

Governing CCS Networks

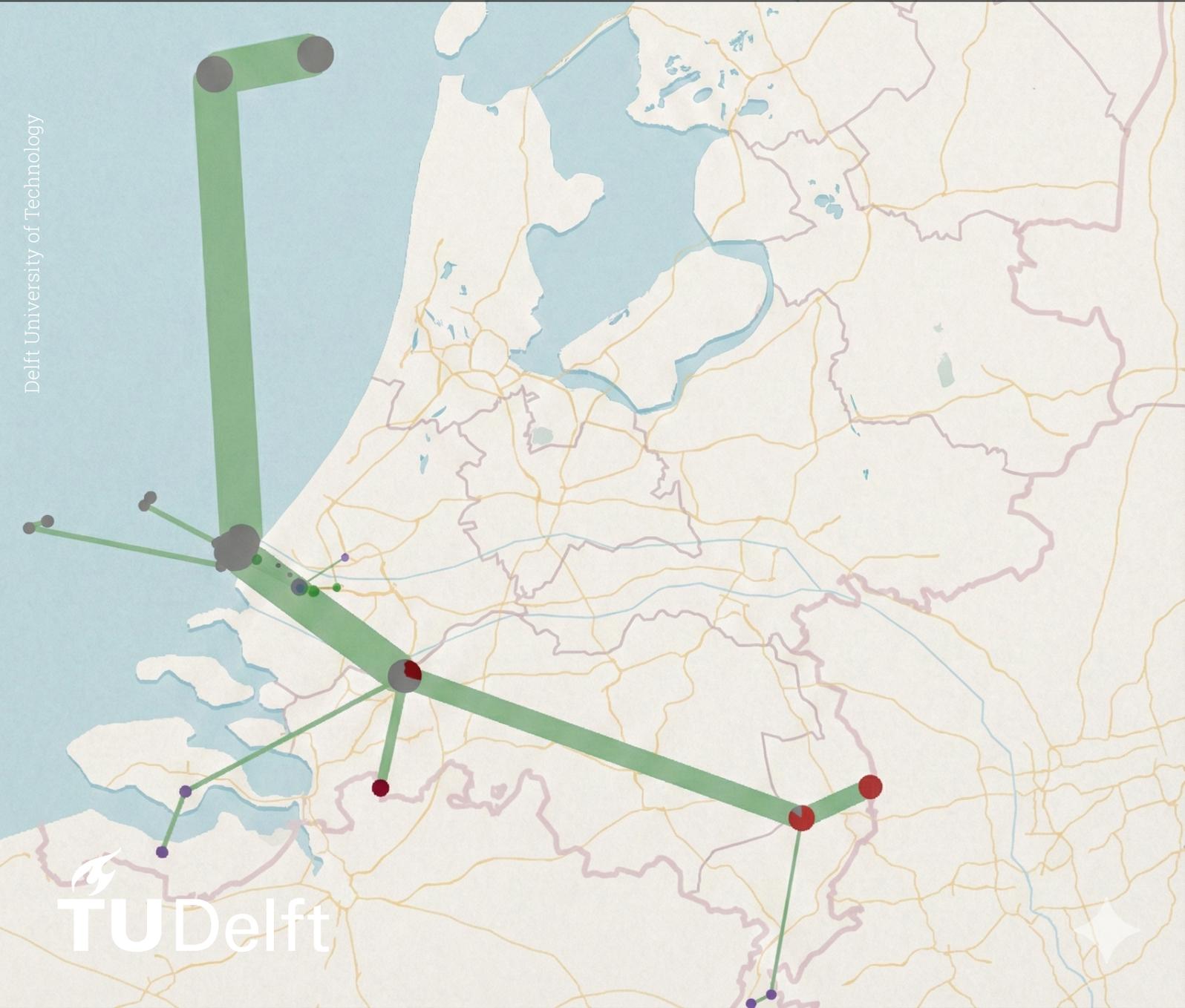
A Techno-Economic Analysis of Governance and Risks in the Developing Dutch CCS Market

Master Thesis

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A Techno-Economic Analysis of Governance
and Risks in the Developing Dutch CCS Market

by

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An electronic version of this thesis is available at <http://repository.tudelft.nl/>. Associated files and models are available at https://github.com/DaanKahmann/MasterThesis_DaanKahmann

Preface

Just as I am writing this preface at the end of my master thesis journey, so is this master thesis the end of my time as a student, both in Groningen and Delft. Writing this master thesis has been challenging at times but even so I enjoyed it. I am very thankful to have had the opportunity to write this master thesis at the Ministry of Climate and Green Growth as part of the NPE-team. Without this internship, I would not have been able to learn as much and as quickly to be able to write the thesis as you will read it now. I am curious to see if and how governance of CCS networks will change in the upcoming years.

As is customary but also very much earned, I would like to thank Erika for supervising me at the Ministry. I had a great first "working" experience and can only admire your drive and passion in your work for achieving a climate-neutral society. I would also like to thank my academic supervisors Laurens, Özge, and Jasper. I feel like I have not had the smoothest and most usual journey towards this final report, having written relatively little at every meeting. Therefore, I am thankful for the confidence you have still given me throughout the process.

Both in Groningen and in Delft I have made some great friends that made my time as a student unforgettable and (apart from sometimes studying) very fun as well. I have had some amazing and memorable moments and am sure more will come. Last, I would of course like to thank my family. Throughout the years, they have not only supported me as a family but we have also gotten closer, becoming good and perhaps best friends. I look forward to the next steps and hope you will all enjoy reading the culmination of my years as an AI and CoSEM student.

*Daan Kahmann
Delft, February 2026*

Summary

The transition to a net-zero energy system by 2050 presents a formidable challenge, particularly for hard-to-abate industrial sectors such as steel, chemicals, and refining. For these industries, Carbon Capture and Storage (CCS) is increasingly recognized as an indispensable bridging technology to abate unavoidable process emissions. At the same time, the deployment of CCS infrastructure enables future negative emissions technologies. However, the deployment of CCS infrastructure at scale faces a fundamental governance challenge: how to coordinate investments across a fragmented value chain characterized by high capital intensity, deep uncertainty, and significant asset specificity. This thesis investigates how governance frameworks can be designed to mitigate the coordination failures, utilization risks, and market power concerns that currently hinder the development of CCS systems.

To analyse these universal challenges, the Netherlands is utilized as a case study. As a potential CCS hub with significant offshore storage capacity, industrial clusters with significant demand, and a strategic location for cross-border transport, it offers a representative context for examining the problems and potential solutions in the development of CCS systems.

System Analysis and Methodology The research adopts a mixed-method approach, combining a qualitative system analysis and stakeholder interviews with a quantitative techno-economic optimization model (PyPSA). The system analysis identifies the Netherlands as a uniquely positioned storage hub, dependent on five major domestic industrial clusters and substantial cross-border flows from Germany and Belgium to achieve necessary economies of scale. To capture the full complexity of this system, the methodology integrates qualitative insights from interviews with key stakeholders, including policymakers, and transport and storage infrastructure operators, with a quantitative multi-period optimization model. This model simulates the cost-optimal rollout of transport and storage infrastructure from 2030 to 2050 under various demand scenarios and variations, allowing for a rigorous stress-test of infrastructure development and costs under demand uncertainty (both in volume and time) and changing economic parameters.

Risk Identification The combined qualitative and quantitative analysis identified distinct risk categories that hinder market development. Qualitatively, the stakeholder interviews revealed that coordination risks are the primary barrier in the start-up phase, a so-called chicken-and-egg problem where neither emitters nor operators are willing to commit first. Additionally, market power risks were identified as a major concern for the mature phase. This split in phases means there are considerable "temporal risks". Last, the reliance on cross-border regulation poses risks which are harder to control through national governance choices.

Quantitatively, the model results substantiated these concerns by identifying utilization risk as the most critical factor influencing economic viability. In high-demand scenarios, the analysis shows that shared pipeline backbones achieve significant economies of scale. However, in low-demand scenarios, infrastructure build-out is postponed or more expensive ship transport is preferred due to low utilization, exacerbating the coordination failures identified in the interviews. A key quantitative finding is the system's high sensitivity to cross-border flows: without substantial imports, the business case for large-scale infrastructure deteriorates, creating a significant risk of stranded assets. Furthermore, the model confirms the natural monopoly characteristics of the network, showing that while ship transport offers flexibility, it remains approximately 38% more expensive than fully utilized pipeline transport.

Governance Performance and Risk Mitigation To address these challenges, a governance options framework was developed based on Transaction Cost Economics and Network Regulation Theory. The research then explicitly links governance instruments to the mitigation of specific risks, demonstrating that no single mechanism is sufficient:

- **Mitigating Coordination Risks:** To resolve the initial chicken-and-egg coordination problem, financial incentives and structural coordination designs can be implemented. State guarantees and supply-side subsidies are necessary to cover the utilization risk that currently stalls Final Investment Decisions (FID). Simultaneously, Public-Private Partnerships (PPPs) in storage and vertical coordination can effectively bridge the trust gap between emitters and operators.
- **Mitigating Market Power Risks:** As the system matures, the natural monopoly characteristics of the pipeline backbone present significant market power risks. The analysis shows that behavioural constraints alone are inadequate. Legal unbundling of transport and storage from capture activities is identified as the most effective structural option to eliminate information asymmetry. This must be complemented by Regulated Third-Party Access (rTPA) and tariff regulation to ensure fair market entry while maintaining operator profitability.
- **Addressing Temporal Risks:** The governance design must address the trade-off between short-term investment certainty and long-term market efficiency. Mechanisms that mitigate early-stage risks (like state-led coordination) can become liabilities later. Therefore, the framework proposes an adaptive governance path, transitioning from active government support in the start-up phase to regulatory oversight as the market matures.

