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Haute école de gestion
Genève

Barriers to the Full-scale Deployment of Carbon Capture Utilization and Storage (CCUS)

Bachelor Project Submitted for the Degree of
Bachelor of Science HES in International Business Management

by

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Geneva, 18th August 2023
Haute école de gestion de Genève (HEG-GE)
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Disclaimer

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Acknowledgements

First and foremost, I would like to express my deepest gratitude to my mentor, Richard Watts, for his unwavering guidance, invaluable advice, and constant encouragement throughout the course of this research. His expertise and insight have been instrumental in shaping this work, and I am forever indebted to him for his support.

I owe a profound debt of gratitude to my parents, whose unending faith in me has been the foundation upon which my academic and personal achievements stand. Their sacrifices, love, and enduring support have been my strength during challenging times and have motivated me to strive for excellence in every endeavor.

To all the experts I interviewed, I extend my sincere appreciation for their time and willingness to share their knowledge and experiences. Their perspectives have enriched this study, adding depth and breadth that would not have been possible without their contributions.

Lastly, to my friends who stood by me throughout this journey - thank you. Your patience, understanding, and camaraderie have been a source of comfort and joy. Whether it was offering a listening ear, giving critical feedback, or simply being there for a coffee break, your presence has made this journey memorable.

Executive Summary

Carbon Capture Utilization and Storage (CCUS) has become an essential tool in strategies to combat impending climate change. While we have seen some CCUS systems initiated worldwide, numerous technical, economic, political, and financial challenges and uncertainties remain. This thesis endeavors to pinpoint challenges tied to the broad deployment of CCUS. It seeks to understand stakeholder perspectives on these barriers and explore potential solutions.

Eight experts spanning science, business, and environmental sectors were consulted; their insights serve as a preliminary indicator. The study indicates that primary challenges and uncertainties include economic and financial feasibility, a lack of appropriate CO2 pricing, public perception, and lack of a clear and reliable legal framework.

In addition to these commonly known challenges drawn from existing literature, the expert interviews shed light on other overlooked barriers. These encompass the political urgency surrounding climate change, willingness to invest more in energy resources, infrastructural deficiencies, efficiency in the CO2 capture process, public ignorance about climate change, an absence of a global strategy, and differing perspectives among stakeholders.

These interviews also highlighted differing views among stakeholders regarding CCUS's full-scale deployment barriers. Notably, opinions diverged most on topics like carbon lock-in and government willingness to intervene. To navigate past these barriers for CCUS deployment, the study suggests that political resolve, multi-sector collaboration, and heightened climate change awareness are paramount.

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1. Introduction

1.1 Background

Our world relies heavily on coal, natural gas, and oil fossil fuels, accounting for approximately 80% of global energy (Environmental and Energy Study Institute, 2021). The problem is that they contribute to air pollution by ejecting CO2 into the atmosphere. The burning of CO2 is impacting the “carbon cycle”. Carbon is the foundation of life on Earth. It is regulated between the Earth and the atmosphere; it helps to regulate the temperature or part of our food. Most of the carbon is stored in rocks and is released into the atmosphere when an organism dies, or a volcano erupts. The use of fossil fuels has destroyed this equilibrium. The amount of carbon in the atmosphere has never been more significant than today (National Ocean Service).

The transition to cleaner or renewable energy has started and is expected to accelerate since the Paris Agreement was signed in 2015. An International Treaty on Climate Change limits the temperature increase to 1.5C above pre-industrial levels. But using only cleaner energy is today impossible, given how much fossil fuels are part of our energy production.

Over the past 30 years, technologies have been developed to capture part of the CO2 emitted by the combustion of fossil fuels to use it or store it. CCUS (carbon capture, utilization, and storage) is an essential technology to meet our goals. An effective technology could allow us to continue to partially use fossil fuels without causing climate issues. In the past ten years, CCUS has begun to be used on a larger scale, but it is far from being used repeatedly and therefore considered unproven (McKinsey, 2022). Each CCUS project is still considered a first of a kind, making it difficult for companies to obtain the assurance to invest. Furthermore, CCUS is still considered by some actors to be an unattractive option, as it slows down the transition to cleaner energy.

CCUS is entering a new phase where it must demonstrate that it can be used on a very vast scale. Government, companies, and any stakeholders must be ready to invest. It needs support to achieve the climate transition before climate change becomes irreversible.

The goal of this thesis is to set the conditions needed to deploy CCUS on a full scale by assessing current barriers and the conditions for the best use in the future.

1.2 *How does CCUS Work?*

1.2.1 Carbon Capture

Carbon capture technologies refer to methods that aim to remove carbon dioxide (CO2) from industrial processes or the atmosphere and store it in a manner that prevents its release back into the environment or its reuse. Carbon capture technologies are currently in use or are being researched to mitigate climate change by reducing greenhouse gas emissions. The four main ways to capture carbon are post combustion, pre-combustion, oxy-fuel combustion capture and direct air capture.

Pre-Combustion Capture:

This technique begins with the fuel undergoing a process known as gasification, turning it into a blend of hydrogen and carbon monoxide. Following this, water is introduced, instigating a water-gas shift reaction that transforms the carbon monoxide into CO2. Once transformed, CO2 is separated, captured, and then safely stored, leaving behind hydrogen for energy purposes. This process is efficient, capable of seizing up to 90% of CO2, but is predominantly suited to a specific kind of power plant named Integrated Gasification Combined Cycle (IGCC). (Global CCS institute)

Post-Combustion Capture:

With this method, CO2 is seized from the emissions resulting from the combustion of fossil fuels. Absorbent solvents are employed to isolate CO2 from the remaining gases, then CO2 is extracted from the solvent and stored. This approach's advantage is its compatibility with pre-existing power plants. Nevertheless, it consumes considerable energy because the solvent needs heating to release the CO2. Also, retrofitting current power plants for this method can require significant changes. (Global CCS institute)

Oxy-Fuel Combustion:

In oxy-fuel combustion, oxygen rather than air is used to burn the fuel. The resultant emissions mainly comprise of CO2 and water vapor. Once the water vapor is condensed, CO2 can be easily captured. This technique can seize up to 90% of CO2 but requires a supply of pure oxygen, the production of which can be quite expensive. (Global CCS institute)

Direct Air Capture (DAC):

This is designed to capture CO2 directly from the ambient atmosphere instead of from a particular emission source such as a power plant. DAC's advantage lies in its capability to capture CO2 emissions from any source, potentially making it a highly effective tool in curbing global CO2 levels.

1.2.2 CO2 Transport

After capturing CO2, it is critical to relocate it to a site for either utilization or storage. This relocation process is most conducted via specially engineered pipelines meant to handle CO2 in a high-pressure, high-density state. Several regions have already adopted these systems, especially for processes like enhanced oil recovery (EOR). To truly implement CCUS on a grand scale, it is essential to further expand these CO2 pipeline networks. In scenarios where pipelines may not be practical, such as trans-oceanic or urban settings, alternative transportation methods, such as shipping (for liquified CO2) or trucking, may be employed. However, these alternatives are generally less common and more costly.

1.2.3 CO2 Utilization

There are multiple avenues for utilizing the captured CO2:

- **Enhanced Oil Recovery (EOR):** EOR is a process where CO2 is injected into oil fields to aid in more oil extraction. The injected CO2 reduces the oil's viscosity and increases its flow, helping in the extraction process. Some of the CO2 remains underground after extraction, effectively providing a storage solution.
- **Industrial Uses:** Captured CO2 can be use in various industries. It can aid in creating chemicals like urea (used in fertilizers), methanol, and other organic compounds. It also finds applications in the food and beverage industry for the carbonation of drinks or as a cooling agent.
- **Carbon Mineralization:** In this process, CO2 interacts with metal oxides to form carbonates, thereby converting CO2 into a solid, stable form. This process can also contribute to the production of building materials.
- **Biofixation:** CO2 can be deployed to cultivate microalgae or similar fast-growing biomass, which can subsequently be transformed into biofuels, animal feed, or other beneficial products.

