CCS: A Framework for Development

A Policy and Project-oriented Framework for the Evaluation of Integrated Carbon Capture and Storage (CCS) Projects; a Case Study Approach

A.A.E. Berck

This page is intentionally left blank.

CCS: Working towards a circular future

Master thesis submitted to Delft University of Technology

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in **Engineering and Policy Analysis**

Faculty of Technology, Policy and Management

by

Alexander Berck

Student number: 4494652

To be defended in public on the 18th of September, 2023.

Graduation committee

Chairperson:	Prof.dr.ir. C.A. (Andrea) Ramirez Ramirez	Engineering Systems and Services
First supervisor:	Dr. P. (Paola) Ibarra Gonzalez	Engineering Systems and Services
Second supervisor:	Dr.ir. I. (Igor) Nikolic	Multi-Actor Systems
External supervisor:	G. (Gorkem) Gumrukculer	Technology Strategy Manager

TUDelft

This page is intentionally left blank.

Preface

Dear reader,

Before you lies the Master Thesis report: 'CCS: Working towards a circular future.' This Thesis was written as part of the completion of the Engineering & Policy Analysis Master of Science program at the faculty of Technology, Policy & Management from the Technical University of Delft. In this research, an evaluation framework is proposed for carbon capture and storage (CCS) projects. Through the conduction of in-depth literature reviews, exploratory expert interviews, and three separate case studies, this research aims to add to knowledge on the development and deployment of future CCS projects, specifically in the North Sea region. Before you start reading what I consider to be my grand finale of life as an academic student, I would like to express my gratitude and sincere appreciation toward a few people who have helped me during this process.

I would like to begin by thanking Miss Ibarra Gonzalez, my first supervisor. Over the past months, Miss Ibarra Gonzalez has been my closest sparring partner by far. Every Friday morning, we would start off by discussing how our weeks had been and how it was going with my drive and motivation to work on this thesis. She made sure that I saw what I was working toward every time I doubted whether I would ever achieve to goals I set for the research. Thank you, Paola! Second, I would like to thank the chair of my graduation committee, Mrs. Ramirez Ramirez, and my second supervisor, Mr. Nikolic, for guiding me during our meetings at the TU Delft. You have provided me with valuable insights from all sorts of directions, helping me in times when I thought I was stuck.

Then I would like to express my gratitude towards my friends and supervisors in the Technology Strategy & Advisory team of Accenture, who have provided me with a lot of guidance and support during my six months on the team. In particular, I would like to thank Gorkem Gumrukculer and Rajae Bolghiran, who have supervised me during my time at Accenture and even beyond. I really enjoyed working with you and experiencing the life of a consultant up close.

Last but certainly not least, I would like to thank my family and friends. My parents and my sister, who have been there for me during my whole education, supporting me every step of the way. I am forever grateful for your love and care. My girlfriend, Carlijn, for always being there for me and getting me through this process when things seemed impossible. My friends, Jeroen, Job, Pepijn, and Wilan, for their everlasting support and laughter during our time studying. And finally, the Technische Matricen, a study group everyone will be jealous of for years to come.

Thank you and I hope you enjoy reading this report.

A.A.E. Berck

Amsterdam, September 2023

Executive Summary

Introduction & problem definition

The world is facing an urgent challenge to mitigate climate change. The Intergovernmental Panel of Climate Change (IPCC) has suggested various strategies, including electrification, hydrogen production, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization, and storage (CCUS). However, the large-scale implementation of these strategies is constrained by factors such as financing, capacity, institutions, and human skill. The IPCC and the International Energy Agency (IEA) have confirmed that carbon capture, and storage (CCS) and carbon capture, and utilization (CCU) are the only capable technologies to decarbonize the largest industries, such as the steel, cement, and petrochemical sectors. However, the implementation of CCU technologies on a larger scale is projected to be further up the timeline of CO_2 emission mitigation as the technologies are, in this stage, less advanced and thus in need of further research and development as opposed to CCS. Globally, around 200 CCS projects are currently active. However, a lot of them suffer under the consequences of financial, organizational, technical or governance aspects. This research will aim to provide an evaluation framework to help deliver insights into the development and deployment of CCS projects. To achieve this goal, the following main research questions is to be answered:

How can an evaluation framework combining both project- and policy-related factors provide a better understanding of the deployment of full-chain CCS projects, and how is it developed and implemented?

In order to answer this question, several methods were applied. First, background research on CCS technologies, existing projects, and current frameworks has been identified and studied to set the stage for this research. Through this process, the knowledge gaps are made up of what is currently lacking in academic research. These knowledge gaps include the analysis of the CCS project using both project- and policy-oriented factors, and the creation of a multicomponent evaluation tool for these projects. These two research goals are addressed through an in-depth review of the literature and expert interviews. The results of these methods are used as the basis for the evaluation framework. The framework created in this research is designed for policy makers, project owners, consultants, and other stakeholders of the CCS project. Another reason for structuring the framework in this way is that this research is performed in collaboration with Accenture, a leading consulting firm. Making the framework usable while providing a complete overview is crucial.

Methodology

The methodology used in this research is comprehensive and multifaceted. The scope of the study was clearly defined and a systematic research approach was adopted. Various methodologies and tools were used, including literature research to identify the most important factors of CCS projects, semi-structured expert interviews to further expand on the key characteristics (up-to-date) of CCS projects, the Best-Worst Method in order to assign impact weights to factors, and a project maturity table, providing the ability to score a project based on the identified factors and a 3-point scale. The research was structured to ensure that the evaluation framework developed was robust and applicable in real-world scenarios.

Framework Development

The development of the evaluation framework was a central component of this research. Factors were categorized into six distinct groups: political-legal, economic, social, technical, ecological, and organizational. By plotting crucial points of attention based on knowledge from past or current projects, a comprehensive framework was created. This framework offers insights and advice regarding the development of CCS projects, ensuring that stakeholders are well equipped to navigate the complexities of CCS deployment.

Case Studies

Two fully integrated CCS projects, ROAD and Longship, were analyzed in-depth. These case studies provided real-life insights into the challenges and successes of CCS projects. Both projects have storage facilities in the North Sea region, aligning with the geographical scope of the framework. The case studies are an instrumental tool for the application of the evaluation framework, ensuring its relevance and applicability.

Results

The research culminated in the development of a comprehensive evaluation framework tailored for CCS projects. This framework, grounded in literature research and insights from expert interviews, offers a systematic approach to assess various aspects of CCS projects. One of the standout features of this framework is its ability to provide a holistic overview of a CCS project, highlighting areas that demand resource allocation.

Through the application of the framework in case studies, such as the ROAD and Longship projects, it was evident that the tool can effectively pinpoint critical factors and stakeholders in CCS projects. The use of a maturity model integrated within the framework further aids in visualizing the project's progression, offering actionable insights and recommendations based on the project's current maturity level. Key recommendations emerging from the creation and application of the framework include the need for clear stakeholder communication, a well-defined legal framework, and a long-term financing plan. The research underscores the importance of financial stability throughout the project's lifespan. However, the main result of the research is the presentation of a usable and dynamic evaluation framework for future CCS projects.

Conclusion

The developed evaluation framework serves as a pivotal tool for CCS project evaluation. Its multifaceted approach, including key factor identification categorization, stakeholder analysis, impact analysis, and maturity assessment, ensures a comprehensive evaluation of CCS projects. By providing clarity on where to allocate resources and how to navigate the complexities of such projects, the framework proves invaluable for stakeholders and project managers alike. Its application can lead to more informed decision-making, ensuring the success and sustainability of CCS initiatives.

Contents

Preface **ii**

Executive Summary **iii**

Nomenclature **vii**

List of figures **viii**

List of tables **ix**

1 Introduction **1**

2 Problem definition & research questions **4**
- 2.1 CCS Background . . . 4
  - 2.1.1 Historical timeline of CCS . . . 4
  - 2.1.2 Current state of CCS technology and projects . . . 4
  - 2.1.3 Opposition and current challenges of CCS . . . 5
  - 2.1.4 Current (CCS) evaluation frameworks . . . 6
- 2.2 Knowledge gaps . . . 8
- 2.3 Research questions . . . 9

3 Methodology **11**
- 3.1 Scope of the study . . . 11
- 3.2 Research approach . . . 12
- 3.3 Methodologies & tools . . . 14
  - 3.3.1 Factor analyzation methods . . . 14
  - 3.3.2 Literature research . . . 15
  - 3.3.3 Semi-structured expert interviews . . . 15
  - 3.3.4 Best Worst Method . . . 16
  - 3.3.5 Project maturity table . . . 17

4 Framework development **19**
- 4.1 Factor categorization . . . 19
- 4.2 CCS Project factors . . . 21
- 4.3 Stakeholders in CCS projects . . . 24
  - 4.3.1 Stakeholder overview . . . 24
  - 4.3.2 Power Interest Grid . . . 27
- 4.4 Expert interview insights . . . 28
  - 4.4.1 Interview 1 . . . 29
  - 4.4.2 Interview 2 . . . 29
  - 4.4.3 Interview 3 . . . 30
  - 4.4.4 Main interview takeaways . . . 31
- 4.5 List of identified CCS project factors . . . 32
- 4.6 Factor impact assessment: Best Worst Method . . . 33
  - 4.6.1 Factor groups . . . 33
  - 4.6.2 Political-legal . . . 34
  - 4.6.3 Economic . . . 35
  - 4.6.4 Social . . . 35
  - 4.6.5 Technical . . . 36
  - 4.6.6 Ecologic . . . 37
  - 4.6.7 Organizational . . . 37
  - 4.6.8 BWM scores . . . 38
- 4.7 CCS Project Maturity Model . . . 39

5 Case studies: ROAD & Longship **42**
- 5.1 Framework steps for users . . . 42
- 5.2 Overview selected projects . . . 42
- 5.3 ROAD . . . 43

5.3.1 Project introduction . . . 43
5.3.2 ROAD project factors . . . 46
5.3.3 Maturity model . . . 47
5.3.4 Results and recommendations . . . 50
5.4 Longship . . . 52
5.4.1 Project introduction . . . 52
5.4.2 Longship project factors . . . 55
5.4.3 Maturity model . . . 56
5.4.4 Results and recommendations . . . 59

6 Discussion and limitations **62**
6.1 Discussion of the applied methodology . . . 62
6.2 Discussion of the results . . . 64
6.3 Limitations . . . 65

7 Conclusions **67**
7.1 Answering the research questions . . . 67
7.2 Recommendations . . . 70
7.3 Future work . . . 72
7.4 Academic relevance . . . 73

References **74**

Appendices **79**

A The Best-Worst Method (BWM) **79**

B Interview protocol **82**

C Consent form **85**

D Interview analysis **86**

Nomenclature

BWM Best-Worst Method

$CaPex$ Capital expenditure

CCS Carbon capture and storage

CCU Carbon capture and utilization

$CCUS$ Carbon capture, utilization and storage

CO_2 Carbon Dioxide

EOR Enhanced oil recovery

$GCCSI$ Global CCS Institute

GHG Greenhouse gas

IEA International Energy Agency

$IPCC$ International Panel of Climate Change

KPI Key performance indicator

$OpEx$ Operational expenditure

List of Figures

2.1 Project success framework by Khang and Moe (2008) . . . 7
2.2 CCS Project framework by Romasheva and Ilinova (2019) . . . 8
3.1 Research Flow Diagram . . . 13
3.2 Best Worst Method by Rezaei (2015) . . . 17
3.3 Example of Maturity Model Score Map by Wagire et al. (2021) . . . 18
4.1 Factor groups in framework . . . 20
4.2 Power Interest Grid . . . 27
4.3 BWM Factor groups . . . 33
4.4 BWM Political-Legal . . . 35
4.5 BWM Economic . . . 35
4.6 BWM Social . . . 36
4.7 BWM Technical . . . 36
4.8 BWM Ecologic . . . 37
4.9 BWM Organizational . . . 38
4.10 Identified relative importance of factor groups and factors . . . 39
5.1 Frameworks steps . . . 42
5.2 Timeline ROAD project . . . 44
5.3 Power-Interest grid ROAD project . . . 44
5.4 Maturity score map ROAD project . . . 50
5.5 Timeline Longship project . . . 53
5.6 Power-Interest grid Longship project . . . 53
5.7 Maturity score map Longship project . . . 59

List of Tables

2.1 Critical choices while assessing policy success by Marsh and Mcconnell (2010) 7
4.1 Main stakeholders in CCS projects 26
4.2 List of CCS project factors 32
4.3 Project factors with assigned weights 38
4.4 Maturity Table 41
5.1 CCS case study projects 42
5.2 ROAD project characteristics 46
5.3 Drivers and Barriers for the ROAD Project 47
5.4 Maturity Table ROAD project (Part 1) 48
5.5 Maturity Table ROAD project (Part 2) 49
5.6 Longship projects characteristics 55
5.7 Drivers and Barriers for Longship project 56
5.8 Maturity Table Longship project (Part 1) 57
5.9 Maturity Table Longship project (Part 2) 58

1 Introduction

One of the most urgent challenges in the world is the need to mitigate climate change. Rising temperatures, melting ice caps, and greenhouse gas emissions are some of the major problems the world is facing. To overcome this challenge, all countries around the world must participate in a reliable solution. In their special report on understanding global warming, the Intergovernmental Panel of Climate Change - IPCC (2022b) has stated the following: "Such CO_2 emission reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen production, sustainable biobased feedstocks, product substitution and carbon capture, utilization, and storage (CCUS)" (p. 15). However, while all these strategies have been proven, their implementation on a large scale can be bounded by various constraints regarding funding, capacity, institutions, and human skill.

To comply with the necessary goals for the reduction of CO_2 emissions, countries or regions could carry out two different types of actions. First, the problem could be partially prevented by demand-side management. For example, by influencing consumers through planned activities, legal restrictions, or other alternatives, CO_2 emissions can be completely eliminated (Gellings, 2017). Alternatives would include investing in technologies that provide a higher conversion rate and a substantially greater use of renewable sources. In addition, Negative Emission Technologies (NETs) are considered a great alternative. NETs are intended to reduce the concentration of greenhouse gases (GHGs) in the atmosphere. For certain activities to be classified as NETs, they must, according to Tanzer and Ramírez (2019), meet a certain set of characteristics. The activity should include the removal of GHGs from the atmosphere with the intention of permanently storing them outside of the atmosphere. Furthermore, the balance of the GHGs stored against the GHGs emitted during this activity should be positive. Another course of action to comply with CO_2 emission reduction goals would be to significantly improve systems that can reduce CO_2 emissions directly from the source (Kalyanarengan Ravi et al., 2017). These systems include the implementation of technologies and practices, as mentioned by the IPCC. One of these potential systems is a combination of carbon capture, utilization, and storage (CCUS) technologies. This technology involves a chain-like process with the aim of CO_2 emission reduction. Through the capture of CO_2 emissions from activities in the industrial sector or from the combustion of fossil fuels, a significant reduction in emissions is possible. The captured CO_2 can then be transported and stored in assigned natural formations formed, such as empty gas fields or aquifers (underground rock structures carrying water with relatively high porosity), converted into products or used in the synthesis of other chemicals. CCUS could be seen as an 'umbrella' term, capturing all technologies that fall under its reach. CCUS technologies can be divided into two different sections: carbon capture and storage (CCS) and carbon capture and utilization (CCU). Where CCS aims to store captured carbon in perpetuity (Haszeldine et al., 2018), CCU aims to reuse captured carbon in processes such as chemical synthesis and the creation of energy products such as methanol or hydrocarbons (Tapia et al., 2018). Captured CO_2 is also a well-known asset as an injection agent for enhanced oil recovery

(EOR), which is the process of injecting supercritical CO_2 (a liquid state of CO_2 where it is kept above a critical temperature and a critical pressure) into oil fields with the aim of altering the chemical composition of oil making it easier to extract and improving hydrocarbon recovery (Lacy et al., 2013). Since the subject of greenhouse gas mitigation is of great importance around the world, various CCUS projects are in critical stages of development or implementation.

Both the IPCC and the International Energy Agency (IEA) have confirmed that to decarbonize the largest industries, such as the steel, cement, and petrochemical sectors, CCS and CCU are capable technologies with a high potential (Global CCS Institute, 2018a). But there is a clear distinction between CCU and CCS technologies, especially when considering the maturity of the technologies. Bui et al. (2018) states that, at present, many CCU technologies are still under research and development, and many projects are still in the pilot stage. Baena-Moreno et al. (2019), on the other hand, confirms that a variety of CCU technologies are already available for use in a variety of applications. From direct utilization of CO_2 as a solvent or for chemical production to the acquisition of fuels or the improvement of EOR technologies, there is the potential for significant reductions in CO_2 emissions and the associated benefits in the industry worldwide. However, the downsides of CCU consist of the emission of CO_2 in utilization processes, the continuous search for utilization processes with higher added value, and the need to adjust to these changing processes.

CCU has frequently been compared to CCS and suggested as an alternative. This point of view could be attractive given the joint capture phase and the use in the literature of the acronyms CCS and CCU for CO_2 reuse. This could also be seen as misleading. Despite the fact that CCU and CCS both aim to reduce climate change, technologies work better together than separately. All CCU routes that emit CO_2 at the end of their cycle could receive a storage step that closes the cycle. However, regardless of current applications, the implementation of CCU technologies on a larger scale is projected to take longer because the technologies are, at this stage, less advanced and therefore require more research and development compared to CCS (IOGP, 2019). Therefore, since the level of research, development, and implementation is not the same, the discussion of CCU and CCS should be separated.

The current landscape of CCS technologies and projects is faced with some difficult challenges and limitations. High energy consumption when applying the technology poses a significant challenge to the advancement of CCS technologies, especially when weighing the high costs against the potential investment in renewable energy sources (Wilberforce et al., 2019). With this in mind, CCS could be considered a temporary solution, making the implementation of successful CCS much harder due to lack of support in the political and social fields (Gunderson et al., 2020). As these arguments show, the current field of CCS is facing diverse challenges coming from various directions, such as political, social, economic, and technical. Therefore, the development and deployment of CCS projects are complex in nature and require a structured and detailed approach. For that reason, to achieve the goal of reducing CO_2 emissions from various sources, a well-designed framework is needed for CCS projects, including different characteristics of the CCS network that are project- and policy-oriented. Project-oriented characteristics include factors such as CO_2 removal technologies, locations where CO_2 can be captured and stored, identification of transport modes and routes, and all different storage options (TNO, 2020). Policy characteristics focus on aspects such as actor involvement, communication between involved parties, and risk management between the involved actors. Currently, several countries in Europe are working on the implementation of CCS value chains that would potentially eliminate 20% of CO_2 emissions by 2050 (IEA, 2021). Therefore, since CCS technologies and projects seem to be on the agenda for the mitigation of GHG emissions, the construction of a clear and concise framework for the development and deployment of CCS projects, including policy and project-oriented criteria, would significantly contribute to the implementation of the technology and its future potential.

Due to the identified differences and the status of CCU and CCS, this research will focus solely on creating an evaluation framework for CCS projects. Furthermore, since CCS projects around the world are being implemented and operate under very divergent circumstances, further scoping will be applied according to the type of CCS project and the geographical location of the project. As for the type of project, this research will focus on being applicable to integrated projects where the entire CCS value chain is considered, from capture to storage. The geographical scope of this research will be centered on the North Sea region. This is due to the relatively high number of operating CCS projects in the region as well as the high number of planned CCS projects in the North Sea region. The scope of this research will be further elaborated in Section 3.1. On the basis of the information presented in this section and the preliminary scoping, the following main research question is proposed.

How can an evaluation framework combining both project- and policy-related factors provide insights for the deployment of full-chain CCS projects, and how is it developed and applied?

During the creation of the evaluation framework, factors divided into various general dimensions will be identified to act as the basis for the evaluation framework. Additionally, by applying the evaluation framework to two different case studies, the effectiveness can be investigated. An additional explanation of the research approach can be found in 3.2. Through the identification of evaluation factors through an in-depth literature study and expert interviews, this framework aims to act as a guide for future projects by providing insight into the deployment of CCS projects in hopes of improving this process in the future.

2 Problem definition & research questions

In this section, the current literature will be evaluated to dive deeper into the subject of CCS technologies and projects. General background information on the history of CCS and the current state of CCS, including the playing field, will add to the foundation of the research. A deeper dive into the background of CCS will provide a first general direction for the construction of the evaluation framework in this research.

2.1 CCS Background

2.1.1 Historical timeline of CCS

Enhanced Oil Recovery (EOR) with the use of CO_2 sequestration has been around since the 1960s when the United States and Canada began applying this technique to improve oil recovery. The first large-scale project, called the Scurry Area Canyon Reef Operating Committee (SACROC) in Texas, was operational from 1971 until 2009, with a total of more than 175 million tonnes of natural CO_2 injected (Ma et al., 2022). However, the concept of CCS as we know it today originated at a later stage and was first proposed by Marchetti (1977). In his research, he emphasizes the crucial role of CO_2 emission mitigation to reduce global warming. He claims that controlling these pollutants is a necessary step in keeping the economic model in place. The most viable solution, according to Marchetti, is to store CO_2 in the ocean floor to dissolve it and thus lessen its effect on global warming. He also considered geological storage, although he stressed the constraints concerning capacity. However, the application of the technology changed and only geological storage was considered a viable alternative following several controversial experiments on CO_2 storage in the ocean (de Figueiredo, 2003).

The first project with the direct aim of performing CCS was the Speipner project, which began in 1996 and is still active today. The project is a first-of-a-kind commercial CO_2 injection project on a larger scale and has stored up to 20 million metric tons of CO_2 since its first operation in 1996 (Ma et al., 2022). The Sleipner project, based on the Norwegian coast, paved the way for CCS projects for decades to come. According to (Steyn et al., 2022), there are now 196 projects in the pipeline of CCS facilities, with a 44% growth in the number of facilities since 2021. However, since less than 50 are operational, there is still a long way to go for CCS technologies.

2.1.2 Current state of CCS technology and projects

CCS technologies are now viewed as a major strategy to mitigate climate change due to their potential to significantly reduce CO_2 emissions into the atmosphere. CO_2 is collected through CCS from large sources, including coal-fired power plants, and stored in underground geological formations. This technology has been developed since the 1970s. From 2009 to 2018, the Department of Energy in the United States allocated \$6 billion to CCS research and demonstration projects (Bui et al., 2018), and CCS technologies have been used in several power plants in Europe. In several investigations, the efficiency of CCS technology has been proven. For example, according to 2015 research from the Massachusetts Institute of Technology, CCS may be able to reduce global CO_2 emissions by up to 90 gigatons by 2050. Additionally, according to research by the International Energy Agency (2016), CCS may cut CO_2 emissions by 20% by 2050 compared to business as usual scenarios.

Although the number of CCS projects around the world is increasing each year, there are still often setbacks within these projects. The implementation cost, which is believed to be up to ten times more expensive than conventional power production technologies, is one of the main obstacles (van der Spek et al., 2019). The safety and environmental issues related to CO_2 storage, as well as potential negative effects on nearby populations, are additional difficulties. Governments and businesses must collaborate to overcome these obstacles to ensure that CCS technology is affordable, secure, and accepted locally. To ensure the security and long-term storage of CO_2, this could involve establishing strict laws and offering incentives such as tax credits or subsidies. In the end, CCS technology has the ability to dramatically reduce global CO_2 emissions; therefore, its proper implementation is crucial in reducing the consequences of climate change. However, over the past few years, there have been some cases of CCS projects being canceled in various industrialized countries. Krüger (2017) states that the main issue of these projects was the high investment costs and local protests. Only with high CO_2 taxes, high carbon pricing, or other significant incentives to reduce emissions can CCS projects be financially successful. These incentives are still rather limited in number at the moment. As a result, several CCS projects were delayed, implemented on a smaller scale, or discontinued. The opposition of locals, environmental organizations, and climate activists is another significant factor that has resulted in the cancellation of CCS projects. Some stakeholders want to switch to offshore projects despite the higher costs in order to avoid similar setbacks in the future (Román, 2011).

Furthermore, due to the multiple actors and factors involved, the large differences in the types and natures of both actors and factors, as well as the numerous related uncertainties, it is difficult to conduct a comprehensive, understandable and reproducible evaluation of CCS projects (Jakobsen et al., 2013). Therefore, a concise but complete framework covering the needs for the successful deployment of CCS projects would improve the timeline for the implementation of CCS technologies and the deployment of CCS projects.

2.1.3 Opposition and current challenges of CCS

CCS technologies are widely seen as a substantial part of the solution to a circular future without GHG emissions. However, there are also parties that are arguing for the instant disruption of investments in CCS technologies. The most common arguments against CCS are based on the notion that the fossil fuel industry should not be fixed, but should be abandoned altogether (Wallquist et al., 2011). When more detail is explored, other significant concerns about the effectiveness, cost, safety, and long-term viability of CCS also come into play.

One of the most prominent concerns is the costs of CCS technologies. Although the cost of CCS technologies can vary widely due to differences in application, geographic location, and scale, every project should prioritize its financial management in the early stages of project development. Due to the high infrastructure and equipment investments required, public and private investors have to be considered to secure the funding needed for the project. Opponents of carbon capture technologies claim that money spent on reducing GHG emissions should be invested in renewable energy sources and see CCS as a dead end, as it does not address the root causes of CO_2 emissions (LOrange Seigo et al., 2014). From their perspective, the reduction of our dependence on fossil fuels should be the primary objective.

In addition, safety is one of the major challenges of CCS. When storing CO_2 indefinitely, extreme safety measures must be in place to ensure that there will be no leaks in the system, preventing the release of CO_2 into the atmosphere or groundwater. The management of the CCS value chain is a long-term task.

2.1.4 Current (CCS) evaluation frameworks

The objective of this research is to provide a framework that could be used for the development and implementation of CCS projects. Academic literature proposes different ways in which a framework could be presented. This research aims to create a holistic framework consisting of both policy and project factors. This section presents generic examples of how these two types of frameworks are often presented and used, and provides a basis for the framework that will be created in this research.

The framework for assessing policy success in Table 2.1 is proposed by Marsh and Mcconnell (2010). This framework is made with the aim of providing structure when assessing situations that are often somewhat chaotic. When dealing with large-scale projects with a multi-actor nature, communication and clear policy between parties involved is vital for success. This framework guides the user through the process of measuring success within projects or processes. Through answering several questions regarding 7 topics, the focus or scope of the user of the framework has to become clear. In short, this framework helps the user to look in the right direction for their personal scope. The questions asked in this framework pose a good starting point for where to look in a certain project when assessing success. Although the main focus of the framework proposed in 2.1 is the success of the project, this research will not necessarily be on measuring success. However, it will try to approach a way to determine which elements of projects need more focus and time to ensure that the project will achieve its goals. This framework presented below asks questions that could help with that.

1. Form of policy success	Which form or forms of success is/are being assessed? Process? Programmatic? Political?
2. Timeframe	What time period(s) is/are being assessed? Short-term? Medium-term? Long-term?
3. Interests	In relation to whose interests is success being assessed, for example, target group? stakeholders? institution? interest group? individual? collective?
4. Reference points	What is the standard by which success is to be judged? Compared to intentions? Compared to policy domain criteria, for example, efficiency and effectiveness? Compared to the past? Compared to ethical or moral principles? Compared to another jurisdiction?
5. Information	Is there sufficient and credible information to assess the extent of success?
6. Policy isolation	With what degree of certainty and credibility is it possible to isolate and assess the impact of a policy from other factors such as other policies or media influences?
7. Conflict and ambiguity	What significance should be given to conflicts and ambiguities, and how should they be weighted in the overall judgment of success?

Table 2.1: Critical choices while assessing policy success by Marsh and Mcconnell (2010)

Figure 2.1 is a project success framework proposed by Khang and Moe (2008). They propose different phases of the project in which success is measured. Each phase owns critical success factors (CSFs) and success criteria (SC). They identify these for each phase so that it becomes clear what needs to be achieved and aimed for in each project phase to establish success.