Conclusion The thesis concludes that successful CCS deployment depends on prioritizing governance instruments that align with specific policy goals. Prioritizing rapid deployment favours stronger state intervention and guarantees, while prioritizing market efficiency favours lighter regulatory mechanisms, albeit with higher risks of delay and possibly failure of projects. By explicitly weighing these trade-offs and utilizing the developed governance framework, policymakers can design a robust strategy that leverages CCS as a vital component of the climate transition while mitigating the inherent risks of this transitional infrastructure.

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Nomenclature

Abbreviations

Abbreviation	Definition
ADAPT	Scenario from TNO energy scenarios (maintain current lifestyle)
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CDR	Carbon Dioxide Removal
CHEM	Chemelot (industrial cluster)
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Storage
DRC	Delta Rhine Corridor
DSC	Delta Schelde Corridor
EBN	Energie Beheer Nederland
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
FID	Final Investment Decision
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LC&I	Low Carbon & Industry (TNO TRANSFORM scenario variant)
LCOC	Levelized Cost of CO ₂
LCOT	Levelized Cost of Transport
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
Mtpa	Megaton per annum
NN	Noord-Nederland (industrial cluster)
NPE	Nationaal Plan Energiesysteem
NPV	Net Present Value
NZIA	Net-Zero Industry Act
NZKG	Noordzeekanaalgebied (industrial cluster)
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PBL	Planbureau voor de Leefomgeving
PoR	Port of Rotterdam
PyPSA	Python for Power System Analysis
RDM	Rotterdam-Moerdijk (industrial cluster)
ROI	Return on Investment
RVO	Rijksdienst voor Ondernemend Nederland
RoR	Rate of Return
SDE++	Stimulering Duurzame Energieproductie en Klimaattransitie
T&S	Transport and Storage
TCE	Transaction Cost Economics
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TRANSFORM	Scenario from TNO energy scenarios (lifestyle change)

Abbreviation	Definition
TRL	Technology Readiness Level
UK	United Kingdom
WACC	Weighted Average Cost of Capital
WtE	Waste-to-Energy
ZWB	Zeeland-West Brabant (industrial cluster)

Symbols

Symbol	Definition	Unit
Indices and Sets		
a	Investment period index	[-]
A	Set of investment periods	[-]
l	Link (branch) index connecting buses	[-]
n	Bus (node) index	[-]
s	Component type index (generator/storage)	[-]
t	Time snapshot index	[-]
T_a	Set of snapshots in investment period a	[-]
Parameters and Variables		
$a(r, n)$	Annuity factor (function of discount rate and lifetime)	[-]
b	Build year	[year]
C	Total capital cost (CAPEX)	[€]
c	Specific capital cost (per unit capacity)	[€/unit]
$C_{I,p}$	Pipeline specific capital cost intensity	[€/t/h)/m]
CF_p	Pipeline capacity factor	[-]
d_p	Pipeline diameter	[inch]
E	Energy storage capacity	[tCO ₂]
f	Flow rate through a link	[tCO ₂ /h]
F	Nominal link capacity	[tCO ₂ /h]
g	Generator dispatch (capture rate)	[tCO ₂ /h]
G	Nominal generator capacity	[tCO ₂ /h]
h	Storage dispatch (injection rate)	[tCO ₂ /h]
L	Length (pipeline) or Lifetime (component)	[m]; [year]
n	Economic lifetime (in annuity formula)	[year]
O	Total operational cost (OPEX)	[€]
o	Marginal cost (variable OPEX)	[€/tCO ₂]
p	Power/Flow dispatch	[tCO ₂ /h]
Q	Flow rate	[tCO ₂ /h]
r	Discount rate; Radius of Earth	[%]; [km]
v	Velocity of fluid	[m/s]
v^o	Objective weighting of investment period	[-]
w^o	Weighting of snapshot	[h]
w^g	Global constraint weighting	[h]
Γ	Global constraint limit (total capture)	[tCO ₂]
η	Efficiency	[-]
λ	Longitude	[rad]
ρ	Specific capture/emission per carrier	[-]
ϕ	Latitude	[rad]

1

Introduction

Achieving net-zero emissions by mid-century represents one of the most complex infrastructure transitions in modern history. While renewable electricity and energy efficiency improvements are essential components of decarbonization strategies, deep emission reductions in energy-intensive industrial sectors including steel, chemicals, and refineries remain technologically and economically challenging (IPCC, 2023). For these hard-to-abate sectors, Carbon Capture and Storage (CCS) has emerged as a critical bridging technology, offering a pathway to substantial emission reductions while alternatives for those industries mature. CCS involves capturing carbon dioxide (CO₂) emissions at their source, conditioning and compressing the CO₂ to required specifications, transporting it via pipelines or ships, and injecting it deep underground into geological formations for permanent storage. The Intergovernmental Panel on Climate Change (IPCC) identifies CCS as indispensable in scenarios limiting global warming to 1.5°C, particularly for industrial decarbonization and future carbon dioxide removal (IPCC, 2023).

The scale of CCS deployment required to meet climate targets is massive and increasingly urgent. Recent analysis by Grant et al. (2025) in the Rescuing 1.5°C report indicates that, to limit overshoot and return global warming to 1.5°C by 2100, the world must rapidly scale engineered carbon removals to approximately 5.5 gigatonnes of CO₂ per year by 2050. While there is debate on the amount of fossil CCS, with Grant et al. (2025) estimating 500 megatonnes per year (Mtpa) in 2050, 80% lower than the IPCC (2023), it is evident that CCS infrastructure and storage capacity must be scaled quickly. Especially because capacities are "close to zero today" (Grant et al., 2025).

However, the deployment of CCS infrastructure at scale faces a fundamental governance challenge: how to coordinate investments across multiple stakeholders in an emerging market characterized by high capital intensity and deep uncertainty about future demand. Unlike established network industries such as electricity or natural gas, CCS systems must be built from scratch while navigating the transitional nature of the technology. CCS infrastructure is essential for near-term emission reductions yet likely superseded by zero-emission alternatives in the long term, while partly still being essential for the realisation negative emissions. The high uncertainties and capital intensity create a coordination problem between emitters, requiring certainty about transport and storage availability, infrastructure operators, demanding volume commitments before investing, and governments balancing public expenditure against alternatives and (climate) goals (Akerboom et al., 2021).

The Netherlands provides a particularly instructive case study for examining the risks and potential solutions. The future Dutch CCS system contains domestic industrial clusters, natural gas fields providing substantial geological storage capacity, and import and export. Current projections indicate that it is highly unlikely that the Netherlands will meet the 55% 2030 emission reduction target ("klimaatwet", 2023), with the probability estimated to be below 5% (PBL, 2025). The large potential for relatively quick emissions reductions compared to less technologically mature alternatives makes CCS increasingly critical for achieving both near-term and the 2050 net-zero targets. Yet, the Dutch system faces several unique complications: dependency on cross-border CO₂ imports from Germany and Belgium

to achieve economies of scale, competition from Norwegian storage parties, and policy uncertainty regarding the role of CCS relative to electrification and hydrogen. These factors make the Netherlands an ideal context for quantifying risks and analysing how governance design can address these risks in developing CCS markets.

1.1. Background and Context

The Carbon Capture and Storage system consists of three parts: emitters capturing CO₂, storage operators developing storage injection capacity, and transport operators transporting CO₂ between the emitters and stores. In this thesis, demand is defined as the demand for **CCS** (encompassing the emitters) and supply as the supply of **CCS** (encompassing the transport and storage operators). This naming indicates an important difference from the electricity, gas, and hydrogen markets. In those markets, the traded commodity has inherent value and therefore demand. CO₂ is a waste product, however, meaning there is no demand for the CO₂, but for the disposing of that CO₂. The reason emitters want to capture and dispose of their CO₂ is to avoid paying for emitting CO₂, which is taxed through the European Emission Trading System (EU ETS). This is a cap-and-trade system, yearly reducing the tradeable credits. In a market with perfect foresight, companies would invest in CCS when the credit price per ton of CO₂ is lower than the unitary cost of disposal (including capture, transport, and storage costs).

In the Netherlands, the potential demand for CCS is concentrated in five main industrial clusters: Chemelot (CHEM), Rotterdam-Moerdijk (RDM), Noord-Nederland (NN), Zeeland-West Brabant (ZWB), and the Noordzeekanaalgebied (NZKG) (Koole et al., 2024). While there is a "cluster 6" (C6), consisting of all other industry outside of the main clusters, these individual companies are smaller and distributed across the country. This, along with the high upfront capital expenditures (CAPEX) (Akerboom et al., 2021) makes building nation-wide infrastructure inefficient. In general, the sectors taken into consideration for CCS are the power, steel, cement, waste processing, and refineries sectors (Turgut et al., 2021), although there is no cement production in the Netherlands. Apart from these sectors, new sources can potentially add demand for CCS. These are the production of hydrogen and the capture of CO₂ from the atmosphere or using biogenic sources through carbon dioxide removal (CDR). Within the five industrial clusters, there are around 60 emitters with emissions above 100 kton/year, which is the level generally considered for potential CO₂ capture (CE Delft, 2024; Martoriello et al., 2024).