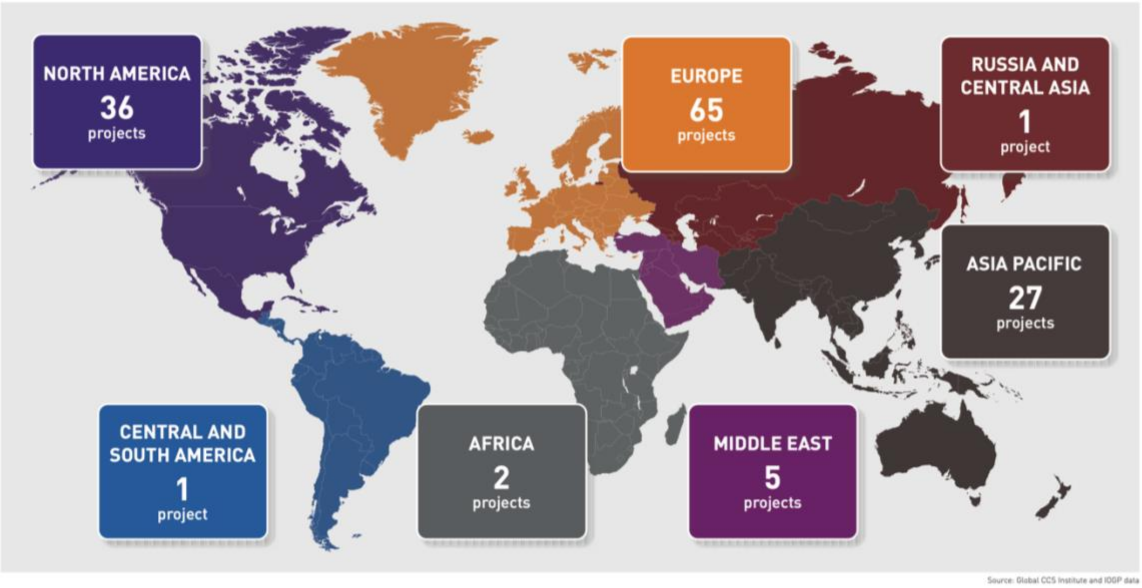
1.2.4 CO2 Storage:

If the captured CO2 is not use, it must be stored, typically underground:

- **Geological Storage:** The most prevalent method of CO2 storage involves its injection deep into appropriate geological formations like depleted oil and gas fields, unmineable coal seams, or deep saline formations. The CO2, in a supercritical fluid state, is made to occupy the pore spaces in the rock, akin to what occurs with oil or natural gas.
- **Mineral Carbonation:** This process enables CO2 to react with certain rock types like basalt or peridotite to create solid carbonate minerals. This form of storage is both permanent and safe, as the stored CO2 cannot leak out. The process, however, is naturally slow and often requires high temperatures and pressures to make it reasonably efficient, with ongoing research aimed at improving its practicality and cost-effectiveness.

1.3 <u>Overview of CCUS Projects around the World</u>

Overview of existing and planned CCUS facilities



https://status22.globalccsinstitute.com/wp-content/uploads/2022/11/Global-Status-of-CCS-2022_Download.pdf

1.3.1 North America

North America, especially the United States, remains at the forefront of global Carbon Capture, Utilization and Storage (CCUS) deployment. The Biden Administration in the U.S. acknowledges that reaching a fair transition to a net-zero economy by 2050 requires policies that substantially fund advanced technologies for the secure and efficient capture, elimination, and storage of carbon dioxide. There is cross-party political support for CCUS in the U.S. Similarly, in Canada, CCUS plays a crucial role in achieving its economic and environmental goals towards its target of net-zero emissions by 2050. The importance of principles regarding environmental, social, and governance (ESG) continues to grow. (Global CCS institute, 2022)

1.3.2 Asia Pacific

CCUS in the Asia-Pacific region presents a mix between considerable advancement and slow execution within the broader context of climate change mitigation. Even though both public and private sectors in the region persist in rolling out climate mitigation strategies and amplifying decarbonization efforts, the urgency for more extensive measures is evident. Complicating the achievement of regional climate goals is the fact that many Asian economies, especially those in Southeast Asia, depend on fossil fuels for their economic expansion. These countries also host a large share of the globe's emissions-heavy industries, underlining the crucial role of CCS in balancing growth and decarbonization.
Over the past year, there have been some noteworthy strides. Numerous new projects, including Thailand's first commercial project, have been announced, and there is clear institutional momentum as CCUS regulations and policy instruments have begun to develop at both national and local levels. Collaborative efforts are gaining speed, as evidenced by an increasing number of Memoranda of Understanding (MOUs) across both private and public

sectors. However, three primary obstacles to CCUS persist across the region to varying degrees - the availability of geological storage resource data, legal and regulatory frameworks, and motivating policy. (Global CCS institute, 2022)

1.3.3 Europe

CCUS projects across Europe have seen another year of optimistic growth. Currently, 65 CCUS facilities are being developed across the continent and the UK.
Favorable climate policy initiatives by the European Commission is a key element fueling this growth. This includes an increase in projects funded through the EU Innovation Fund – a 2020 program aimed at supporting the Commission's 2050 climate neutrality objectives. Similarly, in the Netherlands, the funding under the Sustainable Energy Transition Subsidy Scheme (SDE++), which includes CCUS projects, has surged from €5 billion to €13 billion in just one year. In the UK, the government, through its CCUS Infrastructure Fund (CIF), pledged to build two CCS clusters by the mid-2020s and another two by 2030. The past year has demonstrated a positive trend of industries implementing CCUS projects, building on the existing policy framework. (Global CCS institute, 2022)

1.3.4 Middle East and North Africa Region (MENA)

The Middle East and North Africa (MENA), the world's largest oil-exporting region, contributes around 85% of greenhouse gas (GHG) emissions through energy production, electricity generation, industry, and home energy use.
Countries like Qatar, Kuwait, the UAE, Bahrain, and Saudi Arabia are known as some of the highest per capita carbon emitters globally, making MENA a high carbon-intensive region. Unless energy policies and consumption habits are altered, the region's energy-related GHG emissions are likely to rise. With significant stocks of the world's oil and gas reserves, MENA plays a crucial role in energy geopolitics. Investments in decarbonization and clean energy technologies are necessary to uphold this role.
In this context, CCUS presents a viable solution to cut down CO2 emissions in the region. Three functional CCUS facilities in the UAE, Saudi Arabia, and Qatar already capture about 10% of the global CO2 each year. Furthermore, the region has substantial experience with CO2 injection and storage. The In Salah CCS project in Algeria is a pioneer in onshore CO2 capture and storage, providing invaluable experience for CCUS projects globally. (Global CCS institute, 2022)

1.4 ***Research Questions***

Despite some improvements in the past years, the broader stakeholder community is still encountering significant hurdles regarding the large-scale implementation of Carbon Capture, Utilization, and Storage (CCUS). A principal challenge is the considerable number of scientific, technical, societal, and economic barriers hindering the global deployment of CCUS on a full scale. It is critical for governments to be comprehensively informed about these barriers, as their backing for CCUS plays a pivotal role in shaping climate change mitigation strategies and determining the future trajectory of CCUS itself. Similarly, the endorsement from the energy industry and the business sector is vital, especially considering the numerous obstacles to the full-scale implementation of CCUS, which render investment decisions complex and fraught with risk. Besides support from governmental bodies and the business sector, societal acceptance is equally crucial for the extensive roll-out of CCUS. This necessity arises from the fact that broader society is still largely uninformed about the existence of CCUS, its role in reducing CO2 emissions and the related externalities of CCUS. As a result, governments, the business sector, and society at large confront the following obstacles concerning the full-scale deployment of CCUS, as expressed in the following research questions:

- What are the conditions and incentives required for CCUS to be used as a viable solution for reducing CO2?
- What are the actual barriers to his full-scale development?
- How can these barriers be overcome?

2. Literature Review

The literature review comprises the selection of relevant documents (published and unpublished) relating to the topic of interest, containing insightful information, ideas, data, and evidence. The primary objective of the literature review is to pinpoint the research gap that the thesis aims to fill, situating it within the context of previous studies. Additionally, the literature review seeks to evaluate and synthesize information and concepts linked to the research, thereby generating a rationale or justification for the specific study. The literature review aids in understanding the topic and constructing the framework within which the research either extends or enhances the studies already performed on the related topic. The method for approaching the barriers linked to the full-scale deployment of CCUS in this thesis begins with a literature review from existing social science literature on CCUS. This helps to establish what is already known from a social science perspective and identify gaps concerning technical, economic, financial, political, and societal aspects of CCUS.

2.1 Lack of Legal Framework

The successful upscaling of carbon capture, utilization, and storage (CCUS) technologies requires establishing robust legal and regulatory structures. These structures are necessary to manage CO2 storage sites effectively, protect public health and the environment, and ensure the safety of CCUS operations. Regulatory frameworks for CCUS should encompass all value chain elements, including capture, transport, use, and storage. However, due to its unique and complex regulatory challenges, CO2 storage often becomes the central focus. (IEA)

One of the critical challenges in CO2 storage regulation is clarifying issues related to the ownership, management, and liability of CO2 destined for indefinite storage. Regulatory frameworks must establish clear guidelines on selecting storage sites, safe operations, and risk mitigation throughout all stages of site development, operation, and closure. These frameworks should also address the allocation of property rights and manage resource competition to ensure the efficient and equitable use of CO2 storage sites (Carter & Eaton, 2016). Regulatory considerations for CO2 capture, transport, and use generally align with existing frameworks for industrial activities such as oil and gas, waste management, and environmental considerations.