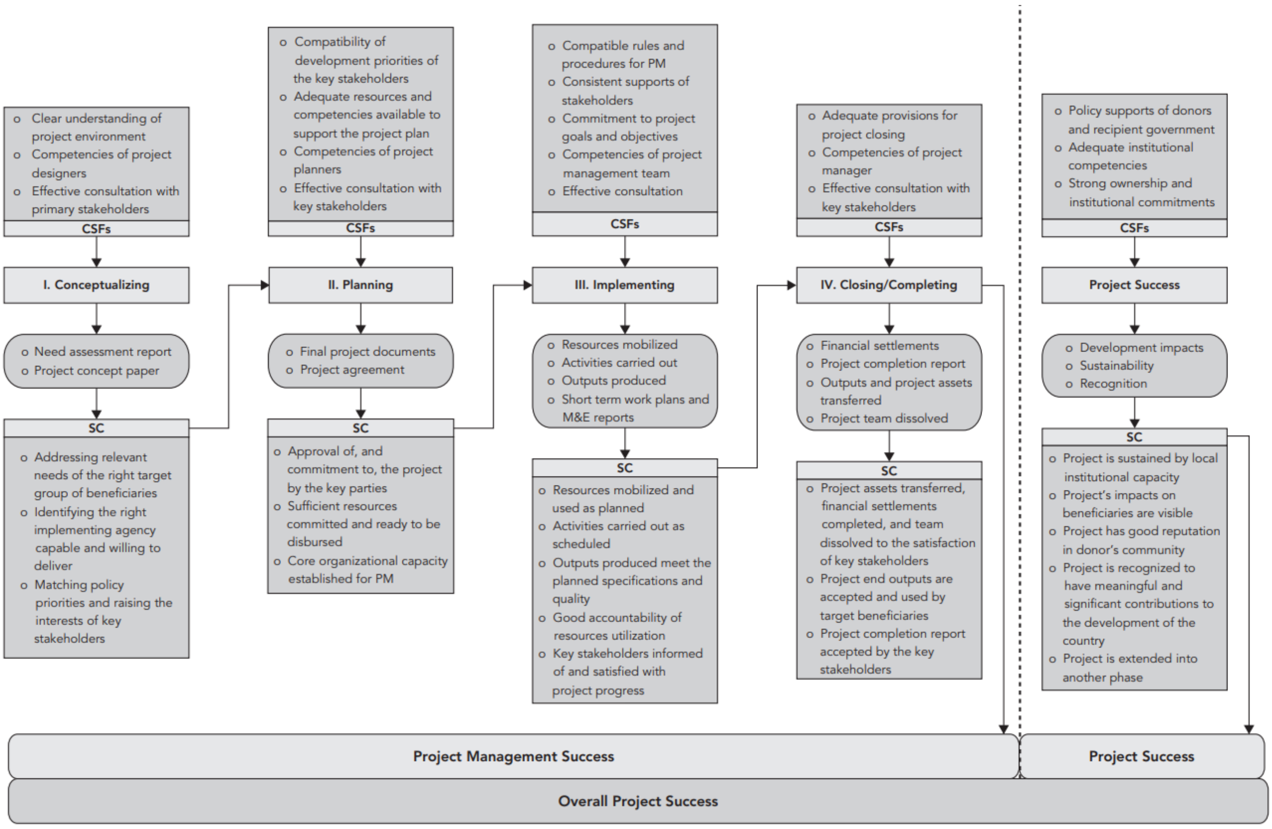

Figure 2.1: Project success framework by Khang and Moe (2008)

The framework in Figure 2.2 proposed by Romasheva and Ilinova (2019) focuses on the different types of factor groups (dimensions) of a CCS project. The nature of this framework is much more detailed. Not only because it focuses on CCS projects instead of projects in general, but also because it provides clear and distinguished dimensions for assessing CCS projects. Where the framework of Khang and Moe (2008) helps the user identify success through different phases of the project, this framework provides separate dimensions of factors to help make success measurable.

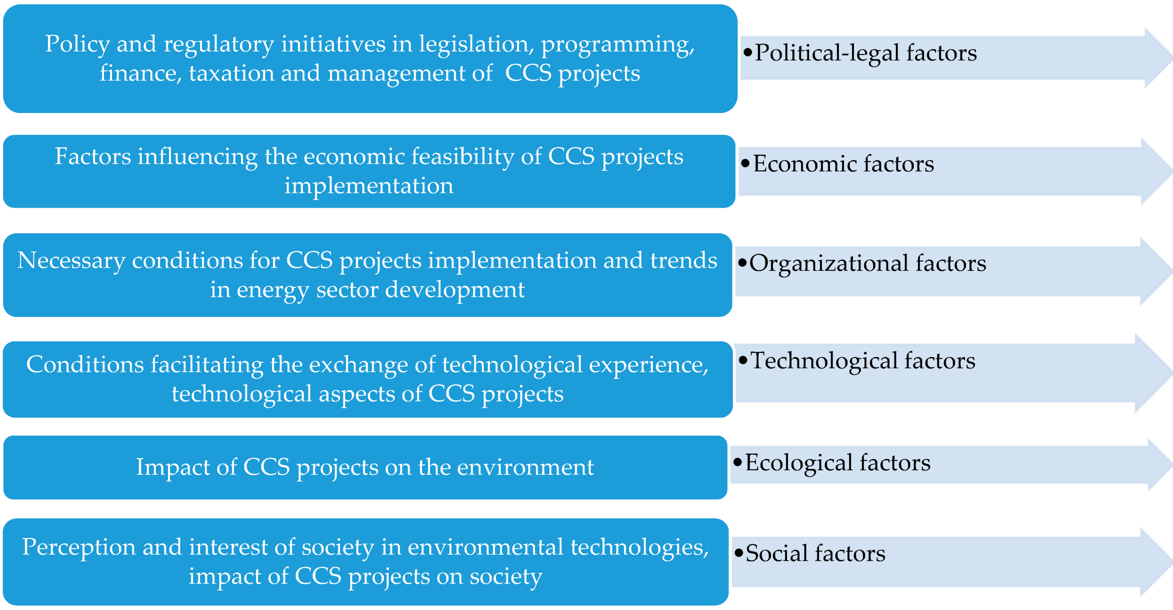

Figure 2.2: CCS Project framework by Romasheva and Ilinova (2019)

In this research, the concept of critical success factors by Khang and Moe (2008) and the concept of factor dimensions by Romasheva and Ilinova (2019) will be combined. Through the implementation of these techniques, the factors of CCS projects can be separated and grouped in a way that makes them easier to assess. Chapter 3 will go into more detail about how the evaluation framework is set up.

2.2 Knowledge gaps

Bridging project and policy components of CCS in academic literature

Despite the abundance of academic literature that focuses on the project and policy components of CCS projects, there is a significant knowledge gap when it comes to combining these two aspects into a unified framework. Specifically, there is a lack of studies exploring how the project-related dimensions (e.g., economic, technological, and geographical) of CCS projects interrelate with policy structures (e.g., actor participation, communication, social stance, and policy) and how this can influence the overall potential of success or failure in these projects. Developing a comprehensive framework that combines both the project and policy aspects of CCS projects would contribute to a more holistic understanding of the difficulties involved in such complex projects and could help guide future research and implementation efforts.

Creation of multicomponent evaluation tool

When diving into the realm of CCS projects, it is evident that there are multiple frameworks available to guide

CCS projects, each offering its unique perspective on how to approach the development of projects. However, a gap emerges when we seek a tool that holistically integrates multiple components, from technical aspects to governance nuances, stakeholder dynamics, and insights from real-world case studies. This multifaceted nature of CCS projects demands a comprehensive tool that combines all possible challenges and barriers into one tool that is capable of providing useful insights into the entire field of CCS projects.

Reflecting on the frameworks discussed in Section 2.1.4, it is clear that while many offer compartmentalized insights, few, if any, provide a cohesive overview that captures the essence of CCS projects in their entirety. This research aims to bridge this evident gap. Gathering knowledge from the literature, expert interviews, and real-world case studies, the goal is to design a multicomponent evaluation tool. Such a tool would not just be another addition to the academic literature, but a practical guide, helping in the successful deployment of CCS projects.

2.3 Research questions

With regard to the topics discussed in the previous sections, the following main research question is proposed for this thesis:

How can an evaluation framework combining both project- and policy-related factors provide insights for the deployment of full-chain CCS projects, and how is it developed and applied?

In order to answer the main research question, multiple sub-questions have been composed. These sub-questions will be answered over the course of this thesis and will all add towards providing an answer to the previously mentioned question. The 4 identified sub-questions are as follows:

SQ1: *What are the current approaches for guiding the deployment of CCS projects, based on academic literature and stakeholder insights?*

The first sub-question of this research aims to provide insights into the background of CCS projects and technologies while connecting this information to the development of an evaluation framework. Current frameworks used in the CCS environment will be analyzed and compared, while also adding more up-to-date knowledge by performing exploratory stakeholder interviews.

SQ2: *What is the role of the different actors present in CCS projects, and how do they contribute to a CCS project?*

While SQ1 will dive deeper into the background of CCS and the current state of CCS technologies and frameworks, SQ2 will add to the policy side of CCS by assessing the player field surrounding CCS projects and the collaboration between public or private instances that work towards the deployment and management of full-chain CCS projects. A combination of SQ1 and SQ2 will create a bridge between the project and policy aspects of CCS, one of the main things that is now missing in the current literature and therefore an important knowledge gap identified in this research.

SQ3: *Which factors need to be considered to develop a framework that can give insights into the deployment and potential success of a CCS project?*

As SQ1 and SQ2 are more focused on collecting information as a basis for this research, SQ3 is geared toward the first step of creating the steps for the evaluation framework. SQ3 is two-fold, its first objective being to provide a general approach to identifying characteristics and criteria on which CCS projects could be scored. As mentioned before, no two CCS projects are the same. Therefore, a general approach to an evaluation framework will only establish the basis of this research. The second part of this question will aim to answer whether the framework could be applied to CCS projects from the past, replicating their outcomes in its results. The use of case studies will help provide more understanding of the application of such an evaluation framework in more real-life scenarios.

SQ4: *How can the created evaluation framework provide valuable insights when applied to case studies?*

The fourth and final sub-question will answer how the evaluation framework and the analyses performed in this research could help provide valuable insights for CCS projects in their development. This will be the basis for answering the main research question that will reflect on the process of this thesis and will try to provide a clear view of the process of creating the insights obtained in this research.

3 Methodology

This chapter will give an overview of the methodologies and methods that will be used in this research. First, the scope of the study will be identified and further discussed in 3.1. After that, the approach of the research will be expanded in 3.2. Figure 3.1 visualizes the research goals and provides insight into the structure of this research using a Research Flow Diagram (RFD). Different phases and components of this research are identified in the RFD while also mentioning which sub-questions are being answered during this process. The RFD also includes a brief section on the expected results of this research. After going into more detail on the different phases of this research, the methods and tools that will be applied are highlighted and justified.

3.1 Scope of the study

This study intends to create an evaluation framework that addresses the unique difficulties related to the implementation of CCS projects in light of the continuous developments in the CCS field and the variety of projects being pursued around the world. This framework will consider a variety of CCS project factors divided into categories with the aim of connecting project-related insights to policy insights. By doing this, this research hopes to add to the body of knowledge and give project managers and policymakers insightful information. The need to close a critical gap in the literature served as inspiration for developing such a framework. Even if there are numerous CCS initiatives underway, it would be nearly impossible to perform an exhaustive analysis of the entire environment. This is due to the variety of project types and regional variations. For the evaluation framework to be effective, this research adopts a focused scope. Policymakers, project owners, and any other public or private party with significant responsibilities in the decision-making processes associated with CCS initiatives are the target users of this framework. Their input is crucial in determining the policies and tactics that control the effective implementation of such projects. Therefore, it is crucial to communicate the research's conclusions and suggestions in a way that these crucial stakeholders can understand and use. Additionally, this research is conducted in partnership with Accenture, a leading international consulting company. This partnership highlights the importance of developing a framework that is easily usable for the stakeholder involved, such as consultants or other supporting parties.

Several scoping choices have been taken in this research. Large-scale CCS projects that include the complete value chain, including CO_2 capture, transportation, and storage, are the primary subject of this research. By narrowing the scope to these specific projects, the research aims to provide comprehensive guidance to stakeholders involved in the deployment of such projects. The first aspect of scoping is focused on the type of CCS projects. As CCS value chains consist of different elements such as capturing CO_2, transportation, and storage, many projects are being developed on different scales. Some consider only parts of the entire CCS value chain, whereas other projects focus on the entire value chain. This research will only consider large-scale projects where the complete CCS value chain is considered. Geographically, the research focuses on the North

Sea region, which has great potential for the development of CCS projects, as it has untapped gas reserves and aquifers that can store CO_2. By choosing this area as its main focus, the study can avoid the difficulties involved in examining projects operating in various contexts around the world. It provides a clear and defined geographical boundary, facilitating a more targeted and effective analysis of the policy environment.

In conclusion, this study intends to provide insightful direction to policymakers, project owners, and consultants by creating a evaluation framework in partnership with Accenture. The ultimate objective is to provide a comprehensive and useful framework that handles the specific difficulties of the sector to support the effective deployment of CCS projects.

3.2 Research approach

The research approach chosen in this Master's thesis is divided into several phases. To gain a basic understanding of CCS technologies, projects, developments, and the history of CCS, some exploratory background research has been performed in Section 2. This is in addition to the background and structure of the research problem in the Introduction. Section 4 also informs on the development of frameworks and the differences and possible combinations between frameworks that are currently available. After the stage has been established, this research is divided into three phases. The different phases are described in the research flow diagram in figure 3.1.

Figure 3.1 shows the RFD of this thesis. Three phases have been identified. A small section aimed at the expected results is included at the bottom of the figure. The three phases of the RFD will be explained and discussed in the following section.

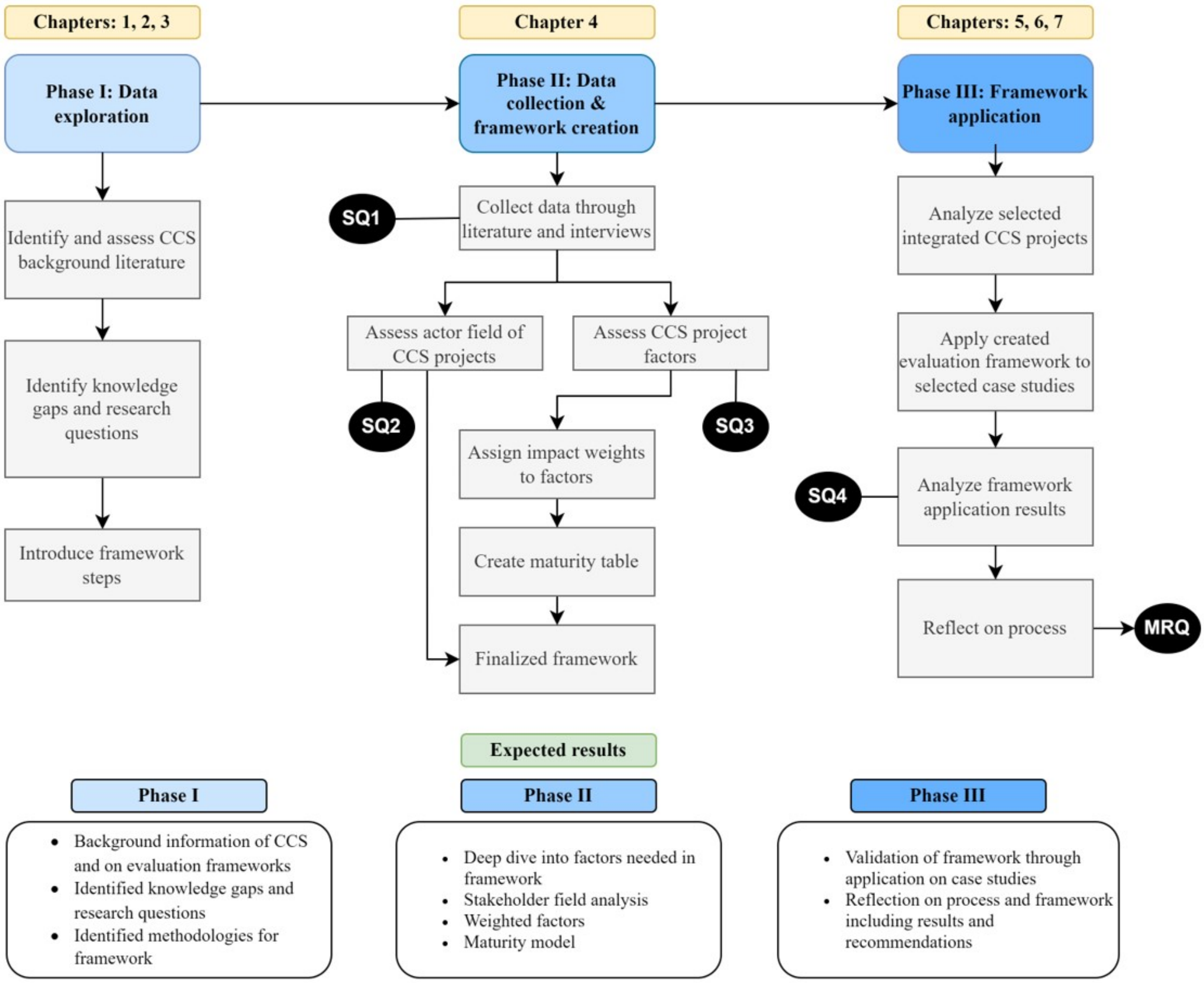

Figure 3.1: Research Flow Diagram

Phase 1: Data exploration

The first phase of the proposed research approach consists of a review of the current literature on CCS projects and current frameworks and includes the first three chapters of this research. As seen on the left side of 3.1, this review will provide information on the current state of CCS technology, including its potential benefits and drawbacks and the challenges associated with its implementation. Reviewing the literature will also help identify knowledge gaps and areas where more research is needed. Reviewing the academic literature on the background of CCS can ensure the foundation of this research, and relevant research questions can be proposed based on the knowledge gaps identified in Section 2.2. With the information gathered in this phase, the necessary steps for an evaluation framework can be identified.

Phase 2: Data collection & framework creation

The second phase (Chapter 4) of this research will consist of multiple steps that form the evaluation framework. The first steps consist of an extensive literature review and analysis of expert interviews, focusing on the factors of CCS and CCS projects. Through review of the literature and interviews conducted, a focus on the different factors and the actor field of CCS projects will help construct the framework. The information collected from the literature and the interviews will provide a structured list of CCS project factors that will be used in the next steps of the framework. First, the application of the best-worst method (more details are given in Section 3.3.4) will provide the ability to give impact weights to identified factors, scoring them based on their importance to a CCS project. The factors and their respective scores derived from this method will then be inserted into a three-point scale maturity model (which is explained in Section 3.3.5. This tool provides the ability to score a CCS project on a quantifiable level. The steps provided in this phase will form the evaluation framework, which will be applied in Phase 3.

Phase 3: Framework application

The third phase of the proposed research approach involves applying the evaluation framework on case studies of fully integrated CCS projects in the North Sea region. These case studies will provide valuable information on how CCS technology has been implemented in different circumstances and the types of barriers these projects have dealt with. The steps proposed in Phase 2 will be applied to these case studies to apply the created evaluation framework and determine whether the framework can provide insights based on CCS projects from the past and, therefore, be used in current or future projects. Based on the effectiveness of the framework when applied to past projects, conclusions can be drawn on its effectiveness on future projects. Phase 3 ends with general conclusions of the methods used in this research and the results of the analysis.

3.3 Methodologies & tools

In this section, the choice of the methodologies used in this research will be discussed and explained.

3.3.1 Factor analyzation methods

Throughout this investigation, two methodologies will be applied for the analysis of factors from CCS projects. These methods and how they will be applied in this research are discussed in the following.

PESTLE Method

The PESTLE method, developed by Johnson and Scholes (1985) and used by Fozer et al. (2017) on CCS projects, categorizes factors into political, economic, social, technological, legal and environmental aspects. This categorization is useful for assessing CCS projects as it makes the approach more manageable. Each category helps to analyze relevant factors, such as government support, economic viability, social acceptance, technological advances, legal compliance, and environmental impact. By organizing these factors, the PESTLE method provides a manageable framework to evaluate and strategize CCS projects. The way this method is applied in this research will be further elaborated in Section 4.1.

MCDA Method

Within the research, a methodology is used that incorporates features of the Multi-Criteria Decision Analysis

(MCDA) approach, which is based on the research of Eisenhardt and Zbaracki (1992) and further applied to CCS projects by Fozer et al. (2017). Traditionally, the MCDA method emphasizes the identification of relevant factors that influence the decision-making process and then scores various alternatives based on these factors. However, in this research, instead of scoring alternatives based on factors, the research will focus on scoring the weights of factors against each other using the Best-Worst Method (Section 3.3.4. This approach aims to provide a deeper understanding of the relative importance of each factor in CCS projects and in the decision-making process.

Once these factors are identified, they are assigned specific weights that reflect their importance in the overall evaluation. Subsequent to the weighting process, each factor is scored using a maturity table. By integrating features of the MCDA approach with the maturity table scoring system, the research not only draws on the strengths of MCDA but also introduces a tailored approach to ensure a comprehensive and structured evaluation. This combination aims to enhance the insights gained from the studied CCS projects, leading to more informed recommendations.

3.3.2 Literature research

The literature study serves as a foundational methodology in this research, primarily to investigate the critical factors that influence the development of CCS projects. The choice of this methodology is rooted in its ability to provide a comprehensive understanding of existing knowledge and findings related to CCS projects and technology. By systematically reviewing the literature, this research aims to identify, analyze, and identify key factors that have previously been explored and documented in the realm of CCS projects.

The primary objective of employing a literature study is to bridge knowledge gaps and build on existing research. As highlighted in Chapter 4, the factors identified in the literature provide a solid basis for further exploration and analysis in the subsequent chapters. This approach ensures that research is grounded in established findings, enhancing its validity and reliability. A literature study offers the advantage of drawing insights from a diverse range of sources, including academic articles, reports, and case studies. This diversity ensures a holistic understanding of the factors that influence CCS projects. Given the dynamic nature of CCS projects and their multifaceted challenges, a literature study provides a structured approach to categorize and prioritize these factors. In a later stage of the framework, these factors will be weighted according to their significance and impact on a CCS project. The literature study lay the foundations for the subsequent phases of research, ensuring that the findings and conclusions are based on established knowledge and supported by credible sources.

3.3.3 Semi-structured expert interviews

Although developing an evaluation framework solely based on historical data, academic papers, and reports would be an option, speaking to actors in the field would significantly add to the accuracy and usability of the framework in current times. Additionally, expert interviews would validate the information found in academic articles and identify what has not yet been considered. As CCS projects exist in a highly dynamic environment, having an up-to-date framework is crucial. Individuals with experience in the CCS field will be approached to gain data and insights into both the policy and governance surrounding CSS projects and the more detailed characteristics of the project. The interview consists of a set of semi-structured questions that will lead the conversation. These open questions allow the interviewees to elaborate on their own experiences in a detailed manner.

The selection of interviewees is performed based on their connection to CCS projects and technologies in combination with the aspired results of the interviews. As the interviews act as a tool to support the information found in the literature and reports, a mixed interviewee profile is preferred, resulting in insights from different points of view of the CCS field. In Appendix B, an interview protocol can be found. This protocol describes how potential interviewees are approached, what questions are asked, and how their data and statements are protected. Appendix C includes a consent form that every interviewee has signed before participating in the interview.

3.3.4 Best Worst Method

The Best Worst Method (BWM) by Rezaei (2015) is a prominent tool in multi-criteria decision making, allowing the classification of characteristics across the six categories that were identified for this framework. Using this method, the BWM-derived scores are integrated into a maturity table, advancing the CCS project assessment framework. To ensure a thorough evaluation of CCS projects, a combination of literature reviews, industry experts' consultations, and stakeholder participation is used to categorize characteristics into these six key categories, which are central to determining the effectiveness and sustainability of CCS projects. Data are sourced from a mixture of technical reports, expert insights, and other relevant materials to form a comprehensive dataset on the chosen characteristics. Within the BWM framework, participants engage in pairwise comparisons of characteristics, shedding light on their relative importance (Rezaei, 2016). This feedback is then transformed into quantitative impact scores, which are subsequently used to design a maturity table. This table offers a granular perspective on the maturity levels of CCS projects, facilitating a nuanced analysis of their strengths and areas for improvement.

Positioned within the Multi-Criteria Decision-Making (MCDM) framework, the BWM adeptly navigates the complexities of evaluating CCS projects, emphasizing the prioritization of characteristics based on their significance. In essence, the application of the BWM in assessing CCS projects not only provides a systematic approach to ranking characteristics but also fosters informed decision-making (Brunelli and Rezaei, 2019). A detailed explanation of the BWM can be found in Appendix A.

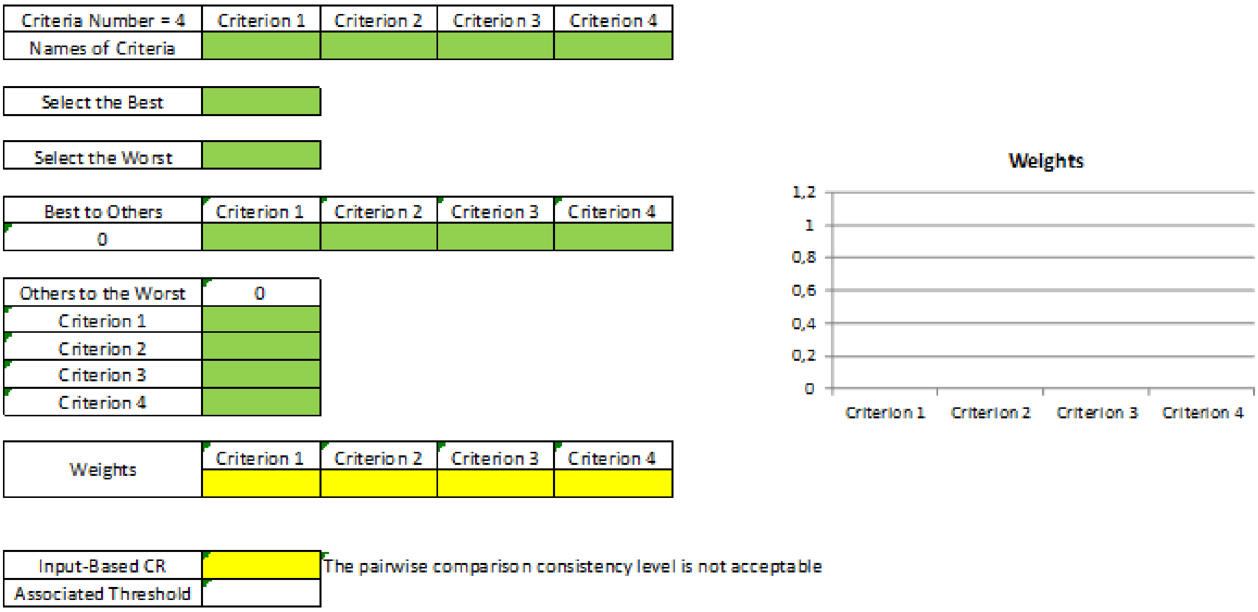

Figure 3.2: Best Worst Method by Rezaei (2015)

3.3.5 Project maturity table

The maturity model serves as a pivotal tool in evaluating the progression and potential success of CCS projects. Rooted in the principles of systematic assessment, the maturity model offers a structured approach to measure the implementation and consideration of various project factors.

According to Becker et al. (2009), a maturity model can be perceived as artifacts designed to determine an organization's current capabilities and derive measures for subsequent improvement. Essentially, it provides a sequence of stages to assess situations and guide potential enhancements (Vivares et al., 2018). Such models are instrumental in identifying the current state of an organization during its transformation journey.

In the context of this research, the maturity table is developed using a 3-point scale, enabling the categorization of each project factor into one of three distinct levels:

- **Level 1:** Represents a preliminary stage in which the factor has not been implemented/considered or has not been adequately addressed.
- **Level 2:** Indicates that the factor has been acknowledged and that there have been efforts toward its implementation/consideration, but it has not been fully realized or optimized.
- **Level 3:** Demonstrates a mature approach where the factor has been thoroughly considered and implemented/considered in a robust way.

By integrating the BWM impact scores with these ratings, a comprehensive scoring system is formulated. This system multiplies the score of each identified factor by its impact weight and the impact weight of the factor group, providing a holistic view of the project's development. This approach not only offers information on areas of improvement, but also guides stakeholders on where to focus their efforts for a successful implementation.

To provide a clear overview of the results from the application of the maturity table to a CCS project, the score map proposed by Wagire et al. (2021) is used. Figure 3.3 shows an example of the score map used to reflect on the results of the maturity table. The average of the project score is depicted by the red line, while the individual factor scores are depicted through the blue line. This score map creates the ability to quickly assess the weaker and stronger points of a project and will therefore be used as a tool in the evaluation framework.