The supply of CCS consists of transport supply and storage supply. Transport is possible by pipeline, boat, train, and truck. Depending on the transport technology, temporary storage, compression, or liquefaction are necessary. The CO₂ is transported to storage sites, which currently consists of (almost) empty oil and gas fields to store CO₂ underground at a minimum depth of 1000m. The total economic storage capacity in the Dutch gas fields is estimated to be 1260-1750 Mt (TNO, 2025). Given the estimations of potential storage demand both inland and from import, this storage capacity is likely sufficient until at least 2050. In addition, Norway, the UK, and Denmark have far greater capacities available, up to 70-80 Gt. Chapter 4 gives a more detailed overview of current and projected projects, both of the demand and supply of CCS.

The key challenges of carbon capture and storage are no longer technical but are mainly larger system organisation and implementation questions. Akerboom et al. (2021) describe the lack of a sound business case and a stable socio-technical narrative as the main barriers to deployment of CCS. CE Delft (2016) argues for public-private partnerships (PPPs) to organize CO₂-infrastructure along with possibly a government-owned transport operating company. However, the current market organisation of CCS is considered to be business-to-business (B2B) (Hermans, 2025), meaning that the private sector is responsible for coordination, planning and risks. While the government has set market rules on safety and fair participation enforced by the regulator, there is no structural governance in place to prevent market power abuse or mitigate investment risks.

The aim of the chosen policy trajectory is to have a good functioning CCS-market in the long-run with no specific government intervention. This is largely based on Mulder (2024), arguing such a mature market can eventually be expected. The rationale is that the CO₂ price will be the driving factor for the CCS market to develop and that minimal government intervention is necessary on the transport and storage (T&S). However, CAPEX subsidies for large transport projects as well as capture facilities (CE

Delft, 2024) have been introduced to cover initial utilization risks and infrastructure timing mismatches. However, current infrastructure operators and potential future users of CCS infrastructure still voice concerns signalling a lack of trust in the development of the market and limited commitment. Large uncertainties in the business-case and market conditions show that more specific government interventions than proposed by Mulder (2024) may be necessary, both in the start-up phase and in the long-run.

1.2. Problem Statement and Research Objectives

Despite the critical role of Carbon Capture and Storage (CCS) infrastructure in the net-zero transition, research effectively combining risk identification with governance mitigation strategies remains limited. Current literature is predominantly dominated by techno-economic optimization, focusing on minimizing system costs and identifying optimal transport routes. While valuable, such optimization leaves out the route to reach such systems. Conversely, while extensive governance theories exist to address coordination failures and infrastructure regulation, these have rarely been systematically applied to the specific context of CCS. This is a critical oversight, as CCS presents unique governance challenges compared to mature networks (like gas or electricity) due to its transitional nature and the distinct risks of a developing market. As substantiated in the literature review (Section 2.6), a clear research gap exists: current literature does not accurately identify and quantify CCS risks, explore the specific governance options, and combine the risks with the governance theories to identify the possible mitigation strategies.

The research objective of this report is to bridge this gap by identifying the risks in the development of the CCS system, both qualitatively and quantitatively, identify the governance options by combining governance theories, and developing a framework of governance options derived from established theory. The research aims to determine which governance structures and mechanisms are best suited to mitigate identified risks. To achieve this, network regulation frameworks are synthesized with Transaction Cost Economics (TCE), providing a theoretical basis for analysing market power and investment incentives. To scope the problem and enable quantification of risks, the Dutch CCS system is taken as a case study. The Netherlands offers an ideal context as it encompasses all functional components of a possible CCS value chain, including inland industrial demand, offshore storage, and cross-border import/export, allowing for a comprehensive assessment of the governance challenges involved.

The current business-to-business (B2B) governance model in the Netherlands (Hermans, 2025) fails to set the right incentives and is found to possibly lead to a hold-up problem: emitters and transport operators both wait for each other to commit (a so-called "chicken-and-egg" problem). With CCS being important to realise quick emission reductions in hard-to-abate sectors and for crucial future negative emission technology (Grant et al., 2025), this shows the societal urgency and relevance of solving this problem.

1.3. Research questions

From the problem statement and research objective the following research question is formulated.

How can governance be designed to mitigate risks in the developing Dutch CCS network?

In order to answer the research question, the risks in the system halting the development of the CCS-system and posing a threat to the future of the system have to be identified. Time is an important factor here: risks in the start-up phase may be different than those while the system is fully operational, as indicated by Mulder (2024). The main form of mitigation is governance. This includes different forms of market organization as well as network regulation and incentives. It is difficult to define when the best development is chosen: it depends on the trade-off of social values, represented by political choices. Identifying these trade-offs while considering the different risks and needs in subsequent stages of the development is therefore the goal of this research question.

In order to answer the main research question, the following sub-questions are formulated. The methods used to answer them are presented as well, but explained in more detail in Chapter 3.

SQ1: *What are the key characteristics and planned developments of the demand and supply of CCS in the Netherlands?*

To identify risks in CCS-systems, the Netherlands is taken as a case study. Therefore, the first step is to characterize the demand sectors and supply for CCS in the Netherlands. The CCS system in the Netherlands is already in development with multiple planned projects, although only a few have taken FID. On the demand side, the five industrial clusters will be taken into account, along with possible inflows of CO₂ from Germany and Belgium. The supply consists of transport infrastructure and injection platforms, including temporary storage and compression. Storage by ship is included through a connection to Norway. The proposed and planned projects, including their progress are identified through desk research and interviews with stakeholders and experts. The goal is to identify realistic future development paths and use these for the development of a model to quantify the risks.

SQ2: *What are the key risks in the development of the CCS network both over time and for different parties in the value chain?*

The goal of this sub-question is to identify risks in the system hindering the development of a future system. "Risks" are defined as financial, behavioural, knowledge or safety concerns delaying or completely stopping the development of the system necessary to reach climate goals. The risks will be identified through two methods:

1. Expert and stakeholder interviews are used to identify qualitative risks and concerns of current market parties with differing objectives.
2. A cost-optimization model is developed to both support the claims from the interviews and identify additional risks. The model also provides quantitative insights into system and unitary costs over varying scenarios. By quantifying the costs, the size of the risks, impact of different development pathways, and the business case of different options are analysed.

The identified risks are then combined and compared. In order to mitigate these risks, governance options need to be identified, which is the goal of the next sub-question.

SQ3: *What are the different governance options to support the development of CCS networks?*

The objective of this research question is to develop a coherent governance framework showing the governance options in the development of CCS systems. This governance framework is grounded in governance theory (presented in Section 2) combined with results from the interviews and how governance is currently organized in different countries. The tradeoffs between different choices as well as the risks they could mitigate are presented. While the framework is designed with CCS-systems in mind, its performance given the identified risks in the second sub-question are not analysed. This is the goal of the last sub-question.

SQ4: *How do different governance options perform in mitigating the identified risks in CCS networks?*

It is important to apply the identified risks to the governance options to show the decisions which are most relevant and effective in CCS-systems. While the previous sub-question identifies all options and trade-offs, some may be more or less appropriate in the context of the CCS-system. Some governance decisions are more robust over several demand projections, while others may show clear trade-offs. Decision-making within this solution space depends on social values and political choices: what is the goal of CCS in the context of emission reductions? Furthermore, reducing risks for market parties likely increases risks for the government and is possibly very expensive.

The Discussion then reflects on the applicability of the governance framework and risk mitigation decision-making to other countries and other networked systems. It also includes policy advice for the Dutch case study.

1.4. Report Structure

Chapter 2 substantiates the research gap and problem statement from Section 1.2 by presenting state-of-the-art literature. At the same time, it describes the governance theories used to develop the governance framework. Chapter 3 presents the methodology to answer the research questions, detailing the underlying optimization method and data of the model as well as how the interviews were conducted. It also further describes how the research questions are connected to reach the research objective.

To answer the first sub-question, Chapter 4 provides a thorough system analysis, subsequently setting the model parameters such as demand, supply, and lay-out. This chapter is then followed by the model results (Chapter 5), answering the second sub-question using the model and interview results. Last, the Discussion (Chapter 6) answers the final two sub-questions, explaining the governance options and performance of those options under the identified risks.

Finally, Chapter 7 discusses the results in light of different contexts, and reflects on the used theories and academic literature as well as the limitations and future research. This all leads to the Concluding Chapter 8, answering the research question and providing actionable policy advise.