However, governments should carefully review domestic and international frameworks to identify and eliminate potential obstacles to CCUS deployment. This scrutiny is necessary to ensure that existing regulations adequately address the unique challenges and requirements of CCUS technologies. In the context of CCUS, it is crucial to consider the role of legal and regulatory frameworks in providing clarity and certainty to project developers and investors. These frameworks delineate the responsibilities and rights of all parties involved in CCUS, including relevant authorities, operators, and the public.(IEA)

By providing a clear legal foundation for CCUS, regulatory structures can foster investment and support the development of a robust CCUS industry. Establishing robust legal and regulatory structures is crucial for successfully upscaling CCUS technologies. These structures must be designed to oversee CO2 storage sites meticulously, safeguarding the environment and public health while ensuring that CCUS operations are conducted with utmost safety and integrity. While all elements of the CCUS value chain should be considered, CO2 storage often presents unique regulatory challenges. Regulatory frameworks should address issues related to ownership, management, and liability of CO_2, site selection, safe operations, and risk mitigation. Additionally, these frameworks should provide clarity and certainty to project developers and investors, supporting the growth of the CCUS industry.

2.2 *Financial Incentives*

The connection between markets and policies is super important to get more investment in carbon capture, utilization, and storage (CCUS). Even though we've known about CCUS since the 1970s, not much money has gone into it. It makes up less than 0.5% of clean energy investment. Why? Well, the 2008 financial crash hurt, and businesses were also worried about a shaky market and unclear policies. (IEA, 2022)

However, from 2017, things started looking up for CCUS. More people became concerned about climate change, and governments, like in the U.S., Germany, China, and Korea, began helping CCUS with better policies and financial support. Because of this, more companies got involved and started creating new CCUS technology.

Still, if we want CCUS to reach its full potential, more needs to be done. The technology is expensive to start up and has some risks. Some ideas to help with these issues include improving the efficiency of plants, dealing with market problems, and spreading out the risks. Also, businesses can work together in things like shared transportation and waste management.

When thinking about investing in CCUS, it's important to weigh the pros and cons. One method, carbon capture and storage (CCS), uses existing tech without changing too much. Another method, carbon capture and utilization (CCU), needs a lot of power. So, it's important to keep these things in mind when making rules and deciding where to put money.

In China, they're taking CCUS seriously. They've made policies to push for green tech, and there are a lot of CCUS projects already running and planned for the future.

To wrap it up, connecting market and policy is key to get more money into CCUS. There's been a bit more investment recently, but we need even more. Good policies that tackle the cost, energy, and risks of CCUS can help it grow. Joining forces in sectors and developing cool new tech will also give the CCUS industry a boost.

2.3 *Public Acceptance*

For carbon capture, utilization, and storage (CCUS) to work well, people need to be on board with it. But getting everyone to accept CCUS isn't easy.

One big issue is that people are worried about the risks of CCUS. They're concerned about whether it's safe for the environment and our health (Wallquist et al., 2010). Some worry about the chance of CO_2 leaking or problems when moving the captured CO_2 around. To make people feel better, it's important to be open about how CCUS works and the steps taken to keep everything safe (Glanz & Schönauer, 2021).

Another challenge is that many people just don't know much about CCUS. They might not understand why it's so important for fighting climate change. To fix this, we can run awareness campaigns, teach people about CCUS, and chat with local communities. The goal is to give clear and simple information about CCUS (Sitinjak, 2023).

Some people also wonder if CCUS is worth the money. They want to know if it's a good investment. To address this, it's a good idea to talk about the money side of things, like how CCUS can create jobs, make energy more secure, and even make money from using carbon (Heek et al., 2018).

Getting people to accept CCUS also means bringing everyone into the conversation. This includes local folks, businesses, and groups interested in the topic. Listening to what everyone has to say and involving them in decisions can build trust (Glanz & Schönauer, 2021).

Lastly, how we talk about CCUS matters. The media and leaders can shape how people feel about it. By highlighting the positive sides, like how CCUS can help fight climate change, create jobs, and lead to cool new tech, we can make CCUS look more attractive (Song et al., 2022).

To resume, we need people to accept CCUS if we want it to work. This means dealing with worries about risks, teaching folks about CCUS, showing its economic value, involving everyone in the conversation, and talking about CCUS in a positive light. By doing all this, we can build trust and get more people on board with this important tool.

2.4 <u>Carbon Pricing</u>

To get more people to use carbon capture, utilization, and storage (CCUS) technology, we need to put a higher price on carbon emissions. Things like carbon taxes or trading systems make it cost more to emit carbon. This way, businesses have a reason to cut down on their carbon footprint (Aldy & Stavins, 2012). But right now, the price isn't high enough to get everyone on board with CCUS.

A big hurdle is setting a carbon price that makes CCUS a good deal. Setting up CCUS projects can be expensive (Fischer & Newell, 2008). If the carbon price is too low, businesses might think it's too costly to capture and store CO2, so they won't invest in CCUS (Ma et al., 2018). We need a higher price on carbon to make CCUS seem like a good investment.

Also, when carbon pricing is too low, CCUS looks less attractive than other clean technologies. Solar or wind energy might look like a better deal compared to CCUS (Fischer & Newell, 2008). This can lead to money being spent on things that might not reduce emissions as much as CCUS would. So, it's crucial to price carbon correctly to show the real cost of emissions and to promote CCUS.¨

Another problem is when carbon prices keep changing. Investors want to know what they're getting into. If carbon prices keep going up and down, they might think CCUS is too risky and not put money into it (Fischer & Newell, 2008). We need a clear and stable carbon pricing system to help CCUS projects grow.

To fix the carbon pricing issue, we can't just rely on one solution. Other policies can help too. Things like funding for research, setting clear standards, and supporting renewable energy can help CCUS grow (Jaffe et al., 2005). These steps can make CCUS even more attractive and work well with a proper carbon price.

In short, the current carbon price isn't helping CCUS grow as much as it should. To get more businesses to use CCUS, we need to make carbon more expensive. This way, it becomes a smart choice for businesses. Plus, adding other supportive policies can give CCUS an extra push.

2.5 Projects are Large and Unproven

CCUS projects are large-scale, and their effectiveness is yet to be fully proven. Establishing these projects is a lengthy process with a history of many early-stage failures. A study from McKinsey, showed that between 1995 and 2018, 263 CCUS projects were initiated, each with the capacity to process at least one ton of CO_2 daily. Of those that could process more than 0.3 MT of CO_2 per year—representing about half the sample size—78 percent have either been canceled or paused. Thus far, each CCUS project has had unique characteristics, representing all the challenges associated with pioneering projects. Simultaneously, these projects often stand on a precarious commercial footing, which makes achieving success a more demanding endeavor. (McKinsey, 2022)

2.6 Carbon Lock-in

The term "carbon lock-in" refers to the self-reinforcing dynamics that lead to the continued use of fossil fuels and the high-carbon systems, making it difficult to transition to a low-carbon economy.
CCUS can be linked to carbon lock-in in several ways:

1. **Perpetuating Fossil Fuel Use**: There is a concern that CCUS technologies might perpetuate fossil fuels by creating a perception that we can continue using them as long as the CO2 is captured and stored or utilized. This could delay the transition to renewable and sustainable forms of energy.
2. **Diversion of Investments**: Investment in CCUS technologies can lead to a diversion of resources that could otherwise be spent on promoting renewable energy sources or energy efficiency measures. The capital-intensive nature of CCUS projects may lock economies into long-term commitments to continue fossil fuel use.
3. **Infrastructure**: The development of CCUS technologies also involves the creation of new infrastructures (like pipelines for CO2 transport, storage sites, etc.). Once in place, these infrastructures could reinforce the commitment to continue fossil fuel use to justify the investments made.
4. **Policy Support**: If policy support prioritizes CCUS, it could solidify systems and structures that maintain the status quo of fossil fuel usage.

2.7 *Insuffisant Choice of CO2 Reutilization*

Carbon capture, utilization, and storage (CCUS) is a way to help reduce the harmful CO2 in our environment. But while we are capturing CO2, we still struggle to use it productively (Dowell et al., 2017).

A big reason for this is that we produce CO2 much faster than we can use it. Factories and power plants release so much CO2, and right now, we can't turn most of it into useful things like fuels or chemicals (Dowell et al., 2017). So, finding ways to use this CO2 in big amounts and in ways that make money is hard.