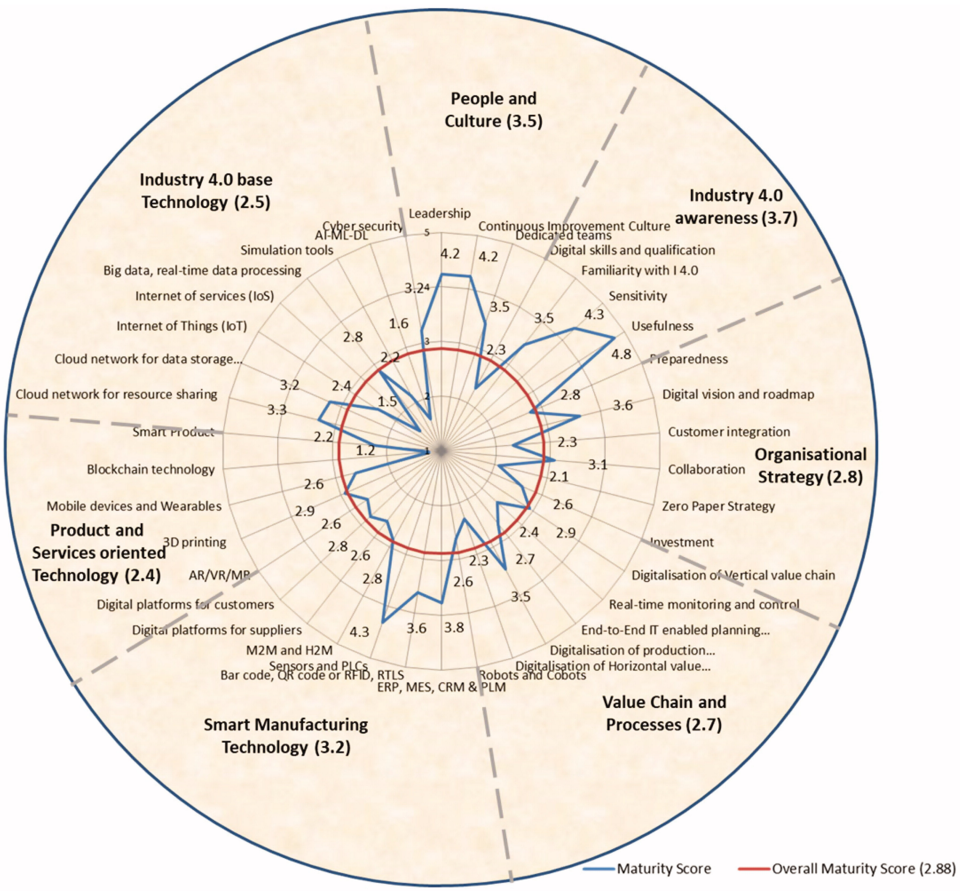

Figure 3.3: Example of Maturity Model Score Map by Wagire et al. (2021)

The maturity table, grounded in the principles of systematic assessment and evaluation, emerges as a crucial decision-making tool for stakeholders and policy makers. It not only facilitates prioritization and resource allocation, but also identifies areas that need improvement. By combining the BWM and the 3-point scale, the maturity table offers a data-driven methodology to evaluate and rank various CCS projects.

4 Framework development

Through the review of current academic literature and analyzing semi-structured expert interviews, the crucial aspects needed in the evaluation framework can be composed. This chapter focuses on three separate themes to identify these characteristics. First, a literature study is conducted in Section 4.2 with the intent of providing an overview of the most important criteria of the framework. These criteria will be evaluated and grouped based on the factor groups identified in Section 4.1. After this, the focus will be on the stakeholder field of CCS projects in Section 4.3. An overview will be presented containing the most important stakeholders, their key expectations and interests, and their potential contribution to the project. This will be supported by a Power Interest grid. The final step of data collection will be the analysis of the expert interviews conducted in Section 4.4. This will provide more up-to-date information on the current state of CCS. When data collection for the base of the evaluation framework is completed, a completed list of project factors will be presented, and additional methods that will be part of the framework will be discussed. First, the identified CCS project factors and factor groups will be weighted using the Best-Worst Method in 3.3.4. After the weights have been assigned, a maturity model is constructed in Section 3.3.5. The steps discussed in this chapter will form the stepwise approach of the evaluation framework and will be applied to case studies in Chapter 5.

4.1 Factor categorization

In evaluating the feasibility of a project, it is crucial to consider various groups of elements that can affect the assessment. This section identifies the optimal approach for this research through a comparison of existing (CCS) project evaluation frameworks. Fozer et al. (2017) employed three methods to analyze alternative CCS processes, including the PESTLE method (political, economic, social, technological, legal and environmental) and MCDA (multi-criteria decision analysis), both introduced in Section 3.3.1. The PESTLE method, based on Johnson and Scholes (1985), identifies factor groups for the evaluation of the project. Although this research accepts these groups, this research introduces a modification to include the policy- and governance-oriented factor. Additionally, inspired by Romasheva and Ilinova (2019), a 'organizational' factor group will be added, along with merging the 'political' and 'legal' groups due to their connection and overlay in the CCS context. The MCDA method used by Fozer et al. (2017) will also be applied here. Qualitative criteria within the identified factor groups will be analyzed, derived from literature reviews and stakeholder interviews. These criteria will contribute to a comprehensive framework for evaluating CCS projects and a detailed approach in subsequent case studies. The next section details each factor group within the evaluation frameworks, as shown in Figure 4.1.

Political-Legal

This factor group encompasses factors such as regulatory landscapes, political stability, governmental CCS initiatives, and legal requirements for projects. Evaluating implications for global climate agreements is essential in this category. The political and legal aspects of a CCS project are particularly important during the early stages of project planning, with their influence spanning the global scale.

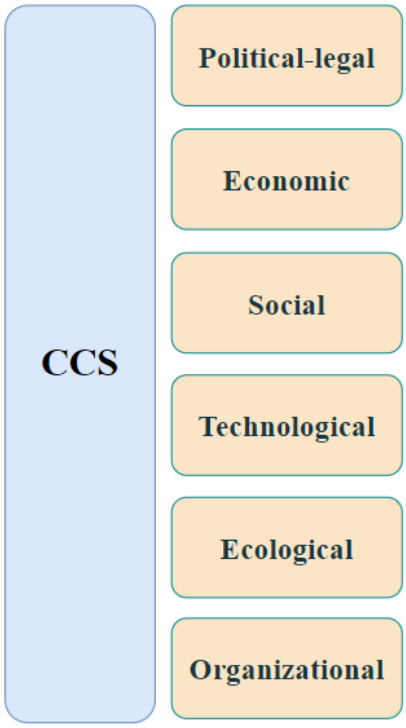

Figure 4.1: Factor groups in framework

Economic

Financial viability depends on the evaluation of the costs related to carbon capture, CO_2 transportation, and storage. As CCS projects demand long operational periods for economic feasibility, an economic evaluation is essential. Long-term financing sources, operating costs, and capital costs will be reviewed.

Social

Assessing social impacts and aligning with climate objectives is crucial. The societal effects, public and community perspectives, and stakeholder cooperation are the points of interest in this category. The tension between CCS and public views demands attention, making the social dimension crucial for project implementation.

Technical

Technical viability involves evaluating the selection of carbon capture technology, CO_2 transportation logistics, storage site suitability, and risk management. While not delving into intricate chemical processes, this research emphasizes the overall technical viability of a project.

Ecological

Environmental aspects require a detailed investigation. Analyzing local ecosystems, storage site impacts, and mitigation measures, such as CO_2 leakage prevention, are vital. Emission reduction is a goal, aligned with legal and environmental standards.

Organizational

Project implementation issues will be investigated through organizational evaluation. Project management approaches, team roles, and required competencies will be analyzed. Risk mitigation, teamwork, and capacity-building strategies are essential.

For the creation of the framework, these six factor groups will be considered to categorize the collected data.

4.2 CCS Project factors

This section will go deeper into the different factors needed for the framework based on available literature. factors will be sorted into the same categories identified in Section 4.1. The academic literature will be reviewed, and the most important factors will be selected and briefly discussed. Also, sources that support these factors are mentioned.

Political-legal

- **Political playing field**
  The political landscape can greatly shape the destiny of CCS projects. A supportive political environment can pave the way for favorable policies and funding opportunities, while opposition can erect regulatory hurdles and foster public skepticism. Factors such as political acceptance of CCS technologies, willingness to allocate resources (mostly financial), or condoning of the necessary building and operating permits are what help the prosperous development of CCS projects. The political playing field is thus a critical factor in the feasibility and longevity of CCS projects (Krahé et al., 2013; Lipponen et al., 2017; van Egmond and Hekkert, 2012)

- **Current environmental legislation and climate agreements**
  Environmental laws, with their ability to facilitate or hinder, play a pivotal role in CCS projects. Strict emission regulations can make CCS a more cost-effective compliance solution, while a lack of clear guidelines on aspects such as liability and monitoring can create a fog of uncertainties, deterring investment (Dixon et al., 2015; Romasheva and Ilinova, 2019). In addition, international climate agreements, such as the Paris Agreement, can serve as a powerful driver for the adoption of CCS. As countries strive to meet their emission reduction targets, CCS can emerge as a key tool in their arsenal, especially for industries where direct emission reduction is challenging (Akerboom et al., 2021; Dixon et al., 2015; Fan et al., 2011; Krahé et al., 2013).

- **Government involvement**
  The role of government can be a game changer in CCS projects. Government support can provide the necessary guidance, facilitate regulatory compliance, and help secure funding, making it a critical factor in the success of CCS projects (Ilinova et al., 2018; Lipponen et al., 2017).

Economic

- **CapEx and OpEx**
  The financial viability of CCS projects is dependent on their capital and operational expenditures. High costs can deter investment and slow implementation, making the economic aspect a key determinant of the success of a project (Budinis et al., 2018; Shen et al., 2022; Singh and Haines, 2014). For operational costs, the most significant challenge is the energy required to capture, transport and store CO_2. These

high costs could make CCS less competitive compared to other low-carbon technologies, unless advances can reduce energy consumption (Budinis et al., 2018; Durmaz, 2018). Operational expenditures must be projected, as CCS projects tend to span a long period of time. In addition, capital costs, mostly consisting of putting the CCS infrastructure in place, can be a great barrier to starting with the development of CCS projects. Financial aid from private and public stakeholders is of crucial importance.

- **Availability of potential subsidies**
  Subsidies can serve as a lifeline for CCS projects, helping offset their high costs and making them more economically viable (Akerboom et al., 2021). For example, in 2007, the EU issued the EU Energy Action Plan from which the NER300 program originated. The NER300 is a program that funds low-carbon technologies, for example, CCS demonstration projects (Herzog, 2017).

- **Long-term financing structures**
  Given the long life of CCS projects, stable and long-term financing structures are not just desirable, but crucial. The availability and terms of such financing structures can greatly influence the feasibility and sustainability of CCS projects. Financial environments could change significantly over the course of the development and deployment of CCS projects, so this aspect is crucial to evaluate in the long term (Budinis et al., 2018; Rassoor et al., 2021; Shen et al., 2022).

Social

- **Social acceptance of CCS implementation**
  The court of public opinion can have a large impact on the implementation of CCS projects. Negative public sentiment, driven by concerns about safety or preference for renewable energy, can lead to delays or cancelations of projects. Hence, public participation and transparent communication are the key (Braun, 2017; Gough et al., 2018; Gough and Mander, 2019; van Egmond and Hekkert, 2012).

- **Public preference for renewable energy**
  The winds of public opinion can greatly impact acceptance and support for CCS projects. If the public strongly prefers renewable energy over fossil fuels, CCS projects might face a headwind (Gielen et al., 2019; van Egmond and Hekkert, 2012).

Technical

- **Maturity of CCS technologies**
  The level of technological maturity can affect the efficiency, reliability, and cost effectiveness of CCS projects. Mature technologies are typically more reliable and better understood, reducing risks and uncertainties (Durmaz, 2018; Shen et al., 2022)

- **Risk mitigation**
  The ability to mitigate risks, such as CO_2 leakage, is a cornerstone of the safety and success of CCS projects.

Effective risk mitigation strategies can prevent accidents, protect the environment, and maintain public trust (d'Amore et al., 2018; Wennersten et al., 2015; Zapantis et al., 2019).

- **Geographical location of CCS project**

  The geographical location of a CCS project can impact various aspects, such as transport costs, storage options, and regulatory requirements. Therefore, location is a key factor in the planning and implementation of CCS projects (Braun, 2017; Rassoor et al., 2021).

Ecological

- **Safety of CCS technologies**

  The safety of CCS technologies is a paramount concern for protecting the environment and gaining public acceptance. Potential CO_2 leakage from storage sites could pose risks to the environment and human health, highlighting the need for safe technologies and practices (Deng et al., 2017; Diao et al., 2015).

- **Effectiveness of CO_2 reduction**

  The effectiveness of a CCS project in reducing CO_2 emissions is a key measure of its environmental impact and its contribution to the mitigation of climate change. First, the projects must be able to contribute to the mitigation of greenhouse gases. The viability of CCS projects strongly depends on their ability to effectively reduce CO_2 emissions while keeping in mind the energy needed for the project (Cao et al., 2020; Steyn et al., 2022).

Organizational

- **Collaborating parties**

  The roles, responsibilities, and relationships of the collaborating parties can greatly influence the success of CCS projects. Effective collaboration between project developers, technology providers, and regulators can facilitate project implementation and compliance with regulations (Ilinova et al., 2018).

- **CCS value chain ownership**

  Ownership of the value chain can affect control over the project, distribution of benefits, and allocation of risks. A project where one entity owns the entire value chain might have simpler decision-making processes but also bear all the risks (Lofstedt, 2015).

- **Risk sharing**

  The way risks are shared among project stakeholders can impact project relationships, financial arrangements, and overall project success. A project with a risk-sharing agreement can attract more investors and partners, as the potential losses in case of failure are spread out (Lofstedt, 2015; Zapantis et al., 2019).

- **CCS infrastructure**

  CCS projects and the implementation of CCS technologies require an efficient and optimal infrastructure where all elements of the value chain are efficiently connected. The use of existing infrastructure and knowledge on geological formations could be highly beneficial in the development of CCS projects (Mikunda et al., 2011).

4.3 Stakeholders in CCS projects

CCS projects consist of multiple elements. There is a need for CO_2-capturing technologies, transportation options, storage facilities, and storage capabilities to develop a complete CCS value chain. Because of this, CCS projects operate in a multi-actor environment, which calls for clear communication and collaboration between the parties involved. The current literature (mostly technology-orientated) often assumes that the CCS value chain operates without any complications between actors or is even owned by a singular actor, while in reality this is not the case.

Other important factors are future economic incentives to avoid emissions, the price of fossil fuels, the further expansion of renewable energy, and the public acceptance of CCS projects in regions with potential storage sites (Stephens and Liu, 2012). Despite the challenges mentioned above, the CCS community is strong and includes participants from the fields of politics, economics, and research. An expanding international network of people whose professional careers are related to the development of CCS evolved as a result of increased commercial and public investments in CCS (Stephens et al., 2011). Representatives from energy companies, trade organizations, governments, colleges, and research institutions make up this network, which serves as the main proponents in the CCS debate (Krüger, 2017).

In this section, an overview of the most important stakeholders in the CCS field is presented. Table 4.1 provides a list of all the actors including their key interest and their potential contribution. The table is based primarily on information collected and provided by Ilinova et al. (2018). In her paper, she describes the most important stakeholders in the CCS field in the same way as presented below. In addition to her claims, other academic literature and insights from the semi-structured interviews back up the information in the table. Expert interviews will be discussed in detail in Section 4.4.

4.3.1 Stakeholder overview

Efficient stakeholder management requires a thorough examination of both internal and external players associated with a project. Unfortunately, no two CCS projects are alike. Therefore, compiling a general list of stakeholders involved in CCS projects is a difficult task. The number of such stakeholders involved may also change frequently throughout the different phases of the projects. However, Table 4.3 below, based on knowledge from Ilinova et al. (2018) and supported by additional sources and interviews, provides a comprehensive list that lists various types of players and their interests or expectations in the CCS field.

Collaboration among these stakeholders is a crucial part of CCS projects, as it enables the integration of diverse perspectives and ensures that the projects align with the social, economic, and environmental goals. By working together, stakeholders can address challenges, share best practices, and leverage each other's strengths to overcome barriers in the deployment of CCS projects. Collaborative efforts also promote knowledge exchange, facilitate technology transfer, and promote innovation, as will also be confirmed in the expert interviews performed. Effective communication is also essential for stakeholders to align their objectives, exchange information, and resolve conflicts. Clear and transparent communication improves understanding, facilitates decision-making, and promotes trust among stakeholders. It allows the identification of common interests, alignment of expectations, and identification of potential synergies. Open communication channels also allow stakeholders to address concerns, manage risks, and engage in meaningful dialogue with affected communities and the general public.

Stakeholder Groups	**Sources**	**Key Expectations and Interests**	**Potential Contribution to the Project**
Policymakers (state level)	Ashworth et al. (2015); Ilinova et al. (2018), Interview 3	• Ensuring the safety of CCS technologies • Minimizing environmental impact • Upholding responsibility to reduce CO_2 emissions • Enhancing the country's global standing	Offering financial backing for projects, lobbying opportunities, additional measures to stimulate emission reduction and CCS technologies development, promoting projects for socio-economic development
Policymakers (municipality level)	Ashworth et al. (2015); Cherepovitsyn et al. (2019), Interview 3	• Prioritizing the safety of CCS technologies • Reducing environmental impact • Boosting the region's investment attractiveness • Fostering socio-economic development • Generating budget revenues from projects	Implementing public-private partnership (PPP) mechanisms, providing opportunities for lobbying
Investors and financial institutions	Cherepovitsyn et al. (2019), Interview 1, Interview 3,	• Promoting sustainable development and socially responsible investment • Establishing and strengthening partnerships with project participants • Diversifying the project portfolio • Accumulating experience in CCS projects	Supplying financial and other resources for project execution
Industry (emitters and participants of the technological chain)	Cherepovitsyn et al. (2019), Interview 1	• Achieving project goals • Ensuring project implementation in line with terms and budgets • Advancing companies' technological development • Increasing business investment attractiveness	Taking full responsibility for project implementation, promoting CCS technologies in the industry
Technology suppliers	Ilinova et al. (2018); Stokke et al. (2022)	• Ensuring buoyant demand for CCS technologies • Influencing project costs (capital and operating)	Implementing new technologies to enhance efficiency and effectiveness in the CCS value chain, influencing project costs (CapEx & OpEx)
Local public	Braun (2017), Interview 1	• Expecting safety surrounding CCS technologies • Providing employment opportunities • Fostering socio-economic development of the region	Providing staffing, purchasing local goods and services, obtaining a "social license to operate"
Non-governmental environmental organizations (NGO)	Lipponen et al. (2017)	• Questioning safety and evidence-based feasibility of CCS technologies • Assuring environmental compliance during project implementation • Minimizing ecosystem impact	Leveraging authority among the public for lobbying opportunities
Media	Ashworth et al. (2015); Lipponen et al. (2017)	• Providing transparency and availability of project information • Maintaining an open dialogue with project participants	Serving as a communication tool to promote positive opinions about CCS technology and the positive reputation of operating companies
Project teams	Lipponen et al. (2017), Interview 2	• Upholding social responsibility of operating companies • Providing decent working conditions and wages • Offering opportunities for professional development	Influencing the achievement of project objectives and effectiveness indicators
Suppliers and contractors	Ilinova et al. (2018)	• Ensuring long-term contracts and stability of interaction	Influencing project performance in terms of cost, time, and quality

Table 4.1: Main stakeholders in CCS projects

4.3.2 Power Interest Grid

In the context of analyzing CCS, a Power-Interest provides valuable insights into effective stakeholder engagement strategies. The four quadrants mentioned below make up the PI grid.

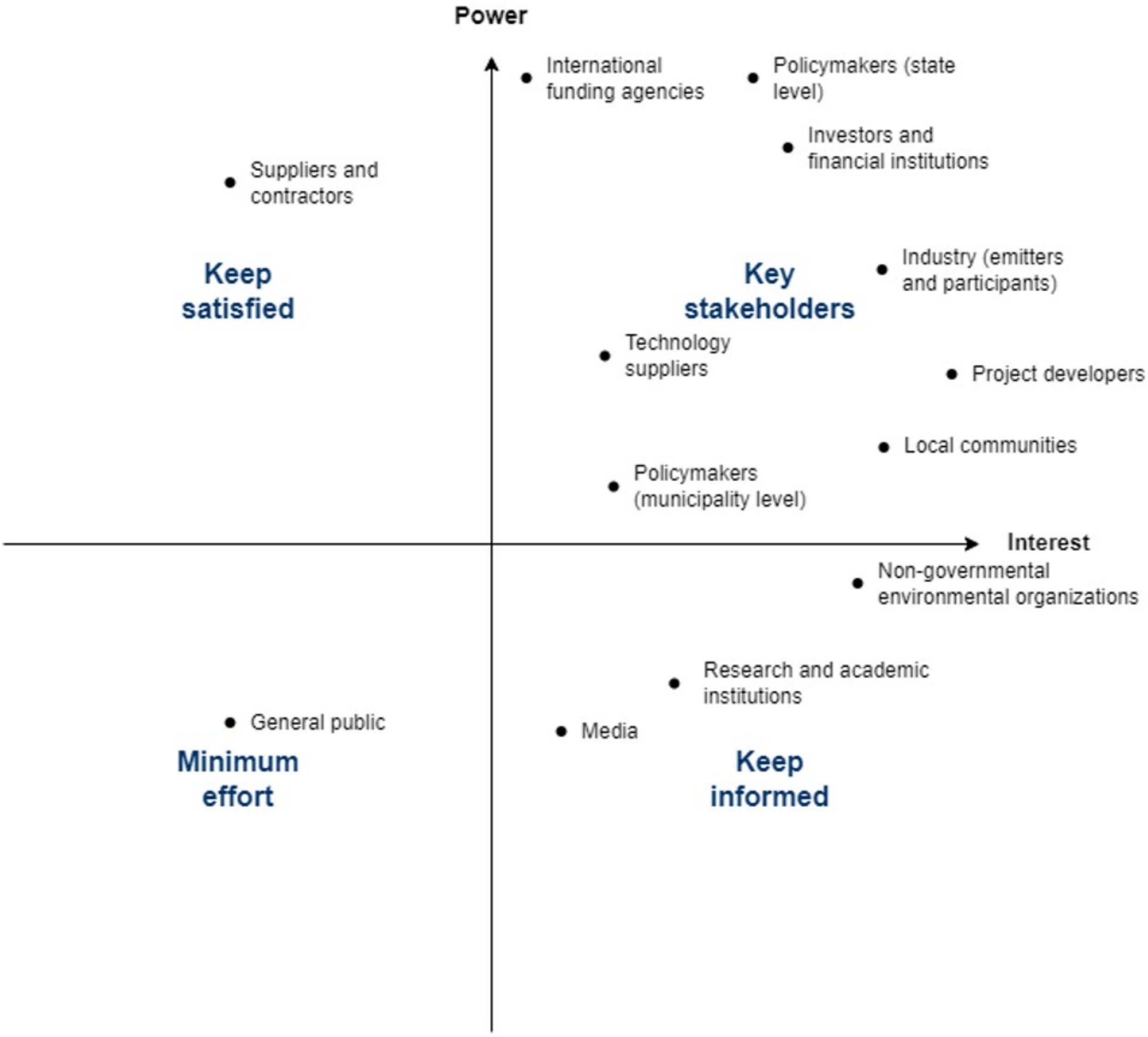

Figure 4.2: Power Interest Grid

Key stakeholders (High Power, High Interest): Stakeholders in this quadrant wield significant power over CCS projects and are deeply invested. Here, policymakers at the state and municipality levels, investors, and industry players are crucial. They can drive project decisions and outcomes, making their involvement critical for success. Among them, policymakers set regulations, investors provide resources, industries influence technology, and project choices, and project teams work on the development of CCS projects. The CCS technology suppliers are also recognized as key stakeholders. They deliver the knowledge to carry out the different parts of the value chain. Ranking within the quadrant: Investors and financial institutions, Project teams, Policymakers (state level), Industry (emitters and participants), Technology suppliers, Policymakers (municipality level).

Keep satisfied (High Power, Low Interest): Stakeholders in this quadrant have substantial power but may not be deeply engaged. Suppliers and contractors typically fall into this category. Their influence can impact project performance as they will be the ones that put in significant amount of hours to work on the project, yet their primary interest lies outside the project's immediate scope. While their opinions matter, keeping them informed while listening to their needs is usually sufficient.

Keep informed (Low Power, High Interest): Stakeholders here hold great interest in CCS projects but lack significant power. Local public, non-governmental environmental organizations (NGOs), and media often fall into this quadrant. Their perspectives and concerns can shape public opinion, project image, and overall morale. Engaging them effectively is essential to garner support and maintain a positive environment. Ranking within the quadrant: Non-governmental environmental organizations (NGO), Reseearch and academic institutions, Media.

Minimum effort (Low Power, Low Interest): This quadrant generally has a lower impact on CCS projects and requires minimal involvement. Those who fit this profile would have limited influence and interest in the project. In this case, the general public falls into this category. While they are in this quadrant, it is important to ensure that they are not neglected completely. Minimal efforts to keep the general public involved in some way could ultimately prevent potential complications in the form of lack of social acceptance.

Ultimately, effective stakeholder engagement depends on understanding their power, interests, and role in the project. The PI grid assists project managers in allocating resources and tailoring communication strategies.

4.4 Expert interview insights

In order to understand the field of CCS technologies and currently operating CCS projects, three exploratory expert interviews were conducted. These interviews will provide a more up-to-date view of CCS projects, technologies, and current developments as opposed to only reviewing academic literature and reports. As the playing field surrounding CCS projects is very dynamic and tends to change often based on different factors, adding knowledge from experts who are currently in the field of CCS and have been for a long time seemed crucial.

In the three interviews, the interviewees are taken through a predefined set of questions. During the interview, this set of questions is used as a guide for the interview, making the interviews semi-structured. On the basis of the knowledge and experience of the respective interviewees, certain questions are more interesting to expand on. The questions, the way to approach the interviewees, and more information on data management, data protection, and consent are presented in Appendix B.

This section will present short summaries of the interviews, while also highlighting and expanding on the most important takeaways that will add to the knowledge needed to create frameworks and insights for future CCS projects. Important phrases that will be linked to the key factors of CCS projects are highlighted in italic font. A more detailed analysis of the interviews, which contains takeaways supported by quotes from all three interviews, is presented in Appendix D.

4.4.1 Interview 1

Summary

The first interviewee (R1) began his research on CCS when the Netherlands Ministry of Environment sought solutions for emission reduction goals in the early 1990s. With experience in risk assessment, management, subsurface application, and governance, R1 focused on developing a comprehensive policy framework for CCS projects in the North Sea. R1 now works at TNO (a Dutch not-for-profit research institute) and has been included in several research groups related to CCS.

In the interview, R1 emphasized the need for a *mature CCS market*, which addresses the challenges related to social issues and long-term liabilities facing companies. The importance of *proper financing structures and government support*, sharing examples of both failed and successful CCS projects, was highlighted as one of the most important aspects of the development of CCS projects. R1 expressed optimism that countries like the Netherlands, the UK, Denmark, and Germany would establish effective financing mechanisms.

In terms of the characteristics of successful and failed CCS projects, R1 again highlighted the importance of *proper financing structures and government support* for the underlying activities. It was pointed out that *risk-sharing along the value chain* played a crucial role in mitigating challenges. R1 shared examples of failed projects due to political reasons, installation issues, and financial concerns while also citing the Sleipner project as a successful case driven by the Norwegian government's taxation law on offshore emissions. R1 also discussed the social aspects of CCS, such as *creating local value* and *involving communities.* The potential for a pan-European network for CO_2 storage and transportation was explored, considering collaborations between Poland, Denmark, Norway, Belgium, and Germany. Alternative storage methods, including aquifers, were mentioned as ongoing pursuits in Norway and the UK. R1's research and knowledge provide valuable insights into the challenges and opportunities of CCS, emphasizing the need for *robust policy frameworks, financing structures, and international cooperation* to achieve emission reduction goals.