The appendices show a further in-depth analysis of the potential demand for CCS (Appendix A), the AI-statement (Appendix B), and the summaries of the interviews (Appendix C)

2

Literature review

The goal of this literature review is to get a better understanding of the state-of-the-art literature on CCS in order to formulate a research gap. The implications of the research gap and state-of-the-art literature are discussed in the introduction (Section 1.2) The first main research topics to investigate are CCS network optimization and allocation problems, since these touch on the techno-economic challenges which are the basis of this research. Optimization studies address the uncertainties in system while allocation is focussed on the division of risks, costs, and responsibilities, which can be used to address those risks. Apart from this, literature on CCS in the Netherlands is important. The Netherlands has a unique position with regards to CCS since, in many EU-wide optimisation scenarios, it is a hub where CO₂ is transported to and from. Therefore, there is reason to suspect that the Netherlands has unique challenges. This, as well as an overview of the grey literature presented at the end, also forms a basis of the system analysis in chapter 4. The obtained literature can be divided into a few useful categories which are presented below.

2.1. How CCS Works

First, the basics of CCS technology along with some of the economics behind the market need to be discussed to get a good understanding of what the thesis is about.

2.1.1. Technology

CCS consists of three main stages: capture, transport, and storage in geological compositions. How they work is discussed below.

Capture There are three main methods for CO₂ capture: post-combustion, pre-combustion, and oxy-fuel combustion. Post-combustion removes carbon right after combustion. In pre-combustion technologies, the fuel is pretreated and then converted into a mix of CO₂ and hydrogen. The hydrogen is then separated from the CO₂ and used to produce the commodities with. Last, with oxy-fuel combustion, the fuel is burned using oxygen rather than air leaving a flue stream of CO₂ and water vapour (Durmaz, 2018). Which technology is most efficient depends on the concentration of CO₂ in the flue gas. The flue gas concentrations from industrial processes is mostly between 3-15%, the rest of the volume is comprised of nitrogen, steam, and smaller quantities of other pollutants (Gaurina-Međimurec et al., 2018). Pure CO₂ needs to be extracted and prepared for transport.

Transport Ship and pipeline are the main means of transport for CO₂ (Gaurina-Međimurec et al., 2018), with pipelines often preferred due to the large quantities. These are further compared in Chapter 4. Transport via pipelines is similar to gas pipelines, but there are three main differences (Lu et al., 2020):

- CO₂ is non-flammable and heavier than air, meaning that it diffuses more slowly than natural gas. Therefore, the main risk of leakage is the environmental impact of CO₂.

- CO₂ operation is different from natural gas and is affected by impurities, pressure, and temperature. This impurity level is less of a concern for natural gas.
- CO₂ pipelines need to be stronger due to the material properties of CO₂.

Transport by pipeline is possible in gaseous phase, liquid phase, dense-phase and supercritical phase (Lu et al., 2020). The former two can be used for short-distance transport, while the latter two are mainly for long-distance transport. Therefore, it is often necessary to condition the CO₂ before long-distance transport, changing its phase and pressurising it. Furthermore, long-distance transport requires stronger compressors or pumps, possibly with booster stations along the way to not have the pressure drop.

Ship transport offers an alternative to pipelines, particularly for long distances and offshore storage sites. CO₂ is liquefied for maritime transport, typically at pressures of 7-15 bar and temperatures between -26°C and -46°C (Roussanaly et al., 2021). This requires dedicated infrastructure including liquefaction facilities at loading terminals that use ammonia-based refrigeration cycles to cool and condense the CO₂, specialized vessels designed for cryogenic liquid transport similar to liquefied petroleum gas (LPG) carriers, and receiving terminals with reconditioning units at storage sites (Simonsen et al., 2024).

Storage CO₂ storage involves injecting captured CO₂ into deep geological formations where it is permanently trapped. The two main options for storage are depleted oil and gas fields and deep saline aquifers (Gaurina-Međimurec et al., 2018). In the Netherlands, depleted gas fields are the primary candidates for initial CCS projects due to their proven sealing capacity and existing infrastructure (TNO, 2025). Only depths of over 1000m are considered due to safety (Gaurina-Međimurec et al., 2018). The criteria for fields considered are: sufficiently high porosity (>20%), permeability (the ability of material to allow fluids to pass through it), available capacity, and the presence of structural traps and impermeable caprock. TNO (2025) consider two scenarios for minimal capacity required for economic viability: 10 Mt and 1 Mt. The actual minimum depends on the demand elasticity and accepted price, further discussed in the next section.

2.1.2. Economics

The key drivers for CCS costs, both for transport and capture are identified by David Kearns et al. (2025):

- Economies of scale: larger scale transport and capture leads to lower costs
- Partial pressure of CO₂ in the source gas, with lower pressure being more challenging, varying costs of CO₂ capture per industry
- Energy costs, especially for capture with high energy and efficiency penalties
- Technological innovation: with the Technology Readiness Level (TRL) of pipelines being significantly higher than for ship transport.

Durmaz (2018) identified technological change, exhaustibility, available capacity of CO₂ reservoirs, and the cost of clean energy as the factors inducing demand. Despite the technical feasibility, the high cost of CCS remains a significant barrier. The value chain is characterized by high upfront capital costs and a "chicken-and-egg" coordination problem between capture, transport, and storage development (Akerboom et al., 2021; ZEP, 2011). Since CCS is a cost-incurring technology that does not produce a valuable product (unlike CCS Enhanced Oil Recovery (EOR)), its deployment is entirely dependent on policy drivers such as carbon pricing or direct subsidies to cover the gap between avoidance costs and market prices (Durmaz, 2018). Holz et al. (2021) substantiates this by noting that the deployment of CCS hinges on "a sufficiently high CO₂ price to compensate for the costs of deploying the CO₂ transport infrastructure".

2.2. System design

CCS may be an important (transitional) technology to create quick carbon emission reductions. However, it is not economically viable for all sectors. The sectors taken into consideration for CCS are power, steel, cement, waste disposal, and refineries (Turgut et al., 2021). The joint use of CCS for these sectors allows for economies of scale and density (Holz et al., 2021), and, therefore, a system

analysis of the potential CCS system should include at least these sectors. Holz et al. (2021) state that "once CO₂ infrastructure is available, CCS will be the preferred mitigation option". This creates a potential risk that (over)stimulation of CCS leads to a delay of fossil fuel phase-out by using alternative energy carriers. Looking at the system configuration, centralized/hybrid capture configurations are preferred due to space limitations (in the Rotterdam-Botlek area) (Berghout et al., 2015). The combination of economies of scale and space limitations shows the importance of coordination and cooperation within the CCS system to reduce costs and increase efficiency. Apart from actual spatial constraints, the design space for a future system is limited by current legal and regulatory frameworks for CCS (Branco de Almeida, 2022; Heffron et al., 2018). This will be analysed further in the system analysis (Chapter 4). Middleton and Yaw (2018) show the importance of correctly allocating storage capacity and planning the infrastructure accordingly, noting that "the costs of getting the original infrastructure design wrong are significant". For this reason, much of the state-of-the-art literature aims to optimize the infrastructure network of CCS, these optimization studies are presented below.

2.3. Optimal infrastructure Planning and Capacity Allocation

Multiple papers have optimized the European CCS supply chain given the main sources of emissions from the sectors mentioned in the previous paragraph (d'Amore & Bezzo, 2017, 2020; d'Amore et al., 2021a, 2021b; Lovisotto & Bezzo, 2020; Oei et al., 2014). The most significant results for these purposes are:

1. Minimum avoidance costs for CCS to be economically preferred to paying for emissions is between 50-100€/per ton CO₂. Higher avoidance costs are mostly due to preference of offshore, which is the only viable option in the Netherlands because of social and political acceptance (Akerboom et al., 2021). Public reaction to CCS infrastructure is a significant issue and taking social acceptance into account for the model increases costs (Derakhti & Santibañez-González, 2024).
2. Older models estimate a lower cost for system optimizations than later models. With only a difference of 4 years between publication dates, this shows the sensitivity of the results and how quickly they can change. These large uncertainties can lead to the postponing of investment for many companies.
3. Most European optimization models show the Netherlands in a unique position as a hub connecting at least Germany but often also Belgium with the North Sea offshore storage sites.

Apart from European CCS system models, the literature shows more regional optimization studies for planning and allocating infrastructure (Becattini et al., 2022; Bjerketvedt et al., 2022; Bumb et al., 2009; Karlsson et al., 2024; Santibañez-González, 2014; Yeates et al., 2024). Combined with results from the optimization on a European scale, the following observations are made:

1. Mixed-integer linear programming (MILP) is used for almost all optimization studies. The objective functions range from emission targets to reduction pathways (e.g. linear vs cumulative).
2. Pipelines are the most cost-effective for large volumes. Barge/ship transport is competitive with pipelines, while rail and truck transport is only attractive for short time horizons and/or small volumes.
3. The research is mostly focussed on the hard-to-abate sectors (either one or all) and transport optimisation. Since alternatives are not technically viable for these sectors, these are not taken into account.

Last, Jones et al. (2022) show the importance of using multi-phased optimization instead of one single solution in order to take advantage of economies of scale. A sub-optimal solution in the first phase (e.g. over-dimensioning a pipeline) may be optimal in the long-run. This is where government support and different forms of market organisation can play a big role, since a business-to-business model may lead to suboptimal solutions and higher risks and costs for late movers. Therefore, it is important to look at the influence of policy on the CCS-network.

The analysis of optimization studies shows what to consider when creating a model of CCS systems, which will later be used as a background for the model development (Chapter 3).