It's very important to find ways to use CO2. Studies say that to stop the planet from getting too hot, we have to release less CO2, aiming for almost zero emissions by the end of the century (Dowell et al., 2017). If we get better at using CO2, reaching these goals will be more achievable.

Even with some actions to fight climate change, our CO2 emissions have still been going up by about 2.6% each year from 2000 to 2014 (Dowell et al., 2017). This means we need more solutions, like using the CO2 we capture.

One idea is using Bioenergy with Carbon Capture and Storage (BECCS). This involves using plants to make electricity and combining them with coal. It's seen as a possible and affordable way to release less CO2 (Yi et al., 2018). This can help us move to cleaner energy sources.

But the big question is: can we make money from using CO2? Some studies show that turning CO2 into food could be profitable. Also, using CO2 to make things like special food for animals and fertilizers for plants is being looked at (Pikaar et al., 2018). We need to check which of these ideas can make money and be done on a large scale.

In short, while we're good at capturing CO2, using it is still a challenge. We need to think about how fast we produce CO2, how we can use it, and if it's worth the money. It's vital to find big and profitable ways to use CO2 if we want to help our planet. We should keep researching and supporting new ways to make the most of captured CO2.

3. Methodology

Step 1: Understanding the Subject

I started by immersing myself in a thorough study of CCUS, aiming to grasp its principles, processes, and significance. Through diligent review of scientific literature, reports, and relevant publications, I acquired a solid foundation in the subject matter. This background research was crucial in formulating research questions and identifying potential knowledge gaps that needed to be addressed.

Step 2: Assessing the Existing Knowledge Gap

To determine the research question, I carefully examined the current state of knowledge in the field of CCUS. This involved critically analyzing existing literature, research papers, and industry reports. By identifying gaps or areas that required further exploration, I was able to develop a research question that contributed to the existing body of knowledge. This step ensured the originality and relevance of my study.

Step 3: Identifying the Current Barriers to CCUS Development

I delved into an investigation of the current barriers impeding the full-scale development of CCUS. This involved an extensive review of literature and examination of industry reports, government publications, and expert opinions. The barriers I identified encompassed technical, economic, regulatory, and social challenges. By thoroughly understanding these barriers, I aimed to develop effective strategies to address them.

Step 4: Expert Interviews and Barrier Ranking

To gather expert insights and validate the identified barriers, I conducted interviews with industry professionals and subject matter experts. During these interviews, I presented the identified barriers and asked the experts to rate their significance on a scale of 1 to 10. The ratings provided by the experts enabled me to quantify the relative importance of the barriers and prioritize my focus accordingly.

Step 5: Data Analysis

I analyzed the data collected from the expert interviews and assigned numerical values to each identified barrier based on the ratings. By aggregating the results, I was able to identify the most significant barriers to CCUS development in both the short and long term. This analysis provided a clear understanding of the challenges that needed to be addressed for successful implementation of CCUS technology.

Step 6: Discussion and Recommendations

I engaged in a critical discussion of the findings, incorporating insights from the expert interviews and other relevant sources. This discussion highlighted the implications of the identified barriers and proposed recommendations to overcome them. My recommendations included suggestions for technological advancements, policy changes, financial incentives, and public awareness campaigns. I supported these recommendations with evidence and examples from the literature and expert interviews.

Step 7: Conclusion

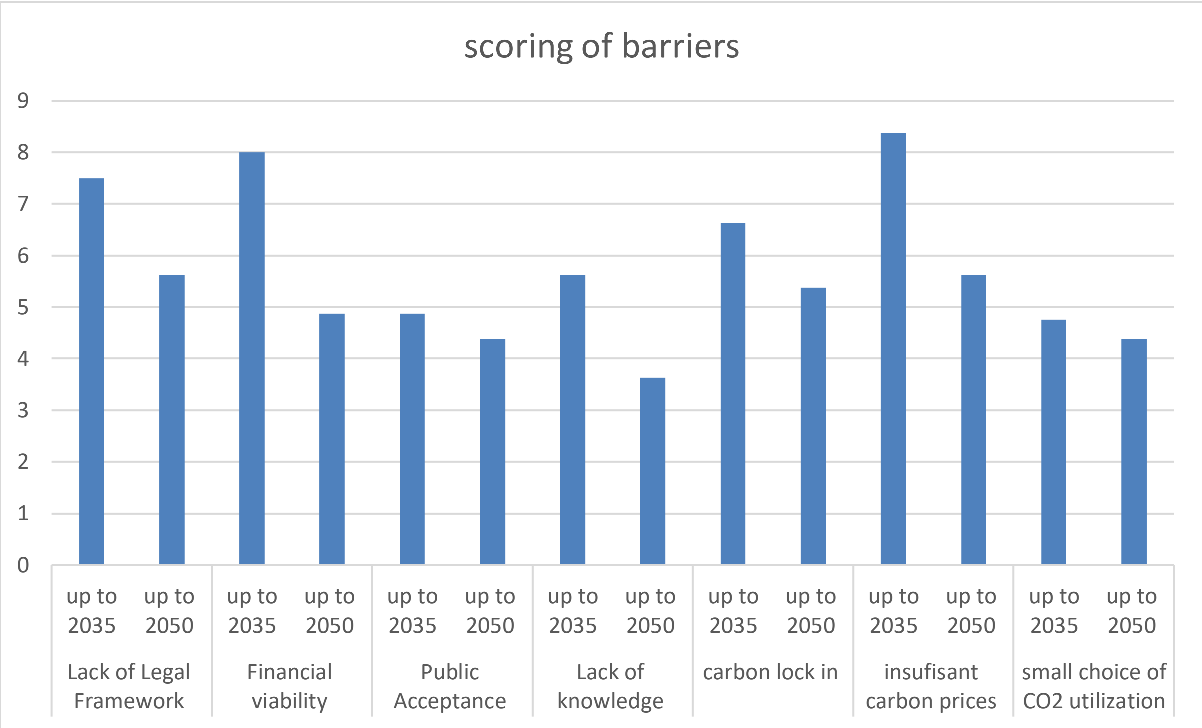
In the conclusion, I summarized the main findings, emphasizing the significant barriers to CCUS development and presenting the recommendations derived from my study. This section reinforced the importance of addressing these barriers and highlighted the potential benefits of implementing CCUS technology. The conclusion served as a concise overview of the research outcomes and provided a clear direction for future efforts in CCUS development.

4. Results

This section provides an overview of the results for barriers to the full-scale deployment of Carbon Capture utilization and Storage (CCUS) in two scenarios: short-term and long-term. The insights are based on interviews conducted with a diverse group of experts, including academics and representatives from the business sector.

In addition to the assessment of identified barriers, this part also highlights other significant barriers identified by the experts. It also explores how the feasibility of CCUS deployment is perceived by these experts and examines variations in their perspectives on barriers as well as global differences in the perception of CCUS.

The evaluation methodology involved scoring the barriers, which are presented in Figure 3.



4.1 Short- and long-term Assessment of Barriers

Lack of Legal Framework

Short term rank : 3 / long term rank : 1

In the short term, the deployment of Carbon Capture and Storage (CCS) faces significant challenges, primarily due to the lack of existing infrastructure. The status can be rated around 7.5, as there are no well-established setups in place. However, there are encouraging signs of progress with some developments on the horizon. The emergence of political support and regulatory measures to incentivize CCS and CCU (Carbon Capture and Utilization) initiatives positions the rating around the middle, underlining the importance of addressing these issues.

Looking towards the long term, the rating for CCUS deployment could be reduced to a 5.625 according to the experts. Although there will still be regulatory hurdles, such as working on carbon credit markets and advancing infrastructure development, they might be less critical compared to the short term. Nonetheless, constant updates and implementations of legislation will remain crucial for long-term success.

On a broader scale, experts generally emphasize the significance of having an appropriate legal framework. It is seen as a fundamental requirement to undertake major infrastructure projects and gain the necessary financial support. Without clear and understood legal certainty, investors may hesitate to invest substantial capital, hampering progress. In countries like the United States, the 45 Q tax credit provides some certainty, leading to increased investment.

Assessing the role of the legal framework from various perspectives, experts offer ratings ranging from 6 to 10 in the short term and 3 to 10 for long term, with some considering it more critical than others. The level of concern depends on factors such as the country-specific policies, funding availability, and overall long-term planning. Countries like Canada have made progress in establishing a solid legal framework for CCUS, but there are still gaps that need addressing, particularly in funding-related policies.

Overall, the evaluation underscores the complexity of CCUS deployment, with different timeframes presenting their unique challenges. In the short term, building the necessary infrastructure and securing political and regulatory support remains crucial. In the long term, continued updates to legal frameworks and policy measures are essential to sustaining progress.