4.4.2 Interview 2

Summary

R2, who joined the Porthos project in June 2022 through Accenture and Gasunie, was interviewed about their work on one of the largest CCS projects in the Netherlands. Porthos is a CCS project in the Netherlands that aims to reduce industrial carbon emissions by capturing CO_2 from multiple sources, including refineries and chemical plants in the port of Rotterdam. In recent events, the project faced legal challenges from an environmentalist organization called Mobilization for the Environment (MOB), which claimed that a partial building exemption had been unfairly granted to the project and that the project would harm nearby Natura-2000 (protected areas of nature) areas due to the project's nitrogen emissions. MOB initiated a review of the project with a court case, leading to the Porthos project coming to a halt at the end of 2022. However, the Dutch Council of State has recently (August 2023) decided that the project can continue because the emissions from the Porthos project were not considered an imminent threat to Natura-2000 areas (Raad van State, 2023). Note that this interview was conducted during the phase in which the Porthos project was paused due to these reviews.

R2's team is specifically tasked with preparing Porthos for operations, which includes setting up the necessary processes, IT systems, and personnel for the project. The Porthos project is a large-scale project that involves approximately 150 people divided into 10 teams. The main components of the project include a pipeline and a compressor station designed to facilitate the pumping of CO_2 into the ground as part of the CCS process. At the time of the interview, the Porthos project was on the cusp of its Final Investment Decision (FID). The design phase for the pipeline and compressor station had already been completed, marking a significant milestone in the progress of the project. However,

R2 discussed the uncertainty surrounding the project due to the lawsuit and the *pending permits*, but expressed the hope that the project would proceed as planned. Despite the challenges, the Porthos project represents a significant step forward in the implementation of CCS technology in the Netherlands.

4.4.3 Interview 3

Summary

R3, an external affairs manager, and R4, a public affairs advisor, are integral members of the Porthos project. R3 joined two years ago and started as a stakeholder manager before becoming a team manager. With a background in engineering and currently working as a management consultant, R3 brings valuable experience to the project. R4, on the other hand, joined Porthos in November 2021, leveraging his experience as a public affairs consultant specializing in the energy transition. Their role involves engaging with external stakeholders and politicians. The interview was initially planned with only R3. However, R3 suggested that R4, with whom he works on the Porthos project, join the call for a more diverse conversation.

During the interview, R3 and R4 discuss their background, expertise, and involvement in carbon capture and storage. They delve into the challenges and crucial aspects of the deployment phase of projects like Porthos, including nitrogen deposition during construction, material and equipment availability, and the significance of a meticulous project startup. The conversation also touches on the interest of other countries in initiating similar projects and stresses *the importance of political support* and *a viable framework for carbon capture and storage*. R3 and R4 highlight the need for *long-term financing*, emphasizing that contracts have been established with all partners involved to ensure *financial stability*.

Both R3 and R4 share their experiences with CCS technologies, noting that the Porthos project marked their direct involvement in CCS. However, they bring relevant experience from their respective fields. R3 and R4 discuss variations in project structures in other countries, such as Antwerp, where emitters are part of the partnership and may potentially become owners of segments of the pipeline system.

4.4.4 Main interview takeaways

1. **Effectiveness of CO_2 storage in depleted gas fields**

   The discourse of the interviewees sheds light on the potential efficacy of CO_2 injection in depleted gas fields for storage purposes. The Porthos project, as an example, is a pioneer in implementing this method.

2. **Societal aspects of CCS**

   The societal dimensions of CCS are explored, with a particular emphasis on the indispensable role of political backing and the necessity for a framework to manage CO_2 storage. The interviewees underscore the pivotal role of public and political acceptance of CCS as a viable solution within the energy transition.

3. **Long-term financing of CCS projects**

   The importance of long-term financing for CCS projects is emphasized. Interviewees indicated that contracts had been established with all partners involved in the Porthos project to guarantee its longevity for the required duration. These contracts, which are long-term, are expected to provide financial stability to the project.

4. **Risk-sharing in CCS projects**

   The interviewees discuss the importance of risk sharing in CCS projects. In the context of the Porthos project, the Dutch Government assumes full accountability for any leakage post the fields' decommissioning.

5. **Importance of collaboration within projects**

   All interviewees spoke in some way about the importance of the stakeholders that exist within CCS projects. Many different types of stakeholders need to work together to achieve project goals, and that can often lead to difficulties in management or execution. R1 spoke about how unbundling of the elements (capture, transportation, storage) could be a viable solution.

6. **CCS in other countries**

   The interviewees note the considerable interest from other countries in understanding the initiation of the new value chain and the nature of CO_2 capturing and storage.

4.5 List of identified CCS project factors

From the literature study conducted and expert interviews, a complete list of the most important factors of a CCS project can be compiled. Factors collected from the analyzes are sorted into identified factor groups and will act as a basis for measuring the state of a CCS project. Table 4.2 also references the interview in which each factor is discussed. Further analysis of the interviews, including quotes, can be found in Appendix D. In Section 4.6, the factor groups and factors will be given weights by applying the best-worst method. The list of factors and their corresponding weights will be used to construct a maturity model in Section 4.7. This maturity table will later be applied to case studies as an exemplary measure. Table 4.2 below shows the complete list of identified factors classified into their respective factor groups.

Factor group	**Factor**	**Interview 1**	**Interview 2**	**Interview 3**
Political-Legal	Political acceptance	✓		✓
	Government support	✓		✓
	Climate agreements			
	Value chain ownership	✓	✓	✓
Economic	Government funding	✓		
	Private financing	✓		
	OpEx	✓		✓
	CapEx			✓
Social	Involvement of public	✓		✓
	Social acceptance CCS	✓	✓	✓
	Local job creation	✓		
Technical	Maturity of CCS technology	✓	✓	✓
	Risk mitigation capabilities		✓	✓
	Development of other environmental technologies		✓	
Ecologic	Contribution to CO_2 emission reductions	✓	✓	✓
	Possibility of leaks from geological formations			✓
	Project effect on nearby area		✓	
	Significant CO_2 emissions for CCS	✓		
Organizational	Risk sharing in value chain	✓	✓	✓
	Efficient and connected CCS infrastructure		✓	✓
	Collaboration between stakeholders	✓	✓	✓

Table 4.2: List of CCS project factors

As can be seen in Table 4.2, most of the factors identified in the literature were also identified and discussed in the expert interviews conducted. Only the factor *'Climate agreements'* is not deliberately discussed or mentioned in the interviews. However, this is not of much concern as information on this factor is easily accessible through literature, reports, and official government websites.

4.6 Factor impact assessment: Best Worst Method

Now that the identification of project factors divided into several categories has been completed, a distinction can be made between the impact of these factor groups and factors. The impact that factors can have on a project will vary according to their respective importance to a specific CCS project. The analysis below is performed on the basis of the information collected from the literature review and the expert interviews conducted in this chapter.

The application of the BWM in this research has one important side note:
The BWM in this research will be applied to general CCS project and policy factors. This means that these factors would apply to all CCS projects. However, as the nature of CCS projects is often diverse and the characteristics of these projects may differ based on the given circumstances, the weighted importance of the identified factors may be different in specific scenarios. For the purpose of this research, the impact scores used in the BWM method and the maturity tables will be determined based on the information collected in this research, from the literature study and expert interviews.

When using the proposed evaluation framework for future and current CCS projects, it is strongly advised to perform a detailed analysis of the relative impact of the identified factors based on the specifics of the CCS project in question.

4.6.1 Factor groups

The aim of the BWM is to assign weights to the identified factors in each factor group. In this way, factors within one specific group are not compared to factors from other groups. Due to this, it is also necessary to apply the BWM to the factor groups. In this way, the factors receive a weighting score that is the product of their individual weight relative to other factors in their group and the weight of their factor group among the other groups. Figure 4.3 shows the BWM applied to the factor groups.

Criteria Number = 6	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
Names of Criteria	Political-legal	Economic	Social	Technical	Ecologic	Organizational

Select the Best	Economic
Select the Worst	Social

Best to Others	Political-legal	Economic	Social	Technical	Ecologic	Organizational
Economic	1	1	4	2	3	3

Others to the Worst	Social
Political-legal	4
Economic	4
Social	1
Technical	3
Ecologic	2
Organizational	2

	Political-legal	Economic	Social	Technical	Ecologic	Organizational
Weights	0,284	0,284	0,063	0,158	0,105	0,105

Input-Based CR	0,167	The pairwise comparison consistency level is acceptable
Associated Threshold	0,221	

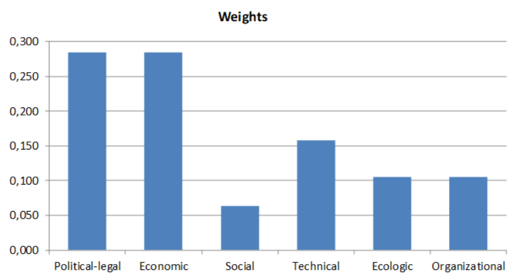

Figure 4.3: BWM Factor groups

The BWM scores provide a nuanced perspective on the relative importance of each factor group in the context of CCS projects. Through this lens, we can discern the priorities and challenges that stakeholders might face. From the literature review and expert interviews, the political-legal factor group emerges as the most important group to consider together with the economic factor group. It is reflecting the critical role of regulatory compliance, political acceptance, and the overarching influence of international climate agreements. Its high score underscores the fact that without a favorable political and legal landscape, even the most technically sound and economically viable projects can face significant hurdles. The economic factor group, given the substantial capital investments and long-term operational costs associated with CCS projects, is of equal and significant importance. The weight emphasizes the need for robust financial planning and the attractiveness of potential subsidies. Technical innovation and adaptability are the foundations of CCS projects. The score for this factor group not only reflects the importance of deploying state-of-the-art technologies, but also underscores the need for future readiness and proactive risk mitigation. However, the economic and political-legal aspects need to be considered before the implementation of actual CCS technologies. The ecological dimension, with its dual facets of environmental benefits and potential risks, is given a balanced score. This weight emphasizes the importance of environmental sustainability while also acknowledging the inherent challenges and risks. The organizational factor group, while essential for the smooth execution of a project, is influenced by the other factor groups. Clear organizational roles and effective collaboration become paramount once the political, economic, technical, ecological, and social dimensions are aligned. The social factor group, although receiving the lowest score, is crucial. Its weight highlights the importance of community participation, social acceptance, and the broader socio-economic benefits. A project without societal support can face challenges that would be hard to overcome, from public protests to delays in implementation.

The BWM scoring offers a hierarchical view of the factor groups, allowing stakeholders to gauge the relative importance of each group and prioritize their strategies accordingly.

4.6.2 Political-legal

Within the political-legal factor group, political acceptance emerged as the most influential factor. Without political support, the foundational support for CCS projects can crumble. This acceptance is closely followed by government support, which often acts as a manifestation of political acceptance. Adherence to international climate agreements further strengthens the legitimacy of the project. Although these factors set the stage, the clarity and structure provided by value chain ownership ensure that project operations continue seamlessly, highlighting its importance despite a lower BWM score.

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Political acceptance	Government support	Climate agreements	Value chain ownership

Select the Best	Political acceptance
Select the Worst	Value chain ownership

Best to Others	Political acceptance	Government support	Climate agreements	Value chain ownership
Political acceptance	1	3	2	6

Others to the Worst	Value chain ownership
Political acceptance	6
Government support	3
Climate agreements	5
Value chain ownership	1

Weights	Political acceptance	Government support	Climate agreements	Value chain ownership
	0,477	0,182	0,273	0,068

Input-Based CR	0,133	The pairwise comparison consistency level is acceptable
Associated Threshold	0,199	

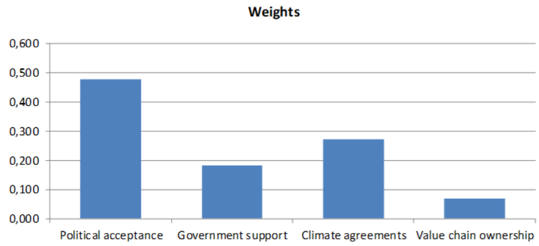

Figure 4.4: BWM Political-Legal

4.6.3 Economic

The economic evaluation highlighted government funding as the most crucial factor. Given the capital-intensive nature of CCS projects, securing initial funding can make or break the project's feasibility. Private financing, while crucial, often follows the lead set by governmental support. However, while these funding mechanisms provide the necessary financial stability, the continuous challenges posed by OpEx and CapEx cannot be overlooked. The balance between these expenditures, especially over the project's lifespan, is crucial for its economic viability. Both OpEx and CapEx will need to be thoroughly mapped during the development of a CCS project. However, as CapEx plays a larger part during the initial stages of a project (infrastructure development) it has a slightly higher BWM score than OpEx.

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Government funding	Private financing	OpEx	CapEx

Select the Best	Government funding
Select the Worst	OpEx

Best to Others	Government funding	Private financing	OpEx	CapEx
Government funding	1	2	3	2

Others to the Worst	OpEx
Government funding	3
Private financing	2
OpEx	1
CapEx	1

Weights	Government funding	Private financing	OpEx	CapEx
	0,429	0,238	0,143	0,190

Input-Based CR	0,167	The pairwise comparison consistency level is acceptable
Associated Threshold	0,167	

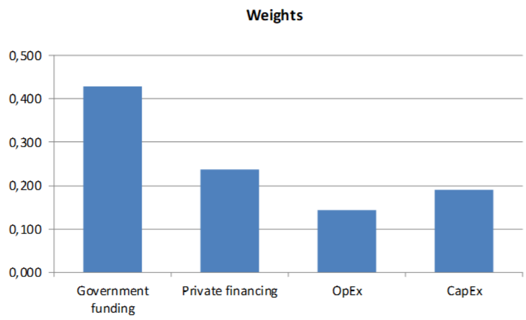

Figure 4.5: BWM Economic

4.6.4 Social

In the societal context, public acceptance is considered the most important factor. The reasoning is clear: a CCS project that lacks public support can face insurmountable challenges, from protests to legal battles. A great example for this is the Barendrecht CCS project (located in the Netherlands). The plans for this offshore

CCS demonstration project were canceled due to strong opposition among the surrounding community. Shell, the initiator of the project, was not prepared for the scale of the not-in-my-backyard opposition (Feenstra et al., 2010). Beyond mere acceptance, tangible benefits like local job creation and the involvement of public can transform passive acceptance into active endorsement, ensuring the project's long-term social sustainability.

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Involvement of public	Social acceptance CCS	Local job creation

Select the Best	Social acceptance
Select the Worst	Local job creation

Best to Others	Involvement of public	Social acceptance CCS	Local job creation
Social acceptance CCS	6	1	7

Others to the Worst	Local job creation
Involvement of public	2
Social acceptance CCS	7
Local job creation	1

Weights	Involvement of public	Social acceptance CCS	Local job creation
	0,138	0,763	0,100

Input-Based CR	0,119	The pairwise comparison consistency level is acceptable
Associated Threshold	0,129	

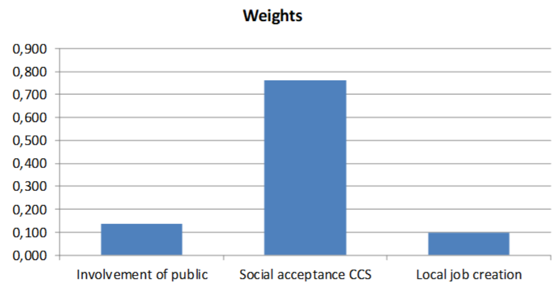

Figure 4.6: BWM Social

4.6.5 Technical

Technical feasibility is at the heart of CCS projects. The maturity of CCS technology, as it dictates the project's foundational strength, has been given a high BWM score. However, other factors, such as risk mitigation capabilities and the development of other environmental technologies, also play a significant role. While technological maturity provides the base, the ability to mitigate risks ensures the project's resilience and long-term success. The development of other environmental technologies influences the viability of CCS projects on a higher scale, as it could determine whether CCS is still an effective option for CO_2 emission reduction, compared to alternatives.

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Maturity CCS	Risk mitigation	Development other environmental technologies

Select the Best	Maturity CCS
Select the Worst	Development other

Best to Others	Maturity CCS	Risk mitigation	Development other environmental technologies
Maturity CCS	1	4	6

Others to the Worst	Development other environmental technologies
Maturity CCS	6
Risk mitigation	2
Development other	1

Weights	Maturity CCS	Risk mitigation	Development other environmental technologies
	0,704	0,185	0,111

Input-Based CR	0,067	The pairwise comparison consistency level is acceptable
Associated Threshold	0,133	

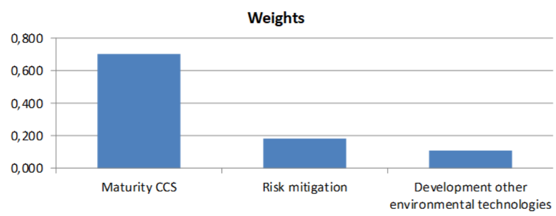

Figure 4.7: BWM Technical

4.6.6 Ecologic

Ecologically, the potential for significant CO_2 emission reductions was the dominant factor. Given the global emphasis on reducing carbon footprints, the main objective of any CCS project is to achieve substantial emission reductions. However, the ecological landscape is also shaped by concerns such as possible leaks from geological formations and the effect of the project on nearby areas. Striking the right balance, maximizing benefits while minimizing risks, is essential. Furthermore, ensuring a consistent supply of CO_2 emissions for CCS further emphasizes the ecological importance of the project.

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Contribution CO2 emission reduction	Possibility of leaks	Ecologic effect on nearby areas	Significant CO2 emissions

Select the Best	Contribution CO2
Select the Worst	Significant CO2

Best to Others	Contribution CO2 emission reduction	Possibility of leaks	Ecologic effect on nearby areas	Significant CO2 emissions
Contribution CO2 emission reduction	1	4	4	7

Others to the Worst	Significant CO2 emissions
Contribution CO2	7
Possibility of leaks	3
Ecologic effect on	3
Significant CO2	1

Weights	Contribution CO2 emission reduction	Possibility of leaks	Ecologic effect on nearby areas	Significant CO2 emissions
	0,595	0,165	0,165	0,076

Input-Based CR	0,119	The pairwise comparison consistency level is acceptable
Associated Threshold	0,246	

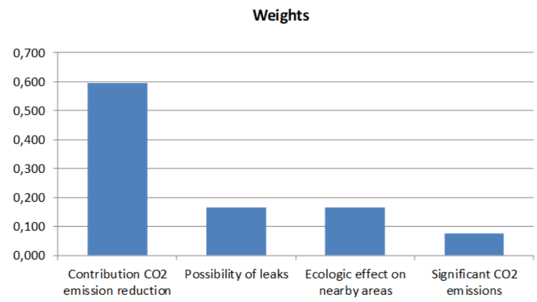

Figure 4.8: BWM Ecologic

4.6.7 Organizational

Behind the scenes of any CCS project is a robust organizational structure. Risk sharing in the value chain, with its highest BWM score, emphasizes the importance of collaboration and mutual trust. Other factors such as the efficiency and connectedness of the CCS infrastructure and the collaboration between stakeholders also play a role in the organizational success of a project. Shared risk can ensure more optimal collaboration between stakeholders, as potential losses are distributed among all parties involved. An optimal CCS infrastructure (positioning and connectedness of the separate CCS elements) also increases the feasibility of the project, reducing costs and potential structural obstacles.

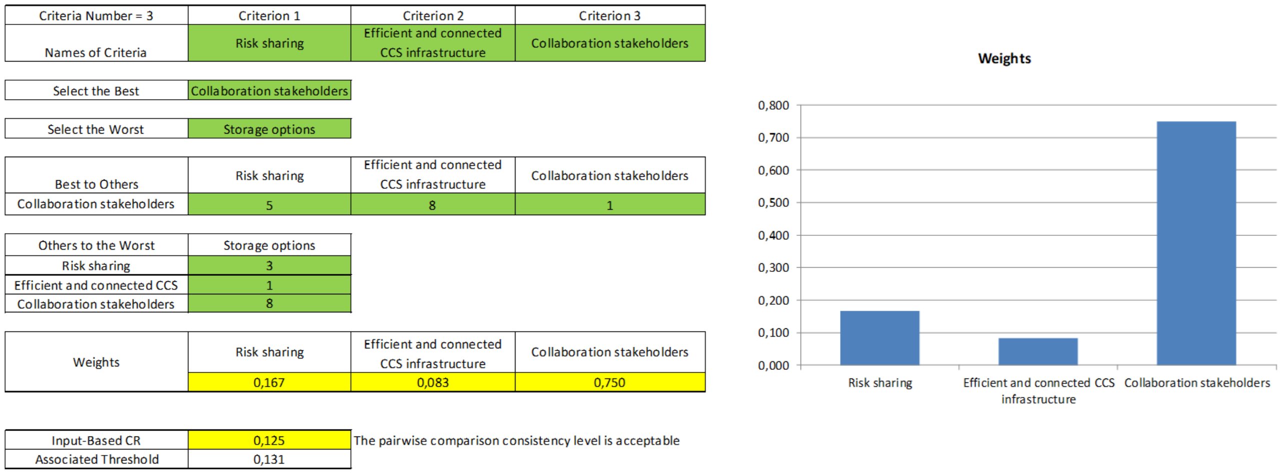

Figure 4.9: BWM Organizational

4.6.8 BWM scores

The weights recovered from the application of the BWM can be found in Table 4.3 below. The table shows the weight for each factor group and for all individual factors. These weights will be added to the maturity table that will be constucted in the next section.

Factor group (weight)	Factor	Weight
Political-Legal (**0.284**)	Political acceptance	**0.477**
	Government support	**0.182**
	Climate agreements	**0.273**
	Value chain ownership	**0.068**
Economic (**0.284**)	Government funding	**0.429**
	Private financing	**0.238**
	OpEx	**0.143**
	CapEx	**0.190**
Social (**0.063**)	Involvement of public	**0.138**
	Social acceptance CCS	**0.763**
	Local job creation	**0.100**
Technical (**0.158**)	Maturity of CCS technology	**0.704**
	Risk mitigation capabilities	**0.185**
	Development of other environmental technologies	**0.111**
Ecologic (**0.105**)	Contribution to CO_2 emission reductions	**0.595**
	Possibility of leaks from geological formations	**0.165**
	Project effect on nearby area	**0.165**
	Significant CO_2 emissions for CCS	**0.076**
Organizational (**0.105**)	Risk sharing in value chain	**0.167**
	Efficient and connected CCS infrastructure	**0.083**
	Collaboration between stakeholders	**0.750**

Table 4.3: Project factors with assigned weights

Figure 4.10 provides a visual presentation on the distribution of the identified impact weights. Both the factor groups and the factor are depicted according to their relative importance to a CCS project.

Figure 4.10: Identified relative importance of factor groups and factors

4.7 CCS Project Maturity Model

The Maturity Table provides a structured framework for assessing the readiness and implementation level of various factors critical to Carbon Capture and Storage (CCS) projects. This table is designed to offer a clear and concise method for evaluating the maturity of CCS projects across multiple dimensions, ensuring a comprehensive understanding of the strengths and areas of improvement of a project.

The table is structured around specific factors, each falling under broader factor groups. These factors have been identified as the key to the successful development and deployment of CCS projects. For each factor, a project can be scored based on three distinct levels of maturity, as seen below:

- **Level 1:** Represents a preliminary stage in which the factor has not been considered or has not been adequately addressed.

- **Level 2:** Indicates that the factor has been acknowledged and there have been efforts towards its implementation, but it has not been fully realized or optimized.
- **Level 3:** Demonstrates a mature approach where the factor has been thoroughly considered and implemented in a robust way.

Table 3.3.5 shows the complete maturity model. All factors and factor groups have weights and the three levels applied to each factor indicate the status of a project regarding that specific factor. In order to apply the maturity table to case studies, the following steps can be followed:

1. Begin by thoroughly reviewing the case study to gather detailed information about the CCS project.
2. For each factor listed in the Maturity Table, assess the project's approach and implementation level.
3. Assign a score (0, 1, or 2 points) based on the level at which the project handled the factors.
4. Sum up the scores, impacted by the weights of the factors and factor groups, to get an overall maturity score for the project. This cumulative score can provide information on the overall readiness and robustness of the CCS project.
5. Compare scores across multiple case studies to identify best practices and areas that require further attention.

By systematically applying the maturity table to case studies, stakeholders can gain a deeper understanding of the current state of CCS projects, identify gaps, and make informed decisions to drive further advancements in the field.

Factor group	Factor	Weight	Level 1 (0 Points)	Level 2 (1 Point)	Level 3 (2 Points)
Political-Legal **(0.284)**	Political acceptance	**0.477**	No evidence of political endorsement or support for the project.	Political entities have shown interest or provided minimal support.	Strong political endorsement, with clear support from major political entities.
	Government support	**0.182**	No government policies, financial support, or initiatives supporting the project.	Limited government support through minor policies or small-scale financial support.	Comprehensive government support through favorable policies, financial support, and initiatives.
	Climate agreements	**0.273**	No alignment with international climate agreements or targets.	Some efforts to align with climate targets but not fully compliant.	Full compliance and active contribution towards international climate agreements and targets.
	Value chain ownership	**0.068**	Unclear ownership structure leading to potential conflicts and inefficiencies.	Partial clarity on ownership with some defined roles and responsibilities.	Clear and transparent ownership structure with defined roles and equitable distribution of responsibilities and benefits.
Economic **(0.284)**	Government funding	**0.429**	No access to government subsidies or financial aid.	Limited government funding or subsidies accessed.	Significant government funding, subsidies, or tax incentives accessed.
	Private financing	**0.238**	No private financing structures in place.	Some private financing secured, but not stable or long-term.	Stable and long-term private financing structures in place.
	OpEx	**0.143**	No detailed projection of operational costs, with potential underestimation of energy consumption costs.	Some projection of operational costs, with a general understanding of energy consumption costs.	Detailed and accurate projection of operational costs, with strategies to reduce energy consumption.
	CapEx	**0.190**	No clear understanding or projection of capital costs.	Basic projection of capital costs without detailed breakdown.	Detailed projection of capital costs with a clear breakdown and strategies for cost optimization.
Social **(0.063)**	Involvement of public	**0.138**	No efforts to involve the public or gather their perspectives.	Minimal public involvement with some efforts to gather feedback.	Active public participation with regular feedback sessions and public awareness campaigns.
	Social acceptance CCS	**0.763**	Negative public perception with no efforts to improve social acceptance.	Neutral public perception with some efforts to improve social acceptance.	Positive public perception with active campaigns promoting the benefits of CCS.
	Local job creation	**0.100**	No focus on local job creation or community benefits.	Some local job opportunities created, but not significant.	Significant local job creation with clear community benefits.
Technical **(0.158)**	Maturity of CCS technology	**0.704**	No clear indication of efforts to innovate applied CCS technology	Some efforts to invest in innovation of applied CCS technologies	Adoption and implementation of the latest, most efficient and proven CCS technologies with continuous efforts to innovate.
	Risk mitigation capabilities	**0.185**	Risk mitigation capabilities of project are in place but not documented and communicated clearly.	Basic risk mitigation strategies in place, with comprehensive documentation and documentation.	Comprehensive risk mitigation strategies, regular reviews, and updates based on project progress and external factors.
	Development of other environmental technologies	**0.111**	No integration or consideration of other environmental technologies.	Some integration of other environmental technologies, but not optimized.	Full integration and optimization of various environmental technologies alongside CCS.
Ecologic **(0.105)**	Contribution to CO_2 emission reductions	**0.595**	Minimal or no significant contribution to CO_2 emission reductions.	Moderate contribution to CO_2 emission reductions.	Significant and measurable contribution to CO_2 emission reductions.
	Possibility of leaks from geological formations	**0.165**	No measures in place to monitor or prevent potential leaks.	Basic monitoring systems in place but not comprehensive.	Advanced monitoring systems in place with proactive measures to prevent potential leaks.
	Project effect on nearby areas	**0.165**	No assessment or mitigation plans for potential negative effects in nearby areas.	Some assessment done with basic mitigation plans.	Comprehensive assessment and robust mitigation plans to ensure minimal negative impact on nearby areas.
	Significant CO_2 emissions for CCS	**0.076**	Limited or inconsistent CO_2 sources available for the CCS network.	Adequate CO_2 sources available but not optimized for maximum efficiency.	Abundant and consistent CO_2 sources available, optimized for the CCS network.
Organizational **(0.105)**	Risk sharing in value chain	**0.167**	No clear risk-sharing agreements or strategies in place.	Basic risk-sharing agreements with some stakeholders.	Comprehensive risk-sharing agreements with all major stakeholders, ensuring an equitable distribution of potential losses.
	Efficient and connected CCS infrastructure	**0.083**	Storage options located far from emission sources, leading to increased transportation costs. There is low availability of usable prior infrastructure.	Storage options close to sources and limited existing infrastructure available for use.	Storage options in close proximity to emission sources with the availability to apply existing infrastructure.
	Collaboration between stakeholders	**0.750**	Minimal collaboration between stakeholders, leading to potential conflicts and inefficiencies.	Moderate collaboration with some structured communication channels.	Strong collaboration between all stakeholders with clear communication channels and aligned objectives.

