is usually justified as long as it delivers benefits to the public. Investment in CCS meets the requirement of benefiting the public in the form of contribution to a stable climate (Zapantis et al., 2019).

There are multiple ways that governments and organizations can support the implementation of CCS. It can happen e.g., by giving tax credits that can reduce a company's tax liability or by giving capital grants to help finance projects. Direct funding could also be given for different purposes, e.g., for research and development of new technology. Another way it can happen is through collaborations between the government and private companies. Pilot and demonstration projects funded by governments can accelerate the pace of the CCS industry, and thus make it easier for others to follow.

2.2.3 Regulations of CCS Activities

The development of laws specific for CCS are at different stages in the world. The Global CCS Institute have tracked the development of legal and regulatory frameworks in 55 different countries and sorted them in three different classes based on their progress, see Figure 2-3. Band A are countries that have laws in place that are applicable across most parts of the CCS project life cycle, Band B include countries that have some laws that are applicable, while Band C are countries that have very few CCS specific laws (Havercroft, 2018).

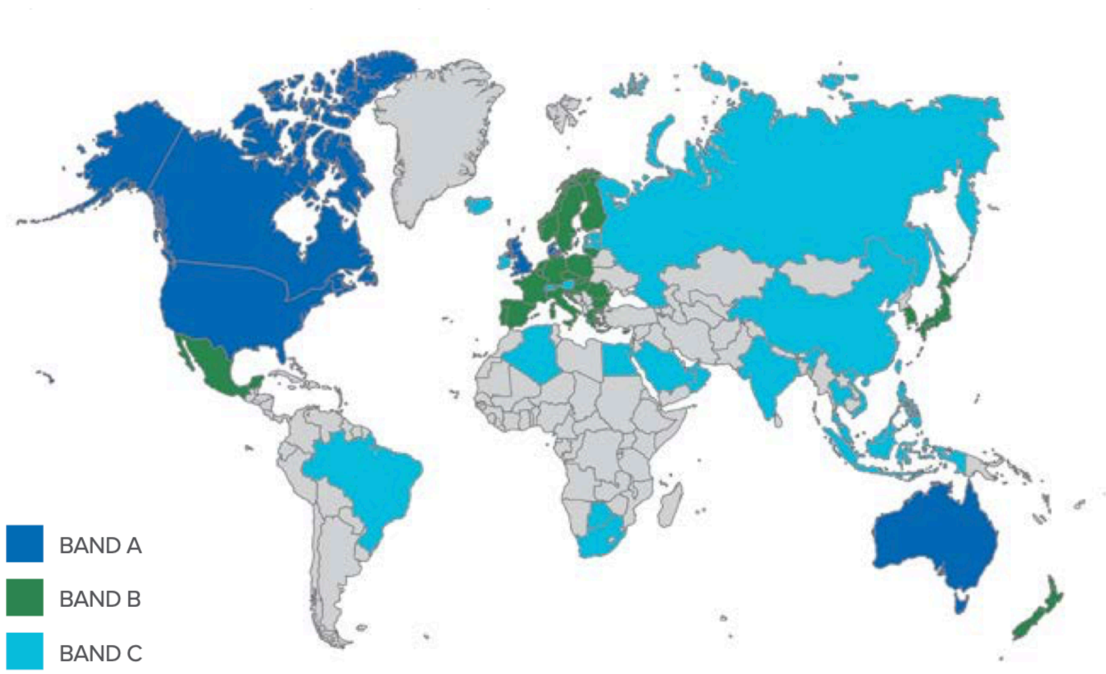

Figure 2-3: Map indicating legal and regulatory readiness for CCS (Havercroft, 2018)

In Norway the storage of CO_2 is governed by three main legislations that cover the process from selection of storage site to decommissioning and responsibilities after. The legislations are closely linked to the legislation of petroleum activities, and in principle there are no real differences in the regulations for drilling and well activities between CO_2 injection wells and conventional oil and gas wells.

Well Barrier Requirements

NORSOK standards are developed by experts from the Norwegian petroleum industry to provide technical and cost-effective solutions to make sure that petroleum activities are managed in the best possible way by the industry and authorities. The NORSOK D-010 is a document that defines the requirements and guidelines related to well integrity in drilling and well operations (Standard, 2021). Both conventional oil and gas wells and CCS wells must comply with the well barrier requirements specified in the document. There are generally two defined well barrier requirements; primary and secondary. The primary well barrier is there to prevent undesired inflow from the reservoir or other sources, while the secondary well barrier is there to provide additional protection from undesired inflow in case the primary barrier fails (Standard, 2021).

2.3 Economy of CCS

CO_2 injection into geological formations was first started in the early 1970's as a way of enhancing oil recovery (Haigh, 2009). In 1996, the Sleipner field in the North Sea was one of the first projects where CO_2 was injected with the purpose of sequestration (Kaarstad, 2008). The natural gas produced at the field contained too much CO_2, and instead of releasing it to the atmosphere and paying CO_2 tax, it was decided to separate the CO_2 and inject it in the Utsira formation, a deep saline aquifer. Since then, there have been several other CCS projects initiated. By the end of 2022, 65 commercial CCS projects were operational and able to capture more than 40 million tonnes of CO_2 per year (Rystad Energy, 2023). However, there is still a need for more CCS projects. An analysis performed by Ringrose and Meckel (2019) indicates that 10-14,000 CO_2 injection wells are needed globally by 2050 to achieve the goals of the Paris agreement. Although this requirement might be achievable from a technical standpoint, it is crucial to reduce the cost of CO_2 injection wells in order to accelerate the market potential of CCS as an abatement option and make it more attractive for commercial implementation (Manum et al., 2023).

From a business standpoint, there are multiple challenges and uncertainties associated with financing carbon capture and storage projects. Taking on a CCS project requires high upfront capital investments, and the revenue streams associated with such projects are uncertain. In contrast to other mitigation technologies, CCS does not generate revenue based on the production of a product, it is instead dependent on monetizing the service of abating CO_2 emissions. This means that the value of CO_2 capture and storage must be higher than the costs associated with it. During the early stages of CCS deployment, the financial support from governments is vital. However, if the CCS industry is to grow and become commercially viable over the next years, there is also a need for more private investment to complement and scale up the implementation (Rassool, 2021). To make the CCS industry more attractive to private companies, the cost associated with the projects needs to decrease. Companies want to ensure that their projects have a positive net present value, and that their investment is paid back within a reasonable time. For a project to be financially feasible, the cumulative revenue needs to be higher than the cumulative capital and operational expenditures (Kapetaki & Scowcroft, 2017).

2.3.1 Economic Incentives to Decrease Emissions

There are multiple economic incentives created by governments and organizations to reduce emission of CO_2 and other greenhouse gases to the atmosphere. Some of these are discussed below.

2.3.1.1 The EU Emissions Trading System (EU ETS)

The EU Emissions Trading System was introduced in 2005 and operates in all the EU countries, as well as in the EEA-EFTA states. It is a market mechanism that incentivises emitters to reduce their carbon footprint. It works by a “cap and trade” principle where a cap is set on the total emissions companies are allowed to have each year. Each allowance gives the holder right to emit 1 tonne of CO_2 or other greenhouse gases (European Commission, n.d.). A limited number of allowances are issued, and these are either bought or awarded for free. The number of allowances is reduced each year, and if a company have more emissions than allowed, it must either buy allowances from other emitters or take measures to reduce its emissions. If it fails to do either of these, it must pay a significant fine. If a company on the other hand has more allowances than needed, it can either save them for the future or sell them. The flexibility of the trading system ensures that emissions are cut where it costs the least. (European Commision, n.d.) By the end of 2030, the cap on emissions will be decreased by 43 % compared with the start in 2005 (Teixidó et al., 2019).

The price of the EU ETS allowances sets an upper bound on the price of carbon capture, utilization and storage. For CCS to be an economically viable option, the cost of greenhouse gas emission to the atmosphere should be higher than the investment needed for CCS deployment. The EU ETS price is expected to increase over the next years, as the number of EU ETS allowances decrease.

2.3.1.2 Tax credit systems

Where Europe incentivizes CO_2 emission reduction through a tax, the US incentivizes it through a tax credit system. Section 45Q is a policy that was first introduced in 2008, and is meant to promote deployment of carbon capture, utilization and storage by providing a tax credit for storing CO_2. In 2022, this policy was further strengthened by the passage of the Inflation Reduction Act (IRA). Section Q45 provides up to 85 USD/tonne of CO_2 stored, and up to 60 USD/tonne of CO2 utilized for CO_2 enhanced oil recovery or other purposes. It also encourages direct air capture by providing a credit amount of up to 180 USD/tonne of CO2 stored and up to 130 USD/tonne of CO2 for utilization. (IEA, 2023).

2.3.2 Cost Drivers

According to Kearns et al. (2021), the cost drivers of CO_2 sequestration is found in three main areas: site selection, deployment and technology advancement. These areas hold noteworthy potential for future cost reductions.

2.3.2.1 Site Selection

When it comes to site selection there are multiple factors that influence the cost. The accessibility and nature of the storage site will have a great impact.

An offshore location is generally more expensive than a location onshore. The main reason for this is that offshore locations require larger and more costly drilling rigs along with more equipment. Rystad Energy (2022) have studied the levelized cost of storage (LCOS) for saline aquifers and depleted oil and gas fields. They found that it is more than doubled for offshore storage sites compared to onshore storage sites in most regions, see Figure 2-4 and Figure 2-5.