Financial Viability and Incentives

Short term rank : 2 / long term rank : 4

The financial viability of Carbon Capture utilization and Storage (CCUS) is a critical factor in determining its successful deployment. Experts recognize that the high upfront costs associated with CCUS projects pose significant challenges in both the short and long term. However, they also highlight potential opportunities for improvement as market conditions evolve.

In the short term, the financial viability of CCUS projects is rated around 8. The substantial and long-term investments required for these projects often deter potential investors, especially when clear financial incentives are lacking. Current voluntary carbon markets do not provide the necessary investment security, making it challenging to secure the funding needed to establish CCUS infrastructure. Despite this, there is a glimmer of hope, as public and private funds are becoming available, indicating potential progress and advancement until 2035.

Looking to the long term, the financial viability barrier is seen as relatively lower, with ratings ranging from 2 to 8 with an average close to 5. Experts believe that as climate change continues to accelerate, there will be growing recognition of the urgency to invest in CCUS technologies. This could lead to clearer regulatory frameworks and more stable markets, which would make CCUS projects more economically feasible over time.

One of the key issues raised by experts is the lack of a well-defined business case for implementing CCS and CCU technologies. Without a clear path to profitability, private investors might remain hesitant to commit resources to these projects. The absence of a well-established market for CCU further complicates the financial viability of such initiatives.

Nevertheless, experts also highlight the potential role of carbon pricing and regulatory support in improving the financial landscape for CCUS. The implementation of carbon taxes and policies can incentivize companies to invest in emissions reduction technologies like CCUS. Additionally, regulatory measures that provide subsidies or financial assistance could help bridge the gap between the high upfront costs and the long-term benefits of CCUS.

In conclusion, the financial viability of CCUS projects is a significant challenge in the short term, but with the availability of public and private funds and increasing interest in carbon pricing, there is hope for progress. In the long term, the financial barrier may diminish as the urgency of climate change becomes more apparent and regulatory frameworks mature, making CCUS projects more economically feasible and attractive for investment.

Public Acceptance

Short term rank : 6 / long term rank : 5

Public acceptance plays a crucial role in the successful implementation of Carbon Capture Utilization and Storage (CCUS) projects. Experts' assessments vary, but overall, they do not consider it a significant barrier. In the short term, public acceptance is generally rated around 5 to 6, as there might be some concerns due to lack of awareness and understanding of the technology. However, it is acknowledged that once people become more informed about the benefits and necessity of CCUS, public perception is likely to improve.

The perception is that CCUS projects are often integrated into existing industries, making them less visible to the public, which contributes to greater acceptance. However, there might still be some challenges in the short term due to potential cost implications for the public, which could be exploited by certain political factions.

Looking to the long term, experts generally believe that public acceptance will likely increase, with ratings around 4 or even lower. As CCUS becomes more familiar and its benefits are better understood, the perception of the technology is expected to become more favorable. Comparable experiences with other technologies, like wind power generation, suggest that public acceptance can improve over time, especially if CCUS projects do not become perceived as a public nuisance.

While some experts remain cautious about the possibility of public opposition in the future, the majority do not consider public acceptance a significant barrier. Instead, they emphasize the importance of education and awareness to overcome initial resistance. As long as CCUS projects are transparent in their intentions, and the public is well-informed about the necessity and benefits of such technologies, public acceptance is not expected to be a major hindrance.

In conclusion, public acceptance is not seen as a major obstacle to the deployment of CCUS technology. The short-term challenges could be addressed through effective communication and education, and as the benefits of CCUS become more evident, public perception is expected to improve in the long term. However, it remains crucial for policymakers and stakeholders to prioritize transparency and communication to ensure continued public support for CCUS initiatives.

Lack of Knowledge

Short term rank: 4 / long term rank : 7

The expanding knowledge base surrounding Carbon Capture utilization and Storage (CCUS) is fostering an atmosphere of optimism and progress. While there is still challenges in the short term with an average of 6, experts believe that ongoing research and technological advancements are rapidly closing the knowledge gaps, propelling CCUS forward with great promise, grading the long term with the lowest score with an average of 3.6.

In the short term, the barrier of knowledge is gradually eroding as more research projects and operational measures, like recycling concrete with captured CO2, demonstrate the feasibility and benefits of CCUS solutions. As awareness grows, experts are increasingly confident that CCUS technologies will become more accessible and viable for various industries.

Moreover, public perception is evolving positively alongside the increasing understanding of CCUS. As the public becomes better informed about the effectiveness and significance of these technologies in combating climate change, acceptance levels are rising. Public support is essential for accelerating the deployment of CCUS on a larger scale, and with enhanced knowledge, communities are likely to embrace CCUS initiatives with enthusiasm.

In the long term, the outlook is even brighter, as experts anticipate a substantial reduction in the barrier of knowledge. Ongoing research endeavors, combined with collaboration among stakeholders and policymakers, are driving progress. Continued investment in research and development is key to unlocking the full potential of CCUS technologies, making them more efficient, cost-effective, and tailored to diverse applications.

CCUS is benefitting from the collective expertise of scientists, engineers, and policymakers who have made significant strides in understanding the intricacies of capturing, storing, and utilizing CO2. As this knowledge spreads, the technological maturity of CCUS is set to soar, opening doors to a greener, more sustainable future.

Carbon Lock-in

Short term rank: 4 / long term rank : 3

Experts recognize the potential of CCU and CCS technologies but are sharply divided on their implications for carbon lock-in. Short-term views rate carbon lock-in as a middle-risk issue (6.5 out of 10), fearing that these technologies may become a justification for continuing fossil fuel usage.

Some experts highlight the lobbyism aspect, where the promise of CCUS might delay the essential reduction in carbon production. This has implications in both the political and industrial sectors, making it a critical short-term concern.

Longer-term perspectives vary. Some see the risk of carbon lock-in decreasing as the realities of the expense and complexity of CCUS become evident. The belief here is that these practical constraints will gradually make reducing CO2 at the source more attractive.

Others maintain a higher level of concern, fearing a more fundamental problem with CCUS. They argue that it increases energy demand to capture and store CO2, thus perpetuating a carbon-intensive path.

A few experts also emphasize public perception and acceptance. The fear of carbon lock-in may even overshadow public mistrust in technology, making it a more profound barrier to adoption.

The consensus, however, lies in the careful balance needed between implementing new technologies like CCU and CCS and the necessity to reduce emissions at the source. Experts stress that the primary focus should be on halting the "digging" into fossil fuels, metaphorically speaking, rather than merely finding ways to fill the hole back in.

In summary, expert opinions on carbon lock-in reveal a complex and nuanced landscape, pointing to both potential benefits and significant risks in the integration of CCU and CCS technologies. They emphasize the need for a strategic approach that prioritizes immediate carbon reduction while cautiously exploring these technologies, to avoid inadvertently endorsing a continued reliance on carbon-intensive energy systems.

Insufficient Carbon Prices

Short term rank: 1 / long term rank : 1

The insufficiency of carbon prices emerges as a critical concern among experts, particularly in the context of promoting Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) technologies.

In the short term, this issue is rated as a high barrier, with some experts placing it at a 9 or even a 10 on a scale of importance. Even though carbon prices are rising in some regions, including under the European Union Emissions Trading System (ETS), they are still viewed as insufficient to provide the necessary financial incentives for companies to invest in carbon capture.

For example, in places like Switzerland or the Netherlands, carbon prices have hit certain milestones, but experts agree that current levels are not enough to cover the investments needed to build CCU and CCS infrastructure. Some experts specifically mention mechanisms such as contracts for difference, where governments can subsidize the difference between the current price and a set target, as potential solutions to this challenge.

In the long term, there are varying opinions on how this barrier might evolve. Some experts predict that carbon prices will increase significantly, potentially reducing this concern to a level 2 or 3 by 2050. Others suggest that the barrier may remain higher at around 6 to 8, depending on how revenue models change, and political decisions are made to make carbon credits more scarce.

The shared sentiment is that insufficient carbon pricing is indeed a major obstacle for CCU and CCS. While it can be a key financial incentive for emitters, current pricing, even in rising markets, falls short of what's needed to encourage the adoption of carbon capture technologies.

In summary, insufficient carbon prices are seen as a significant barrier in both the short and long term for implementing carbon capture strategies. There is a call among experts for more determined financial incentives and policy interventions to bridge the gap between current carbon prices and the levels required to support substantial investments in CCU and CCS.

Utilization of CO2

Short term rank : 7 / long term rank : 5

The utilization of captured CO2 is seen as a steppingstone rather than a long-term solution by some experts. In the short term, CO2 can be used in various products like recycled cement or fertilizers, which provides an environmental benefit and a business stream. However, this is often viewed as merely postponing the emission since utilization in certain products may only delay the release of CO2 back into the atmosphere.