Table 4.4: Maturity Table

5 Case studies: ROAD & Longship

Now that the most crucial characteristics of CCS projects have been reviewed based on academic literature and expert interviews, the evaluation framework can be applied to several case studies. This chapter will dive deeper into two cases of integrated CCS projects in the North Sea region: Rotterdam Opslag en Afval Demonstratieproject (ROAD) based in the Netherlands and Longship based in Norway. These two projects will be evaluated according to the framework proposed in Chapter 4. However, before proceeding to the evaluation of the projects, an overview of how to apply the framework steps proposed in Chapter 4 is presented in Figure 5.1 .

5.1 Framework steps for users

The framework steps in Figure 5.1 show the steps necessary to perform a detailed analysis of a CCS project using the evaluation framework created in Chapter 4. This figure creates an overview for potential users of the evaluation framework, whether they be stakeholders involved in CCS projects or outside parties wanting to evaluate CCS projects.

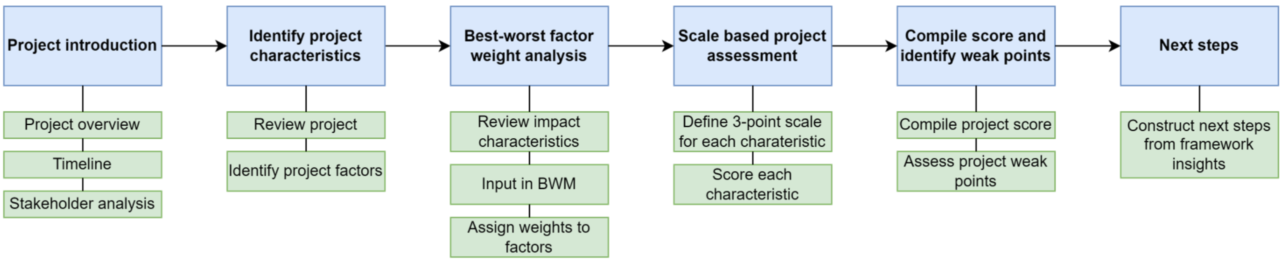

Figure 5.1: Frameworks steps

5.2 Overview selected projects

The projects in this chapter will be evaluated by reviewing the available literature and reports. Table 5.1 provides an initial overview of general information for both projects.

Project	Location	Capacity	Project developers	Status
ROAD	Rotterdam, The Netherlands	1.1 million tonnes per year	Consortium of E.ON (now Uniper) and Electrabel (now Engie Nederland)	Canceled due to lack of economic viability
Longship	Various locations in Norway	Initially 1.5 million tonnes per year, expandable to 5 million tonnes	Partnership between the Norwegian Ministry of Petroleum and Energy and Gassnova (a state-owned enterprise supervised by the Ministry of Petroleum and Energy)	Set to be operational in 2024-2026

Table 5.1: CCS case study projects

The application of case studies in this research is a vital part of the creation of a holistic evaluation framework. A framework based solely on academic literature and expert interviews would lack knowledge based on real-life advancements and dynamics. Adding knowledge based on past and current CCS projects into the development of the framework significantly increases the ability to apply the framework in the future. Future CCS projects would be able to measure and compare their specific circumstances with events that have happened in the past, while also adding knowledge on where things have gone wrong or right in the past. However, it should again be noted that no two projects are the same, and therefore, the framework created in this research should always be tailored to the specific circumstances of a project.

5.3 ROAD

5.3.1 Project introduction

The ROAD project, initiated in 2009, was a collaboration between E.ON and Electrabel (now known as Uniper and Engie Nederland, respectively). Its primary objective was to demonstrate CO_2 capture from industrial units in the Rotterdam harbor and subsequently transport it for offshore storage in the North Sea. By 2010, the project had successfully secured a substantial €180 million in funding from the European Commission's EEPR.

Despite a promising start, the project faced multiple challenges (Global CCS Institute, 2018c; Read et al., 2019). According to various reports (Date, 2013; Global CCS Insitute, 2011; Henry et al., 2011; Read and Toonssen, 2018) Preliminary studies, assessments, and planning were conducted in 2011, leading to the submission of permit applications to the Dutch authorities. By 2012, the necessary permits were granted, allowing the project to progress. However, by 2013, uncertainties regarding the economic viability of the project led to the postponement of the final investment decision. This decision was further delayed in 2016 as the consortium awaited clarity on regulatory and policy changes. The estimated cost of the project was around €200 million, covering investments in CCS technology, pipeline construction, and offshore engineering (Global CCS Institute, 2018b). However, in 2017, the project was officially canceled. The primary reasons cited were the increasing challenges related to economic viability, technical complexities, and regulatory changes. Although the Dutch government had previously extended funding through its Energy Research and Development program, the consortium felt that it was insufficient to offset the project's expenses (Global CCS Institute, 2018c; Read et al., 2019).

The termination of the ROAD project marked a significant impediment to the advancement of CCS technology in the Netherlands. It was perceived as a pivotal demonstration project that could have validated the technology's feasibility in the region. However, lessons learned from the ROAD CCS project have supported the development of later CCS project, like the earlier discussed Porthos project that is currently in development in the Port of Rotterdam. The pursuit of CCS projects continues both in the Netherlands and globally, as nations strive to decrease their carbon footprints and achieve their environmental objectives.

Project timeline

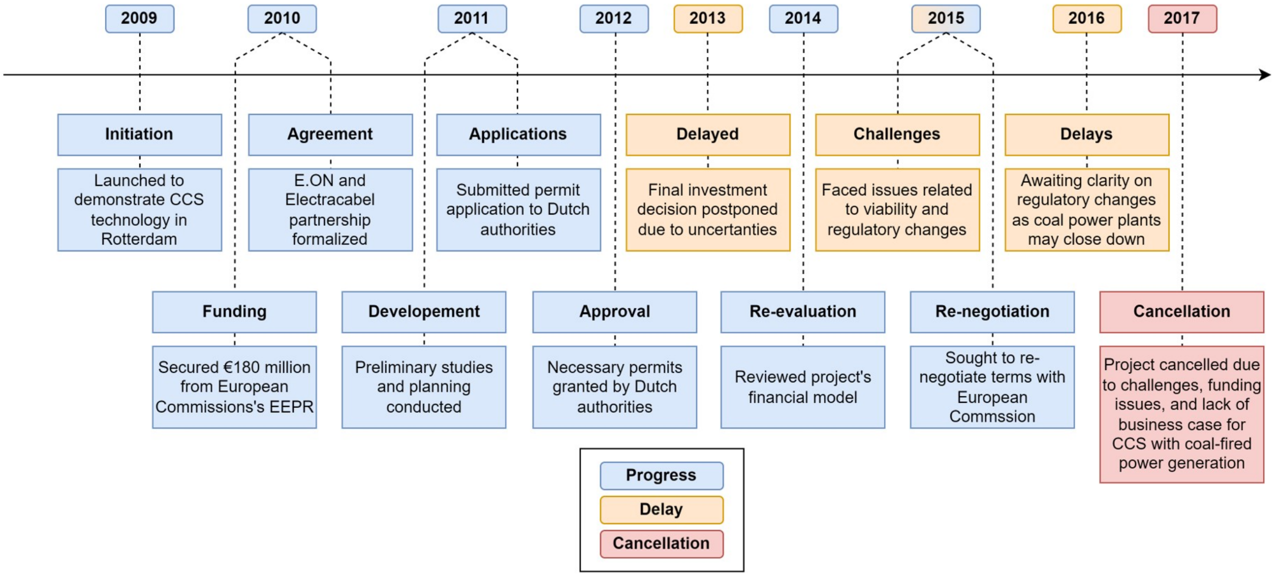

Figure 5.2: Timeline ROAD project

Power Interest grid

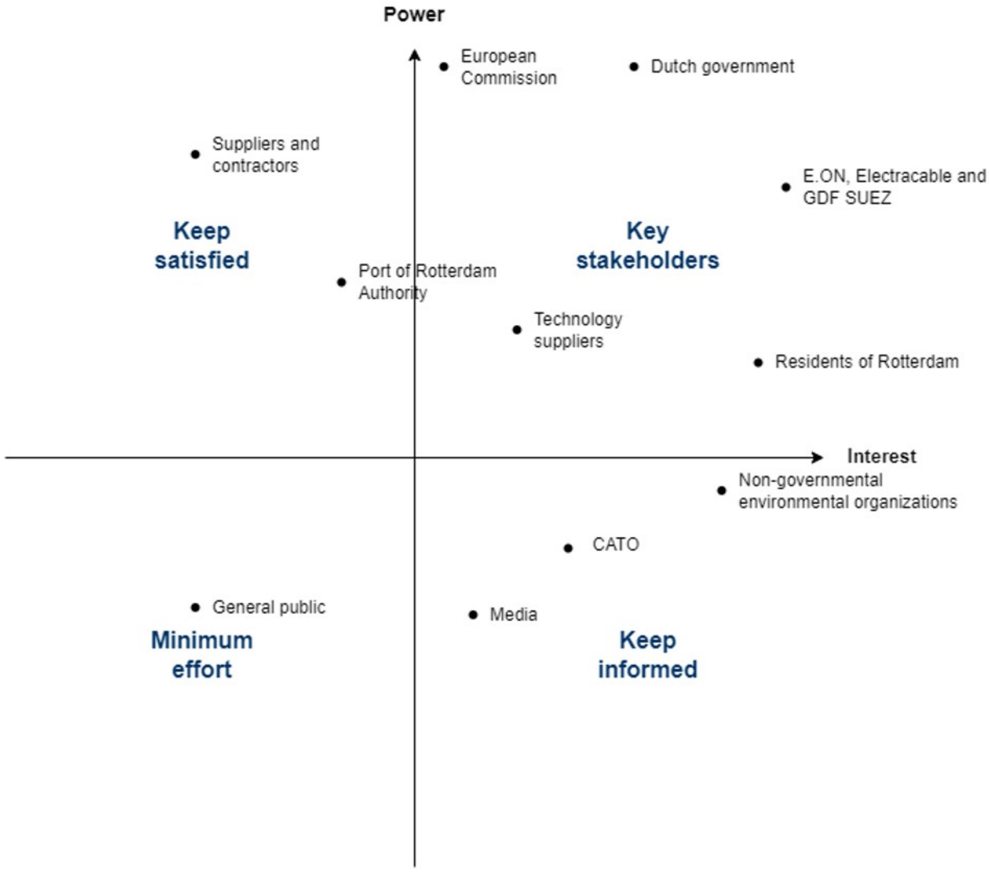

Figure 5.3: Power-Interest grid ROAD project

- **Key stakeholders:** The European Commission, the Dutch Government, and the consortium of E.ON (now Uniper) and Electrabel (now Engie Nederland) formed the heart of the project's dynamics. The consortium, as the driving force, was responsible for the project's management and execution (Kombrink and Jonker, 2011). The European Commission provided substantial funding through the European Energy Programme for Recovery (EEPR), underlining its interest in advancing CCS technology (Read and Toonssen, 2018). The Dutch Government offered both financial support and regulatory backing, aligning with its commitment to reducing carbon emissions and pioneering CCS in the country. Residents of Rotterdam (location of the selected industry for the ROAD project) are a crucial group to consider, as they are directly involved in the application of CCS in their city. As discussed, the lack of social acceptance could form a big obstacle for the continuation of CCS projects. Technology suppliers are also essential in the process of establishing the CCS value chain, adding knowledge and experience to the project.
- **Keep satisfied:** The Port of Rotterdam Authority saw potential economic benefits and global recognition in Rotterdam becoming a hub for CCS technology (Global CCS Institute, 2018c). Suppliers and contractors, critical to the project execution, were essential in ensuring the technical feasibility of the CCS process. By keeping local communities, including the residents of Rotterdam and the Port of Rotterdam Authority, engaged and addressing their environmental and economic concerns, the project could have secured the much-needed social acceptance and support.
- **Keep informed:** Environmental NGOs and the media were interested in staying informed. Local residents were concerned about environmental impacts, potential job opportunities, and disruptions (Kombrink and Jonker, 2011). The environmental organizations aimed to ensure a balanced assessment of both the project's positive carbon reduction effects and its potential risks (Read et al., 2019). Media, acting as a medium between stakeholders, the public, and project developers, maintained an open dialogue by relaying project information. Also, the CCS research and development institute CATO is an actor to keep informed. The consortium of approximately 40 partners provided knowledge and support for the project.
- **Minimum effort:** The general public, although not actively involved in the development of the project, is still included in the PI grid as they could potentially play a pivotal role. This is because the social acceptance of CCS projects is always something to consider, as it could potentially harm the project's progress when large groups or communities are not accepting of the development of a CCS project. In the case of the ROAD project, Rotterdam residents are identified as separate actors from the general public, as they are more directly affected by the project, whether it be positive or negative. The general public (generally other inhabitants of the Netherlands) are less involved and therefore in this quadrant of the PI-grid.

5.3.2 ROAD project factors

Factor Group	Sources	Key Characteristics
Political-legal	Akerboom et al. (2021); Kombrink and Jonker (2011); MIT (2016); Read et al. (2014)	• ROAD project funding from the Dutch government and political support for CCS technology development • Compliance with Dutch and EU environmental regulations for CO_2 emissions and offshore carbon storage • ROAD project to be an example for future CCS projects • Project director Andy Read states the project is getting "mothballed." While no further funding was granted, the project eventually came to a stop in 2017 after primary stakeholders Uniper and Engie left the project due to the lack of economic viability
Economic	Global CCS Institute (2018b,c); MIT (2016); Read et al. (2019); Read and Toonssen (2018)	• Estimated project cost: €1.2 billion (estimated €400 million CapEx and €45 million yearly OpEx) • Financial viability challenges without enough government subsidies or incentives due to high cost of CCS technologies • €180M EU funding from European Energy Programme for Recovery • €150M funding by the Dutch government
Social	Global CCS Institute (2018c); Kombrink and Jonker (2011); Read et al. (2019)	• Potential for local job creation and economic benefits • Management team brought to life that handle public engagement • Addressing concerns of local communities regarding offshore carbon storage risks
Technical	Arts et al. (2012); Carbon Capture Journal (2014); Date (2013); Global CCS Insitute (2011)	• Use of carbon capture technology for capturing and transporting CO_2 via pipelines to an offshore storage site in the North Sea • Capture CO_2 from E.ON coal power plant • Utilization of proven technology for safe and secure long-term CO_2 storage in offshore sites • Partnership with CO_2 Capture, Transport, and Storage (CATO) program • Engineering studies completed in 2014
Ecological	Carbon Capture Journal (2014); MIT (2016); Read et al. (2014); Steeghs and Mikunda (2014); Steyn et al. (2022)	• Capture of CO_2 from Rotterdam harbor area industrial facilities and transport to offshore storage sites in the North Sea • Significant reduction of carbon emissions from oil refining and power generation industries (1.1Mt CO_2/year • Risk management plan in place • Careful selection and monitoring of offshore storage sites to prevent negative impact on the marine environment
Organizational	Bijkerk (2012); Global CCS Institute (2018c); Kombrink and Jonker (2011); Read and Toonssen (2018)	• Consortium by energy companies E.ON, Electrocable, and GDF SUEZ called Maasvlakte CCS project • Collaboration among industrial companies, the Dutch government, and offshore carbon storage providers for the ROAD project • Research backing by Global CCS Institute • Partnerships with CATO and TNO for research purposes

Table 5.2: ROAD project characteristics

Drivers	
Government support	The Dutch government's financial and regulatory support was a significant driver, emphasizing its commitment to pioneering CCS technology in the Netherlands.
European funding	The European Commission's funding through the European Energy Programme for Recovery (EEPR) provided substantial financial backing, indicating strong European support for CCS initiatives.
Environmental goals	The global push towards reducing carbon emissions and combating climate change served as a driving force for the project.
Technological innovation	The ROAD project represented an opportunity to showcase CCS technology on a commercial scale, potentially setting a precedent for future projects in Europe and globally.
Economic potential	The successful implementation of the ROAD project could have positioned Rotterdam as a hub for CCS technology, attracting further investments and projects to the region.
Barriers	
Economic viability	The changing economic landscape, especially the low price of CO_2, made the project less financially attractive.
Technical challenges	As with any pioneering technology, there were uncertainties and risks associated with the capture, transport, and storage of CO_2.
Changes in energy market	The rapid evolution of the energy landscape, with an increasing emphasis on renewable energy sources, might have made the CCS approach less attractive in comparison.
Regulatory and policy changes	Fluctuations in government policies and regulatory frameworks can impact the feasibility and attractiveness of projects like ROAD.
Public perception	Potential concerns from the public about the safety and environmental impact of storing CO_2 underground could have posed challenges to the acceptance and progress of the project.

Table 5.3: Drivers and Barriers for the ROAD Project

5.3.3 Maturity model

With enough information on the ROAD CCS project, the maturity model provided in 4.7 can be used to score the project. Each factor has been given a score on the following scale:

- **Level 1:** Represents a preliminary stage in which the factor has not been implemented/considered or has not been adequately addressed.
- **Level 2:** Indicates that the factor has been acknowledged and that there have been efforts toward its implementation/consideration, but it has not been fully realized or optimized.
- **Level 3:** Demonstrates a mature approach where the factor has been thoroughly considered and implemented/considered in a robust way.

Factor group	Factor	Weight	Level 1 (0 Points)	Level 2 (1 Point)	Level 3 (2 Points)	Score
Political-Legal **(0.284)**	Political acceptance	**0.477**		The project received initial endorsement from the Dutch political field. This changed when the project did not seem economically viable over time.		**0.136**
	Government support	**0.182**		The Dutch government's involvement and funding state some of the support. However, not enough funding (public or private) was provided to continue the project.		**0.052**
	Climate agreements	**0.273**			The project's aim aligns with climate targets. The project was supposed to be a demonstration for the CCS technology, adding to the knowledge for CO_2 emission reduction.	**0.155**
	Value chain ownership	**0.068**			The project involves multiple major entities, suggesting a clear ownership structure with defined roles and responsibilities.	**0.039**
Economic **(0.284)**	Government funding	**0.429**		The funding of the Dutch Government and the European Commission totaled €330 million. This is a significant amount, however, not enough to ensure the continuance of the project together with the private funding.		**0.122**
	Private financing	**0.238**	The project's parent parties contributed around €100 million to the project. The lack in economic viability was due to several elements, including the lack of funding for a project of this magnitude.			**0**
	OpEx	**0.143**		Yearly Opex of the project was anticipated at €45 million. As CCS projects tend to be active for a long time to be effective, this could pose funding problems in the future.		**0.041**
	CapEx	**0.190**		CapEx of the project was anticipated on €400 million. High investment costs create difficulties for CCS projects to get to the operational phase.		**0.054**
Social **(0.063)**	Involvement of public	**0.138**			The ROAD project, together with partners such as the Global CCS Institute, made sure the actively involve the public in project advancements	**0.017**
	Social acceptance CCS	**0.763**		Although the public involvement was optimal, acceptance was low as CCS could be seen as a temporal solution		**0.048**
	Local job creation	**0.100**		This was not a specific selling point of the project. However, the Port of Rotterdam mentions the local benefits of the project.		**0.006**

Factor group	Factor	Weight	Level 1 (0 Points)	Level 2 (1 Point)	Level 3 (2 Points)	Score
Technical **(0.158)**	Maturity of CCS technology	**0.704**		The project was meant to provide a demonstration of the CCS technology, but did not manage to do so.		**0.111**
	Risk mitigation capabilities	**0.185**			FEED studies showed that the project was well analyzed and risk measures were in place.	**0.058**
	Development of other environmental technologies	**0.111**		It was questioned whether investing in other renewable solutions for CO_2 emission reduction would be a better option.		**0.017**
Ecologic **(0.105)**	Contribution to CO_2 emission reductions	**0.595**			The project aims to reduce CO_2 emissions and act as a first demonstrative CCS initiative in the Netherlands.	**0.125**
	Possibility of leaks from geological formations	**0.165**			Detailed mapping of the geological formations in the North-Sea provided optimal insights into leak prevention.	**0.035**
	Project effect on nearby areas	**0.165**		Project's effect on nature and people was questioned by local communities. However, the location of industry CO_2 sources and storage facilities were well thought out.		**0.017**
	Significant CO_2 emissions for CCS	**0.076**		Sources of CO_2 were selected. However, the CCS network would likely be affected by private investors.		**0.008**
Organizational **(0.105)**	Risk sharing in the value chain	**0.167**		The project was a joint venture with initial government backing. (Economic) Risks were deemed to high for project continuance.		**0.018**
	Efficient and connected CCS infrastructure	**0.083**			The project aimed to transport CO_2 for offshore storage in the North Sea, whose geology was mapped and investigated to a large extent.	**0.017**
	Collaboration between stakeholders	**0.750**			The project was a collaboration between major entities, the Dutch government, and offshore carbon storage providers, indicating strong collaboration between stakeholders.	**0.158**
						1.234

Table 5.5: Maturity Table ROAD project (Part 2)

5.3.4 Results and recommendations

Results from the Maturity Table

The evaluation of the ROAD project using the maturity table yielded a score of 1.234 out of a possible 2. This score indicates that while the project had a moderate level of maturity, there were areas where it could have been improved to ensure a higher likelihood of success. Figure 5.4 shows a visual presentation of the results of the maturity table. This representation is based on the score map proposed by Wagire et al. (2021) and has taken design inspiration from a thesis by Dimitriou (2023).

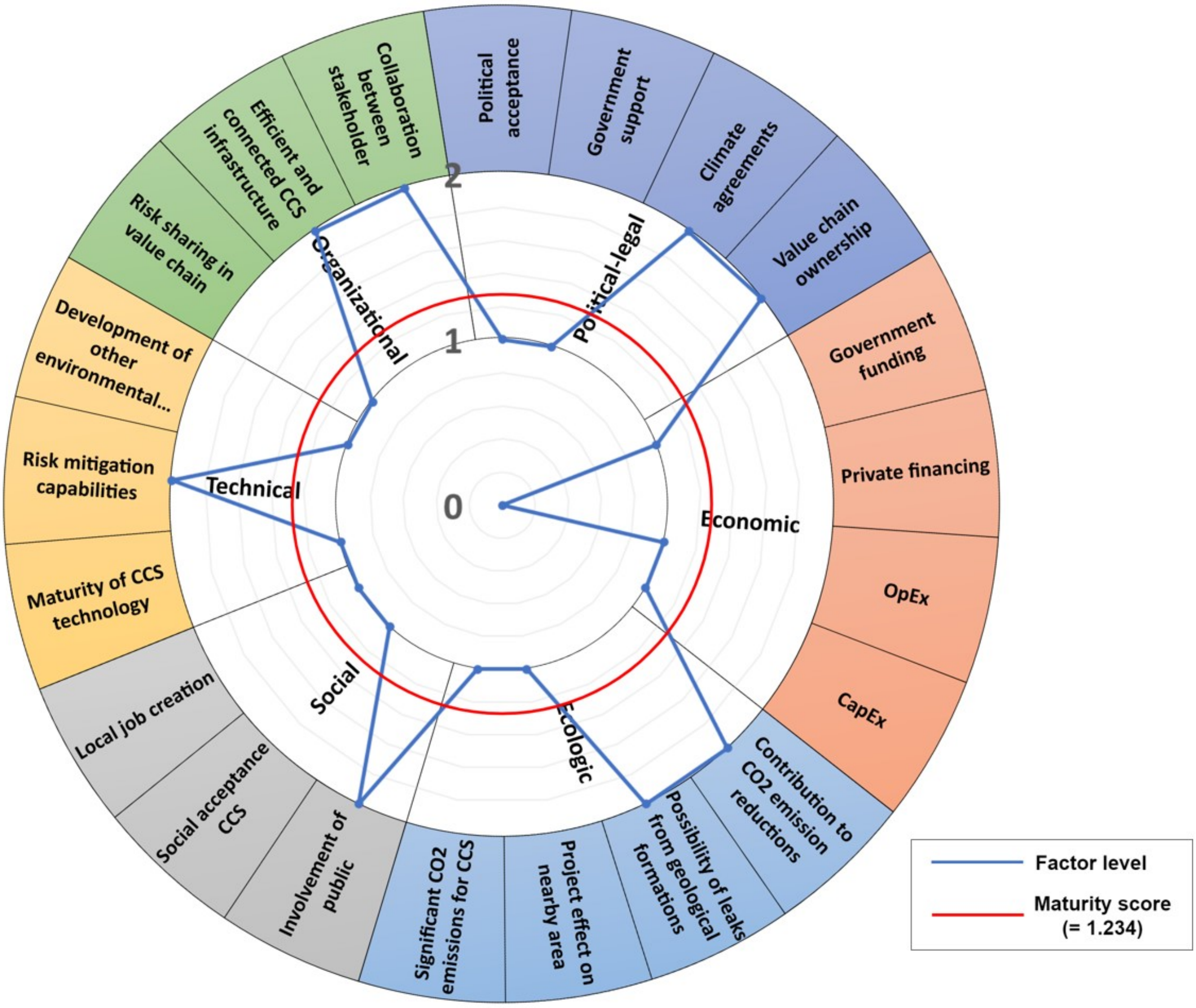

Figure 5.4: Maturity score map ROAD project

The figure provides an easy overview of the project's maturity score and the level each factor achieved in the maturity table. From this figure, some things immediately stand out. First, the maturity score. With a score of 1.234 out of 2, the ROAD project could have performed better on all fronts. This score reflects the fact that the project never reached an operational state. However, the maturity score is still not as low as one would expect for a canceled project. This could be explained by the variety of factors that were considered and implemented thoroughly in the ROAD project despite its eventual cancellation. The second thing that stands out is the low overall score of the economic factors. Even with the project scoring relatively high on the other dimensions, overcoming the economic challenges would see the project eventually come to a halt.

Discussion of the Results

The ROAD project's score indicates that it had a reasonable foundation in several areas, but there were significant opportunities for improvement. In particular, the economic factor group stands out as an area that could have been better addressed. Economic viability is crucial for the success of any large-scale project and, for CCS projects, it becomes even more critical given the high capital and operational costs involved.

Limited access to stable and long-term private financing, combined with uncertainties in government funding, could have posed challenges. CCS projects are long-term projects. Making sure that the financial situation of a project is secured over the whole potential timeline of a project is essential. Keeping in mind that projects will always face unforeseen challenges while developing, a network of public and private stakeholders can make sure to divert from cancelation when these challenges arise.

Recommendations ROAD project and future CCS initiatives

1. **Secure stable financing:** Projects should prioritize securing long-term and stable financing, both from private and public sources. Detailed studies on project costs (OpEx and CapEx) connected to a strong financial foundation ensured by the involved parties are crucial in the preliminary stages of project development. This ensures that the project can weather economic downturns and other unforeseen challenges.
2. **Engage stakeholders early:** Early engagement with all stakeholders, including the public, can help to understand potential challenges and proactively address them.
3. **Change management:** CCS projects can always be subject to rigorous changes of any kind. In the case of the ROAD project, regulatory changes surrounding the application of CCS to coal-fired power plants led to the decline of the economic viability of the project. Although some challenges prove to be insurmountable, being able to act upon these kinds of change through, for example, stakeholder collaboration and clear communication significantly strengthens the resilience of a project.

In conclusion, while the ROAD project had its challenges, the insights gained from its evaluation using the maturity framework can serve as valuable lessons for future CCS initiatives. By addressing the identified gaps and leveraging the framework's systematic approach, future projects can increase their chances of success and make meaningful contributions to CCS efforts globally. The ROAD CCS project serves as a notable case study that highlights the intricate interaction between stakeholders, market dynamics, and technology. Although the project was canceled, it contributed to a greater understanding of the implementation of CCS technology, addressing challenges, and aligning stakeholder interests.