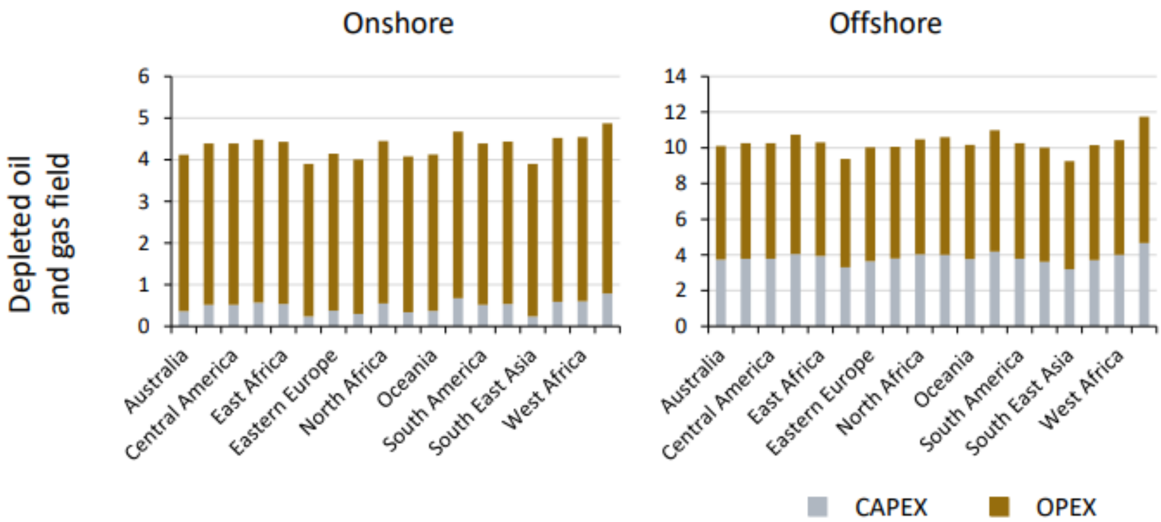

Figure 2-4: Levelized cost of storage for depleted oil and gas fields in different regions (Rystad Energy, 2022)

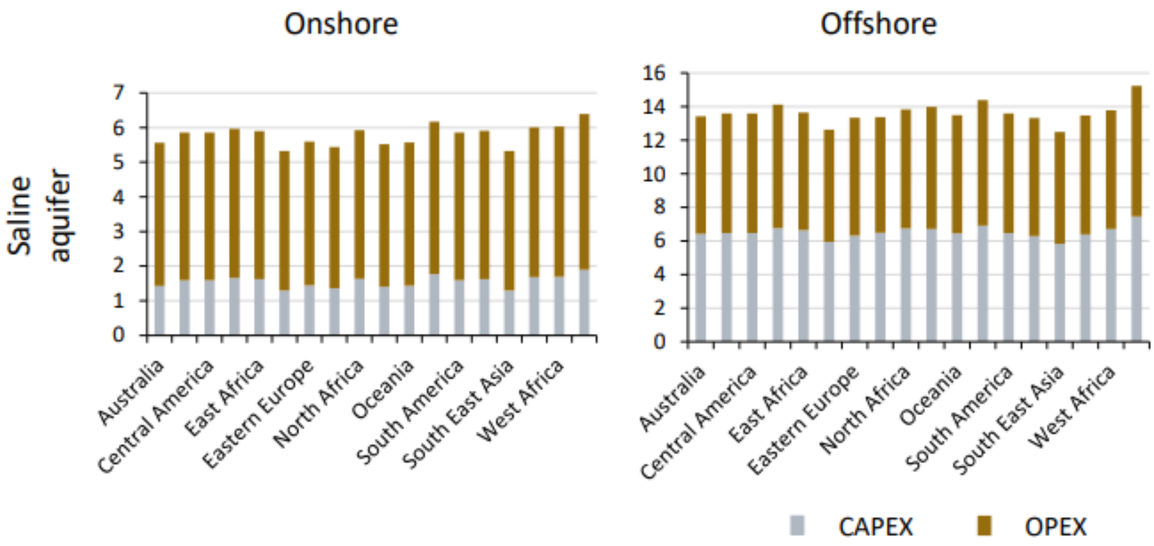

Figure 2-5: Levelized cost of storage for saline aquifers in different regions

The type of storage site chosen is also important for the cost. The LCOS is higher for saline aquifers than for depleted oil and gas fields. This is related to the fact that well-characterized sites like depleted oil and gas fields have lower development costs than sites that are not yet explored (Kearns et al., 2021). Legacy wells and old infrastructure can be reused for CO_2 injection, which would be a lot cheaper than building new.

2.3.2.2 Deployment

The increased deployment of CCS is important for reducing the overall cost of CO_2 storage (Kearns et al., 2021). As the industry gains more experience and knowledge about CCS, and the bigger the projects get, the more likely it is that it will become cheaper. Lessons learned from past projects can be used to optimize the project's process, reduce risks, and improve overall cost-efficiency.

2.3.2.3 Technology Maturation

Significant cost savings can also be achieved through technology maturation. Technology related to the CCS industry is still in its early stages and requires investment in research and development (R&D) to make it more cost-efficient. The technology currently used in CCS projects relies on technology used for oil and gas wells. Advances in materials and equipment specialized for CCS wells could bring down the costs for the construction of CO_2 injection wells.

2.4 CCS Wells and Well Design

A lot of the knowledge, skillset and technology needed for CCS closely mirror those utilized in the oil and gas industry (Hastings & Smith, 2019). Although the oil and gas industry has extensive knowledge and experience in well construction, there are new challenges associated with CCS wells which requires a different well design approach (Ceyhan et al., 2022). Some of the differences between conventional oil and gas wells and CCS wells are listed below:

Pressure in the reservoir

While the pressure in oil and gas reservoirs gradually decreases, the storage reservoirs for CO_2 increases throughout the lifespan of the project and are highest at the time of abandonment.

Long regulatory life

The regulation of conventional oil and gas wells typically ends after closure, while CCS wells needs to have regulatory oversight beyond their service lives to monitor long-term integrity and potential CO2 leakages.

Corrosive environment

Pure CO_2 is not corrosive by itself, but when encountered with water it results in an acidic environment which in turn will lead to corrosion of carbon steel. This happens by the following reaction:

$$\mathrm{Fe} + \mathrm{H_2CO_3} \rightarrow \mathrm{H_2} + \mathrm{FeCO_3}$$

The main source of water in a CO2 injection well and pipeline comes from water condensation in the injected CO_2 stream, but the well could also be exposed to water from the formation during well intervention and longer shut-in periods (Ceyhan et al., 2022; Haigh, 2009)

Impurities

Impurities like H_2S, SO_2, NO_2, and O_2 can be present in the CO_2 from the capture process. The presence of these in the CO_2 stream can alter the physical properties and water solubility of the

CO_2, which could lead to the pH getting lower (Millet et al., 2021). The presence of impurities may also lead to problems like pitting corrosion and different types of cracking.

Payback time

The expenses related to a conventional oil and gas well is expected to be paid back relatively fast after the field has started production, while the costs related to a CO_2 injection well will take significantly longer to pay back.

2.4.1 Challenges with CO_2 injection

There are different challenges to consider when injecting CO_2.

Phase Behaviour of CO_2

Understanding the phase behaviour of CO_2 is essential when planning and designing a CCS project. The phase diagram in Figure 2-6 gives a visual representation of how CO_2 transitions between phases as temperature and pressure changes. At low temperatures and pressures, it is in a solid phase known as dry ice, while it is in a gaseous state at standard conditions. As temperature and pressure increase it will change into a liquid. The critical point of CO_2 is at a temperature of 31 °C and pressure of 73.8 bar, and above this point there no longer exist any distinction between liquid and gas phase (English & English, 2022).

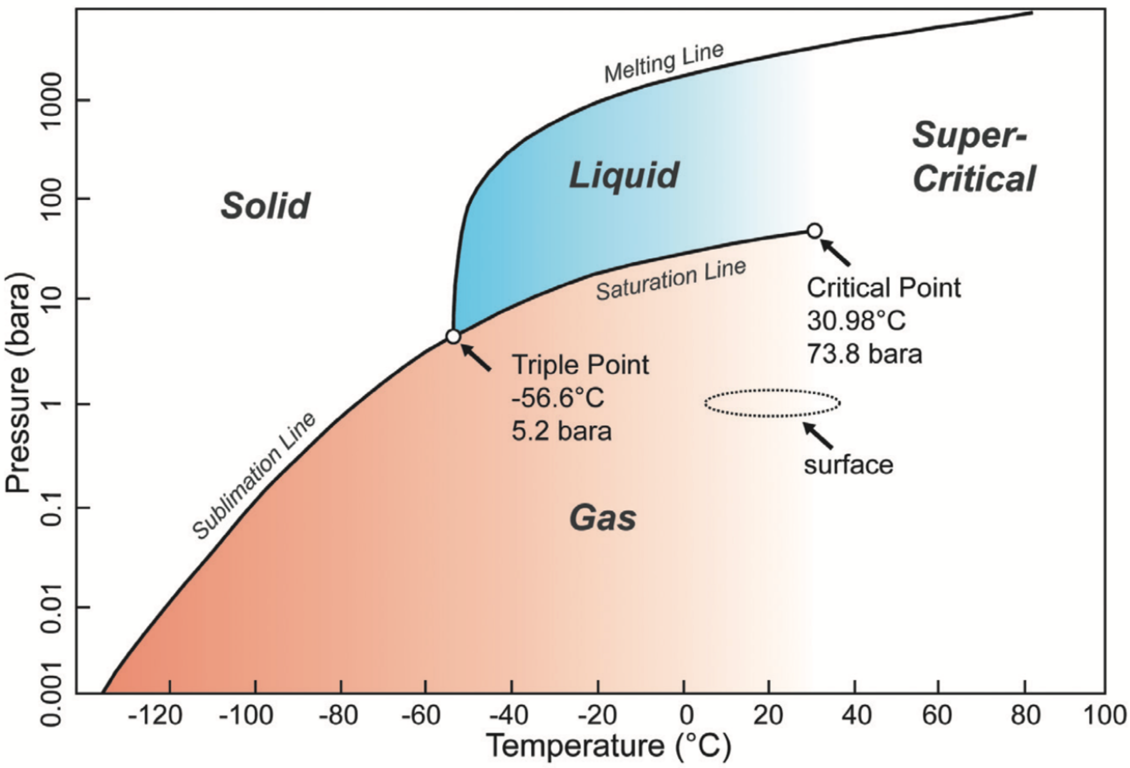

Figure 2-6: Phase diagram for CO_2 (English & English, 2022)

During transportation, injection and storage of CO_2 it is preferred to compress it into a dense form, either as a liquid or as a super-critical fluid. This is because it takes up less volume as density increases, thus making it more efficient to transport and store (Ringrose, 2020, p. 14).