Several interviewees believe that in the long term, the focus will need to shift towards durable storage. While utilization might be appropriate for the small amounts of CO2 currently captured, future efforts must move towards more permanent solutions. This shift is reflected in various assessments of the barrier, ranging from a rating of 1 to 9 in the short term to 1 to 9 also in the long term. It all depends on perception the expert has on the utilization of C02.

There are differing opinions on whether this constitutes a significant barrier. Some see it as not being a major obstacle, particularly from a climate target perspective, and others point to it being more significant.

The economics of CO2 utilization are also a concern, with financial incentives possibly reducing over time as the emphasis shifts from selling CO2 to merely storing it to mitigate climate impacts. This dynamic further underscores the complexity of the utilization issue and the need for a strategic approach that aligns with long-term climate goals.

In summary, while there are various ways to utilize CO2 in the short term, these methods are often seen as insufficient and temporary. The long-term focus must shift towards more permanent storage solutions, aligning with the need to meet climate targets rather than merely postponing emissions. The insufficiency of current utilization methods is recognized as a barrier, but opinions vary on its significance, reflecting the multifaceted nature of this challenge.

4.2 Other Barriers Mentioned by the Experts

1. **Transition Risk and Responsibility Allocation**:
    - *Short Term*: The immediate barrier is deciding who should take the first step in providing use pathways or capturing CO2. Questions surrounding who pays for the process—taxpayers, companies, or a mixture—complicate the situation.
    - *Long Term*: Over time, the responsibility issues should resolve with the establishment of best practices.
2. **Energy Input and Renewable Energies**:
    - *Red Flag*: Many CCU (Carbon Capture and Utilization) and CCS (Carbon Capture and Storage) pathways need a substantial amount of energy. Extracting carbon from CO2 is energy-intensive, making it a significant concern for scalability.
    - *Renewable Energy Dependency*: For the process to be climate-friendly, it must use entirely green energy, without diverting resources from other sustainability transformations.
3. **Permanence and Leakage Concerns**:
    - *Storage Issues*: Storing CO2 underground raises concerns about potential leakage and doubts about the permanence of this solution, contributing to hesitance in its adoption.

4. **Monitoring, Reporting, and Verification (MRV)**:
    - *Quality Control*: There must be standards and methods to ensure that CO2 is properly stored and not leaked, demanding continuous monitoring for potentially hundreds of years.
    - *Short and Long-term Considerations*: The MRV aspect is vital in both immediate and distant future, necessitating constant attention.
5. **Infrastructure Development**:
    - *Transportation Challenges*: Without infrastructure like pipelines across regions, the transportation of CO2 for storage becomes a logistical and financial challenge.
    - *Investment Needs*: The build-up of infrastructure for CO2 management is capital-intensive, demanding substantial investments.
6. **Emissions reversal:**
    - *Accounting emissions*: Specific cases, like concrete carbonization, bring up arguments about how to account for emissions reversal, adding complexity to the process.

5. Discussions

Carbon capture utilization and Storage (CCUS) is currently viewed as an essential tool in the carbon reduction strategies pursued by various nations and global entities. When operational, such carbon sequestration systems could permit continued fossil fuel usage, lessening fears of climate imbalance. However the full-fledged efficacy of this technology still needs to be proven, especially considering factors such as its sustainability, advancement, and overall implications. While some stakeholders perceive CCUS as indispensable, others argue it may not be a vital step toward a carbon-neutral future.

Currently, the demonstration of CCUS on a comprehensive, integrated scale is underway in diverse global locales. Nevertheless, notable technical, financial, political, and economic ambiguities exist surrounding CCUS. Such uncertainties present hurdles for proponents keen on its wide scale adoption as a cornerstone of global climate conservation efforts. A significant obstacle remains the sheer volume of challenges and ambiguities associated with the widespread adoption of CCUS. Therefore, this study's goal was delineating and evaluating these challenges. An integral aspect of the investigation also revolved around understanding stakeholder perspectives on these barriers and contemplating strategies for their resolution.

The investigation involved expert consultations from scientific, business, and academic. This selection aimed to represent a comprehensive spectrum of stakeholders to derive meaningful perspectives and address the core research query about stakeholder perceptions of challenges. The initial presumption was that the knowledge base of all consulted experts was at par; hence, no preferential weighting was accorded during the evaluation phase. Future endeavors could benefit from a broader expert panel and specialized consultations within each category for more in-depth and diversified insight. Regarding the wide scale adoption of CCUS, the research underscored the following pivotal conditions.

5.1 Government Strategies

The role of governments in implementing Carbon Capture, Utilization, and Storage (CCUS) technologies is a central theme echoed by experts in the field of climate change. Governments are urged to create and adopt an all-encompassing strategy that seamlessly integrates CCUS into their broader climate agendas.

Such integration calls for detailed targets that are linked with enduring climate plans. By setting measurable, tangible goals related to CCUS, governments can demonstrate their commitment to this essential technology and provide a clear roadmap for its implementation and growth. These targets should not be isolated, but rather, coupled with overall climate strategies, reinforcing a unified approach to sustainability.

Experts also emphasize the importance of continued technological support from governments. This includes investing in research and development, fostering innovation, creating incentives for private sector participation, and offering guidance for the deployment and operation of CCUS technologies.

In summary, the comprehensive government strategies advocated by experts underline the need for a holistic approach. Governments must align their climate goals with the technical and economic realities of CCUS, providing both direction and support. By doing so, they pave the way for meaningful progress towards a more sustainable future, leveraging CCUS as an essential tool in the global fight against climate change.

Here is an example of Indonesia where the Government has decided to develop a clear legal and regulatory framework. (IEA)

Indonesia has made substantial strides towards enabling CCUS investment to reach its net zero target by 2060. It has gathered preliminary experience from the Gundih Pilot Project and shown strategic commitment to CCUS through the initiation of the Institut Teknologi Bandung Centre of Excellence for CCS and CCU in 2017 and the early progression of multiple planned commercial CCUS projects.

To expedite the implementation of CCUS, the Ministry of Energy and Mineral Resources has developed a draft regulatory guideline for CCUS, the first in Southeast Asia. This draft regulation, based on a 2019 draft Presidential Decree detailing regulatory areas for a CCUS structure, establishes the groundwork.

The draft framework, embedded in the nation's existing oil and gas rules, calls upon oil and gas lease holders to drive CO2 storage development and operations. Storage endeavors, comprising both dedicated storage and those connected with enhanced hydrocarbon recovery, are to be executed within existing lease territories, like depleted oil and gas fields. It also features a transfer mechanism that lets the government take over long-term monitoring, stewardship, and liability after site closure approval.

Besides the necessary technical and legal prerequisites for safe CO2 storage, the draft framework also presents various economic and business elements. For instance, it outlines potential routes for project partners to capitalize on carbon credits. Additionally, it details the conditions under which storage operators may allow third-party access to storage facilities. The Ministry of Energy and Mineral Resources has proposed that this draft regulation, which needs to be aligned with other ministries and gain presidential approval, be a top priority for 2022.

5.2 Regulation and Technology:

Regulation and technological innovation are central themes in the ongoing discourse on climate change, specifically in the context of carbon emissions management. Experts in the field stress the need for stricter regulations that are free from loopholes, particularly for large point source emitters. The goal of such regulation is to create a uniform, accountable system that doesn't allow significant polluters to bypass their responsibilities.

In parallel with regulatory changes, experts advocate for the development and enhancement of technologies specifically designed for monitoring, reporting, and verification of emissions (MRV). Such advancements must also include the evolution of carbon accounting methodologies to ensure accuracy, transparency, and adherence to global standards.

The intersection of regulation and technology is not solely a technical issue; it is inextricably linked to public trust. By creating a robust framework that combines strict rules with state-of-the-art technology, the public's confidence in the system's efficacy is bolstered. It assures people that the technology works as intended, that emissions are accounted for accurately, and that governments and industries are held accountable.

In summary, the expert opinion emphasizes a multifaceted approach, where rigorous regulations and technological innovation intertwine to create a trustworthy and effective system to manage and reduce carbon emissions. This synergy is vital for building public trust and driving collective efforts toward a sustainable future.

5.3 ***Economic Incentives and Business Models:***

Emphasis was placed on building comprehensive business cases for emitters. In the short term, these may require subsidization due to inadequate market prices. By establishing a regulatory framework that includes financial incentives, governments can encourage emitters to invest in CCUS. The financial side will govern everything, and without an economically viable model, technological readiness alone will not lead to deployment.