2.4. Overview of Grey Literature

Apart from academic literature, there is a vast amount of grey literature, often commissioned by the government and performed by knowledge institutes or consultancies. The most important of these, along with their main findings, are presented here.

First, it is important to reiterate the role of the NPE (EZK, 2023). The NPE sets out how the Netherlands develops an energy system fitting to a climate neutral society. It therefore carefully considers public values in its selection of choices for the energy system. These public values include affordability, reliability, sustainability, fair participatory processes, and transparency. Mulder (2024) highlights the importance of these public values when looking at different governance options for the development of the CCS market and infrastructure. He adds the public value of keeping industrial sectors and applies the values to the CCS system. The report concludes that, in the long term, the CCS market does not need any additional government intervention for a functioning market. However, during the development of the CCS-market and infrastructure, he highlights the importance of government supervision on tariffs and entry conditions. The reasons for this are as follows:

- The market position of the first planned storage and transport infrastructure in the Netherlands (Aramis) has a strong market position, largely equal to a monopoly in the short term.
- The shareholders in the storage and infrastructure project Aramis are also offering CO₂ transportation. This can lead to information asymmetry, making it more difficult for other parties to enter the market (market foreclosure).
- While infrastructure managers should provide non-discriminatory and transparent third-party access, monitoring is mostly ex post and lacking.

Apart from the above risks during the development of the CCS system, the letter to parliament on the development of CCS highlights more risks (Hermans, 2025). These are the risks of delay due to a lack of coordination between different projects and permits, capacity utilisation risks, and the risks of cost surges endangering the business case. The letter to parliament also states that the government currently only supports market development through state participation under market conditions. Given the described risks in this literature review, there is reason to question whether this is sufficient.

Apart from policy documents within the Netherlands, there are also international reports on CCS business models and policies. The IEA (IEA, 2023) describe different policy options. These should be selected based on institutional, economic, and political factors.

- Incentives- or penalty-based systems: these are mechanisms like tax incentives or fees to influence investment decisions. This is currently how the EU operates.
- Shared cost allocation approach: these are public-private partnerships, mostly to realise infrastructure projects. The UK uses this model.
- Full control: here, a state-owned enterprises (SOEs) finance, build, own, and operate projects.

2.5. Governance and market organization

It is crucial to know which policies affect the development of CCS and the CO₂ market in order to identify the effectiveness of certain policies and where there is a gap. Bishop and English (2025) looked at the early movers (the Netherlands, UK, and Norway) and their success factors. They conclude that clear policy, additional financial incentives, leveraging existing assets, and collaboration are essential. This is supported by van den Broek et al. (2011), who show that the CO₂ price is the most important driver but is, on its own, either too low or too uncertain, highlighting the need for additional policy. However, for this policy to be effective, a systems perspective with dependencies of CCS on other systems and vice versa is crucial. Heitmann et al. (2012) note that embedding the CCS infrastructure in the current (electricity) is a policy coordination problem. They argue that coordination is essential; infrastructure should be shared and governments should have a central planning role in this coordination. Without a clear picture of this future system and its development, strategic coordination is not possible. Once there is a clear vision, the effective policies described above can be used to coordinate and plan the

system. This all shows the need for policy and governance in the CCS system. Therefore, general governance literature on (network) infrastructure is presented below.

2.5.1. Insights from Institutional Economics

Institutional economics provides a good basis on how markets should be designed given the characteristics of that market. Institutions are the constraints set by humans to structure political, economic, and social interactions (North, 1991). Within institutional economics, this characterization is based on transaction cost economics (TCE), which uses transactions as a basic unit to decide which governance structures are appropriate. Williamson (1998) distinguishes four levels of social analysis, seen in Figure 2.1. The layers exert a downward pressure in terms of constraints and they feed back to the layer above. This framework shows how governance is affected by norms which are embedded in public values and how it influences resource allocation, which is essential in the CCS supply chain. TCE is mostly concerned with the third layer (governance) and, in TCE, transaction costs depend on three different dimensions: frequency, uncertainty, and asset specificity of the transaction. When asset specificity is high, the threat of opportunistic behaviour increases. Therefore, authoritative rules (hierarchical organization) are often necessary (Williamson, 2005). When uncertainty is high, this increases the incompleteness of long-term contracts and the risk of maladaptation to disturbances. This also creates the need for hierarchy.

Figure 2.2 shows what governance forms are considered best in terms of minimizing transaction costs under different characteristics of transactions. An ongoing trend in market regulation for networks (e.g. gas and electricity) is to move away from vertical integration, where firms control multiple stages of the supply chain, towards unbundling of services. With unbundling, ownership of the transportation infrastructure and operation of it are separated. This increases transaction costs but also increases competition on the network and prevents the firm with the infrastructure to leverage its monopolistic market position (Glachant, 2012). This is a move from hierarchical governance towards a hybrid model. Unbundling does leave the regulator with the complexity of forecasting future network usage, which can lead to inefficiencies. (Glachant, 2012) Whether this is an issue depends on the extent of the uncertainties in the system.

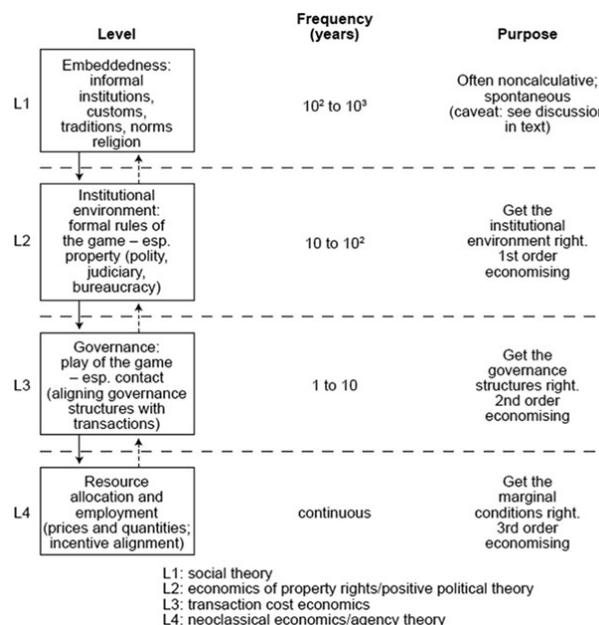


Figure 2.1: Williamson four layer model of social analysis (Williamson, 1998)

Jaag and Trinkner (2011) use the background of TCE to create a general framework for regulation in network industries. They argue that the free market sets the right incentives and is socially optimal if they function properly. Markets do not function properly when there are market imperfections (e.g. asymmetric information), markets are incomplete due to externalities affecting other actors, or/and there is a monopolistic bottleneck, meaning that there is a natural monopoly, considerable sunk costs, and

		Asset specificity		
		Low	Medium	High
Frequency	Occasional	Market Purchasing standard equipment	Trilateral hybrid Purchasing customised equipment	Trilateral hybrid or Hierarchy Constructing a plant
	Recurrent	Market Purchasing standard material	Bilateral hybrid Purchasing customised material	Hierarchy Site-specific transfer of intermediate product

Figure 2.2: The possible governance schemes depending on transaction characteristics from Williamson (2005)

a lack of substitutes. In these cases, they argue for network specific regulation. Table 2.1 shows the type of regulation they propose for different market failures.

Table 2.1: Regulatory measures for different types of market failures, based on Jaag and Trinkner (2011)

Market Failure	Regulatory Measures
Market imperfection	Flanking measures: supporting measures designed to safeguard demand, protect consumers, and ensure minimum standards
Incomplete markets	Internalize externalities: through public obligations, taxes, quotas, or the allocation of property rights
Monopolistic bottleneck	Ensure non-discriminatory access, multiple levels of regulation are possible. More regulation infringes more on property rights and innovation and investment incentives. This includes price regulation, like a rate of return, access regulation, unbundling of activities, and ownership regulation.

2.5.2. Governance Mechanisms

The above literature describes the market organization options: unbundling/integration and ownership, as well as measures for it. These are mostly concerned with layer three in Figure 2.1. Based on the choice of ownership and unbundling along with other market characteristics, there are other options for regulation. The regulator can set the access regime, which constitutes a choice between negotiated third-party access (nTPA) and regulated third-party access (rTPA). With nTPA the infrastructure operator decides who can access the infrastructure based on privately negotiated terms. The operator can therefore decide who is allowed access and under what terms. Alternatively, with rTPA, the regulator mandates transparent, non-discriminatory terms to ensure a level playing field (CATF, 2024). This becomes especially important when the CCS projects are not only individual projects but become part of a larger network.

Another regulatory tool is capacity allocation, which can be an extension to the access regime. Without regulation, this defaults to bilateral contracting. Based on private information on capacity demand, the infrastructure owner decides how much capacity to build and who gets the capacity. However, this is not transparent and can, especially in markets with high information asymmetries, become a barrier to market entry for users. An open season (Pickl & Wirl, 2011) is an alternative: where everyone can bid for capacity which is then "take-or-pay" meaning that the bid is binding. While this is more transparent, the infrastructure is likely built for first-movers, since late-movers cannot join in the initial bidding. To solve this, central planning can be introduced, meaning that the regulator or government decides on capacity either by reserving it or creating incentives/subsidies for additional capacity. While the infrastructure will be less efficient in the short-run, this could save building additional infrastructure later on which could be more expensive. This is the argument for current CCS projects to be build with a larger capacity (Xodus Group, 2024).