Joule-Thomson Effect

The Joule-Thomson effect refers to the temperature change that happens when a gas expands adiabatically as it is moves from a region of higher pressure to a region of lower pressure (Oldenburg, 2007). Depending on the properties of the gas, the temperature will either decrease or increase. When captured CO_2 decompresses or flashes from liquid to gas this will cause a cooling effect, and temperatures down to -78 °C can potentially be observed. The temperature drop can be hard to predict, especially if the stream contains impurities, as this can alter the critical point and the phase behaviour of CO_2 (Manum et al., 2023). The low temperatures that can occur during CO_2 injection give rise to different challenges, including formation of hydrates, freezing of residual water and fracturing of the formation (Oldenburg, 2007). Some well components might also be susceptible to damage or failure under the low temperature conditions. These complications can affect the injectivity and integrity of the well.

2.5 Risk Assessment

There are multiple risks that needs to be assessed when taking on a CO_2 storage project. A risk is described as “an uncertain event or condition that, if it occurs, has a positive or negative effect on a project outcome” by the PMI’s Guide to the Project Management Body of Knowledge (Gardiner, 2017, p. 161). Risk management involves the continuous identification, assessment, treatment and evaluation of risk. Pawar et al. (2015) have classified risks related to geological CO_2 storage into four different groups based on experiences from different field projects:

Site performance risks

The risk related to site performance mainly concerns potential operational challenges at the storage site. These are typically related to the capacity and injectivity. The injectivity of a CO_2 injection well refers to its ability to deliver CO_2 into the storage formation, while the capacity of a storage site refers to the available volume for CO_2 sequestration. The injectivity performance is limited by wellbore effects, near-wellbore reservoir heterogeneities, and far-field reservoir effects, and therefore challenges associated with those should be assessed (Pawar et al., 2015). Discontinuous injection should be avoided as it increases the risk of injectivity impairment.

Containment risks

For a CO_2 sequestration project, it is crucial that the brine and injected CO_2 remain contained within the storage formation. Leakages can happen through wellbores and faults in the storage complex, or through breaches and vulnerabilities in the caprock. Abandoned legacy wells in the area of a CCS project are especially important to assess, as these can pose leakage threats. Most of these wells were abandoned using conventional oil and gas techniques, and may not be properly plugged and sealed, meaning they could serve as conduits for CO_2 to escape (Ceyhan et al., 2022; Pawar et al., 2015)

Public perception risks

The public perception of a CO_2 storage project is important for the social acceptance, regulatory approval and long-term viability of a project. To mitigate public perception risks it is important to use effective communication strategies (Pawar et al., 2015).

Market failure risks

There are several financial risks concerned with the deployment of CO_2 storage projects. The CO_2 market can be hard to predict, and it is important to consider the market risk perspectives of different stakeholders when evaluating CO_2 storage opportunities. Each stakeholder has the option whether to support financial investment decisions or not, and their perception of project risk may vary (Pawar et al., 2015). Market failure risks associated with the management of CO_2 can have a direct impact on the viability of CCS projects. One of the most essential market failure risks in Europe is related to the EU ETS price. If the cost of CO_2 capture, transport and storage is higher than the cost of emitting CO_2 to the atmosphere, there is no incentive to invest in the CCS business (Zapantis et al., 2019).

2.6 Longship and Northern Lights Projects

Longship is a full-scale CCS project that was initiated by the Norwegian government in 2014. The short-term goal of the project is to demonstrate that CCS can be implemented technically, regulatory and commercially, while the long-term goal of the project is to contribute to reaching climate goals in a cost-efficient way (CCS Norway, n.d.). The total cost of Longship is estimated to be approximately 27 billion NOK, where the Norwegian Government will cover about 18 billion NOK (Olje- og energidepartementet, 2021) The project will capture carbon from two of the biggest emitters in Norway, Heidelberg Materials cement factory in Brevik and Hafslund Oslo Celsio's waste incineration facility in Oslo. From there the CO_2 will be liquidised and transported by ship to a receiving terminal in Øygarden, before it is further transported offshore by pipeline, and then ultimately injected into a deep saline aquifer. An illustrated overview of the process can be seen in Figure 2-7.

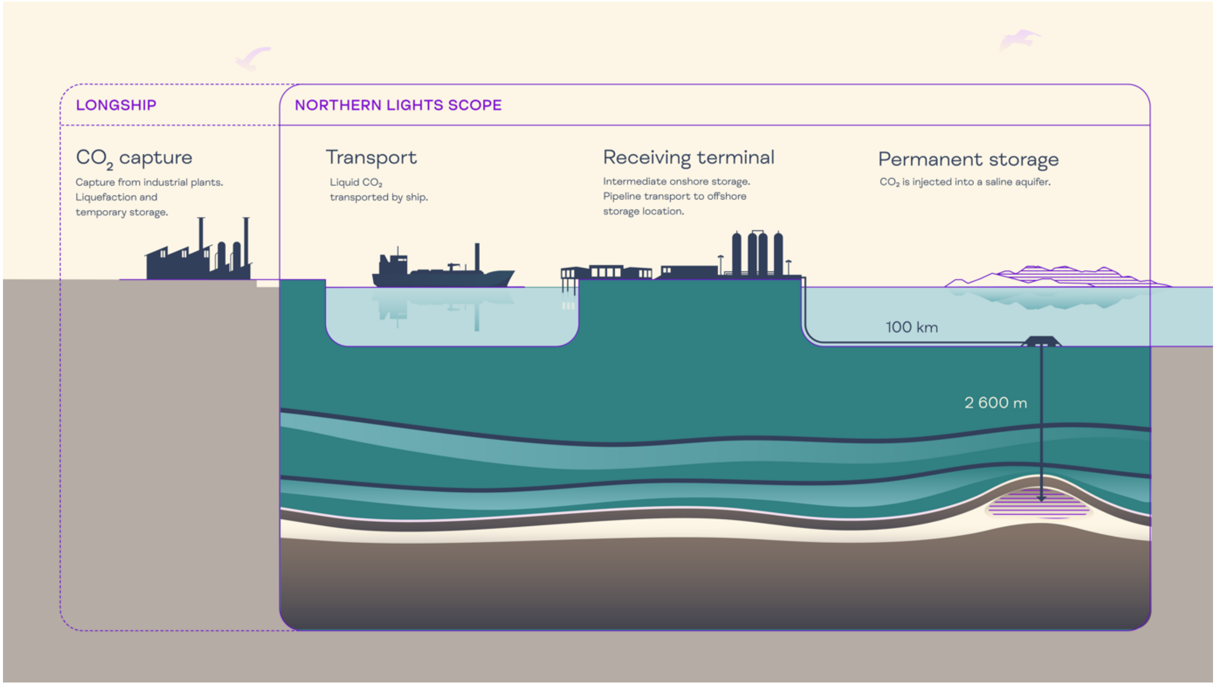

Figure 2-7: Scope of the Longship and Northern Lights projects (Northern Lights, n.d.)

Northern Lights is a joint project between Equinor, Shell and TotalEnergies, and is responsible for the transportation and storage part of the Longship project. Northern Lights is divided into two phases, where the first phase is aiming to store 1.5 million tonnes CO_2 per year. As the market demand for CO_2 storage increases, the project plans on increasing its storage capacity to a total of 5 million tonnes. In addition to receiving captured carbon dioxide from Heidelberg Materials and Hafslund Oslo Celsio, Northern Lights will also accommodate for reception of CO_2 from companies across Europe (IEA, 2021b). The Northern Lights project is estimated to cost 14.2 billion NOK. The Norwegian government is funding 10.4 billion NOK, while the partners of the project will cover the remaining 3.8 billion NOK (Helgesen, 2020).

2.7 Neptune Energy and CCS

In January 2022, Neptune Energy announced its commitment to go beyond net zero by 2030. The company aims to achieve this by storing more carbon than what is produced through its operations and sold products (Neptune Energy, 2022). Neptune Energy has experience from carbon storage in the Netherlands and was recently awarded three licenses for CO_2 storage in the UK. In Norway, Neptune Energy have applied for two CO_2 storage licences, Errai and Trudvang. The company ended up not getting awarded Errai, but is still, at the time of writing, waiting on a decision about Trudvang.