5.3.1 From Government

United States of America (USA)

Initiatives such as tax credits, subsidies, and pricing mechanisms have already started to promote investments in the CCUS sector. A notable example in the U.S. is the 45Q tax credit that offers a stipulated amount per ton for each carbon dioxide captured and either stored or utilized. The Internal Revenue Agency (IRA) has enhanced the effectiveness of this credit, raising the amount from $50 to $85 for each ton of CO2 from industrial or power sectors and up to $180 per ton for emissions directly captured from the atmosphere and sequestered.

These adjustments by the IRA include simplifying the claim process, providing direct payments for a five-year period, and offering the option to transfer credits to others. Nonetheless, these tax credits, such as 45Q, mostly serve the interest of established companies with high revenue, leaving startups and innovators with minimal tax burdens with less to gain.

The original 45Q credit successfully catalyzed projects with a lower capture cost, like in the ethanol industry. The revised 45Q aims to stimulate developments in sectors with higher capture costs, including cement and steel production. However, it's worth noting that, unlike the solar incentives introduced a decade ago, CCUS involves higher capital expenditure and extended build times, which can slow progress and limit economies of scale often utilized in industries like solar manufacturing to reduce costs. (IEA, 2022)

Canada

The CCUS Investment Tax Credit (ITC) unveiled in 2022, is designed to offer a 50% credit for equipment linked with point-source CCUS projects, promoting early adoption by decreasing this percentage in 2030 and 2040 (Finance Canada 2022a). Additionally, the proposed ITC incorporates a clause for sharing knowledge publicly, a step that could result in considerable cost reductions for subsequent projects as they can glean insights from preceding ones (Finance Canada 2022c).

Canada's Clean Fuel Regulations (CFR) enable installations to generate compliance credits by employing projects such as CCUS, which decrease the carbon intensity of fossil fuels (ECCC 2022a). CFR credits apply to fuels utilized domestically, implying that upstream oil production would typically yield fewer credits due to its primary export focus. On the other hand, this could mean substantial additional credits for refineries that integrate CCUS, given that the majority of their fuel production is intended for domestic use.

The newly proposed Canada Growth Fund plans to introduce several financial mechanisms to expedite the adoption of CCUS across Canada, though the details regarding eligibility and policy design are yet to be determined (Finance Canada 2022b). The Fund's concessional financing implies it may offer equity stakes or loans with expected returns below market rates. Nevertheless, the objective of the Fund's portfolio is to recoup its investment in the long run. The Canada Growth Fund is considering offering Carbon Contracts for Differences that could ensure a base carbon price for projects. These contracts could help mitigate the risks and uncertainties related to carbon revenues, which could be influenced by changes in carbon pricing policies and the performance of credit markets.

Example of different incentives

Financial Incentives	Tax Credits	Tax credits are reductions in the tax liability of firms if they implement CCUS. Credits can be provided for stored carbon but also for capital investment.
	Tax-Exempt Private Activity Bonds	PABs are a form of "tax-exempt bond" that lowers the cost of capital for projects by providing debt financing at more favorable interest rates. Instead of being an incentive that impacts federal taxes of project owners, this incentive affects the federal taxes of the lender (i.e., the bond owner).
	Transition Bonds	Helps the seller issue debt to clean up its operations and present a key financing opportunity for CCUS projects aimed at mitigating emissions in energy-intensive industries.
	Accelerated Depreciation	A capital incentive that lowers the net present value of taxes paid over the life of a project.
	Master Limited Partnerships (MLP) Tax Advantages	An MLP is a special hybrid corporate structure that offers the tax advantages of a partnership combined with the stock market access and liquidity normally available only to corporations.
	Contract for Difference (CfD)	An agreement between two parties whereby one party agrees to pay the other party the difference between the actual value of a commodity at a point in time – the market price – and a value which the parties agreed at the point the CfD was entered into – the strike price.

https://www.ief.org/_resources/files/events/strategies-to-scale-carbon-capture-utilization-and-storage/ccus-report.pdf

5.3.2 From client

Premium prices

Numerous businesses hold the view that customers and corporations are ready to shell out higher prices for environmentally friendly products. These could range from a vehicle manufactured from net-zero materials to a cleaning product encased in net-zero plastic, or homes built with carbon-free cement. Indeed, recent survey data suggests that consumers in the UK might be opened to paying twice the normal price for carbon-neutral plastic bottles. This readiness to bear additional costs is being reflected in actual market prices. Presently, PET bottles are selling at 10 to 20 percent more, and similar trends are observed across other sectors. For instance, multiple car manufacturers have entered agreements with steel producers to procure eco-friendly steel.

Zero or near-zero carbon products may see the highest green premiums, especially in areas like cement where CCUS is a top decarbonization strategy. The construction industry, which uses a lot of cement, is being pushed to become more eco-friendly due to new policies like France's RE2020. Moreover, many consumers are willing to pay extra for green homes that are energy efficient or carbon neutral. For instance, a recent study found that top-tier urban offices with LEED certification were sold at a price 25.3% higher than their uncertified counterparts. Some of this extra cost can be offset by energy savings and could help cover the additional cost of using green cement.

However, not all industries or areas will see the same willingness to pay for green products. For maximum benefit from green premiums, companies should understand what their customers want, identify market segments ready to pay more, and target areas that lack green products. Initial demand might come from businesses aiming for significant decarbonization or niche markets for refined products. Luxury markets could also be a good starting point as material costs are a smaller part of the total cost for luxury goods, meaning higher green premiums won't dramatically increase final prices. However, this focus on luxury markets limits the potential for decarbonization from lower carbon-intensive products. Therefore, a thorough understanding of different markets is essential for companies to effectively link consumer green premiums to their supply chain.

5.4 Inclusion in Existing Schemes

Europe has a system called the EU Emissions Trading System (ETS), the biggest system for trading greenhouse-gas emissions globally. It covers around 10,000 facilities in the manufacturing and power sector. Low-carbon fuel standards, like those used in California, also create incentives for reducing the carbon intensity of fuels. Additionally, many developed countries give direct grants to support the cost of capturing and storing carbon. This should enable large-scale deployment of CCUS by the end of the decade.

Ideas like integrating CCUS into existing trading schemes and providing additional incentives for storage were often mentioned by the experts. This could further promote CCUS technologies by tying them to compliance requirements and fostering commercial benefits.

The Innovation Fund, created in 2018, aids in developing technologies to reduce carbon emissions in energy and industry sectors. Its budget, funded by the EU ETS, is approximately 10 billion euros. The Fund prioritizes carbon capture and utilization (CCU) projects. To qualify for funding, projects must substantially aid in climate change mitigation, leading to a net decrease in emissions and ensuring the prevention or long-term storage of CO_2 (EC, 2019a). In the Innovation Fund's 2020 call for large-scale projects, about 70% of proposed projects were for energy-intensive industries, with a third involving CCUS technologies, often alongside hydrogen projects for synthetic fuel production (EC, 2021j). Of the seven proposals granted, one incorporated CCU as a technological route (EC, 2022c)

5.5 Increase in Carbon Pricing

In the context of combating climate change, experts are emphasizing the need to raise carbon pricing, as evidenced by systems in Europe or Switzerland's CO_2 tax. The prevailing sentiment among these experts is that current low pricing fails to stimulate sufficient investment in reducing emissions or pursuing cleaner energy alternatives.

The argument posits that by making CO_2 emissions more expensive, businesses will be more inclined to seek out and invest in cleaner, more efficient technologies. This is not just a theoretical construct; experts point to practical applications where this strategy has been effective.

However, this approach's success is contingent on implementing the right balance of pricing and regulation. Experts warn that the present market conditions often allow for loopholes, leading to inconsistencies and inefficiencies in carbon pricing strategies across different regions.

In essence, the experts' consensus is clear: increasing carbon pricing is an essential tool in the climate change mitigation toolbox. It requires a comprehensive, unified approach that aligns carbon pricing globally, closes existing loopholes, and sets a course towards a more sustainable and environmentally responsible future. By doing so, the incentive to innovate and reduce emissions becomes a tangible and effective economic reality.

5.6 Role of Science and Public Awareness

The role of scientists in the realm of Carbon Capture, Utilization, and Storage (CCUS) extends beyond laboratories and academia. In an era grappling with climate change, their responsibility to engage with the public and politicians is paramount.

Scientists are urged to step out of their professional bubbles and simplify complex CCUS technologies into understandable language for the masses. This involves conducting educational outreach, media engagement, and interactive displays to translate technical knowledge into everyday vernacular. Trust-building is equally vital, requiring transparent communication about how CO_2 is securely captured, used, and stored. Strategies such as real-time monitoring and regular reporting foster confidence and ensure accountability.