Apart from these options, the regulator can implement financial regulation, changing who bears the volume risk. Price regulation can be especially important when there is a monopolistic bottleneck

creating strong market competition (Jaag & Trinkner, 2011). There are two options. First, a price cap, where market power is restricted, but all risk is for the operator. This does incentivize innovation since higher efficiency means more profits. The second option is an allowed rate of return (RoR) for the operator. Additionally, the government can choose to take the volume risk through guaranteeing a certain RoR when there is consistent underutilization (Jamison, 2007). It is important to set the right incentives for efficiency, i.e. by increasing the allowed RoR when there are efficiency gains or when the company invests in innovation. To reduce risks for the state, the regulator can increase the allowed RoR when there is temporary underutilization, effectively letting the user pay for a part of the underutilization risk. This is close to the model chosen in the UK (CATF, 2024).

The last regulatory option is the tariff design. This dictates how the allowed revenues are collected from specific users. Apart from no regulation, where negotiation or any structure is possible, the options are distance-based and a flat fee. Distance-based tariffs reflect the physical cost of transport, being more expensive for emitters further from storage and/or the main transport routes. A flat fee is also possible, where distance is not part of the tariff calculation. This socialises the costs, increasing availability of CCS for industrial clusters further from storage or for cluster 6 (but increasing prices for other emitters). The flat fee option is what the UK is using (CATF, 2024). However, their industrial clusters are not connected through pipelines, which means that distance plays a smaller role.

2.6. Research Gap

The literature review reveals three distinct research streams: (1) quantitative optimization studies focused on cost-efficient infrastructure planning, (2) qualitative governance literature on network regulation and institutional design, and (3) policy reports identifying risks in CCS deployment. However, significant gaps emerge when these streams are considered together, particularly for the Dutch context.

First, while optimization studies (Becattini et al. (2022), d'Amore et al. (2021a), and Jones et al. (2022)) provide optimal network configurations under perfect foresight, they show limited stress-testing of systems under demand uncertainty or exploration of how costs and risks are distributed across different stakeholders over time. The identified coordination problem between capture, transport, and storage development (Akerboom et al., 2021) is acknowledged but not systematically addressed through governance design. Second, existing governance literature on network industries (Jaag and Trinkner (2011) and Williamson (2005)) provides theoretical frameworks, yet CCS presents unique characteristics that limit direct application: it is inherently transitional (short- to medium-term), produces no marketable product (unlike gas or electricity), and faces deep uncertainty in both supply and demand. Mulder (2024) identifies governance risks for the Netherlands, but stops short of proposing concrete governance solutions that account for the temporal evolution of these risks from start-up phase to mature system. Third, the combination of quantitative risk assessment with governance design is missing. A systematic evaluation of how different governance structures (ownership models, access regimes, tariff designs) perform under varying risk scenarios has not been conducted.

This research addresses these gaps by: (1) quantifying infrastructure risks and cost allocation through scenario-based modelling that explicitly accounts for the time dimension and demand uncertainty, and (2) developing a governance framework tailored to the transitional characteristics of CCS, evaluated against identified risks and Dutch public values. This integrated approach bridges the gap between techno-economic optimization and institutional design, providing actionable policy recommendations for navigating CCS infrastructure development under deep uncertainty. The next chapter provides the system analysis necessary to ground this research in the specific Dutch context.

3

Methodology

In this chapter, the methodology to answer the research questions is discussed. First, the usage of the mixed-method approach is discussed, along with the relationship between the different sub-questions. Next, the main methods (interviews and modelling) are discussed in more detail; explaining how the interviews were conducted (Section 3.2) as well as elaborating on modelling method, underlying optimization mechanisms, and the cost data (Section 3.3).

3.1. A Mixed-method Approach

This research uses a mixed-method approach, consisting of desk research, interviews, and modelling. Figure 3.1 shows how the sub questions relate to one another and which methods are used for each research question. They are ordered in the chapters they appear in. The first sub-question, identifying the characteristics of the Dutch CCS system, is the basis of the model for sub-question 2. It set the model parameters: the possible connections between emitters, storages, and clusters, as well as the (minimum) capacity requirements and supply and demand scenarios. Therefore, these are discussed as results in Chapter 4. This first sub-question serves a dual purpose, however: part of its results also provide insight in the identification of risks. For example, which actors operate at different parts of the value chain can impact the risks for market power. This is represented by the arrow from the output of the first to the output of the second sub-question.

The Dutch system is unique in that it shows all components of a possible CCS system: domestic demand and storage as well as import and export of CO₂. The different emitters and clusters can be connected with each other but there are also clusters which will likely not be connected. All these characteristics make the Netherlands a good candidate to show and quantify the costs and risks. This is what the second sub-question answers using modelling and interviews. The third sub-question aims to find the governance options from literature and interviews. The results of the second and third sub-question are then combined to answer the fourth sub-question which measures the performance of the governance options with the identified risks. The case study of the Netherlands helps to make this more concrete. The fourth sub-question is then the basis for answering the main research question.

3.2. Interviews

The interviews were conducted with a semi-structured setup, where questions were prepared beforehand but there was room to elaborate on certain topics and ask more specific questions if called for. The questions were designed to be open questions, ensuring the stakeholders and experts were not steered to the beliefs and hypotheses of the researcher. While the questions were designed and changed based on the expertise and interests of the interviewed expert or stakeholder, the following subjects were included in all interviews:

- The role of the company, advisory group, or expert in the current and future development of the CCS system. The goal here was to identify the different projects which could be taken into account for the model and to be able to value the claims made by the participant.

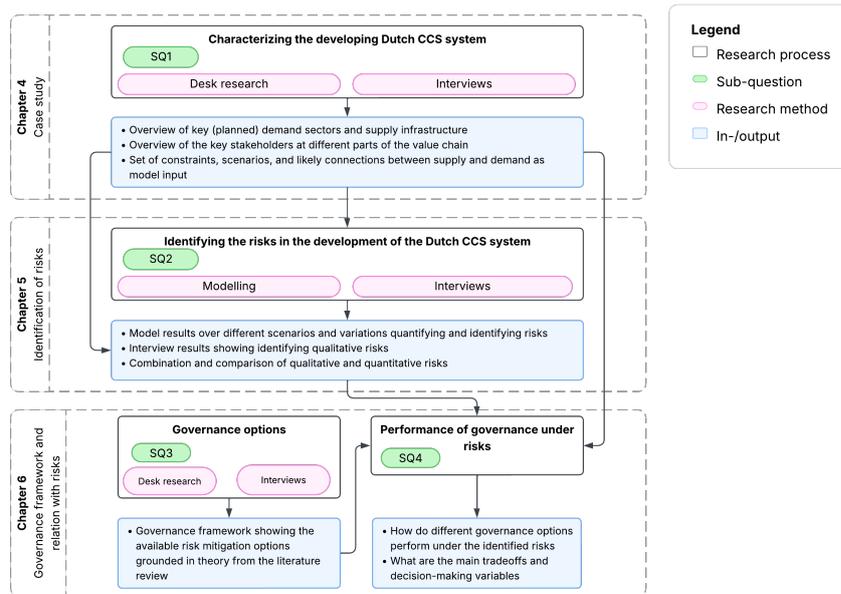


Figure 3.1: The Research Flow, i.e. how the sub-questions are related to one-another. The horizontal, dotted blocks show the chapters in which the sub-questions are answered.

- The risks the participant identifies as important hurdles hindering the past or future development system.
- The options the participant sees as possible mitigation strategies for the identified risks in the future.

All interviews were conducted anonymously with only the company and/or background of the participants being included. Interviews were selected based on initial results of the system analysis. Eight interviews were conducted in total, representing all sides of the transport and storage infrastructure as well as experts with more unbiased views. The stakeholders that are under-represented in the interviews are the emitters, i.e. the future demand for CCS. While the interviews with the Port of Rotterdam (PoR) and Netherlands Enterprise Agency (RVO) provide some insight into the concerns the emitters have, they do not directly represent them. Some potential future demand sectors have been contacted, but besides some informal conversations no official interviews were conducted due to the confidential nature of many projects in this phase of the development. Table 3.1 shows the interviewed stakeholders and experts as well as their role in the CCS system. All participants signed a consent form and summaries of the interviews were sent to the participants for examination. This ensures that no confidential, false or misunderstood information is included in the summaries. The summaries can be found in Appendix C.

3.3. Model development

In order to provide quantitative insights into the system costs and who bears them, along with utilization risks and competitiveness, a PyPSA (Brown et al., 2018) model has been developed. PyPSA is an open-source (mixed-integer) linear programming tool developed for power systems analysis over multiple periods. The literature review showed mixed-integer linear programming (MILP) to be a proven way to find cost-optimal sizing of pipelines and other components. While PyPSA is developed for power systems, its structure and features can be adapted to CO₂ infrastructure. Specifically, PyPSA includes the following features which were useful for this purpose:

- inclusion of many types of physical and capacity constraints, as well as the ability to include custom constraints.
- easy cost input for different types of costs as well as flexibility in annuitization and other cost.