2.7.1 The Errai Project

Horisont Energi and Neptune Energy Norge applied for the license of a CO_2 storage project in the southern North Sea on the Norwegian Continental Shelf in 2022, called Errai. This project was intended to become the first commercial CO_2 storage project in Norway, with the potential to store 4-8 Mtpa of CO_2. The concept of the project consisted of vessels picking up CO_2 at capture sites and transporting it to an onshore CO_2 reception facility connected to 3-6 injection wells by a ~200 m pipeline. An illustration of the Errai project scope can be seen in Figure 2-8.

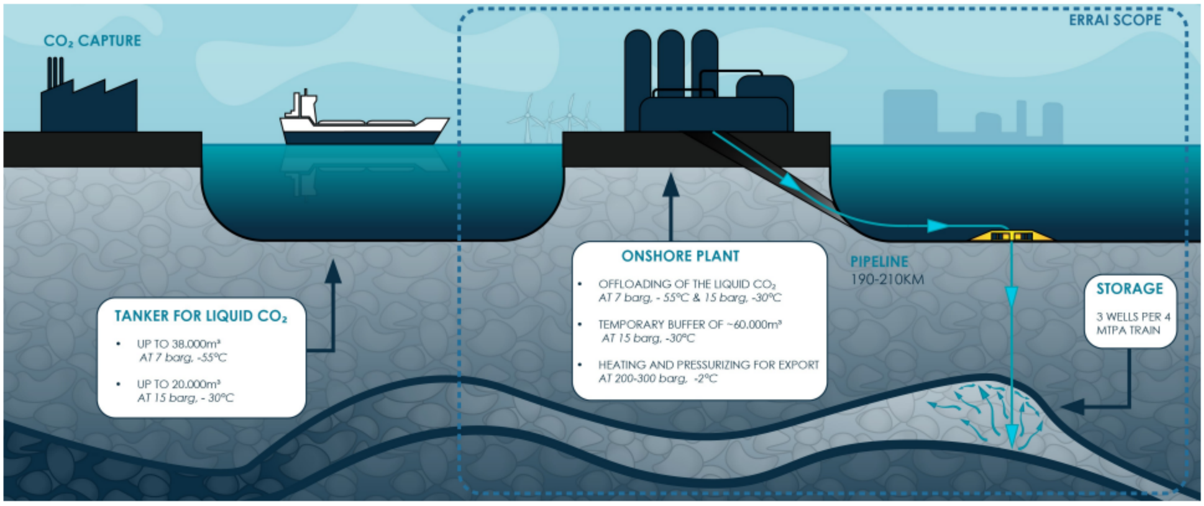

Figure 2-8: Project scope of Errai (Horisont Energi, 2022)

The planned timeline of the Errai project is illustrated in Figure 2-9. The storage licence was ultimately not awarded to Neptune Energy and Horisont Energi.

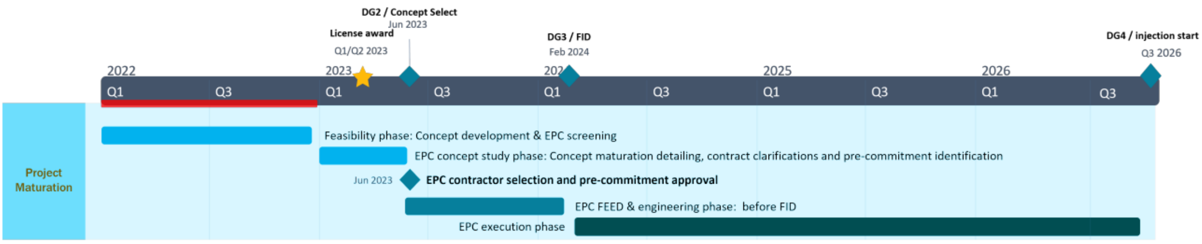

Figure 2-9: Timeline of the Errai project (Horisont Energi, 2022)

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3 Method

3.1 Data collection

The financial input parameters used in this master's thesis is based on the DG1 estimates of the capital and operational expenditures of the Errai storage project, as well as estimations and information provided by experienced drilling and completion engineers in Neptune Energy. The estimated costs of the Errai project are compared to the estimated costs of the Northern Lights project, which have been collected from publicly available sources and may not be completely accurate. Even though the calculations are based on a specific project, the findings can be transferrable to other CO_2 storage projects. The potential cost-savings have been scaled up to find the possible cost reduction for the decarbonization of hard-to-abate industries (300 Mtpa of CO_2).

3.2 Levelized Cost

There is no established standard for how to calculate and compare the cost of CCS projects. However, to evaluate the feasibility of a CCS project and be able to compare it to other projects and the ETS price, levelized cost is often used. The levelized cost of CCS represents the average cost per tonne of CO_2 captured, transported and stored over the lifecycle of the project, and is calculated by dividing the estimated total cost of the project by the total amount of CO_2 emissions avoided.

$$\frac{CAPEX + OPEX * Lifetime}{Total\ amount\ of\ CO_2\ stored}$$

4 Calculations and Results

Before potential cost saving measures can be assessed, the levelized cost of storage per tonne of CO_2 needs to be calculated. As previously mentioned, the financial input parameters used in this master's thesis is based on the early estimates of the investment and operation costs of the Errai project. The estimated CAPEX and OPEX of Errai are listed in Figure 4-1 and Figure 4-2, respectively.

CAPEX	Mean (Prob.)	P10	P50	P90
Pipeline	2'584'520'044	2'089'692'093	2'538'883'429	3'146'291'218
SPS incl. installation	590'829'167	444'039'641	572'899'024	768'822'218
DFCO incl. installation	283'167'099	152'744'559	288'550'238	402'376'539
D&W 2	2'385'737'609	1'951'503'568	2'413'235'243	3'032'966'897
Onshore site preparation	463'859'507	344'048'746	458'065'710	590'628'578
Temporary storage	210'585'042	129'473'569	198'274'336	309'161'283
Plant	1'742'523'004	1'033'756'377	1'692'194'889	2'490'885'491
Plant extension to 8MTPA	370'917'487	224'126'197	357'721'548	539'396'553
Land acquisition	63'333'333	44'993'465	59'955'870	87'181'296
Sume w/o owner & conti	8'695'472'292	6'414'378'213	8'579'780'286	11'367'710'073
Owners Cost	397'361'762	255'031'860	405'939'979	528'101'442
Sum CAPEX w/o conti	9'092'834'055	6'669'410'073	8'985'720'264	11'895'811'516
Contingency	1'818'566'811	1'333'882'015	1'797'144'053	2'379'162'303
Total CAPEX	**10'911'400'865**	**8'003'292'088**	**10'782'864'317**	**14'274'973'819**

Figure 4-1: Estimated CAPEX for the Errai project

OPEX	NOK / year	P10	P50	P90
Pipeline	10'338'080	7'265'426	10'037'431	13'626'727
SPS & DFCO	32'650'000	26'093'658	32'649'485	39'178'298
D&W	119'286'880	58'784'360	120'198'422	191'611'790
Onshore Plant (maintenance & people)	38'341'232	25'683'355	37'090'703	53'290'343
Onshore Plant EXT (maintenance & people)	19'170'616	12'841'677	18'545'351	26'645'171
Power	67'544'539	40'680'914	65'447'797	96'715'493
CO2 emission cost (NOK)	65'567'326	14'382'493	58'120'575	130'370'927
Reservoir surveillance	1'884'073	520'815	1'734'989	3'492'947
Total OPEX / year	**354'782'746**	**186'252'698**	**343'824'753**	**554'931'697**

Figure 4-2: Estimated OPEX for the Errai project

The business case of the Errai project was based on 4-8 Mtpa CO_2 stored, where it would start with 3 injection wells and 4 Mtpa, and then increase to 6 injection wells and 8 Mtpa at a later stage. The cost of storage per tonne of CO_2 is calculated for both the 4 Mtpa of CO_2 and 8 Mtpa of CO_2 scenarios.

4 Mtpa of CO_2 stored scenario

To find the CAPEX for the 4 Mtpa of CO_2 stored scenario, the plant extension to 8 Mtpa cost needs to be subtracted from the CAPEX sum w/o contingency listed in Figure 4-1:

$$10\,911\,MNOK - 371\,MNOK = 8\,722\,MNOK$$

With a contingency of 20 %, the CAPEX is then:

$$8\,722\,MNOK * 1.20 = 10\,466\,MNOK$$

The OPEX is listed in Figure 4-2, and equals 355 million NOK.

Based on an estimated lifetime of 25 years, the cost estimate of storing 4 Mtpa CO_2 would be:

$$\frac{10\,465\,MNOK + 355\,\frac{MNOK}{year} * 25\,years}{100\,million\,tonnes} = 193.40\,\frac{NOK}{tonne\,of\,CO_2}$$

8 Mtpa of CO_2 stored scenario

The project could have expanded to 8 Mtpa at a relatively low cost. All the necessary costs related to the onshore plant extension is covered by the 371 million NOK listed in Figure 4-1. A doubling in the stored volume of CO_2 would require a doubling in the number of wells. The intended pipeline is already accommodated for the doubled injection volume, thus the only other additional expenses are related to the two posts "SPS incl. installation" and "D&W 2", which would be the double amount. The CAPEX w/o contingency for the storage expansion is therefore:

$$9093\,MNOK + 591\,MNOK + 2\,386\,MNOK = 12\,070\,MNOK$$

With a contingency of 20 %, the CAPEX for the 8 Mtpa of CO_2 stored scenario equals:

$$12\,070\,MNOK * 1.20 = 14\,484\,MNOK$$

The OPEX for the 8 Mtpa of CO_2 stored scenario is estimated to be 50 % more than the OPEX for the 4 Mtpa of CO_2 stored scenario:

$$355\ MNOK * 1.5 = 533\ MNOK$$

With an expansion to accommodate for 8 Mtpa of CO2 stored, the storage cost per tonne of CO_2 is reduced to:

$$\frac{14\ 483\ MNOK + 533\ \frac{MNOK}{year} * 25\ years}{200\ million\ tonnes} = 138.98 \frac{NOK}{tonne\ of\ CO_2}$$

Comparing this to the Northern Lights project, the levelized cost of Errai is significantly lower. The Northern Lights project is as previously mentioned in section 2.6 expected to cost 14.2 billion NOK. Phase 1 of the project aims to store 1.5 Mtpa of CO_2, and when assuming this storage capacity and a lifetime of 25 years, the estimated cost per tonne is:

$$\frac{14\ 200\ MNOK}{37.5\ million\ tonnes} = 378.67 \frac{NOK}{tonne\ of\ CO_2}$$

4.1 Cost Saving Measures

There are several areas where technology maturation can enhance the cost-efficiency of CCS wells. The total estimated cost of a CO_2 storage project consists of various components, including site characterization expenses, the construction of a CO_2 reception facility, well construction costs, personnel expenditures, and operation and maintenance expenses. Within this cost breakdown, the focus of this thesis will be on cost saving measures within the area of well construction.