Furthermore, scientists must actively collaborate with policymakers, contributing to legislation and influencing decision-making in favor of environmentally sustainable practices. Engaging with community members and government at various levels ensures that CCUS is not only understood but embraced as part of broader climate goals.

Through these multifaceted efforts, scientists can bridge the gap between technological innovation and public perception, facilitating a collective move toward a greener future.

5.7 Limitations

The primary objective of this thesis was to evaluate the obstacles surrounding the comprehensive deployment of CCUS and understand the perceptions of these challenges among various stakeholders. Expert interviews incorporated a limited sample of eight diverse specialists spanning across sectors: scientific, business, and environmental. This little sample serves merely as an indicative measure. Also, no emphasis was placed on the barriers during the evaluation process, stemming from the preliminary belief that the expertise level of all interviewed experts was consistent. Had this been considered, the outcomes might have varied. The interviews highlighted interdependencies among barriers, and the evaluations relied heavily on the experts' interpretations. Additionally, new obstacles and delays surfaced throughout the interview process that were not initially factored into the review.

5.8 Further research

This study can catalyze extended research, delving not just into the barriers the author pinpointed but also into those that emerged during the interview phase. Recognizing that there is variance in the expertise level among the experts, it would be pertinent to apply weights to the scores of each criterion and reevaluate the requirements based on how dependencies are addressed. Engaging a broader spectrum of specialists from governmental, scientific, business, environmental, and societal sectors will undoubtedly yield more comprehensive and reliable findings.

6. Conclusion

The global crisis of climate change necessitates a multi-pronged response. Central to this response is integrating Carbon Capture, Utilization, and Storage (CCUS) technologies within broader climate strategies, and this responsibility, as experts suggest, falls predominantly on governments. Their role is to set clear, measurable targets linked to enduring climate plans and foster innovation, providing both funding and regulatory incentives for private sector participation in CCUS initiatives. This commitment must align with both the technical and economic realities of CCUS to usher in a sustainable future.

Technological advancements, coupled with stricter regulatory frameworks, are also of paramount importance. Both elements can transform our ability to manage carbon emissions effectively. While technical solutions can provide accurate monitoring, reporting, and verification of emissions. Robust regulations ensure a consistent and accountable approach to reducing emissions across sectors and geographies. This fusion of technology and law is essential to instill public trust, assuring communities worldwide that we are making genuine strides in combating climate change.

Financial considerations are inextricably tied to these efforts. As demonstrated by systems like the EU Emissions Trading System (ETS) and the Innovation Fund, governments need to incentivize CCUS adoption and investment financially. The reality is apparent: economically viable models and supportive business cases are necessary for the technological readiness of CCUS to translate into large-scale deployment.

Furthermore, carbon pricing emerges as an influential tool in the fight against climate change. By increasing the cost associated with CO2 emissions, governments can steer businesses towards cleaner, more efficient technologies. Such an approach, however, necessitates a balanced combination of pricing and regulation, discouraging potential loopholes and inefficiencies.

Yet, while technology, regulation, and economics form a critical triad, the power of science communication and public awareness is undeniable. The onus falls on scientists to innovate and communicate their findings and the significance of CCUS in relatable, understandable terms. By stepping into the public sphere and building trust through transparency, scientists can bridge the gap between complex technological advancements and everyday understanding.

In essence, the fight against climate change demands collective commitment and action. Governments, scientists, businesses, and the public must converge, each playing their part. Through unified strategies, rigorous regulations, technological advancements, economic incentives, and informed public discourse, the vision of a sustainable future, with CCUS at its heart, can be realized. We can make meaningful progress in our global mission to counteract climate change with the help of this technology.

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Appendix 1: Interview type 1

Please rate each barrier or uncertainty based on its relative significance for the near to middle-term, full-scale deployment of CCUS (up to 2035).

Please rate each barrier or uncertainty based on its relative significance for the middle to long -term, full-scale deployment of CCUS (up to 2050).

Lack of Legal framework

Financial viability and incentives

Public acceptance

Lack of knowledge (project are large and have not totally be successful-> a lot of failure

Carbon lock in

carbon prices

a small choice of CO2 reutilization

Other barriers

Could you identify any obstacles or uncertainties not previously mentioned that must be addressed for the complete implementation of CCS?

For you what is the most important factor to accelerate the deployment? Based on the barriers talked before or others

What can we do to make aware the public of the existence of CCUS?

Would you consider investing in CCUS today? why?

Do you have any other things that you want to add that could be relevant for me to investigate?

Appendix 2: Interview type 2

Could you present yourself? what do you do?

Do you think carbon capture is the future of the world at same level of renewable?

What are the conditions to make carbon capture more interesting?

From what type of carbon capture, you are creating diamond?

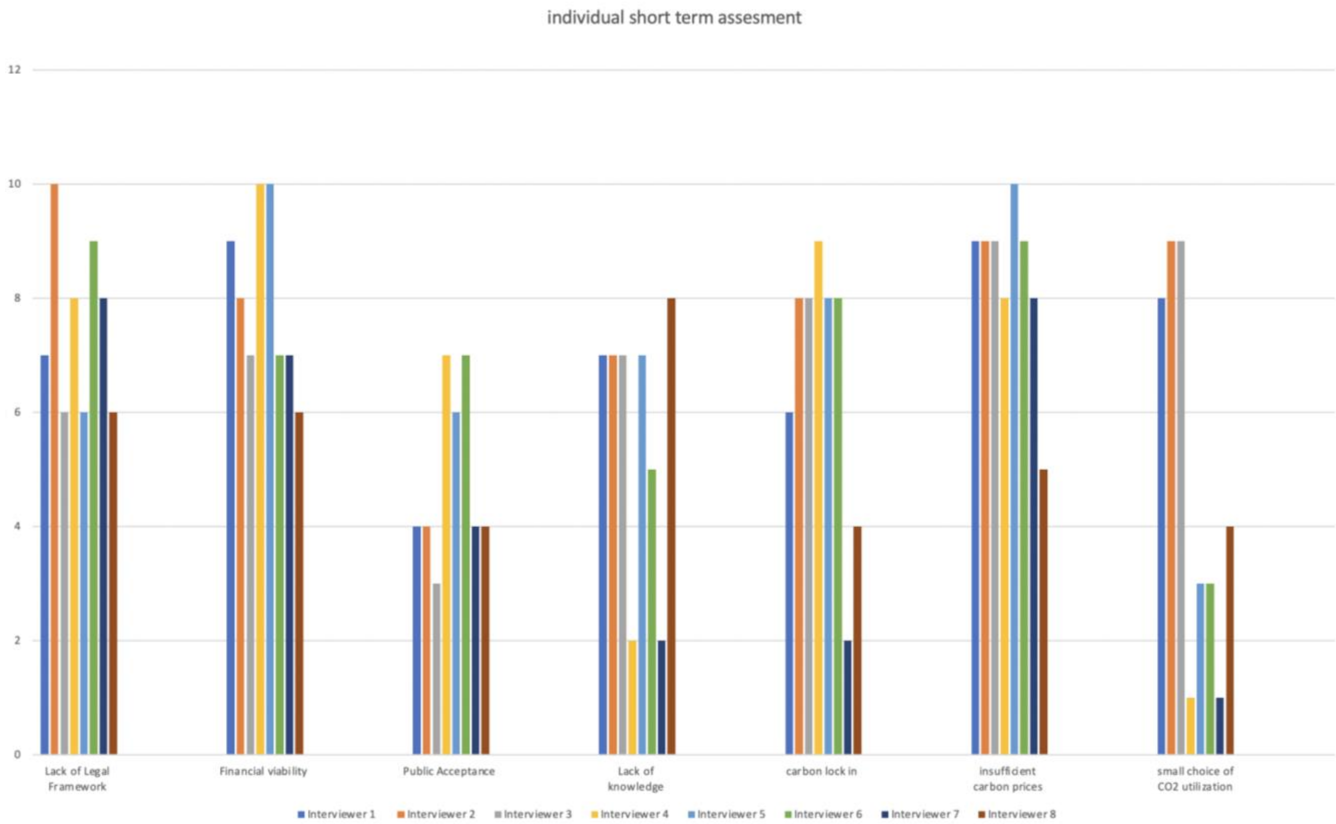
How does the process of creating diamonds from captured carbon differ from traditional diamond mining and production methods?

What are some of the environmental benefits of creating diamonds from carbon capture, and how do these compare to traditional diamond mining and production methods?

What are some of the technical challenges associated with creating diamonds from carbon capture, and how have you overcome these challenges?

Could you please explain in detail de process of making diamond from capture to end?

Appendix 3: Individual short-term assessment of barriers



Appendix 4: Individual long term assessment of barriers