Table 3.1: Overview of interviewed stakeholders and experts and why they were selected

Organization/Expert	Reason for Interview
Netherlands Organisation for Applied Scientific Research (TNO)	The interviewed expert from TNO has knowledge of offshore CO ₂ storage and transport infrastructures, providing insights into geological storage capacity, safety, and monitoring requirements.
TU Delft Professor	This professor has expertise in governance structures and institutional frameworks for infrastructure systems, and particularly also CCS. This provides an academic perspective on regulatory challenges and governance solutions.
State Energy Company of the Netherlands (EBN)	EBN is a state-owned company managing subsurface gas exploration assets and CO ₂ storage development. Therefore, they offer perspective on storage site development, subsurface coordination, and general risks and governance opportunities in offshore infrastructure. EBN is stakeholder in all current storage projects and also (as a one-off) in the Porthos and Aramis transport infrastructure.
Port of Rotterdam (PoR)	The PoR is a key infrastructure hub- and cluster-manager for industrial CO ₂ sources, providing insights into demand-side requirements, cluster development, and infrastructure planning. They are also a stakeholder in the Porthos and Aramis projects and therefore provide insights in the development hurdles and possible mechanisms to mitigate these problems.
Netherlands Environmental Assessment Agency (PBL)	PBL conducts policy analysis and scenario studies, offering an independent perspective on policy effectiveness and system-level development pathways. They do independent analysis for which CCS applications are eligible for the largest sustainable energy production subsidy of the Netherlands.
Gasunie	Gasunie is the national gas grid operator, currently also a stakeholder in almost all developing CO ₂ transport infrastructure. They provide insights into onshore and offshore transport network planning, associated risks and governance solutions which could mitigate the risks they experience.
Netherlands Enterprise Agency (RVO)	RVO implements government CCS support schemes and helps companies navigate in the vast range of available subsidies. They offer perspective on subsidy mechanisms, project selection criteria, and demand-side concerns.
Porthos	Porthos is a first-mover CCS transport and storage project in the Rotterdam area. They provide practical insights into project development risks, business case challenges, and regulatory hurdles.

- inclusion of investment periods over which investment decisions are made.
- good documentation on the features including examples.

These features as well as the underlying optimization mechanisms are explained below.

3.3.1. Optimization model

PyPSA uses linear programming (LP) to optimize for total system costs, i.e. the annualized CAPEX and total OPEX over a given time period. These time periods divided in snapshots. The model consists of multiple components: generators, links, buses, and stores. Generators are the CO₂ capture facilities, buses are the connection points between different components, links connect buses, and stores are the permanent storage fields. The optimization objective is shown in Equation 3.1. Here, n denotes the bus, s the type of generator/store at the bus, and l the link between the buses. The CAPEX is only

included in the objective when components are set as extendable, meaning that they are optimized and not set at a pre-determined value. t is the snapshot, with w_t^o the weight of that snapshot. This means that one snapshot can include multiple hours, increasing optimization speed while still representing a full year of operation. The sum over all snapshot weights should therefore be equal to 8760 hours per annum.

$$\begin{aligned} \min(C_t + O_t) = & \left(\sum_{n,s} c_{n,s} G_{n,s} + \sum_{n,s} c_{n,s} E_{n,s} + \sum_l c_l F_l \right) \\ & + \sum_t w_t^o \left(\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t} h_{n,s,t} + \sum_l o_{l,t} f_{l,t} \right) \quad \forall c_{n,s}, c_l \in \mathcal{E} \end{aligned} \quad (3.1)$$

Constraints

The solution space is limited by constraints. For this model, the most important constraints are capacity and dispatch constraints. Capacity constraints limit the installable capacity for links and generators. These can be upper, lower, fixed, and modularity constraints. Dispatch constraints limit the allowed flow at time t and are limited by the capacity constraints. The set of equations in 3.2 shows the formulation of these constraints. The dispatch constraint (3.2a) ensures that the operational flow $p_{n,t}$ for any component n at time t does not exceed its installed nominal capacity P_n , scaled by the temporal availability factor $\bar{p}_{n,t}$. The capacity constraints (3.2b) bound the optimization of P_n between defined minimum and maximum potentials. Finally, where discrete investment is required, the modularity constraint (3.2c) forces the capacity to be an integer multiple (N_n) of a standardized block size P_n^{step} . Adding this modularity changes the problem from a purely LP problem to an MILP problem since some decision variables are restricted to integers (\mathbb{Z}). This modularity is used to simulate the non-linear expansion of stores.

$$0 \leq p_{n,t} \leq P_n \cdot \bar{p}_{n,t} \quad \forall n \in \mathcal{C}, t \in \mathcal{T} \quad (3.2a)$$

$$P_n^{min} \leq P_n \leq P_n^{max} \quad \forall n \in \mathcal{C} \quad (3.2b)$$

$$P_n = N_n \cdot P_n^{step} \quad \text{where } N_n \in \mathbb{Z}_{\geq 0} \quad (3.2c)$$

Additionally, global constraints can be added to the model. These global constraints are used when creating scenarios by setting the capture rate per sector as well as import and export flows. The primary energy constraint is used here, which limits the by-products of primary energy consumption of a carrier. Therefore, in order to use this constraint and easily sort emissions from different sectors, every sector has a different carrier (e.g. *CO₂_refinery*, *CO₂_chemical*, etc.). These constraints are defined as in Equation 3.3, assuming no emissions from stores (leakage). Here, ρ_s is the amount of capture per carrier s , and $\eta_{n,s,t}$ the efficiency.

$$\sum_{n,s,t} w_t^g \cdot \eta_{n,s,t}^{-1} \cdot g_{n,s,t} \cdot \rho_s = \Gamma \quad (3.3)$$

The last type of constraint added to the model is implemented by attaching an extra functionality function to PyPSA. This feature is one of the features why PyPSA was chosen for this project. This custom functionality changes the behaviour of expansion for specified components. These components can still be linearly expanded, but have a minimum capacity to be built. This means that the component either is built with a minimum capacity of P_n^{min} or it is not built. The difference with the built-in capacity constraint in Equation 3.2b is the possibility to decide to not built the component. This is shown in Equation 3.4

$$P_n^{min} \cdot b \leq P_n \leq P_n^{max} \cdot b \quad \forall n \in \mathcal{C}, b \in \{0, 1\} \quad (3.4)$$

Components

Generators generate a certain amount of CO₂, which is limited by the current emissions per emitter as analysed in 4. Generators are extendable, meaning that the model optimizes the amount of CO₂ they capture.

Buses take CO₂ flows as input, mix all flows from different directions and balance the energy. The input at a bus therefore has to be the same as the output, excluding any spillage or efficiency losses, which are not included in this model, assuming no CO₂ losses during transport. The energy balance equation for every node (bus) is shown in Equation 3.5. Buses take inputs from generators or links, and output to links or stores.

$$\underbrace{\sum_{g \in \mathcal{G}_n} p_{g,t}}_{\text{Capture (Source)}} + \underbrace{\sum_{\ell \in \mathcal{L}_{in,n}} \eta_{\ell} \cdot f_{\ell,t}}_{\text{Pipeline Inflow}} = \underbrace{\sum_{\ell \in \mathcal{L}_{out,n}} f_{\ell,t}}_{\text{Pipeline Outflow}} + \underbrace{\sum_{s \in \mathcal{S}_n} p_{s,t}}_{\text{Storage Injection}} \quad \forall n \in \mathcal{N}, t \in \mathcal{T} \quad (3.5)$$

Links connect the buses and can represent pipelines, compression or liquefaction costs, shipping routes, or part of the store costs. Links have marginal costs and capital costs. Marginal costs need to be defined in €/tCO₂ and capital costs in €/tCO₂(h)/y. The costs for pipelines is highly dependent on length and, therefore, capital costs for links representing pipelines are inputted per meter and multiplied by the length of the pipeline. Because capital costs are defined per year, the input data needs to be annualized. Equation 3.6 shows the annuity formula with r the discount rate and n the economic lifetime of the asset.

$$a(r, n) = \frac{r}{1 - (1 + r)^{-n}} \quad (3.6)$$

Stores are the final component in the model, representing the permanent storage of CO₂. Because storage is permanent, they are non-cyclic, meaning they cannot discharge CO₂. The capital costs of stores are defined in €/tCO₂ instead of per tCO₂(t/h). The marginal costs of stores represent the cost of holding energy in storage. This means that, because the stores hold CO₂ indefinitely, using marginal costs would inflate the price of storage massively. Therefore, the marginal costs are represented by fictive links connected to the stores that all CO₂ must flow through before reaching the store.

Optimization modes

The model can be run in two modes: single-period optimization, representing one year of operation, and multi-year investment optimization.