Substitution of metallurgy

One area where there is great potential for making wells more cost-efficient is in the selection of metallurgy. The casing and tubing material of a well normally constitutes about 30 % of the well cost. The tubing material utilized in CO_2 injection wells must be able to withstand the acidic environment, and many projects, including Northern Lights, are using expensive high chromium tubing. A completion engineer in Neptune Energy has investigated the cost of drilling and completing three wells with approximately 3000 m top completion. The alternative that is readily available today is 25 Cr tubing, which would give a total cost of 102 million NOK. If GRE lined carbon steel could be used, the total cost would be 24 million NOK instead, meaning that it would be possible to save 78 million NOK on the three wells planned in the Errai project (S.T. Svenningsen, personal communication, 10. May 2023). This would give a cost reduction of 26 million NOK per well.

For the Errai project, the estimated cost savings per tonne of CO_2 stored would be 0.78 NOK.

$$\frac{26\ MNOK * 3\ wells}{4\ Mtpa * 25\ years} = 0.78 \frac{NOK}{tonne\ of\ CO_2}$$

This equals a cost reduction percentage of 0.4 % for the 4 Mtpa scenario and 0.6 % for the 8 Mtpa scenario:

$$\frac{0.78 \frac{NOK}{tonne\ of\ CO_2}}{193.40 \frac{NOK}{tonne\ of\ CO_2}} = 0.4\%$$

$$\frac{0.78 \frac{NOK}{tonne\ of\ CO_2}}{138.98 \frac{NOK}{tonne\ of\ CO_2}} = 0.6\%$$

As mentioned in the introduction, there are approximately 300 Mtpa of CO_2 emissions that come from hard-to-abate industries where CCS is regarded as the best method for emission mitigation. If this volume were to be stored using the technology today, the cost would be:

$$300\ Mtpa * 193.40 \frac{NOK}{tonne\ of\ CO_2} = 58\ 024\ MNOK$$

With an estimated cost reduction of 0.4 % per tonne of CO_2 stored, the cost savings of switching to GRE lined carbon steel would be:

$$58\,024\ MNOK * 0.4\% = 234\ MNOK$$

Testing and verification of the use of GRE lined carbon steel is planned to be carried out in the fall of 2023 and is estimated to cost approximately 2 million NOK.

The substitution of metallurgy is just one small measure that can be taken to make CCS wells more cost-efficient. The drilling of CCS wells has numerous other areas where it would be possible to reduce the costs. Many of these areas are however dependent on regulation changes. Currently, there are no real difference between the legislations for CCS wells and conventional oil and gas wells in Norway. However, there are significant differences between the risks associated with CO_2 injection and the risks associated with oil and gas production. In conventional oil and gas wells there are uncertainties regarding the characteristics of the hydrocarbons being produced, and they could potentially be hazardous and explosive. With CO_2 injection, the content is already known, and CO_2 is neither flammable nor toxic (Blunt, 2010). The lower risk associated with CCS wells could therefore allow for some adaptations in barrier requirements.

With a revision of the regulations, it would be possible to tailor-make Christmas trees for CO_2 injection wells. These trees would be conceptually different than the ones used for conventional oil and gas wells; they would be simpler, lighter, and cheaper. As an estimate, Neptune Energy's subsea experts estimates a cost reduction from approximately 50 million NOK for a standard subsea tree down to approximately 30 million NOK for a tailor-made CO_2 injection tree, or 4-6000 million NOK if assuming 1-1.5 MTA per well (J. Råen, personal communication, 02.05.23. These trees would for instance have electrical valve control and no umbilicals/hydraulic lines put through for downhole control systems. Trees like this do not currently exist, as no one can use them before there is approval given from regulatory authorities.

Another well element worth mentioning where requirements and regulations could be challenged to reduce costs, is the downhole safety valve (DHSV). During CO_2 injection the temperatures can get very low because of Joule-Thomson cooling, and the DHSVs currently on the market has not been tested under such conditions (Manum et al., 2023). Other metallurgy or technology could be used for downhole barrier. Instead of using a DHSV, a simpler deep set check valve could potentially be used where no hydrocarbons are present.

5 Discussion

5.1 The CO_2 Market

For the CO_2 sequestration market to be profitable, the carbon storage sales price must be lower than the EU ETS price and higher than the cost of storage. An illustration of the profit associated with the CCS industry can be found in Figure 5-1. The house represents the profit of CCS projects, where the foundation of the house consists of the costs related to CO_2 storage, and the ceiling of the house represents the cap the EU ETS allowance price sets on the CO_2 storage market. The space between the foundation and the ceiling represents the revenue potential.

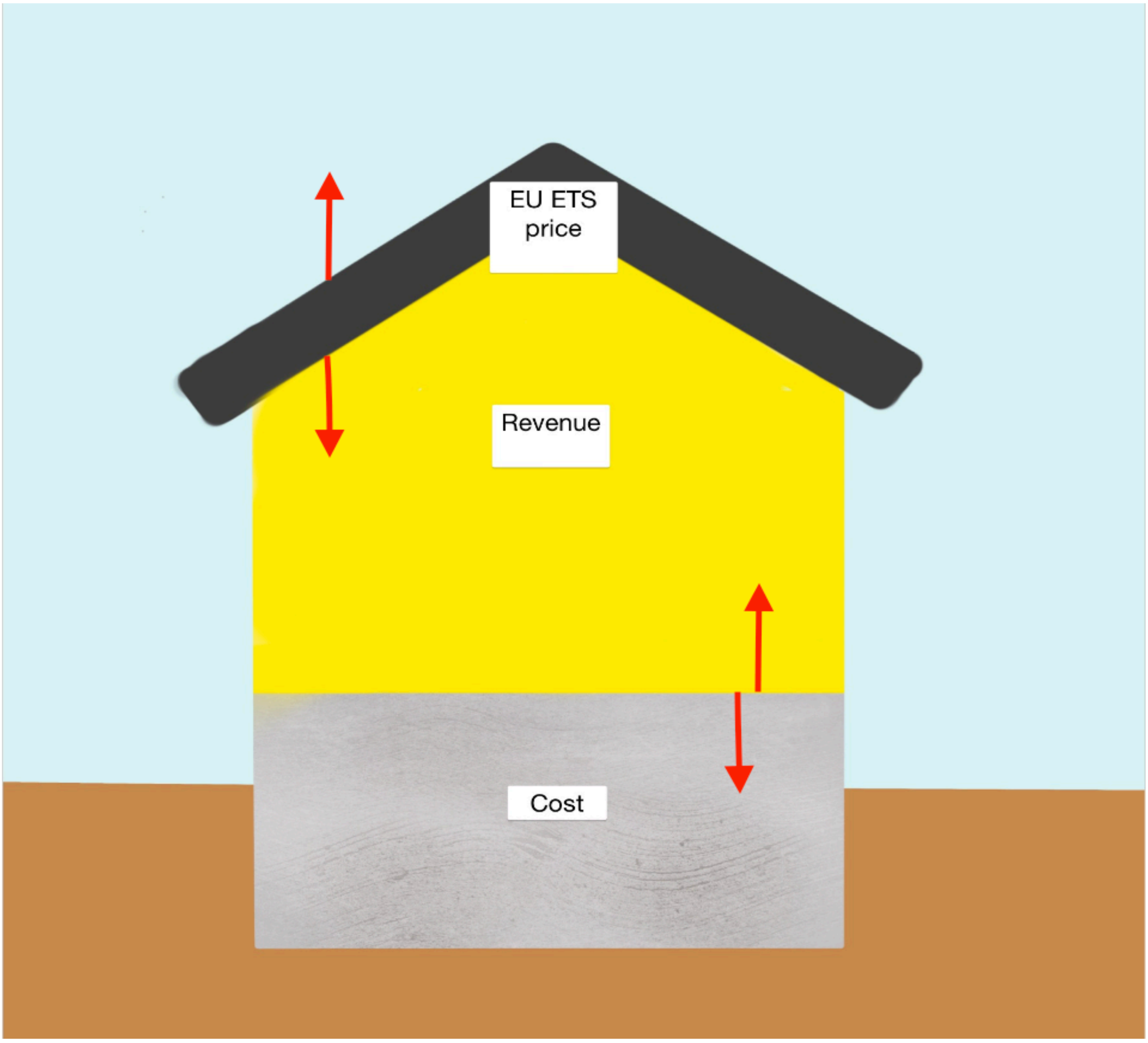

Figure 5-1: Illustration of the profit associated with CCS projects

By increasing the EU ETS allowance price and lowering the storage costs, the revenue space within the house will be expanded, which in turn will provide greater profit margins for the

CCS industry. The choices made by storage site developers will impact the revenue space within the house. Factors like storage site selection, deployment selection, injectivity rate and duration will all have an influence on the cost of storage and will either contribute to raising or lowering the foundation in the house analogy. The different factors affecting the cost of storage are described in more detail in section 5.2.1.