5.4 Longship

5.4.1 Project introduction

The Longship CCS project, initiated in the early 2000s with Norway's growing interest in CCS, is a partnership between the Norwegian Ministry of Petroleum and Energy and Gassnova (a state-owned enterprise supervised by the Ministry of Petroleum and Energy). Gassnova was established in 2005 by the Norwegian government with the primary objective of acquiring knowledge and advancing the development of CCS technologies (Equinor, 2019). Longship is a full-scale CCS project that, as of 2020, has received full backing from the Norwegian government (CCSNorway, 2020).

Although Longship oversees the entire CCS value chain, the Northern Lights project, officially launched in 2019, is responsible for the transportation and storage of CO_2 and is an integral part of the Longship project (Northern Lights, 2023). Northern Lights is a joint venture between Equinor, Shell, and Total. The carbon capture segment of the project involves the construction of a new carbon capture plant at a cement factory owned by Heidelberg Materials (a Norwegian cement manufacturer, formerly Norcem) in Brevik, Norway. This initiative was solidified between 2016 and 2017 when Norcem's cement factory in Brevik and Hafslund Oslo Celsio (a Nordic energy company, formerly Fortum Oslo Varme) waste-to-energy plant were selected as the primary capture sites. The captured CO_2 will then be transported by ship to an onshore terminal at Øygarden near Bergen, from where it will be piped to offshore storage sites in the North Sea.

The Longship project stands out as the first open-source CCS project where third parties can supply their CO_2 (CLIMIT, 2022). Although the project, including Northern Lights, is structured as a public-private partnership (PPP), its design distinctly differentiates it from the ROAD project. The project has received support not only from the Norwegian government, but also from the European Union. It is anticipated to capture and store up to 5 million tonnes of CO_2 annually once fully operational (Gassnova, 2020). Furthermore, project partners have unveiled plans to provide CCS services to other European companies, aiding them in carbon emission reduction.

Currently, the Longship CCS project is in its development phase, as of 2021. The carbon capture plant and the onshore terminal are projected to be operational by 2024 (CCSNorway, 2021). The offshore storage site is expected to commence operations in 2026. The project partners remain steadfast in their belief that CCS technology is pivotal in reducing global carbon emissions and achieving climate goals. They are ardently committed to the further development and deployment of this technology.

Project timeline

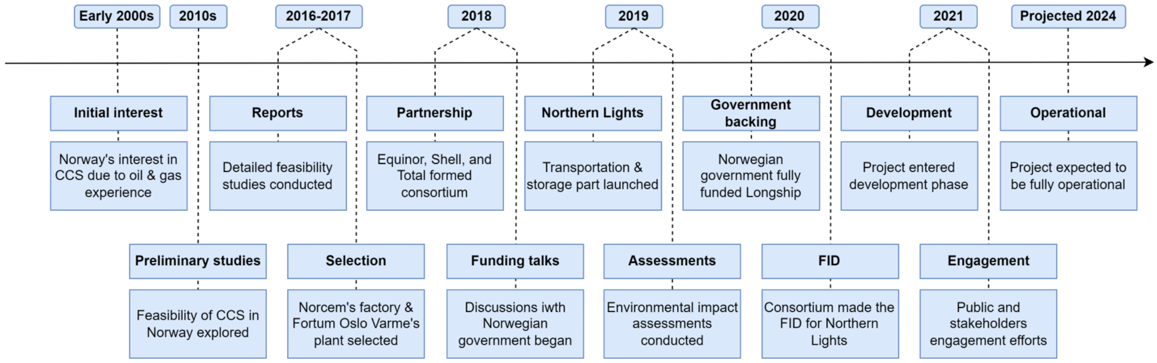

Figure 5.5: Timeline Longship project

Power Interest grid

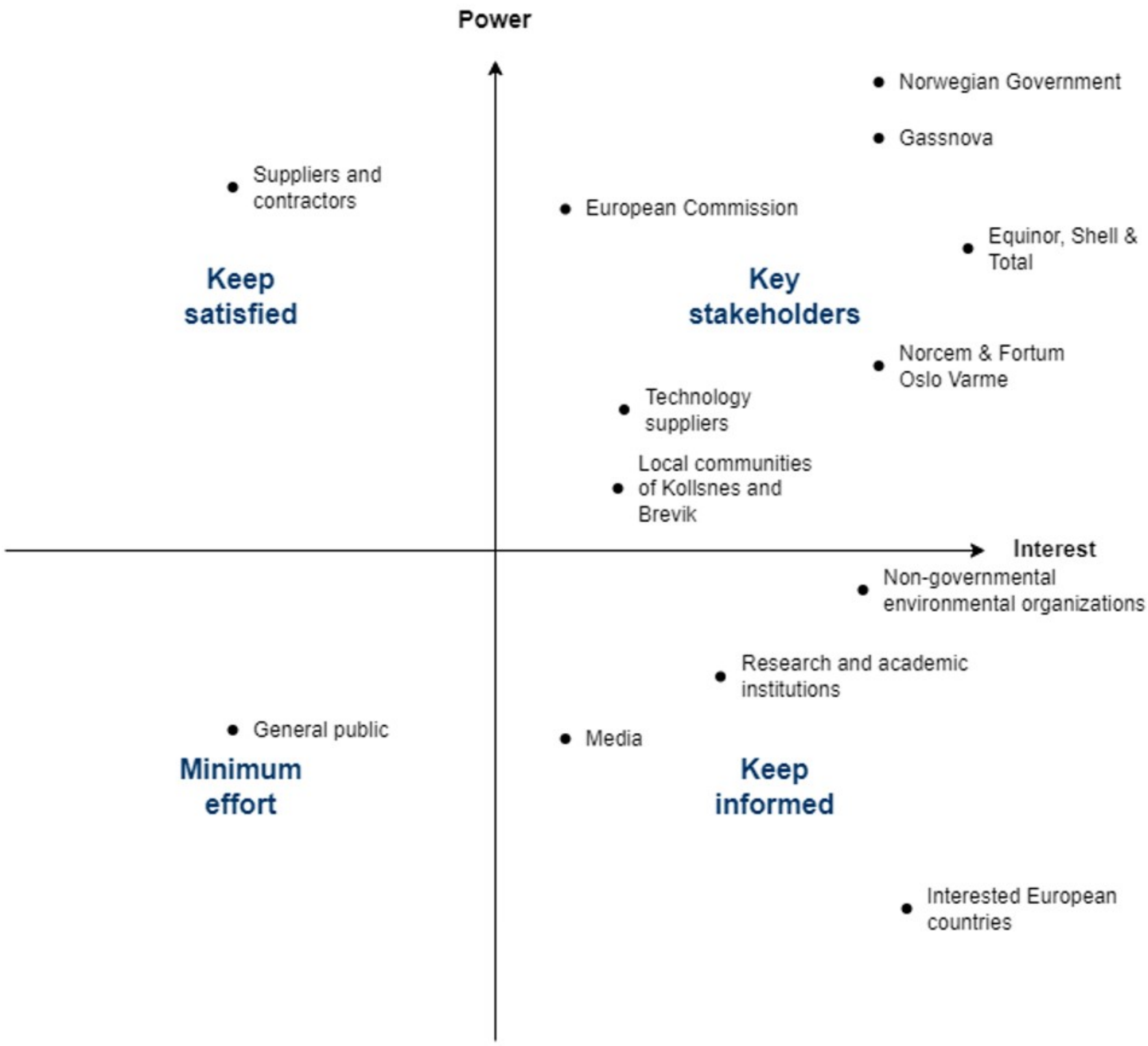

Figure 5.6: Power-Interest grid Longship project

- **Key Stakeholders:** The Longship CCS project is orchestrated by the Norwegian government, exemplifying its commitment to carbon reduction. Equinor, Shell, and Total constitute the consortium responsible for the Northern Lights project, a cornerstone of Longship, managing CO_2 transportation and storage. In particular, Norcem (HeidelbergCement) and Fortum Oslo Varme are pivotal in the capture phase. The local communities of Kollsnes and Brevik, vital players in the immediate surroundings of the project, are kept informed to address potential environmental, economic, and social concerns. In the case of Longship, technology suppliers are of great importance. The project infrastructure is large as the different elements of the value chain are spread among multiple locations. Technology suppliers are crucial for the implementation of different technologies across the value chain.

- **Keep Satisfied:** Suppliers and contractors play an instrumental role in the technical aspects of the project and the execution of the project. These stakeholders must be satisfied to ensure the seamless execution of the complex CCS value chain.

- **Keep Informed:** Non-governmental environmental organizations, research institutions, and media maintain an informed stance, monitor environmental impact, and communicate information to the public. These three actors do not play a critical role in the development of the Longship project, but should be considered nonetheless. By maintaining a close bond with NGOs and research institutions, the effects of knowledge sharing can speed up the implementation of the project. The media could be used as a medium to inform the general public and local communities.

- **Minimum Effort:** The general public, representing potential beneficiaries and concerned citizens, contributes minimal influence, but remains aware of the environmental implications of the project. This actor group could be kept up to date through the reports or media outputs.

5.4.2 Longship project factors

Factor Group	Sources	Key Characteristics
Political-legal	CCSNorway (2021); Equinor (2019); Norwegian Ministry of Petroleum and Energy (2019)	• Initiative of the Norwegian government • Partnered by Equinor and Shell for Northern Lights project (transportation and storage of Longship) • Longship is Project of Common Interest (PCI) • The London Protocol poses challenges. The protocol outlines monitoring and safety measures for the transnational export and storage of CO_2
Economic	CCSNorway (2020); Government.no (2020); Helgesen et al. (2021)	• Due to the modular nature of the Longship CCS network, project costs are hard to estimate. The projected cost is around €2.5 billion • For 2/3 funded by the Norwegian government • Commercially challenging due to high investment costs of CCS technologies • Potential for local job creation during construction and operation • Reliance on future third-party collaboration and funding if the network is to be expanded
Social	Gassnova (2020, 2021); Government.no (2020)	• Potential for local job creation and economic benefits • Longship first commercial open source project. Global example for future CCS projects.
Technical	CCSNorway (2021); Equinor (2019); Helgesen et al. (2021)	• Transport and storage regulated by subsidiary project Northern Lights • Capture of CO_2 is the responsibility of the emitting facilities • Aim to story 1.5 - 5 Mt CO_2 per year • Aim to be operational in 2024
Ecological	CCSNorway (2021); Gassnova (2020); Gruben and Macdonald (2022)	• Aim to provide a CCS network for international third parties, adding to the amount of CO_2 that can be stored through their infrastructure • Project sets a global example for future CCS projects • Goal to expand CCS network beyond 5Mt CO_2/year storage
Organizational	CCSNorway (2021); Equinor (2019); Reyes-Lúa et al. (2021)	• Collaboration between the Norwegian government, Equinor, Shell, and offshore carbon storage providers • Divide management and risk through the unbundling of value chain components • Organizational challenges in managing technology complexity and stakeholder collaboration • Open to collaboration from third-party (international) projects. Swedish Preem project to be added to Longship network

Table 5.6: Longship projects characteristics

Drivers	
Government support	The Norwegian government's strong financial and regulatory backing has been pivotal in propelling the project forward.
Industry collaboration	The partnership with major energy companies brings in technical expertise, resources, and a shared vision for the project's success.
Strategic importance	Norway's existing infrastructure in the North Sea and its experience in the oil and gas sector provide a strategic advantage.
Environmental commitment	Norway's dedication to meeting international climate targets and its broader environmental sustainability goals drive the emphasis on CCS projects such as Longship.
Barriers	
Technical challenges	As with any pioneering technology, there are uncertainties and risks associated with the capture, transport, and storage of CO_2.
Economic viability	The changing global economic landscape, including fluctuating energy prices, can impact the long-term financial sustainability of the project.
Public perception	While there is a generally positive outlook, any potential environmental risks associated with CCS can lead to public skepticism or opposition.
Regulatory changes	Even with current support, future changes in government or regulatory policies can pose challenges.

Table 5.7: Drivers and Barriers for Longship project

5.4.3 Maturity model

Now just as with the ROAD project, enough information has been gathered on the Longship CCS project to begin filling in the maturity model provided in 4.7. Each factor has been given a score on the following scale:

- **Level 1:** Represents a preliminary stage in which the factor has not been implemented/considered or has not been adequately addressed.
- **Level 2:** Indicates that the factor has been acknowledged and that there have been efforts toward its implementation/consideration, but it has not been fully realized or optimized.
- **Level 3:** Demonstrates a mature approach where the factor has been thoroughly considered and implemented/considered in a robust way.

Factor group	Factor	Weight	Level 1 (0 Points)	Level 2 (1 Point)	Level 3 (2 Points)	Score
Political-Legal **(0.284)**	Political acceptance	**0.477**			The project is an initiative of the Norwegian government and has received backing from the European Union, indicating strong political acceptance and support.	**0.271**
	Government support	**0.182**			The Norwegian government's strong financial and regulatory backing, as well as the project being a "Project of Common Interest" by the EU, showcases robust government support.	**0.103**
	Climate agreements	**0.273**			Norway's dedication to meeting international climate targets and its broader environmental sustainability goals drive the emphasis on CCS projects like Longship.	**0.155**
	Value chain ownership	**0.068**			The project is a collaboration between major entities like Equinor, Shell, and Total, indicating clear ownership and defined roles.	**0.039**
Economic **(0.284)**	Government funding	**0.429**			The project is funded 2/3 by the Norwegian government, indicating strong financial support.	**0.244**
	Private financing	**0.238**			Although the project is describes as "commercially challenging" due to high investment costs, collaboration with major energy companies provide a significant amount of private financing	**0.135**
	OpEx	**0.143**		The modular nature makes exact operational costs hard to estimate, but there's a clear projection of the project's financial needs.		**0.041**
	CapEx	**0.190**		The projected cost is around €2.5 billion, but the modular nature of the project makes exact capital costs hard to determine.		**0.054**
Social **(0.063)**	Involvement of public	**0.138**			The project aims to be an open-source CCS project, allowing third parties to supply their CO_2, indicating a high level of public participation and collaboration.	**0.017**
	Social acceptance CCS	**0.763**			While the project has potential for local job creation and economic benefits, public perception and potential environmental risks can lead to skepticism.	**0.096**
	Local job creation	**0.100**			The project promises local job creation during both construction and operation phases, indicating significant local economic benefits.	**0.013**

Table 5.8: Maturity Table Longship project (Part 1)

Factor group	Factor	Weight	Level 1 (0 Points)	Level 2 (1 Point)	Level 3 (2 Points)	Score
Technical **(0.158)**	Maturity of CCS technology	**0.704**			The project has clear plans for capture, transport, and storage of CO_2, with the aim to store 1.5 - 5 Mt CO_2 per year, showcasing advanced technical planning.	**0.222**
	Risk mitigation capabilities	**0.185**		While there's a partnership with major energy companies, there are uncertainties and risks associated with the pioneering technology.		**0.029**
	Development of other environmental technologies	**0.111**			The project's design allows for the integration of other environmental technologies, indicating a forward-thinking approach.	**0.035**
Ecologic **(0.105)**	Contribution to CO_2 emission reductions	**0.595**			The project aims to capture and store up to 5 million tonnes of CO_2 annually, indicating a significant contribution to emission reductions.	**0.125**
	Possibility of leaks from geological formations	**0.165**			The project's design and partnership with experienced energy companies suggest advanced monitoring systems to prevent potential leaks.	**0.035**
	Project effect on nearby areas	**0.165**			The project's comprehensive assessment and robust mitigation plans ensure minimal negative impact on nearby areas.	**0.035**
	Significant CO_2 emissions for CCS	**0.076**			The project's open-source design allows third parties to supply their CO_2, indicating a consistent source for the CCS network.	**0.016**
Organizational **(0.105)**	Risk sharing in value chain	**0.167**			The project divides management and risk through the unbundling of value chain components, indicating a well-structured organizational strategy. Industry emitters are responsible for capturing their own CO_2.	**0.035**
	Efficient and connected CCS infrastructure	**0.083**			The captured CO_2 is transported to an onshore terminal and then piped to offshore storage sites in the North Sea, indicating optimized storage options and connectivity. Multiple transportation methods are applied (shipment and pipeline).	**0.017**
	Collaboration between stakeholders	**0.750**			The project involves collaboration between the Norwegian government, major energy companies and offshore carbon storage providers, demonstrating strong collaboration between stakeholders.	**0.158**
						1.875

Table 5.9: Maturity Table Longship project (Part 2)

5.4.4 Results and recommendations

Results from the Maturity Table

The evaluation of the Longship project using the maturity table yielded a score of 1.875 out of a possible 2. This score indicates that the project has a high level of maturity, especially compared to the ROAD project. However, there are still areas where improvements can be made. Figure 5.7 shows a visual presentation of the results of the maturity table. This representation is based on the score map proposed by Wagire et al. (2021) and has taken design inspiration from a thesis by Dimitriou (2023).

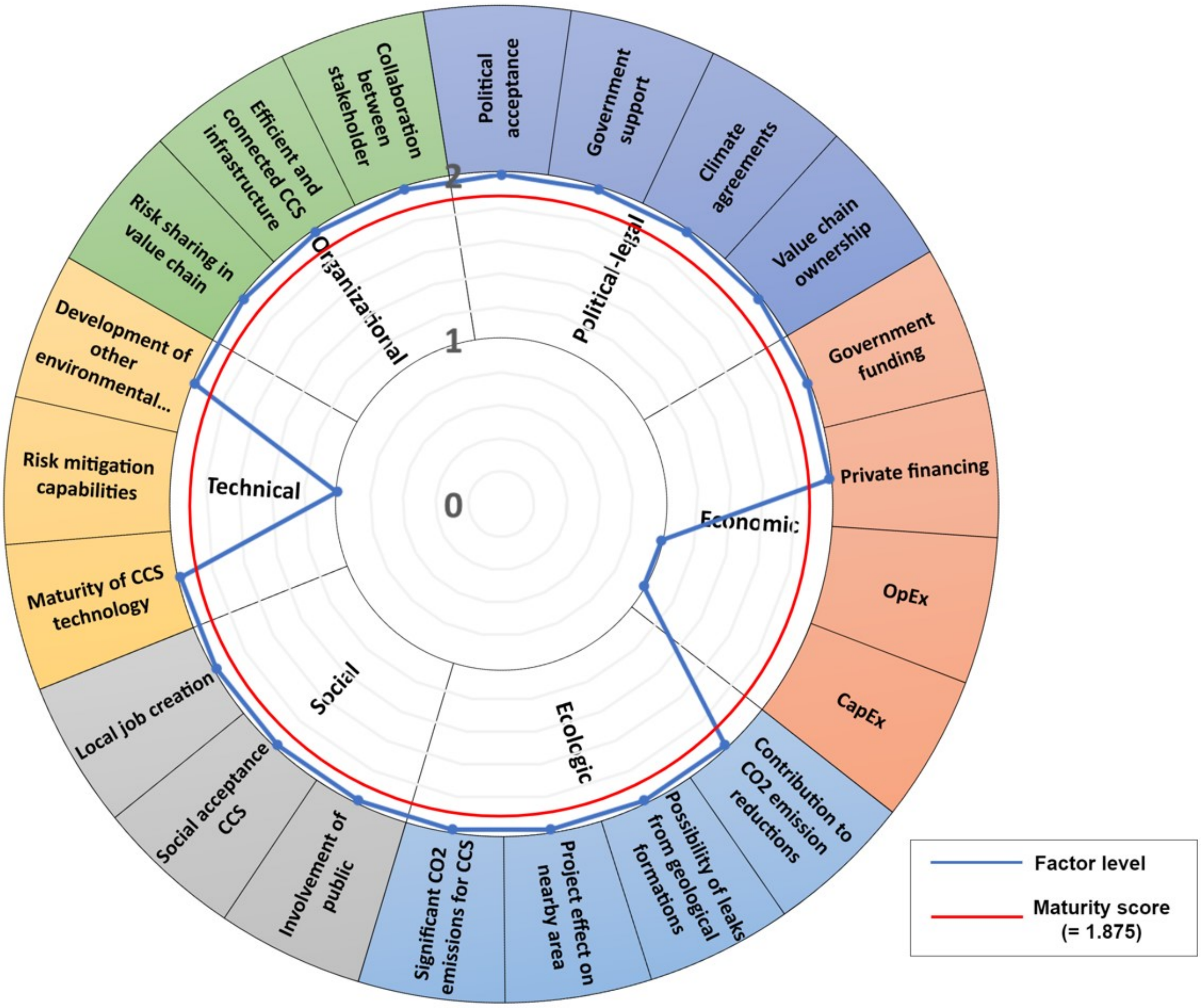

Figure 5.7: Maturity score map Longship project

The figure offers a succinct overview of the project's maturity score and the level each factor achieved in the maturity table. With a maturity score of 1.875 out of 2, the Longship project has made significant strides in its planning and execution. This score mirrors the project's ambitious goals and the comprehensive support it has garnered from both the Norwegian government and the European Union.

Discussion of the results

The Longship project score suggests that it has been well-conceived and executed in many areas, particularly in terms of political-legal support and technical planning. Strong backing from the Norwegian government and collaboration with major energy companies such as Equinor, Shell, and Total have been instrumental in its success. The project's public-private partnership structure, combined with its open-source approach, sets it apart. This unique configuration can offer advantages in terms of resource pooling and knowledge sharing, but also presents challenges in terms of alignment and decision-making. However, the economic factor group stands out as an area that could be further improved. The modular nature of the project makes exact costs difficult to determine, and while there is significant government funding, the project is described as "commercially challenging" due to the high investment costs of CCS technologies.

It should be noted that the Longship project consistently scores a level 2 across nearly all identified factors in the maturity table. This consistent score brings to light a potential limitation of the 3-point scale used in the maturity table. Although the scale provides a broad overview of a project's maturity, it might lack the granularity needed to capture the nuanced differences between various factors. A project as complex and multifaceted as Longship could benefit from a more detailed scale, allowing for a finer differentiation between the maturity levels of different factors. Expanding the scale could offer a more precise representation, helping stakeholders identify even minor areas of improvement, and ensuring a more comprehensive evaluation. Because of this limitation, it is difficult to propose definitive recommendations based on the project's maturity score and map. Therefore, the recommendations in the following could be seen as potential steps to expand the success of the Longship project in the future.

Recommendations for Longship and future CCS initiatives

1. **Financial overview:** Given the expansive nature and future ambitions of the Longship project, it's imperative to maintain a rigorous overview of all associated costs. As the project evolves and plans expand, unforeseen expenses can emerge, potentially impacting the overall budget and financial feasibility.

2. **Strengthen public perception:** While the project has a generally positive outlook, efforts should be made to further educate the public about the benefits and safety of CCS to mitigate any skepticism.

3. **Expand collaboration:** The open-source design of the project is a great asset. Efforts should be made to encourage more third parties to join the network, improving its impact and economic viability. As the project serves as a model for other CCS initiatives, there is an opportunity to share knowledge, best practices, and lessons learned with the broader community. This not only elevates the project's stature, but also contributes to the global CCS ecosystem.

4. **Leverage technological advancements:** As a frontrunner in CCS technology, the Longship project should remain at the forefront of technological advancements. Investing in research and development can

further solidify its position as a leader in the field.

In conclusion, the Longship project, with its innovative approach and strong backing, sets a positive precedent for CCS projects. The strong stakeholder field, with extensive financial backing from the Norwegian government, ensures that the project viability stays positive. The options for expansion of the CCS network keep the door open for further financial help and even stronger collaborative parties. The insights gained from its evaluation using the maturity framework can guide future initiatives toward even greater success.

6 Discussion and limitations

CCS is a technology that has been around for a long time. As the first project originated in 1996 (the Sleipner project), we have come a long way, and the development of CCS technologies adds significant possibilities for GHG mitigation. For technology to be implemented in a way that will make a difference in climate change, CCS projects will need to adapt to a range of current circumstances.

The purpose of this research was to create an evaluation framework for future CCS projects. The framework should be easily applicable by project owners, policymakers, consultants, and other stakeholders connected to CCS projects. To achieve this goal, several methods have been implemented. The methodologies used in this thesis, including the use of project success frameworks proposed by Khang and Moe (2008) and Romasheva and Ilinova (2019), have proven to be an effective way of evaluating CCS projects. Literature studies and expert interviews have provided enough information on the field of CCS to create the first steps of the framework. And the case studies have provided a real-life scenario aspect. The combination of methodologies applied in this research allowed for a comprehensive evaluation of the factors of the CCS project and showed how a project can be scored and analyzed using the proposed framework.

This section will reflect on the performed analyzes and provide more insight into how the results should be interpreted. Furthermore, the limitations of the analyzes are discussed, as they are fundamental when considering using the results of this research for any future work.

6.1 Discussion of the applied methodology

The methodology used in this research was designed to be comprehensive, with the aim of creating an evaluation framework for future CCS projects. This framework was intended to be used effectively by project owners, policymakers, consultants, and other stakeholders related to CCS projects.

Literature study and interviews

One of the primary challenges faced during the methodology's application was the identification of factors through literature studies and expert interviews. Striking a balance between specificity and generality was a recurring issue. On the one hand, going into too much detail with the factors made it challenging to link them to the case studies, potentially limiting the framework's applicability to a broader range of projects. However, being too general could weaken the significance of the results, potentially leading to a framework that lacked depth and actionable insights. This balance was crucial, as the framework's effectiveness hinges on its ability to provide both broad applicability and detailed, actionable recommendations.

Data availability and reliability

Literature studies and expert interviews formed the foundation of the research, providing a rich source of information on the field of CCS. However, the effectiveness of the methodology was somewhat compromised due to the dependency on the availability and reliability of the data. For example, challenges were faced when collecting data on the ROAD project. With official websites being closed and government information sites inaccessible, the reliability of the data could be questioned. This limitation underscores the importance of data availability and the challenges of relying on secondary sources. This problem could be solved by conducting interviews with individuals or parties that have been involved in the ROAD project. Given that the ROAD project has been canceled in 2017, it might still be difficult to find the right people to talk to. However, when applying the framework to more recent or active CCS projects, this would be more manageable.

Another point of contention is the adaptability of the framework. While the developed evaluation framework provides a structured approach to assess CCS projects, its applicability to projects with unique or unconventional characteristics remains uncertain. The generalizability of the methodology may be a concern, especially when dealing with projects under very specific or different circumstances.

Best-Worst Method

The research incorporated the best-worst method as a means of evaluating the importance of various factors. While this method offers a structured approach to factor evaluation, its effectiveness could be significantly improved when combined with stakeholder interviews. Engaging stakeholders directly in rating the importance of factors would not only provide a more grounded perspective but would also ensure that the framework aligns closely with the real-world challenges and priorities of CCS projects. Furthermore, when applying the framework to a specific CCS project, conducting an internal best-worst method analysis would add another layer of precision. This would tailor the framework more closely to the project's unique characteristics and challenges, ensuring that the recommendations are both relevant and actionable.

In conclusion, while the methodology used in this research offers a structured approach to the development of an evaluation framework for CCS projects, it is not without challenges. Future research should aim to refine the methodology, incorporate more direct stakeholder engagement, and ensure a balance between specificity and generality in factor identification.

Maturity Table

Incorporating the maturity table into this research has proven to be a key tool in the structured evaluation of CCS projects. The maturity table serves as a systematic instrument that allows for a quantitative assessment of all identified factors related to a CCS project. By assigning different scores to each factor, the table facilitates a nuanced understanding of a project's strengths and potential areas of improvement. This structured approach not only simplifies the complex landscape of CCS projects, but also pinpoints specific weak points that might otherwise go unnoticed in a more holistic assessment. However, while the maturity table's three-point scale provided a foundational structure for evaluation, there is room for refinement. Expanding the scale to, for instance, a five-point scale could offer a more precise approximation of the levels achieved for each factor. Such an extended scale would allow for a more detailed differentiation between factors, capturing subtle nuances that a three-point scale might overlook. This could be particularly beneficial in projects where factors might not distinctly fall into one of the three categories but rather lie somewhere in between.

Looking ahead, as we consider the application of the maturity table to future CCS projects, there is an undeniable value in integrating stakeholder interviews into the evaluation process. Engaging directly with those intimately involved in the projects can provide invaluable insights that transcend mere numerical scores. By allowing stakeholders to assign scores to factors based on their first-hand experiences and perceptions, the evaluation becomes more grounded in the realities of project implementation. Having stakeholders score the factors could be achieved through surveys and questionnaires. This participatory approach not only enriches the evaluation process, but also fosters a sense of ownership and collaboration among stakeholders.