Another factor that influences the CO_2 storage cost, and which is beyond the storage site developers' control, is support from the government. Government support can come in various forms, such as subsidies, grants, and tax incentives, and can alleviate the costs for storage site developers.

Market failures

There are market failures associated with the management of CO_2 that can have a direct impact on the viability of CCS projects. One of the most essential market failures is the already mentioned risk of the price of climate gas emission being lower than the societal costs related to the emissions. This means that there is no real incentive for potential capture plants to invest in the CCS business. Another market failure is related to the development and deployment of new technology. Early movers will acquire knowledge and develop new technology that can lead to reduced costs for others following. This can result in "wait and see" approach, where no one wants to be the first to move (Zapantis et al., 2019).

Drivers for CCS investment

It can however be an advantage for operators to be among the first to offer CO_2 storage, as they can get a competitive advantage in the market and get the opportunity to establish themselves as a leader within the industry. Early movers can get a head-start at securing long-term contracts and partnerships with governments and other companies, which will provide financial predictability for the project. CO_2 storage is capital intensive, and the payback period is significantly longer than it is for conventional oil and gas projects. Where oil and gas projects are usually paid back within a couple of years, CO_2 storage projects are expected to take significantly longer, up to several years. Another reason for traditional oil and gas companies to invest in CO_2 storage, is to continue getting insurances and loans with favourable interests from banks. In 2021, the IEA published a report where they stated that there is no need for further investments in fossil fuel supply in their pathway to transition to a net-zero energy system by 2050 (IEA, 2021c). Consequently, multiple banks such as HSBC, BNP Paribas and Danske Bank, have announced that they will no longer provide any loans for the development of new oil and gas fields (Euronews Green, 2022; Holter, 2023; Hummel, 2023). In addition, insurance providers are also increasingly refraining from giving coverage for fossil fuel projects (Elton, 2022). Such initiatives are driving the E&P industry to explore and invest in more environmentally friendly options such as CCS to demonstrate their willingness to mitigate climate change, and thus be able to position themselves as socially responsible entities in the eyes of banks and insurance providers.

5.2 Cost of Storage

According to Rystad Energy, the levelized cost of CCS is estimated to be around 50-150 USD/t of CO_2 for most projects, where capture accounts for about 30-150 USD/t of CO_2, while transport and storage each account for approximately 5-30 USD/t of CO_2 (Huseby, 2023). An illustration of this can be seen in Figure 5-2.

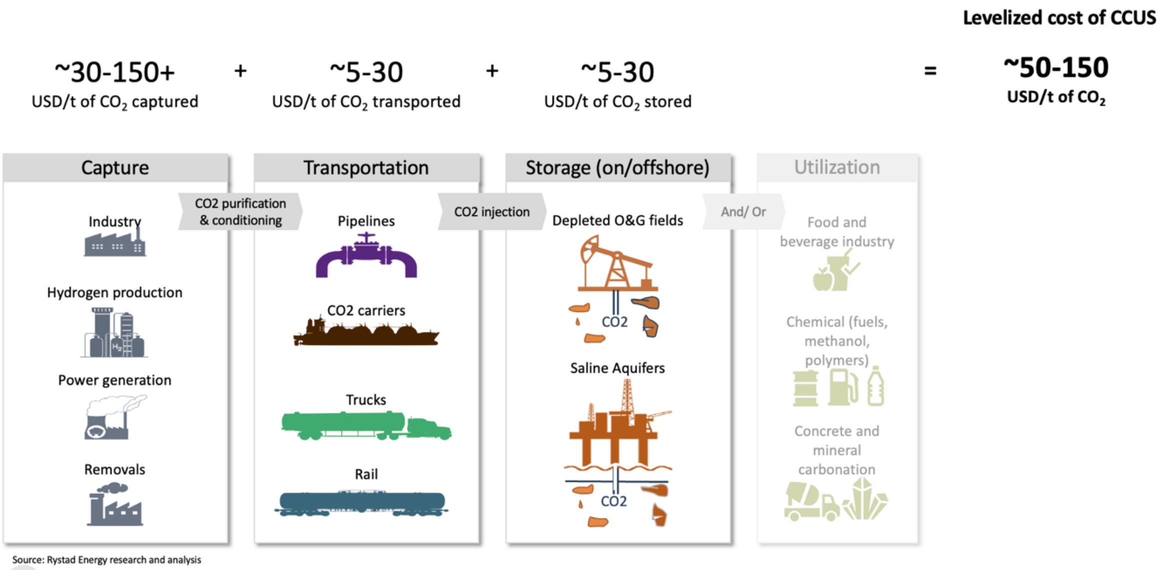

Figure 5-2: Levelized cost of CCS in USD/t of CO_2 (Huseby, 2023)

In comparison to Rystad Energy's estimated cost of storage of 5-30 USD/t of CO_2, the Errai project's estimated cost of storage is approximately 18 USD/t of CO_2, while the Northern Lights cost of storage is approximately 35 USD/t of CO_2 with the current currency. The Northern Lights project is expensive, but important for accelerating deployment of CCS and creating a European market for CO_2 storage.

The historical price of the EU ETS allowances is illustrated in Figure 5-3. An increasing trend can be observed, but the allowance price is still under 100 €/t of CO_2 emitted, which equals 108 $/t of CO_2 emitted. The EU ETS price is still low compared to the levelized cost of CCS at ~50-150 USD/tonne of CO_2.

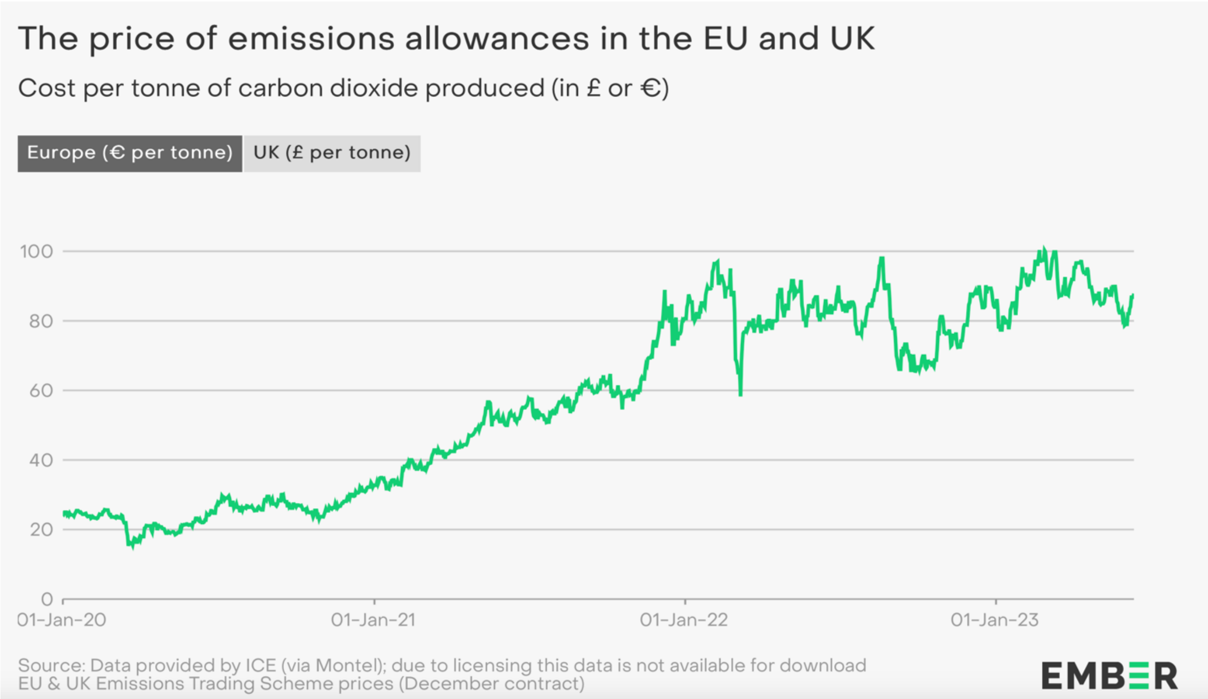

Figure 5-3: Historical price of EU ETS allowances (Ember, 2023)

5.2.1 Factors Affecting the Cost of Storage

In order to reach the goals of the Paris Agreement there is, as previously mentioned, an estimated need for 12-14,000 wells by 2050. This means that there will have to be drilled roughly 500 wells per year. In Europe, there is a potential for capturing and storing 300 Mtpa of CO_2 from hard-to-abate industries (Huseby, 2023). The costs related to storage of this volume is dependent on the different parameters illustrated in Figure 5-4.

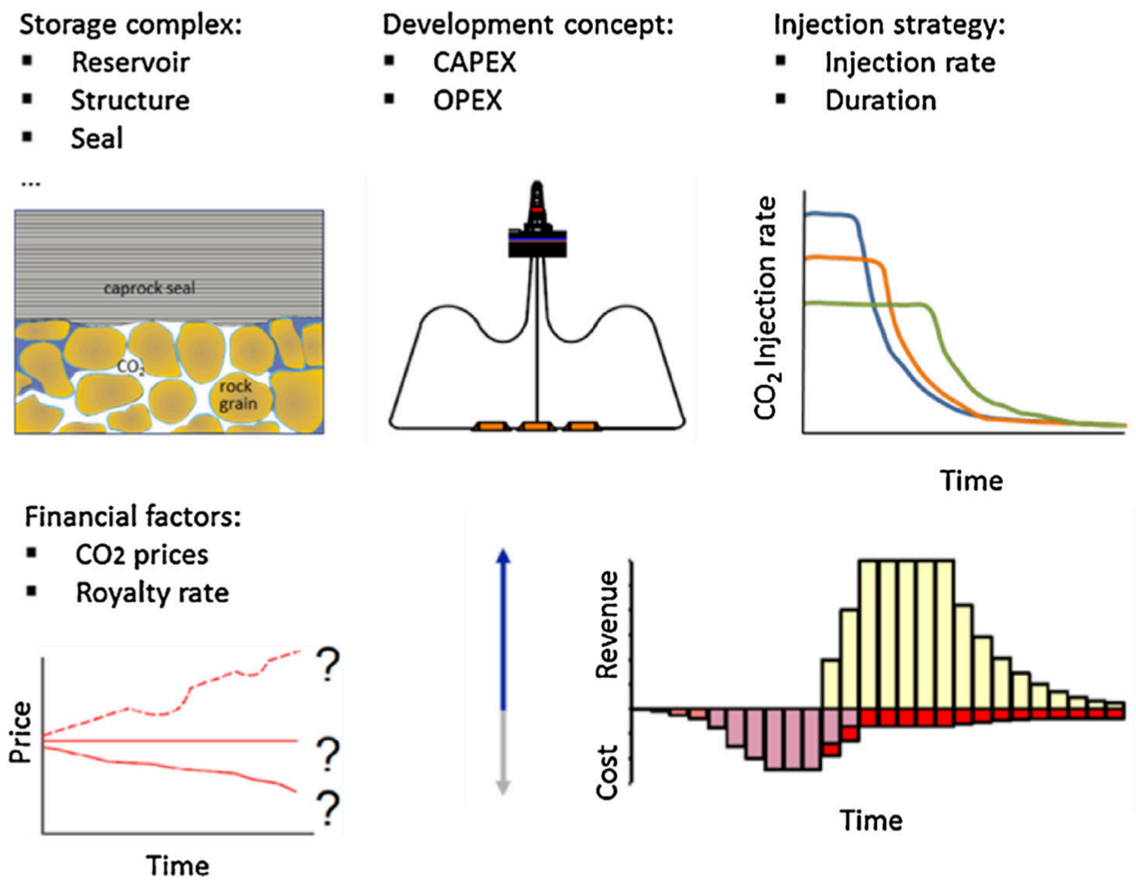

Figure 5-4: Factors determining the CO_2 storage cost (Pawar et al., 2015)

The choice of storage site will influence the storage cost significantly. Depleted oil and gas reservoirs will generally be less expensive than saline aquifers due to well-known site characteristics and reusable infrastructure. The estimated capacity of the storage site will also be reflected in the levelized cost of storage.

The development concept chosen is also a contributing factor in the storage cost. Developers of CO_2 storage sites must decide on how the CO_2 will be transported to the storage location and whether to build a CO_2 reception facility or not. The alternative is to inject the liquidized CO_2 directly into the storage reservoir by ships through an unloading buoy. The CAPEX associated with development of an onshore CO_2 terminal and pipeline is higher than developing an offshore CO_2 terminal or injecting it directly through a buoy. However, the operational cost related to an offshore terminal or direct injection is estimated to be higher. The unstable weather conditions offshore may affect the availability of CO_2 supply, and this could lead to batch-wise injection, which again could cause problems for the injectivity and increase OPEX (Horisont Energi, 2022). Other important concept selections include the design of CCS wells. Lower storage costs can be achieved by choosing a well design that is more adapted for management of CO_2 instead of petroleum. Although many of the adaptations needs regulation changes to be implemented, it is still important to identify the well elements where significant cost-efficiency could be achieved.

Other important factors in determining the levelized cost of storage is the injection rate and operational lifetime of a CO_2 storage project. These are both closely related to the capacity and permeability of the storage site. The higher the injection rate and duration, the lower the costs per tonne of CO_2 stored. This can be observed when comparing the estimated cost of storage for the two different storage scenarios in the Errai project, where the levelized cost of storing 4 Mtpa was 193.40 NOK/tonne of CO_2, while it was 138.98 NOK/tonne of CO_2 for storing 8 Mtpa. Large-scale projects are thus more cost-efficient than smaller-scale projects.

There are multiple ways of attacking the high-cost regime currently dominating the offshore industry. CCS requires a new way of thinking, both with respect to material choice and solutions, but also aspects like risk mitigation and subsequently rules and regulations.

The rules for CCS should be tailor made for the CCS case instead of being similar to what is in place for the oil and gas industry. A lot of the potential areas for cost reduction are limited by current legislations and regulations. These legislations are designed based on a worst-case consequence understanding from the oil/gas industry, and a more tailor-made and down-scaled regulation/legislation is justified.

Increased Research and Development is needed to cut cost in the CCS industry. Based on experience from the years of R&D in the hydrocarbon industry, one can expect the future CO_2 operators to act quickly and innovatively when a robust governmental framework incentivizes such investments. To be able to reduce cost significantly, there is a need for increased dialogue and cooperation between legislative bodies and private companies entering the CCS market. In the oil and gas industry, 2 % of any license budget can within the legal framework be used by the operator for research and development with a large degree of autonomy (G.V. Sund, personal communication, 14. June 2023);(Norwegian Petroleum, n.d.). If similar arrangements were adapted to the CCS industry, there would likely be more and quicker development and progress in cost-efficient measures. All parties are interested in abating CO_2 emissions and increasing the scale of CCS deployment, and changes in regulations and more economic support from governments could increase the progress significantly. First deadline is set at 2030, based on commitments made in the Paris agreement, so time is of the essence.

5.3 Project Control

Before a project is taken on, and at several points during the early phases of a project, decision gates are implemented to evaluate the status of the project. At these points the stakeholders and decision-makers review the project's progress and decides whether the next phase of the project should be authorized or not. The decision gates are important to control that the project is still feasible. This is done by ensuring that the project is within schedule and budget, and that the scope is the same. For a storage site developer, it is important to evaluate both economic and technical risks at each storage gate. There are three different outcomes of a decision gate; the project could either be continued, terminated, or delayed and reconsidered. (Gardiner, 2017; Parth, 2015)

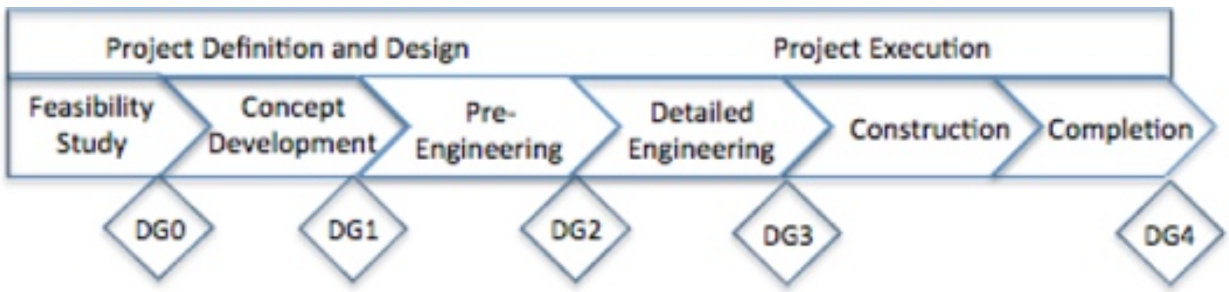

Figure 5-5: Decision gates of a project (Parth, 2015)

There are typically 5 decision gates over the course of a project (Parth, 2015):

- DG0 is the first decision gate in a project. At this stage, the idea of the project is recognized, and it is decided that the project can enter the business planning and concept development phase.
- DG1 is where the initiative is accepted for further investigation.
- DG2 is where the choice of concept is taken.
- DG3 is where the decision about project financing and execution is
- DG4: At this point the decision is taken to accept the project deliverables and commence operations.

5.4 Floating Offshore Wind Power as an Energy Industry Example

The floating offshore wind industry is an example of a similar industry to carbon capture and storage. Both industries are important in the process of reaching climate goals and require significant investment and policy support to be able to develop on a commercial scale. Floating offshore wind farms have a huge potential to contribute to the world's electricity needs. Norway has an ambition of allocating areas for offshore wind production for 30,000 MW by 2040, which is close to Norway's total power production in 2022 (Statsministerens kontor, 2023). Most of the offshore wind turbines today are fixed to the seabed and can therefore not be placed in waters deeper than around 60 meters. Floating wind turbines can be placed further out at sea where the winds are stronger and steadier and can therefore be more efficient (Equinor, n.d.). For floating wind power to be a competitive option, it is necessary to lower the costs. This is turning out to be a challenge, as several projects have had to put their progress on hold. The offshore wind power project Trollvind was initiated by Equinor and partners Petoro, TotalEnergies, Shell and ConocoPhillips to solve challenges related to the electrification of the oil and gas fields Troll and Oseberg. This project was postponed indefinitely during Decision Gate 1 due to challenges regarding technology availability, rising cost and a strained timetable (Equinor, 2022).