6.2 Discussion of the results

The results derived from the application of the evaluation framework offer a multifaceted perspective on CCS projects. The results taken from the evaluation framework could have a significant effect on resource allocation in CCS projects.

Insights into project factors

One of the primary outcomes of the evaluation framework is the detailed insight it provides into the characteristics of CCS projects. By systematically evaluating various factors, the framework sheds light on the strengths and weaknesses of a given project. This can guide project owners and stakeholders in identifying areas that require more attention, resources, or innovation. For example, if a project scores low in stakeholder engagement, it could be an indication to invest more in community outreach or public relations campaigns.

Legal and governance implications

The framework's results underscore the importance of robust legal and governance structures for the development and deployment of CCS projects. Projects that align well with existing legal frameworks and have clear governance structures in place are more likely to navigate regulatory challenges, secure funding, and gain public trust. The evaluation framework can serve as a diagnostic tool, helping policymakers and project owners identify potential legal and governance roadblocks before they become insurmountable challenges.

Stakeholder engagement

Another crucial insight from the framework's results is the role of stakeholders. Projects that prioritize and effectively manage stakeholder participation are more likely to secure the necessary permits, gain public acceptance, and navigate potential conflicts. The evaluation framework offers a structured approach to assess stakeholder engagement, providing project owners with actionable insights to improve their stakeholder management strategies.

While the evaluation framework provides a comprehensive assessment of CCS projects, it is essential to interpret the results with caution. The effectiveness of the framework is dependent on the quality and completeness of the data fed into it. Furthermore, while the framework offers a broad overview, each CCS project is unique and the results should be adapted to the specific context and challenges of individual projects.

In conclusion, the results of the evaluation framework offer a valuable roadmap for the successful implementation of CCS projects. By providing detailed information on project characteristics, legal frameworks, technological readiness, and stakeholder participation, the framework equips project owners, policymakers, and stakeholders with the tools they need to drive the success of their CCS projects.

6.3 Limitations

The diverse nature of CCS projects

As research has shown, CCS projects are characterized by a wide array of unique characteristics and challenges. This diversity, while a testament to the potential of CCS technology, also presents a challenge when trying to combine all the necessary information within a single evaluation framework. However, this is less a limitation and more an acknowledgment of the rich complexity of CCS projects. It underscores the need for flexibility and adaptability in applying the evaluation framework, allowing customization according to the specific needs of each project.

Limited depth and coverage

The research presents a holistic framework that includes both policy- and project-orientated characteristics. While this wide coverage ensures a comprehensive understanding of the project landscape, it may limit the depth of focus on each individual factor. This aim of providing a framework that captures all dimensions of CCS project also comes with other difficulties. To accurately score a CCS project based on identified factors and their corresponding impact weights, it must be assumed that the list of factors covers the entity of the project and does not have any correlation between factors. Only when this is true can the weighting and scoring of the factors be considered significant. The task of covering all aspects of a project is extremely difficult, especially given the diverse nature of CCS projects mentioned above.

This limitation invites future researchers for further exploration. It provides a solid foundation on which more detailed factor-specific studies can be built, fostering a more nuanced understanding of CCS projects.

Changing CCS landscape

The research acknowledges that safety is one of the main challenges of CCS and that managing the CCS value chain is a long-term task. This constant evolution can make it challenging to maintain an evaluation framework that remains current and fully reflective of the latest trends. However, this is less a limitation and more a reminder of the exciting, ever-evolving nature of the field. It emphasizes the importance of continuous learning and adaptation, ensuring that the evaluation frameworks remain relevant and effective in guiding CCS projects toward success.

These points are not limitations in the traditional sense but rather considerations to bear in mind when applying the proposed frameworks. They highlight the need for flexibility, continuous learning, and deeper exploration in the exciting and dynamic field of CCS.

7 Conclusions

As global warming, climate change, and the need to preserve the Earth for future generations take center stage in the great challenges of today's world, the societal relevance of CCS and CCU could not be greater. According to the IPCC (2022a), CCS could contribute to around 20% of climate change mitigation by 2050. Additionally, to achieve the EU aspiration of full circularity by 2050 and limit global temperature increases to 2 ° C or below, CCS is indispensable (IEA, 2016). CCS and surrounding technologies will play a major role over the coming decades. In the near future, the need for the development of CCS to ensure the first big steps toward reducing climate change is crucial. And in a longer timeline, the implementation of CO utilization$_2$ is one of the key drivers toward full circularity.

This chapter will answer the research questions proposed for this research. In addition, recommendations will be made based on the analyzes performed, potential future work will be identified, and the academic relevance of this research will be highlighted.

7.1 Answering the research questions

SQ1: *What are the current approaches for guiding the deployment of CCS projects, based on academic literature and stakeholder insights?*

In Chapter 2, a number of evaluation frameworks are discussed based on which certain elements have been identified as the basis for the framework created in this research. Insights from the literature show that current project evaluation frameworks focus on making project evaluation more manageable by dividing the approach into multiple parts. This compartmentalization and structuring of the project into separate elements and parts adds to the creation of a complete framework. Khang and Moe (2008) proposed the use of critical success factors (CSFs) and success criteria (SC) when evaluating projects. This approach has been used in this research by identifying key factors that can be used to analyze every aspect of a CCS project. Romasheva and Ilinova (2019) proposes a set of categories on which CCS projects can be assessed, thus compartmentalizing using another dimension than that used by Khang and Moe (2008). By applying this technique, the identified factors were grouped and therefore easier to evaluate and score.

The insights gained from expert interviews help answer this research question in another way. R1 spoke about the structure of the current Porthos CCS project. To enable a clear sense of ownership and responsibility within projects, a clear management and operating structure needs to be in place. Within the Porthos project, this consists of several teams within overarching departments, all responsible for their own part of the project. This makes sure that a clear overview of project activities can be kept and that people within the respective teams can better address other teams within the project.

Within this research, the examples mentioned above have been taken into account when creating evaluation frameworks. Knowledge from current frameworks has been combined to create a framework with multiple dimensions that is capable of presenting a cohesive overview of the characteristics of the CCS project to aid with their implementation.

SQ2: *What is the role of the different actors present in CCS projects, and how do they contribute to a successful CCS project?*

Different actors play a crucial role in the development and deployment of CCS projects. In Section 4.3, a table was presented that contains a list of actors that you would generally find attached to a CCS project. Important to mention is that this list might not be entirely consistent with real-life project scenarios. The role of the different actors involved is very diverse. Policymakers on a national and international level set the regulatory landscape, influencing the feasibility and direction of CCS initiatives while also potentially providing financial support to projects. Project developers and supporting parties, such as suppliers and contractors, are the actors actively working on the development of the CCS value chain. The industrial parties that are associated with the projects will have to implement the technical application of CO_2 capture in collaboration with the suppliers of CCS technologies. These actors all work towards the development of CCS projects while also having to inform and involve external parties such as the local communities surrounding the project.

As also seen while analyzing the different CCS projects in Chapter 5, projects are set up in many different ways, with stakeholders (public or private) playing different roles in each of them. However, the success of a project is strongly dependent on collaboration and communication between the stakeholders involved. In the Longship project, discussed in Section 5.4, the government plays a crucial role in the development of the project. As the project is a government initiative, large funding is made available and partnerships are built to achieve established climate change reduction goals. The structure and the way certain stakeholders are involved with the Longship project make it more manageable and prone to success. However, achieving this type of structure in a CCS project is certainly not always possible. As was shown in the ROAD project, a stakeholder structure with more ownership and involvement through private companies occurs more regularly.

Regardless of the specific configuration, one overarching theme remains consistent: the success of a CCS project hinges on effective collaboration and communication among its stakeholders. The intricate collaboration between these actors, their interests, and their contributions highlights the multifaceted nature of CCS projects and the importance of a unified approach to ensure their successful implementation. Insights through expert interviews have also confirmed the importance of stakeholder management. All three interviewees have in some way been involved in the deployment of CCS projects and all three of them mentioned the importance of having a clear and manageable structure in a project.

The collaboration between stakeholders involved is widely incorporated in the created evaluation frameworks in the research. One of the categories identified by Ilinova et al. (2018) and also described in the created frameworks in this research is the 'organizational' category. This section is driven by the importance of healthy relationships between stakeholders.

SQ3: *Which factors need to be considered to develop a framework that can give insights into the deployment and potential success of a CCS project?*

This sub-question is widely answered in Chapter 4. A list of project factors has been identified in Chapter 4 using knowledge from academic literature and expert interviews. The categories proposed by Ilinova et al. (2018) formed the basis for answering this research question. To compile a list of factors that would need to be evaluated to accurately score a CCS project, the categories applied helped as a guide for their identification.

From a political-legal perspective, the regulatory and policy landscapes had to be assessed, as they form the playing field in which the project has to abide by certain laws. Furthermore, the potential support of government bodies could greatly help the implementation of a CCS project. Economically, the viability of the project needed to be evaluated, taking into account both the initial capital expenditure and the ongoing operational costs, but also the financial support to a project, public or private. Socially, the importance of public perception and acceptance was recognized, with community support emerging as a key determinant in the project's long-term success. Technically, aspects such as the maturity of CCS technologies and the presence of alternatives to CCS needed to be analyzed. Ecologically, the project's alignment with sustainability goals and its effectiveness in reducing carbon emissions were evaluated. Lastly, from an organizational point of view, stakeholder engagement and management were deemed paramount, as collaboration between various actors, from policy makers to investors, could have a profound impact on CCS projects.

From these categories and further points of attention, a list of identified factors was created and presented in Section 4.2. This knowledge is then taken as the basis for the creation of the evaluation framework, which is then applied to case studies. The results in this chapter show that, based on the knowledge found in reports, project websites, government websites, and the literature, an evaluation framework can be created that replicates the results of previous CCS projects. The benefit of creating a framework based on past projects is the ability to learn from certain actions taken in different project circumstances. Learning from past mistakes is one of the best ways to ensure future success.

SQ4: *How can the created evaluation framework provide valuable insights when applied to case studies?*

The application of the evaluation framework can help identify critical point of attention for CCS projects by providing a clear and distinguished factors on which the project will be scored. It can show what needs to be achieved and aimed for in order to help with the development and deployment of the project. Through the application of BWM and maturity tables to score projects in a quantitative manner, the evaluation framework provides an easy and visual understanding of were the weak points may occur in a project.

As discussed in Chapter 6, the evaluation of real-life situations would perform better with a more tailor-made approach for each project. This could then include a deeper exploration of the BWM impact scores through the use of surveys filled out by involved stakeholders or by performing expert interviews to discuss on what levels the factors score in the maturity table. However, learning from these past projects and recognizing what actions and challenges have led them to deployment or cancelation provide a better understanding of how the deployment of CCS projects should be handled.

Main research question: *How can an evaluation framework combining both project- and policy-related factors provide insights for the deployment of full-chain CCS projects, and how is it developed and applied?*

The evaluation framework in this research combines both project- and policy-orientated factors so it can provide a better understanding of the deployment of full-chain CCS projects by providing a comprehensive view of the most important factors to consider during the development of a project and scoring them using various methods. It combines the concept of project success criteria and factor group categories (SQ1), which helps to identify the most crucial characteristics of CCS projects that can act as a basis for evaluating the project. By reviewing the literature and analyzing expert interviews, a complete list of project factors can be identified which are to be considered as points of attention when developing future CCS projects (SQ3). Also, since stakeholder management is of the utmost importance in this process, further research on the stakeholder field, their expectation and potential influences on projects will also contribute to making the evaluation framework more complete (SQ2). Then, to demonstrate the proposed framework, case studies are analyzed. Their historical data and information on past activities and characteristics provide the possibility to test the framework against real-life scenarios. Lastly, the information gained from the case studies could help provide relevant insights for the analyzed projects even for future CCS projects(SQ4).

This stepwise approach adopted in this research to create an evaluation framework, coupled with the application of the framework on case studies, showed that by combining project- and policy-related factors into a structural framework, valuable insights could be provided for the development of CCS projects.

7.2 Recommendations

The goal of this research was to make a holistic and visual evaluation framework for the deployment of CCS projects. Policy-makers, decision-makers, consultants, and project stakeholders can use the outcomes of this research as a tool for the evaluation past projects or for the implementation of future projects. Based on the performed analyses in this research, the following recommendation can be made:

Financial management as a top priority

As shown in the case studies in this research, the financial capability of CCS projects is crucial for the chances to make it to their deployment phase. Projects, especially those that have to operate for a long time period, are under a lot of financial pressure. Several different situations can lead to easy delays, which in time also lead to additional costs. Also, CCS technologies are still very expensive to deploy. An impenetrable long-term financing structure is one of the most crucial elements needed in future projects. Whether projects are owned by public instances, private instances, or both, the need for financial stability must be considered throughout the whole project timeline.

Promote collaboration

In addition to the recommendation of superior financial management, the promotion of collaboration is also an important objective. Having a project made up of stakeholders that have the knowledge, skills, expertise, and financial capabilities adds immensely to the chances of success. Policymakers and project owners should foster collaboration between different stakeholders in the CCS field. This could involve creating platforms for knowledge sharing, fostering partnerships between academia and industry, or coordinating international efforts in CCS research and implementation.

Develop robust legal frameworks

To ensure that projects are not held up by any unexpected developments, a detailed legal framework should be in place. These should address issues such as ownership, liability, and environmental impact. Project owners should work closely with legal experts to develop these frameworks. Projects should also always hold close ties to public institutions such as governments and municipalities. They play a big part in a project's chance to succeed, as regulations should always be followed, permits are needed, and possible public funding could help a project massively.

Implement and refine evaluation frameworks

Project owners should make use of knowledge gathered from past projects. Learning from past mistakes or challenges could form a big part of CCS project success in the future. Literature on past projects or interviews with stakeholders of these projects could inform on how to handle certain situations. Also, the implementation of available frameworks, such as the one proposed in this research, could help structure the processes while developing CCS projects. Frameworks should be continually refined based on feedback and new research findings.

Ensure transparency

Just as the importance of strong collaboration, transparency also provides better CCS projects through knowledge sharing and combined efforts. Stakeholders should first and foremost be transparent towards other stakeholders attached to their CCS projects. But transparency towards the public is also of great importance. To build public trust and support for CCS projects, project owners should ensure transparency in their operations. This could involve publishing regular reports on the project's performance, environmental impact, and financial aspects.

Use of framework

In the research undertaken, the proposed evaluation framework emerges as a valuable tool for CCS projects. However, its strength lies not just in its structured approach, but in its adaptability. While it serves as a foundational guide, it is essential to tailor the framework to the unique nuances of each CCS project. A universal approach might overlook specific challenges or opportunities inherent to individual initiatives. To further enhance its precision, it is crucial to integrate first-hand insights from stakeholders currently involved in the projects under review. Through interviews and dialogues, the framework can capture the real-world complexities of CCS projects, ensuring a more comprehensive and accurate assessment.

7.3 Future work

In this research, the evaluation framework has provided a broad overview of the factors relevant to CCS projects. However, there is potential for further exploration and depth of each of these factors. Future research can focus on studying individual factors, studying their nuances and implications in greater detail. For example, a dedicated study could analyze the financial challenges associated with CCS projects, including funding models, potential investment sources, and cost optimization strategies. Such research would not only enhance our understanding of specific factors but also strengthen the robustness and utility of the framework. To validate the evaluation framework, they could be tested on a wider range of CCS projects. Future research could involve conducting case studies on various types of completed and ongoing CCS projects in different geographical and regulatory contexts. These case studies would provide valuable insights into the diverse realities of CCS projects, adding toward the refinement of the evaluation frameworks.

Another element that could provide added potential for this framework would be a more detailed approach for the Best-Worst method. In this research, the respective impact of the identified factors is proposed based on information from literature study and expert interviews. When applying this framework on an active CCS project, it would be extremely beneficial to perform an internal study into how these factors and factor groups should be ranked according to the goals of the CCS project in question. This could be done be creating surveys for stakeholders to fill in.

As the CCS field is dynamic and continuously evolving, future research should prioritize staying updated with emerging trends and incorporating them into the evaluation frameworks. This can be achieved through regular literature reviews, participation in industry conferences and seminars, and collaboration with experts and practitioners. By consistently updating the frameworks, they will reflect the latest state of the art, ensuring their ongoing relevance and effectiveness.

One of the interview insights suggested the possibility of international collaboration, where clients from other countries could utilize the storage capacity in the North Sea, as is the plan in the Longship project. This presents an exciting opportunity for future research. Studies could be conducted to explore the feasibility of such collaborations, examining technical, regulatory, and logistical challenges. Comparative studies of CCS landscapes in different countries, analysis of international laws and agreements relevant to CCS, and development of models for international cooperation in CCS projects would all contribute to understanding and facilitating this potential for collaboration.

7.4 Academic relevance

To complete my Master of Engineering and Policy Analysis (EPA), a subject that is appropriately connected to the master's program is mandatory. The criteria that are specified when it comes to connecting my research to EPA are listed below, as is their link to my research.

- **The work is analytical in character.**
  This thesis is focused on the analysis of a multi-actor system. Multiple components (technical, financial, and logistical) of the system will be considered and analyzed through an in-depth literature review and expert interviews. The results of these analytical methods will be put together to develop a framework for future CCS projects.

- **The work exhibits both a system and a multi-actor perspective.**
  The CCS infrastructure and its multi-faceted and multi-actor nature is the central point of this research. Where current research often lacks the assessment of the multi-actor nature of a CCS network, this research will make sure not to assume current CCS networks as systems owned by only one party. The actor field of CCS project is discussed through the application of stakeholder analysis and PI-grids.

- **EPA methods and techniques for problem analysis and exploration are used systematically, and (conceptual) modeling and/or simulation techniques have been employed.**
  The analytical tools that are used in this research consist of an in-depth literature study, semi-structured expert interviews, and framework design including the Best-Worst Method and maturity tables. This research design and the eventual construction of the framework for CCS projects will be supported by analytical techniques for decision-making that are applied in the System Engineering, Policy Analysis & Management and Engineering & Policy Analysis programs.

- **The subject is related to Grand Challenges, aims to inform decision-makers and is relevant in the public(policy) domain or on the interface between public and private domains.**
  CCS technologies and infrastructures are deeply connected to one of the largest grand challenges of today: Global warming. Large governmental institutions will have to work together with private businesses to achieve the development of CCS technologies that can mitigate climate change. Also, as this research will be performed in collaboration with Accenture, a large technology-orientated consulting firm, the real-life application of this research in a private domain will play a role in this research.

References

Akerboom, S., Waldmann, S., Mukherjee, A., Agaton, C., Sanders, M., and Kramer, G. J. (2021). Different This Time? The Prospects of CCS in the Netherlands in the 2020s. *Frontiers in Energy Research*, 9.

Arts, R., Vandeweijer, V., Hofstee, C., Pluymaekers, M., Loeve, D., Kopp, A., and Plug, W. (2012). The feasibility of CO2 storage in the depleted P18-4 gas field offshore the Netherlands (the ROAD project). *International Journal of Greenhouse Gas Control*, 11:S10–S20.

Ashworth, P., Wade, S., Reiner, D., and Liang, X. (2015). Developments in public communications on CCS. *International Journal of Greenhouse Gas Control*, 40:449–458.

Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Alonso-Fariñas, B., Vilches Arenas, L. F., and Navarrete, B. (2019). Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 41(12):1403–1433.

Becker, J., Knackstedt, R., and Pöppelbuß, J. (2009). Developing Maturity Models for IT Management. *Business & Information Systems Engineering*, 1(3):213–222.

Bijkerk, M. (2012). Handling and allocation of Business Risks. *GCCSI.*

Braun, C. (2017). Not in My Backyard: CCS Sites and Public Perception of CCS. *Risk Analysis*, 37(12):2264–2275.

Brunelli, M. and Rezaei, J. (2019). A multiplicative best–worst method for multi-criteria decision making. *Operations Research Letters*, 47(1):12–15.

Budinis, S., Krevor, S., Dowell, N. M., Brandon, N., and Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews*, 22:61–81.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., Puxty, G., Reimer, J., Reiner, D. M., Rubin, E. S., Scott, S. A., Shah, N., Smit, B., Trusler, J. P. M., Webley, P., Wilcox, J., and Dowell, N. M. (2018). Carbon capture and storage (CCS): the way forward. / *Energy Environ. Sci*, 11:1062.

Cao, C., Liu, H., Hou, Z., Mehmood, F., Liao, J., and Feng, W. (2020). A Review of CO2 Storage in View of Safety and Cost-Effectiveness. *Energies*, 13(3):600.

Carbon Capture Journal (2014). CCS in the Netherlands - and the future of ROAD.

CCSNorway (2020). The Longship CCS project in Norway | Learn more about the project.

CCSNorway (2021). Knowledge from the CCS-project Longship - CCS Norway.

CLIMIT (2022). Programme Plan. Technical report.

d'Amore, F., Mocellin, P., Vianello, C., Maschio, G., and Bezzo, F. (2018). Economic optimisation of European supply chains for CO 2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures. *Applied Energy*, 223:401–415.

Date, T. J. (2013). Special Report ROAD permitting process. *GCCSI.*

de Figueiredo, M. A. (2003). The Hawaii Carbon Dioxide Ocean Sequestration Field Experiment: A Case Study in Public Perceptions and Institutional Effectiveness by Mark Anthony de Figueiredo. Technical report.

Deng, H., Bielicki, J. M., Oppenheimer, M., Fitts, J. P., and Peters, C. A. (2017). Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation. *Climatic Change*, 144(2):151–163.

Diao, Y., Zhang, S., Wang, Y., Li, X., and Cao, H. (2015). Short-term safety risk assessment of CO2 geological storage projects in deep saline aquifers using the Shenhua CCS Demonstration Project as a case study. *Environmental Earth Sciences*, 73(11):7571–7586.

Dimitriou, K. (2023). *An integrated self-assessment and maturity model for the urban smart factory.* PhD thesis, Technical University of Delft.

Dixon, T., McCoy, S. T., and Havercroft, I. (2015). Legal and Regulatory Developments on CCS. *International Journal of Greenhouse Gas Control*, 40:431–448.

Durmaz, T. (2018). The economics of CCS: Why have CCS technologies not had an international breakthrough? *Renewable and Sustainable Energy Reviews*, 95:328–340.

Eisenhardt, K. M. and Zbaracki, M. J. (1992). Strategic decision making. *Strategic Management Journal*, 13(S2):17–37.

Equinor (2019). Northern Lights Project Concept report.

Fan, Y., Zhu, L., and Zhang, X. (2011). Analysis of Global CCS Technology, Regulations and Its Potential for Emission Reduction with Focus on China. *Advances in Climate Change Research*, 2(2):57–66.

Feenstra, C., Mikunda, T., and Brunsting, S. (2010). What happened in Barendrecht? Case study on the planned onshore carbon dioxide storage in Barendrecht, the Netherlands. Technical report.

Fozer, D., Sziraky, F. Z., Racz, L., Nagy, T., Tarjani, A. J., Toth, A. J., Haaz, E., Benko, T., and Mizsey, P. (2017). Life cycle, PESTLE and Multi-Criteria Decision Analysis of CCS process alternatives. *Journal of Cleaner Production*, 147:75–85.

Gassnova (2020). Updated CO2 footprint calculation. Technical report.

Gassnova (2021). Regulatory Lessons Learned form Longship. Technical report.

Gellings, C. W. (2017). Evolving practice of demand-side management. *Journal of Modern Power Systems and Clean Energy*, 5(1):1–9.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., and Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, 24:38–50.

Global CCS Insitute (2011). Non-confidential FEED study report. Technical report, GCCSI.

Global CCS Institute (2018a). Carbon capture and storage remains essential to beating climate change.

Global CCS Institute (2018b). Public close-Out Report: Project Costs and Funding. Technical report.

Global CCS Institute (2018c). ROAD: Public Close-Out Report. Technical report.

Gough, C., Cunningham, R., and Mander, S. (2018). Understanding key elements in establishing a social license for CCS: An empirical approach. *International Journal of Greenhouse Gas Control*, 68:16–25.

Gough, C. and Mander, S. (2019). Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS. *Current Sustainable/Renewable Energy Reports*, 6(4):116–123.

Government.no (2020). The Government launches 'Longship' for carbon capture and storage in Norway - regjeringen.no.

Gruben, G. and Macdonald, K. A. (2022). Advances in running ductile fracture assessment for the Longship full-scale CCS project.

Gunderson, R., Stuart, D., and Petersen, B. (2020). The fossil fuel industry's framing of carbon capture and storage: Faith in innovation, value instrumentalization, and status quo maintenance. *Journal of Cleaner Production*, 252:119767.

Haszeldine, R. S., Flude, S., Johnson, G., and Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119).

Helgesen, L. I., Cauchois, G., Nissen-Lie, T., Prestholdt, M., Carpenter, M., and Røsjorde, A. (2021). CO2 Footprint of the Norwegian Longship Project. *SSRN Electronic Journal*.

Henry, X., Jonker, T., Schoonwater, A., and Wattenberg, V. (2011). Special Report ROAD permitting process Title The permitting process Special report to the Global Carbon Capture and Storage Institute.

Herzog, H. (2017). Financing CCS Demonstration Projects: Lessons Learned from Two Decades of Experience. *Energy Procedia*, 114:5691–5700.

IEA (2016). 20 years of carbon capture and storage.

IEA (2021). Carbon capture, utilisation and storage - Fuels & Technologies.

Ilinova, A., Cherepovitsyn, A., and Evseeva, O. (2018). Stakeholder Management: An Approach in CCS Projects. *Resources*, 7(4):83.

IOGP (2019). The potential for CCS and CCU in Europe. Technical report.

IPCC (2022a). Climate Change 2022: Mitigation of Climate Change. Technical report, IPCC.

IPCC (2022b). *Global Warming of 1.5° C.* Cambridge University Press.

Jakobsen, J. P., Roussanaly, S., Mølnvik, M. J., and Tangen, G. (2013). A standardized Approach to Multi-criteria Assessment of CCS Chains. *Energy Procedia*, 37:2765–2774.

Johnson, G. and Scholes, K. (1985). Exploring corporate strategy. *Strategic Management Journal*, 6(3):297–297.

Kalyanarengan Ravi, N., Van Sint Annaland, M., Fransoo, J. C., Grievink, J., and Zondervan, E. (2017). Development and implementation of supply chain optimization framework for CO2 capture and storage in the Netherlands. *Computers and Chemical Engineering*, 102:40–51.

Khang, D. B. and Moe, T. L. (2008). Success Criteria and Factors for International Development Projects: A Life-Cycle-Based Framework. *Project Management Journal*, 39(1):72–84.

Kombrink, M. and Jonker, T. (2011). Stakeholder Management ROAD. *GCCSI.*

Krahé, M., Heidug, W., Ward, J., and Smale, R. (2013). From demonstration to deployment: An economic analysis of support policies for carbon capture and storage. *Energy Policy*, 60:753–763.

Krüger, T. (2017). Conflicts over carbon capture and storage in international climate governance. *Energy Policy*, 100:58–67.

Lacy, R., Serralde, C., Climent, M., and Vaca, M. (2013). Initial assessment of the potential for future CCUS with EOR projects in Mexico using CO2 captured from fossil fuel industrial plants. *International Journal of Greenhouse Gas Control*, 19:212–219.

Lipponen, J., McCulloch, S., Keeling, S., Stanley, T., Berghout, N., and Berly, T. (2017). The Politics of Large-scale CCS Deployment. *Energy Procedia*, 114:7581–7595.

Lofstedt, R. (2015). Effective risk communication and CCS: the road to success in Europe. *Journal of Risk Research*, 18(6):675–691.

LOrange Seigo, S., Dohle, S., and Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, 38:848–863.

Ma, J., Li, L., Wang, H., Du, Y., Ma, J., Zhang, X., and Wang, Z. (2022). Carbon Capture and Storage: History and the Road Ahead. *Engineering*, 14:33–43.

Marchetti, C. (1977). On geoengineering and the CO2 problem. *Climatic Change*, 1(1):59–68.

Marsh, D. and Mcconnell, A. (2010). Towards A Framework For Establishing Policy Success. *Public Administration*, 88(2):564–583.

Mikunda, T., van Deurzen, J., Seebregts, A., Kerssemakers, K., Tetteroo, M., and Buit, L. (2011). Towards a CO2 infrastructure in North-Western Europe: Legalities, costs and organizational aspects. *Energy Procedia*, 4:2409–2416.

MIT (2016). ROAD Fact sheet.

Northern Lights (2023). Northern Lights: What we do.

Norwegian Ministry of Petroleum and Energy (2019). Longship-Carbon capture and storage.

Raad van State (2023). Porthos-project mag doorgaan.

Rassoor, D., Havercroft, I., Zapantis, A., and Raji, N. (2021). CCS in the Circular Carbon Economy: Policy and Regulatory Recommendations. Technical report, Global CCS Institute.

Read, A., Gittins, C., Uilenreef, J., Jonker, T., Neele, F., Belfroid, S., Goetheer, E., and Wildenborg, T. (2019). Lessons from the ROAD project for future deployment of CCS. *International Journal of Greenhouse Gas Control*, 91:102834.

Read, A., Tillema, O., Ros, M., Jonker, T., and Hylkema, H. (2014). Update on the ROAD Project and Lessons Learnt. *Energy Procedia*, 63:6079–6095.

Read, A. and Toonssen, R. (2018). Public Close-Out Report Project Costs and Funding. *GCCSI.*

Reyes-Lúa, A., Gardarsdottir, S. O., Biermann, M., Lundqvist, K., and Harvey, S. (2021). Potential Impact of the Preem-CCS Project . *Trondheim CCS Conference*.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, 53:49–57.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, 64:126–130.

Román, M. (2011). Carbon capture and storage in developing countries: A comparison of Brazil, South Africa and India. *Global Environmental Change*, 21(2):391–401.

Romasheva, N. and Ilinova, A. (2019). CCS projects: How regulatory framework influences their deployment. *Resources*, 8(4).

Shen, M., Kong, F., Tong, L., Luo, Y., Yin, S., Liu, C., Zhang, P., Wang, L., Chu, P. K., and Ding, Y. (2022). Carbon capture and storage (CCS): development path based on carbon neutrality and economic policy. *Carbon Neutrality*, 1(1):37.

Singh, P. and Haines, M. (2014). A Review of Existing Carbon Capture and Storage Cluster Projects and Future Opportunities. *Energy Procedia*, 63:7247–7260.

Steeghs, P. and Mikunda, T. (2014). The Rotterdam Capture and Storage Demonstration Project (ROAD). *Energy Procedia*, 63:6036–6042.

Stephens, J. C., Hansson, A., Liu, Y., de Coninck, H., and Vajjhala, S. (2011). Characterizing the international carbon capture and storage community. *Global Environmental Change*, 21(2):379–390.

Stephens, J. C. and Liu, Y. (2012). The Evolving International CCS Community. *The Social Dynamics of Carbon Capture and Storage: Understanding CCS Representations, Governance and Innovation*, pages 127–148.

Steyn, M., Zapantis, A., Gebremedhin, R., Al Amer, N., Havercroft, I., Ivory-Moore, R., Yang, X., Abu Zahra, M., Pinto, E., Rassool, D., Williams, E., Consoli, C., and Minervini, J. (2022). Global Status of CCS 2022. Technical report.

Stokke, R., Kristoffersen, F. S., Stamland, M., Holmen, E., Hamdan, H., and De Boer, L. (2022). The role of green public procurement in enabling low-carbon cement with CCS: An innovation ecosystem perspective. *Journal of Cleaner Production*, 363:132451.

Tanzer, S. E. and Ramírez, A. (2019). When are negative emissions negative emissions? *Energy & Environmental Science*, 12(4):1210–1218.

Tapia, J. F. D., Lee, J. Y., Ooi, R. E., Foo, D. C., and Tan, R. R. (2018). A review of optimization and decision-making models for the planning of CO2 capture, utilization and storage (CCUS) systems. *Sustainable Production and Consumption*, 13:1–15.

TNO (2020). CCUS Network.

van der Spek, M., Roussanaly, S., and Rubin, E. S. (2019). Best practices and recent advances in CCS cost engineering and economic analysis. *International Journal of Greenhouse Gas Control*, 83:91–104.

van Egmond, S. and Hekkert, M. P. (2012). Argument map for carbon capture and storage. *International Journal of Greenhouse Gas Control*, 11(SUPPL):S148–S159.

Vivares, J. A., Sarache, W., and E. Hurtado, J. (2018). A maturity assessment model for manufacturing systems. *Journal of Manufacturing Technology Management*, 29(5):746–767.

Wagire, A. A., Joshi, R., Rathore, A. P. S., and Jain, R. (2021). Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. *Production Planning & Control*, 32(8):603–622.

Wallquist, L., Visschers, V. H. M., Dohle, S., and Siegrist, M. (2011). Adapting communication to the public's intuitive understanding of CCS. *Greenhouse Gases: Science and Technology*, 1(1):83–91.

Wennersten, R., Sun, Q., and Li, H. (2015). The future potential for Carbon Capture and Storage in climate change mitigation – an overview from perspectives of technology, economy and risk. *Journal of Cleaner Production*, 103:724–736.

Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A. H., and Olabi, A. G. (2019). Outlook of carbon capture technology and challenges. *Science of The Total Environment*, 657:56–72.

Zapantis, A., Townsend, A., and Rassool, D. (2019). Policy priorities to incentivise large scale deployment of CCS. Technical report, Global CCS Institute.

Cherepovitsyn, A. E., Ilinova, A. A., and Evseeva, O. O. (2019). Stakeholders management of carbon sequestration project in the state (business) society system. *Journal of Mining Institute*, 240(6):731–742.

Appendices

A The Best-Worst Method (BWM)

The BWM, developed by Jafar Rezaei of Delft University of Technology in 2015, addresses discrete multi-criterion decision-making (MCDM) problems. In these problems, a set of alternatives is evaluated against various indicators to select the optimal alternative and provide weights for each alternative. The BWM comprises five sequential steps, which are discussed below.

Variables for BWM:

c_j : Decision element j

c_B : Best element

c_W : Worst element

a_{Bj} : Preference of the best element over others

A_B : Best-to-Others vector

a_{jW} : Preference of element j over the worst

A_W : Others-to-Worst vector

w_j : Weight of element j

w_B : Weight of the best element

w_W : Weight of the worst element

d.o.f. : Degrees of freedom

ξ : Consistency factor

Step 1:

Define the set of decision elements as $\{c_1, c_2, ..., c_n\}$. In this set, there can be a number of elements ranging from 3 to 9. If the number of elements exceeds 9, Rezaei (2015) recommends further grouping of the elements.

Step 2:

Identify the best ($c_B \in \{c_1, c_2, ..., c_n\}$) and worst ($c_W \in \{c_1, c_2, ..., c_n\}$) elements, ensuring $c_B \neq c_W$.

Step 3:

Determine the preference $a_{Bj} \in \{1, 2, ..., 9\}$ of the best element c_B over other elements $c_j \in \{c_1, c_2, ..., c_n\}$, forming the Best-to-Others vector $A_B = (a_{B1}, a_{B2}, ..., a_{Bn})$. a_{Bj} indicates c_B's preference over element c_j, with $j \in \{1, ..., n\}$. It follows that $a_{BB} = 1$ since c_B is most preferred over itself.

Step 4:

Establish the preference $a_{jW} \in \{1, 2, ..., 9\}$ of elements c_j over the worst element c_W, resulting in the Others-to-Worst vector $A_W = (a_{1W}, a_{2W}, ..., a_{nW})$. Here, a_{jW} denotes element c_j's preference over c_W, with $j \in \{1, ..., n\}$. Notably, $a_{WW} = 1$ because it captures the preference of the worst element over itself. The values 1-9 signify:

1 : Equally important

2 : Somewhat between Equal and Moderate

3 : Moderately more important than

4 : Somewhat between Moderate and Strong

5 : Strongly more important than

6 : Somewhat between Strong and Very Strong

7 : Very strongly more important than

8 : Somewhat between Very Strong and Absolute

9 : Absolutely more important than

Step 5:

Seek optimal weights $(w_1, w_2, ..., w_n)$. Optimality is achieved when for each j, $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. To satisfy these conditions, the solution minimizes the maximum absolute differences between $w_B/w_j - a_{Bj}$ and $w_j/w_W - a_{jW}$ for all j.

This leads to the following problem formulation:

$$\text{Minimize} \max_j \left(|w_B/w_j - a_{Bj}|, |w_j/w_W - a_{jW}|\right)$$

Subject to:

$$\sum_j w_j = 1, \quad w_j \geq 0 \,\text{for all}\, j$$

Such a problem can be reformulated as the following optimization problem:

$$\text{minimize } \xi \text{ d.o.f.}$$

$$a_{Bj}, \text{ for } j \in \{1, \ldots, n\}$$

$$a_{jW}, \text{ for } j \in \{1, \ldots, n\}$$

Subject to:

$$|w_B/w_j - a_{Bj}| \leq \xi, \text{ for all } j$$

$$|w_j/w_W - a_{jW}| \leq \xi, \text{ for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all } j$$

Solving this problem provides the optimal weights $(w_1, w_2, \ldots, w_n)$ of the elements and provides ξ, referred to as a consistency factor. A higher value of ξ indicates a less reliable comparison.

B Interview protocol

Request for interview

Dear reader at . . . ,

I am a student currently writing my master's thesis for the study Engineering and Policy Analysis at TU Delft. For my research, I am constructing a framework/checklist for the deployment of carbon capture and storage projects with storage facilities in the North Sea region. This consists of identifying a list of factors/characteristics that are needed to holistically approach the deployment of CCS projects and presenting this in a manageable framework. As a part of my research, I am looking to interview key stakeholders and experts in the CCS environment to back up academic literature and gain further insights into what is needed and considered indispensable for the deployment of CCS projects.

My interest reaches towards characteristics with a technological, economic, social, organizational, and political-legal nature but also aims to provide insights into the governance surrounding CCS projects (actor involvement, communication between these actors, etc.). I think the expertise of your organization fits very well into my research. Therefore, I would love to arrange a meeting to ask some questions and gain some expert insights from your side. Do you have some time on one of the following dates and times: xxx

Thank you in advance. I look forward to your response,

Kind regards,
Alexander Berck

Interview questions

Interview introduction

1. Appreciation for the cooperation and time
2. This interview will be mainly to as data for my Master thesis
3. You will be participating anonymously
4. Permission for an audio recording of the interview
5. Interview will be transcribed / notes were taken for approval, e-mail within one week to your mailbox
6. You have the right to request access to and rectification or erase of personal data
7. Non-response on the sent transcript after 2 weeks is assumed as a permission to use the data

Background and expertise

1. *How and when did you first direct your career towards CCS technologies and projects*

2. *What are the main changes in the CCS environment since then?*

3. *Have you worked on or with CCS projects? And in what capacity?*

4. *What is your current affiliation with CCS technologies or CCS projects?*

5. **Unique for each interviewee:** *What is your current function, and how does that link to CCS technologies or projects*?

Current/past CCS project/research contribution

1. *One of my research questions is the following SQ1: How and under what circumstances have CCS projects around the world succeeded or failed? (Background) What do you think is the mean reason a CCS project fails or succeeds?*

2. *What is needed for future projects to be deployed successfully and more efficiently?*

3. *Do you have any examples of moments where a CCS project has failed or succeeded due to a specific course of action?*

CCS deployment KPIs

1. *I am trying to compose a detailed list of KPIs or characteristics that are deemed indispensable for creating a policy framework for the deployment of CCS projects in the North Sea region. What would you deem crucial/essential for the success of CCS projects?*

2. *Would you say there is a need for a clear and comprehensive policy framework for the deployment of CCS projects?*

CCS actor field

1. *In the CCS projects that you have managed or have experience in, could you give me a short explanation of how many different actors were involved and what their roles were?*

2. *How do these individual actors contribute towards the deployment of CCS projects?*

3. *How do these actors collaborate towards the deployment of CCS projects?*

4. *Which actor roles do you deem crucial for the deployment of CCS projects?*

CCS governance

1. *Do you think regulations in CO_2 storage are up to date for large-scale CCS deployment?*

2. *What is the most important point on the agenda to further and better CCS project deployment?*

3. *IPCC claims CCS and CCU could help mitigate 20% of our GHG emissions by 2050, do you think this is still possible?*

4. *Large-scale CO_2 transport and storage infrastructure development and cost estimation in the Netherlands offshore. Do you think a pan-European CCS network would be possible, looking at the difficulties that would bring regarding governance and regulation?*

Interview conclusion

1. Again, gratitude for time/cooperation
2. Is there anything you would like to add to your answers?
3. Do you have any questions or remarks regarding this interview and my research?
4. Is there any information that you have shared confidential, if so, can it be used anonymously?
5. State that the notes/full transcript will be sent for approval
6. Approval within 2 weeks, otherwise, it is assumed that permission is given to use the data for the research.
7. You have the right to request access to the provided information or to withdraw from the study
8. Do you know other people relevant to my research?
9. Are you interested to receive the final research report?
10. Is it possible to ask follow-up questions?

Ethics and Data Management

Close attention has been paid to the anonymity of the research participants and their informed consent regarding participating in the research. Furthermore, data protection is an important topic since data has been gathered from consumers. All data is stored on TU Delft project data storages, only accessible to the research group.

Informed consent participants

All research participants must fill in the informed consent form and read the information sheet (see next page). The researcher provides additional information about the content of the research, purpose, risks of participating, and data storage and access. The participant must read and provide consent on a set of statements that are made explicit on the informed consent form. These statements are related to the extent to which the participant is informed about the research and that it will be used for academic purposes and data storage. This ensures that the participants have been adequately informed and given free consent. The participant is also informed about what they can withdraw without any implication.

Data protection

All audio recordings are stored on the TU Delft project data storage and will be later uploaded to the 4TU data folder. This data management strategy has been approved by the data office of TPM faculty of TU Delft and is approved by the HREC application.

C Consent form

Informed consent form

You will be interviewed as part of a research project on carbon capture and storage. This research aims to develop a policy framework intended to give insights into the deployment of CCS projects surrounding the North Sea region. This research will be in collaboration with TU Delft and Accenture.

What you agree with:

- No personal data will be shared with Accenture. Only the master thesis research including anonymized interview summaries will be made available to Accenture.
- The interview will be recorded and transcribed.
- Summaries of the interview will be published. Before publication the summaries will be sent to the you to give you the opportunity for rectification or adjustments.
- Access to the interview transcript will be limited to Alexander Berck and academic colleagues and researchers from the TU Delft with whom he might collaborate as part of the research process. The transcripts will be deleted after one month of completing the master thesis.
- The summary of the interviews will be made publicly available with the master thesis in the TU Delft education repository.

Interviewees are participating in this research voluntarily and are free to answer questions or not. At any time they may decide to end participation. The recording and transcript will be considered confidential. Only the TU Delft research team of the interviewer has access to the recording and transcript from this interview.

The data at all times will be secured within the systems of TU Delft. The summary will be anonymized. For questions, please contact main investigator Alexander Berck at a.a.e.berck@student.tudelft.nl.

Please tick the box that is applicable:

◦ **I consent to the use of the information collected about me for this research project.**

◦ **I consent to direct anonymous quotes being used in the master thesis project.**

Date:

Name:

Signature:

D Interview analysis

As addition to and substantiation of the main takeaways from the interviews identified in Section 4.4, this appendix will provide a more detailed analysis of the expert interviews conducted. From all interviews, the most important points of discussion are highlighted and supported by quotes taken directly from the transcripts. These takeaways form the basis of the main interview takeaways presented in Section 4.4.4.

Interview 1

Takeaways

1. **Background of R1:** R1 started researching CCS technologies when the Netherlands Ministry of Environment was looking at CO_2 capture, transport, and storage as a solution for emission reduction goals. R1's work involves risk assessment, risk management, subsurface application, and governance and societal issues related to CCS.

2. **Challenges in CCS:** R1 mentions that the CCS market still needs a lot of maturation. *Societal issues and long-term liabilities* can be hurdles for companies looking to develop CO_2 storage activities.

   "*Yeah, financial, and societal. Societal, I would say, when it comes to onshore storage in the Netherlands, it was quite a sensitive matter. But also from the financial point of view. The risk-sharing point of view along the value chain. That was quite difficult and still is maybe a little bit of could be a hurdle for some of the companies that would develop CO_2 storage activities because of the long-term liabilities.*"

   "*Yeah, and different views with different business models, let's say the business model for oil and gas expectation is different from the business model of generating energy or of producing goods.*"

3. **Characteristics of successful and failed CCS projects:** According to R1, a *proper financing structure*, including public or private solutions for companies to embark on new activities, is crucial. The *government's support* for underlying activities, such as power generation, is also essential. Examples of failed projects were due to political reasons, installation issues, and financial concerns. Success stories include the Sleipner project, which was successful because the Norwegian government had a taxation law, paying tax on offshore emissions.

   "*In the Netherlands, we have really a combination. In principle, the market in the Netherlands is orientated on being a private market. Somewhat of a liberal market where the private players are really the main players, and the government is there to create the conditions so that these private players can operate a sound business.*"

   "*If it comes to storage, it is mainly the current oil and gas companies or operators that are active. And that's for two reasons. The one important reason is they have the knowledge; they have the expertise. They* *also have the drive to reduce their emissions. And then there is the government, let's say, governmental entities. That they have to reach an emission reduction goal, let's say every country has to reach certain emission reduction targets. So, there is also a stake with the government in how to reach this target."*

4. **Risk-sharing and unbundling:** R1 talks about the importance of *risk-sharing along the value chain*, including long-term liabilities, and how *unbundling the capture, transport, and storage components* can minimize risks.

   "*That is something they have a problem with. Including these long-term risks in their business case. Which is something that got some attention already. They now are looking at unbundling. Unbundling the capture component, the transport component, and the storage component with different entities, also contractual entities.*"

   "*So that the burden is not with the company alone, but also, well actually, it is shared or maybe even taken over by the government.*"

5. **Societal aspect of CCS:** R1 mentions the societal aspect of CCS, such as *creating local value*, which is crucial in onshore storage.

   "*If it comes to onshore storage, I think the social aspect is quite important. They have this nice term. It is almost a technical term for this. But you have to create the local value. You may have to make a local value proposition.*"

   "*You must make it interesting for people as there are always people living around onshore storage.*" (Page 8)

6. **Pan-European network for CO_2 transportation and storage:** AB and R1 discussed the possibility of a pan-European network for CO_2 storage and transportation. R1 explained that Poland would connect more to Denmark and Norway for their CO_2 storage needs, while the Netherlands would likely connect with Belgium and Germany.

   "*So that more eastern countries like Poland would also have the possibility to store CO_2 through a European network.*"

   "*I think Poland would connect more to Denmark and Norway with their position at the Oost Zee. They are now thinking about having a terminal in Gdansk, the big port of Poland, and then thinking of having a few megatons per year being conditioned and transported to an offshore location before 2030, which could be in Norway or in offshore Norway or Denmark.*"

7. **Finite storage capacity:** They also talked about the *finite storage capacity of empty gas fields* and the need for *transnational solutions for storage.* R1 mentioned that while he was not involved in transnational projects, he had developed scenarios for them.

"*We have quite some storage opportunities but when it comes to storage in empty gas fields it is finite. So at some stage, let's say after the first generation capture installations, let's say in 25 to 40 years from now. Also, the Netherlands might look have to look for storage capacity beyond the Dutch sector of the North Sea. Or maybe looking at other alternatives like storage in aquifers instead of depleted gas was. Yeah. Yeah. So that requires that, at some moment, there is a need for transnational solutions.*"

"*Not less, it might grow. Actually, it does grow, but there is a there is time, let's say, depending on the demand for storage capacity. And the availability of the storage potential. The total estimated capacity is limited and can be phased out maybe in 25 years or 40 years. It just depends on the demand.*"

8. **Mitigating GHG emissions:** AB asked how the International Panel of Climate Change's goal of mitigating 20% of GHG emissions by 2050 through CCU and CCS could still be viable if gas reservoirs and storage options deplete over time. R1 responded by saying that all options will be needed, including storage in aquifers, which is being pursued in Norway and the UK.

   "*And then to follow up on that, maybe a bit of a broader question, the International Panel of Climate Change claimed that CCU and CCS will be able to mitigate 20% of GHG emission by 2050. But how is this done and still viable if these gas reservoirs and options deplete over time? You will also need all options. Let's say the storage in aquifers is being pursued in Norway and the UK also. And maybe in the future, also in the Netherlands, although our current view is that the aquifer storage potential in the Netherlands sector is limited and not that sizable.*"

Interview 2

Takeaways

1. **Challenges in CCS projects:** AB and R2 discuss the challenges in implementing CCS projects, including the need for *long-term financing strategies*, the complexity of involving many different players, and the risks involved in moving and storing CO_2. They also discuss the issue of *ownership and responsibility* in the event of problems.

   "And the last thing I come across is actually risk. There's just a lot of risk involved in moving and storing CO_2. Who owns the risk? When might the government even want to take some of the risks as well? And how are we actually going to evaluate the different parts of the whole value chain? And if something goes wrong, who is to blame?"

   "We did work with Porthos to foresee these kinds of operational problems. For example, what if an emitter suddenly wants to start sending in more CO_2 or less? Or the combined flow is suddenly much too low? What to do with that, then? We do end up running into more practical cases when asking 'whose responsibility is it?' And within the Porthos project, there would also be a lot of focus on the question

'who bears risk?'."

2. **Examples of CCS projects:** R2 mentions the Porthos and Athos projects. The Athos project was discontinued because Tata Steel decided to switch to the hydrogen method, eliminating the need for CO_2 emissions analysis. The Porthos project, on the other hand, is still ongoing and has been working to foresee potential operational problems.

   "Yes, I dare not say so well where that all went wrong, But I do know an example. Besides Porthos, you also had Athos. Are you familiar with that? They pulled the plug on that because Tata Steel had figured out that they were going to switch to the hydrogen method and thus not do any more analysis for CO_2 emissions. So where does that actually lie? The biggest CO_2 producer or CO_2 emitters suddenly pulled out of the project and by another strategy."

3. **Actor field of CCS projects:** R2 describes the various actors involved in the Porthos project, including Gasunie, EBN, and the Port of Rotterdam. Each of these actors plays a specific role in the project, leveraging their unique expertise and resources.

   Porthos itself is a joint venture of Gasunie, EBN, and the port of Rotterdam. And within Porthos itself, we have all kinds of subgr oups. We have a commercial team, finance team, public affairs, compressor station, offshore pipeline and offshore pipeline. Group for permits. We ourselves are the Porthos operations team."

   "In terms of parties that are involved, there is Gasunie. This is because they have knowledge of gas transport. You will also see that their knowledge about gas transport and the compressor station will be included. Then you have EBN (Energiebeheer Nederland). That has a lot of knowledge about everything that is under the ground, so subsurface. These are gas fields under the North Sea. They also have a lot of offshore experience. So that is a party that helps with that. Port of Rotterdam actually deals with the area around the port of Rotterdam and also the market."

4. **Regulations and future of CCS:** AB and R2 discuss the current state of *regulations for CCS projects* and the potential need for updates. They also discuss the future of CCS, noting that while it's a crucial solution for achieving a circular economy by 2050, the ultimate goal is to move away from CCS towards CCU. When R2 is asked whether he/she thinks regulation on CCS is up-to-date, the following answers are given:

   "I don't think it's completely up to date. I think it could definitely be updated some more. I think it still has some things being figured out. But exactly also what you're saying if at some point that gas field is completely full of CO_2 and in 20 years all of a sudden that does happen or something. Then who is really responsible for that?"

   "Yes, because it is, of course, as is often said, a crucial solution to achieve a circular economy by 2050. But ultimately, we're looking to get away from that altogether, of course. So then you really want to move

away from CCS and maybe move on to CCU."

Interview 3

Takeaways

1. **Urgency of CCS:** The interviewees stress the urgency of implementing CCS. They believe that it is already late, and we need to speed up getting CO_2 out of the atmosphere or prevent CO_2 from getting into the atmosphere as far as possible.

2. **Technical aspects of CCS:** The technical aspects of CCS have been discussed, including the specifications for the captured CO_2, the process of injecting CO_2 into depleted gas fields, and the considerations for decommissioning these fields after they have been filled. They mention that the Porthos project will be the first project to inject the CO_2 in depleted gas fields, which is expected to be very effective for storage.

3. **Societal aspects of CCS:** The interviewees discuss the social aspects of CCS, including the importance of *political support* and the need for a framework for dealing with CO_2 storage. They mention that in many countries the basic framework is not yet there although that really helped their project.

   "I think that those are important to mention, and maybe looking back, our project has started in 2017 and one of the first things we have been working on or my colleagues have been working on was the public acceptance and the political acceptance of CCS as a solution within the energy transition."

4. **Long-term financing of CCS projects:** Just as in interview 1, the importance of *long-term financing* for CCS projects is discussed. R3 & R4 mention that contracts have been created with all partners involved in the Porthos project to ensure that the project can continue for the necessary number of years. These contracts are long-term and should provide *financial safety* to the project. All potential problems in the future should be addressed while also thinking about potential solutions to those problems.

   "So we need to show that it is possible, and we need to do that in a secure way. And in an economically viable way. So, what is also part of our contracts is that there is an inflation possible on the tariff because we needed to give a tariff quite early in the project, but you're not certain what the tariff will be in the end."

5. **Risk-sharing in CCS projects:** The interviewees discuss the importance of *risk sharing* in CCS projects. They mention that in the Porthos project, the Dutch Government takes full responsibility for any leakage after the fields are decommissioned.

   "There was a lot of debate on what kind of partnership we want and who's taking which stake in the companies that were created for this project."

6. **Decommissioning of CCS projects:** The considerations for decommissioning CCS projects after they have been filled is one of the things to think about after the deployment of CCS projects/networks. They mention that the Dutch Government takes full responsibility after the fields are decommissioned.

7. **CCS in other countries:** The interviewees mention that they get a lot of interest from other countries who want to know how to start up with the new value chain and what CO_2 capturing and storage will be.

   "Yeah, we have been to Antwerp last month, and what we see there is that the emitters themselves, they are part of the partnership. They will become the owner of the pipeline system or parts of it or the compressor station of the liquefaction terminal."

8. **Examples of CCS projects:** R3 and R4 mention several CCS projects, including the Porthos and Gorgon projects. The Gorgon project faced technical problems due to the wet composition of the captured CO_2, leading to corrosion in the pipeline system.

   "So, the Aramis project is the second project that is being developed. It will become available a few years later after Porthos, and it will maybe have a longer life because it will connect to more fields offshore than the P18 field with larger capacities."

9. **Actor field of CCS projects:** R3 describes the various actors involved in the Porthos project, including Gasunie, EBN, and the Port of Rotterdam. Each of these actors plays a specific role in the project, leveraging their unique expertise and resources.

   "We know the sand layers; we know the behavior of the wells where we are extracting. One thing to mention is that Porthos is a combination of the Port of Rotterdam Authority, Dutch Gasunie BV, and IBN. IBN, they are a state-owned company in the Netherlands. They are to be in every oil and gas production activity for a limited number of partnerships. They have knowledge of the geology below the North Sea. They are a very important partner, and they have drawn up the permits for storing CO_2."

   "Well, specifically on the Porthos project, I think these three actors are working quite well together. And since Porthos is a joint venture of these three actors. And I think in that sense everything is going quite well. What is interesting to see is that, especially in the Netherlands, the Minister of Climate and Energy is rethinking the role of the different state-owned companies."

10. **Regulations and Future of CCS:** AB and R3 discuss the current state of regulations for CCS projects and the potential need for updates. They also discuss the future of CCS, noting that while it is a crucial solution for achieving a circular economy by 2050, the ultimate goal is to move away from CCS towards Carbon Capture and Utilization (CCU).

11. **Challenges in CCS Projects:** The interviewees discuss the challenges in implementing CCS projects, including the need for *long-term financing strategies*, the *complexity of involving many different play-*

ers, and the *risks involved in moving and storing CO_2*. They also discuss the issue of *ownership and responsibility* in the event of problems.

12. **Pan-European CCS Network:** The possibility of a pan-European network for CCS is discussed. They mention that there are technical, economic, and geological aspects to consider. For instance, the further you want to transport your CO_2 from an emitter to a sink, the more energy you need. There will be a maximum distance to which it is still logical to transport CO_2, or it will take so much energy that it is not sufficient or it is not logical to do that.

    "You first need the first clients to be locally and I think in adding more clients to the system and the next development of CO_2 and the amount of storage capacity that we have in the North Sea. Is not only enough for Dutch clients, but we will also be sufficient for our clients coming from Belgium or coming from Germany."