5.5 Metallurgy Selection

CO_2 injection wells serve as conduits to transport captured CO_2 from its source to suitable storage sites deep underground. These wells must meet stringent requirements to ensure the safe and efficient injection of CO_2, while maintaining long-term integrity and preventing leakage. Metallurgy plays a pivotal role in addressing these challenges, as it involves the study and application of materials for the construction of well casings and associated components.

One of the primary concerns associated with CO_2 injection wells is corrosion caused by the highly corrosive nature of CO_2 when combined with water. To mitigate this, new metallurgy techniques have been developed to enhance the corrosion resistance of materials used in well construction. Specialized alloys, such as corrosion-resistant steels, high-chromium-nickel alloys, and nickel-based alloys, have shown exceptional resistance to CO_2-induced corrosion, thereby ensuring the long-term integrity of the well infrastructure. Most CO_2 injection wells today use tubing with a high proportion of chrome, usually 22% Cr or 25% Cr stainless steel.

CO_2 injection wells require materials with high mechanical strength to withstand the extreme pressures encountered at significant depths. Advances in metallurgy have led to the development of alloys with superior strength-to-weight ratios, allowing for the construction of well casings capable of withstanding high-pressure environments. For instance, high-strength steels with enhanced toughness and tensile properties are now being employed, providing robustness and reliability in CO_2 injection operations.

Materials used in CO_2 injection wells must also exhibit excellent compatibility with CO_2 to prevent any adverse interactions that could compromise the integrity of the well system. New metallurgical approaches focus on selecting materials that minimize the risk of CO_2-induced embrittlement, stress corrosion cracking, and hydrogen-induced cracking. These considerations have led to the development of alloys specifically tailored to withstand the unique conditions encountered during CO_2 injection, ensuring long-term performance and operational safety.

In addition to the selection of suitable materials, advancements in metallurgy have contributed to the development of barrier monitoring and maintenance techniques for CO_2 injection wells. Advanced sensors and monitoring systems enable real-time monitoring of well integrity, detecting potential material degradation or leaks. Moreover, improved corrosion-resistant coatings and protective measures, such as inhibitors and cathodic protection, help mitigate corrosion risks, ensuring the longevity and reliability of the infrastructure.

The development of new metallurgy techniques has and will continue to significantly advance the field of CO_2 injection wells, making substantial contributions to sustainable carbon sequestration efforts. By improving corrosion resistance, mechanical strength, and compatibility with CO_2, these advancements have enhanced the integrity, reliability, and safety of CO_2 injection operations. Continued research and innovation in metallurgy will further refine materials and technologies, enabling the widespread implementation of CCS technologies and supporting the global transition to a low-carbon future. However, this comes with a cost, and further innovation will have to have a focus on cost reduction. Considerable cost reductions could be achieved by choosing different materials.

Artificial Intelligence (AI) and Technology

The oil and gas industry has had numerous technological improvements over the years, which, although often resulting in increased costs, have not been of any concern because of the robust profit margins of the industry. E&P companies can, according to the law, use 2 % of any petroleum related license budget for research and development (R&D) without any involvement from other parts. For the CCS industry there is no such arrangements. Investments in CO_2 storage projects forces conventional oil and gas companies to think differently when developing or implementing new technology, as the profit margins are much lower. While new innovations have historically emerged from within the oil and gas industry, exploring alternatives used in other industries can offer cost-saving opportunities.

One way of finding alternative technologies is by use of artificial intelligence (AI). According to the World Economic Forum (2018), artificial intelligence is “a term for computer systems that can sense their environment, think, learn, and act in response to what they sense and their programmed objectives”. These computer systems can, among other things, be used to conduct searches for alternative technology. Neptune Energy have used an AI tool called Findest to find potential new cost-efficient and corrosion resistant materials to use in CO_2 injection wells. The AI tool has comprehensive data analysis abilities and allows for searches across other industries to find solutions adaptable to the CCS industry. The same technology scouting would have taken a lot longer for a human to perform. The results from the search have provided suggestions from industries like aircraft, space travel, chemistry and food and beverage. An overview of the first draft is provided in Figure 5-6.

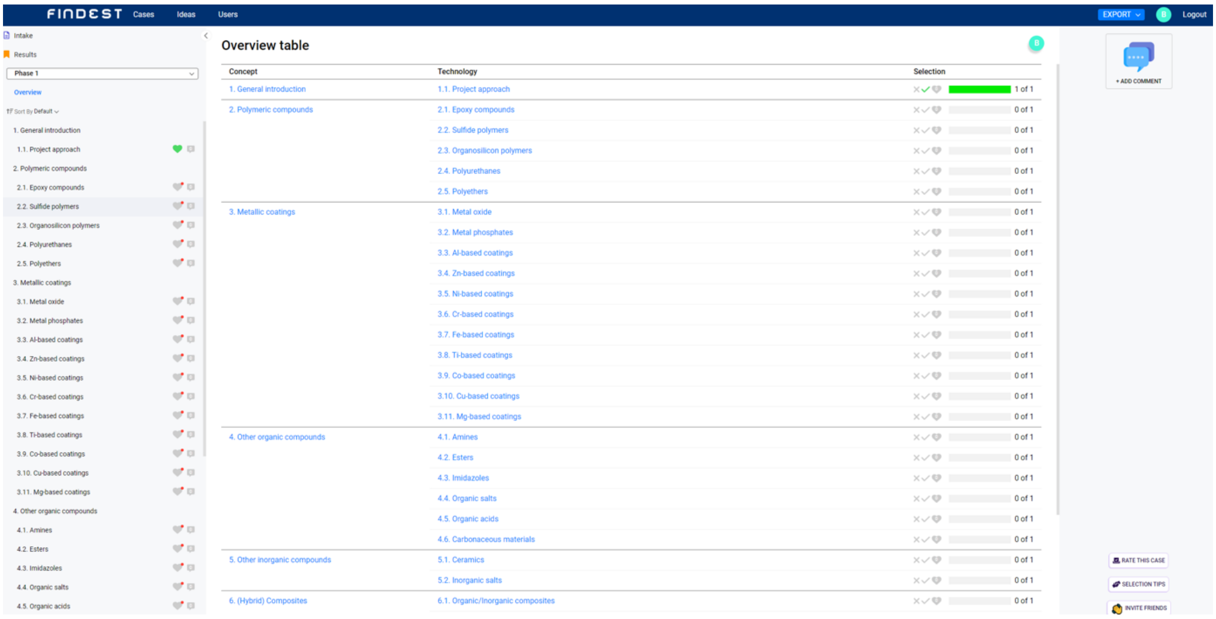

Figure 5-6: First draft of AI search for cost-saving technology

Findest came up with 6 main categories of solutions that could be transferrable to the CCS industry. Each category contains different technologies which are described and accompanied by relevant research papers.

Internal Plastic Coating

To protect the carbon steel from corrosion an internal plastic coating could be added. The plastic coating should cover the whole internal surface of the tubing, as any uncovered areas will be susceptible to corrosion. The downside of using a material like plastic is that there is a risk of it getting damaged during well interventions, leading to exposed steel and loose plastic bits that could potentially clog components in the well completion (Duthie et al., 2019).

GRE Lined Carbon Steel

Glass reinforced epoxy (GRE) lined carbon steel have been used in the oil and gas industry for over 50 years as an alternative for corrosion protection (Radhakrishnan et al., 2018). The GRE lining is inserted into the steel tubing, and the annular space between is filled with cement, making the finished product strong and corrosion resistant. If GRE lining can be used in CO_2 injection wells, it could potentially lead to cost reductions of 0.4 %-0.6%. The technology has still not been tested under conditions likely to be encountered in CCS wells, and it is therefore not yet known if this material can be used. Neptune Energy have recently received several offers to test GRE lined carbon steel under such conditions.

6 Conclusion

Even small cost improvements will make significant impact in the marginal CCS regime. To make CCS investment attractive and profitable, it is critical that the costs related to deployment gets reduced as the income is capped at the alternative cost of paying more taxes. There are multiple measures that can be taken to make CCS wells more cost-efficient. In this thesis the potential cost reductions related to metallurgy selection have been investigated. An investment of 2 million NOK in testing and verification of the use of GRE lined carbon steel in CO_2 injection wells could possibly reduce the costs by 0.4-0.6 %, or by 234 million NOK when storing 300 Mtpa of CO_2.

Other initiatives identified as quick wins are:

- Dedicated injection trees for CCS applications, with a cost-reducing potential of 20 million NOK per tree, or 4-6000 million NOK if assuming 1-1.5 MTA per well.
- Increased spending on R&D through funding mechanisms similar to what is in place for conventional hydrocarbon licenses in Norway, 2% of license budget per annum.
- Well construction legislation for CCS wells with proven hydrocarbon free lithology column. Without jeopardizing personal safety, review regulation in terms of barrier philosophy compared to regulations when drilling i.e., for minerals in Rogaland.

In addition to the measures mentioned in this thesis, there are multiple other areas where the costs could be reduced – from CCS capturing, via transport to all the elements in the CO_2 injection factory. Any small improvement from a small-scale investment in technology advances can make a significant difference on a larger scale.

7 Further Work

This thesis has only explored a few areas where there is potential to make CCS projects more cost-efficient. The focus has been on cost-saving measures within the storage phase of CCS, and more specifically within the design of CO_2 injection wells. There are multiple other small changes and adaptations that could be made to make the total costs decrease, and it is important to explore all possible options. It is also necessary to reduce the costs related to the capture and transportation of CO_2 as the levelized total cost of the whole value chain must be lower than the EU ETS allowance price. Ultimately further work should aim to reduce greenhouse gas emissions, improve the CO_2 capturing process, as well as improving all aspects of CO_2 transportation and storage. Everything – at once.

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