Single-period optimization In the single period, 24 snapshots represent one year, and so every snapshot is 365 hours. Since flow is assumed constant in the model, increasing this resolution has no effect on the results, although it can easily be increased if variability is introduced. The single-period optimization can be run for $y \in \{2030, 2035, 2040, 2045, 2050\}$, since the demand scenarios include those years. The objective of the optimization (minimized system costs) is returned in €₂₀₂₄, which is the net present value (NPV). The main purpose of the single-period optimization is to optimize the system for a single year without the binary constraints of the extra functionality. This leads to different (less realistic) behaviour, e.g. not building Porthos since Aramis can fully supply demand in the first years. Single-period results are not presented in this thesis, and were mainly used for testing purposes.

multi-year investment To capture the temporal dynamics of infrastructure expansion, multi-period investment optimization was implemented. Unlike single-period modelling, optimizing a single target year in isolation, this method simultaneously optimizes capacity planning and system operation across multiple discrete investment periods of 5 years each with the starting periods $Y \in \{2030, 2035, 2040, 2045, 2050\}$. In PyPSA, this is implemented by indexing decision variables, specifically the nominal capacity of extendable components, by their build year. The availability of any asset during a specific simulation period is governed by its technical lifetime: an asset remains active only if the current simulation period falls within its operational lifespan ($\text{build_year} \leq t < \text{build_year} + \text{lifetime}$). This mechanism allows the model to account for the decommissioning of infrastructure. The objective function is consequently

formulated to minimize the NPV of total system costs over the entire planning horizon, discounted at the social discount rate. This leads to the following objective

$$\min_{G_s, g_{s,a,t}} \sum_{a \in A} v_a^o \left[\sum_{s | b_s \leq a < b_s + L_s} \left(c_{s,a} G_{s,a} + \sum_{t \in T_a} w_t^o O_{s,a,t} g_{s,a,t} \right) \right] \quad (3.7)$$

with $a \in A$ the investment periods, b_s the build year of component s with lifetime L_s , T_a the set of snapshots in investment period a , and v_a^o the objective weighting of the investment period. This weighting accounts for the time preference, it tells the optimizer that, if possible, delaying investment is better and how much. This ensures that infrastructure is not already built in 2030 even though it is only needed in 2040. For a period p with a duration of n_p years, starting T_p years after the base year, the weighting is defined as in Equation 3.8. This means v_a^o for the period in 2030 equals approximately 4.31, while the weighting for 2050 equals 0.93. Therefore, investing in a later investment period has a lower effect on the NPV compared to investing in later periods.

$$v_a^o = \sum_{k=0}^{n_p-1} \frac{1}{(1+r)^{T_p+k}} \quad (3.8)$$

3.3.2. Verification and Sensitivity Analysis

Verification was conducted to ensure the internal consistency and logical correctness of the model structure. Therefore, the MILP formulations described above were stress-tested. If capacity constraints are incompatible, the model should become infeasible. Infeasibility of the model was indeed observed when demand exceeded the set maximum capacities of storage injection, infrastructure to the storages, or (sector-specific) generator constraints. Furthermore, comparing the total generated CO₂ with the total stored CO₂ shows whether the nodal balance constraint was conserved. Since there are no losses in the system, these should be equal, which was indeed observed. Furthermore, looking at the built storage capacities in the different scenarios shows the modularity constraints were not violated. For the extra functionality minimum constraints, a small scale test was used with a low demand scenario. In this test, the model showed that, even though it far from optimal, the minimum capacity constraint was not violated and the minimum capacity was built. When adding a second link with the same constraint, that link is not built, showing that the binary functionality works.

To further test if the model behaved as expected, a sensitivity analysis was run on the TRANSFORM scenario, both in single-period and multi-period optimization mode. Pipeline CAPEX and lifetime, as well as storage lifetime, and discount rate were varied, Figure 3.2 shows all of these results in both single-period and multi-period mode.

The sensitivity analysis of the lifetimes and discount rates show expected behaviour based on the annuity formula (Equation 3.6). The figure shows costs increase almost linearly with the discount rate. This is because, for fixed lifetime n , the numerator r increases linearly while the denominator $1 - (1+r)^{-n}$ changes relatively slowly at typical infrastructure discount rates (5-10%). Therefore, the annuity factor, and consequently total system costs, increase approximately linearly with r .

In contrast, varying the economic lifetime shows a non-linear relationship. Short lifetimes result in significantly higher annualized costs, as the capital investment must be recovered over fewer years. However, as lifetime increases, the marginal benefit diminishes because $(1+r)^{-n}$ approaches zero as n increases. For example, with $r = 8\%$, increasing the lifetime from 25 to 50 years reduces the annuity factor from 0.0937 to 0.0817 (12.8% reduction), while increasing from 50 to 75 years only reduces it to 0.0802 (1.8% reduction). This diminishing return explains the non-linear, convex relationship observed in the sensitivity analysis.

This all shows that the underlying principles of the model work as expected. The results of the sensitivity analysis are further discussed in more detail in Chapter 5 as part of the model results. The model validation is discussed in Section 4.5.4, which compares the model outcomes to the planned real-world applications and projections.

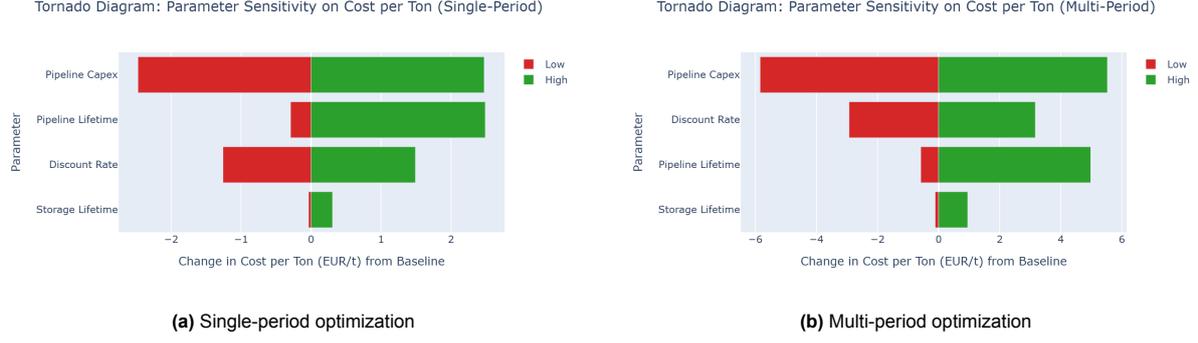


Figure 3.2: Sensitivity analysis results showing impact of parameter variations on total system costs.

3.4. Data

Tables 3.2 and 3.3 show the techno-economic data and costs for the model. Pipeline capital costs values are taken from ZEP (2011) and (along with all other cost data) corrected for inflation to €₂₀₂₄. Even though these estimations are relatively old, they are the most complete, covering contingencies and soft costs and including all necessary distances and sizes for both offshore and onshore transport. To verify using more recent sources, Solomon et al. (2024) estimate onshore pipeline costs to be 40 €/inch/m. The required diameter depends on both distance and flow. IEAGHG (2025) provides estimates for the required diameter of pipelines for certain distances. The flow rate (Q) through the pipeline equals

$$Q = A \times v = \pi r^2 \times v \quad (3.9)$$

with A the cross-sectional area and v the velocity of the fluid. Since the area grows by the square of the radius r , larger pipelines are less expensive per ton of CO₂ transported (assuming equal utilization). Verifying these costs with the costs from ZEP (2011), the difference is around 20-25% for large pipelines and 50% for smaller pipelines. Considering the ZEP (2011) estimations take the soft costs such as permitting (with higher unitary costs for smaller projects) and a contingency of 30% into account, the 40 €/inch/ton rule of thumb is close to these costs. Offshore pipeline costs are in line with Wildenborg et al. (2021), a case study estimation in the Netherlands.

Since a linear optimization model cannot handle the non-linear relationships from Solomon et al. (2024) or extracted from the ZEP (2011) data, pipeline costs are estimated for different lengths and yearly flows. The total annualised CAPEX C_t is then calculated by

$$C_t = (C_{I,p} \times d_p \times (a + O\&M_p)) \times CF_p^{-1} \quad (3.10)$$

with $C_{I,p}$ the pipeline capital costs in €/t/h/m, a the annuity factor, $O\&M_p$ the fixed operating and management costs and CF_p the capacity factor for the pipeline. The capacity factor indicates the amount of time in a year the pipeline can operate effectively. Solomon et al. (2024) assume 0.9, which is approximately 8000 hours. d_p is the distance of the pipeline (i.e. link), which is the straight-line distance between the two buses using the haversine formula, which determines the great-circle distance between two points on a sphere given their latitudes and longitudes

$$L_p = 2r \arcsin \left(\sqrt{\sin^2 \left(\frac{\phi_2 - \phi_1}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left(\frac{\lambda_2 - \lambda_1}{2} \right)} \right) \quad (3.11)$$

with ϕ_1, ϕ_2 and λ_1, λ_2 the latitudes and longitudes respectively (in radians) and r the radius of earth.

Apart from pipeline investment costs, booster costs can significantly influence pipeline costs. Booster stations are pumps that make sure the pressure in the pipeline does not drop below the allowed minimum. However, at the distances and flow rates of pipelines planned in the Netherlands, these booster stations are likely not needed (Solomon et al., 2024). A compressor station, pressurising the CO₂ before offshore transport through the pipelines, is necessary however. This compressor station adds significant costs. The unitary cost for this compression is around 11.3 €/t, with around 70% being variable costs and 30% CAPEX and fixed O&M costs (Holm et al., 2025; Roussanly et al., 2017). These

costs, along with ship transport, storage OPEX, and capture costs are treated as marginal costs in the model and therefore 3.3 shows unitary costs. Storage CAPEX is handled as the capital costs per ton of stored CO₂ and therefore annualised. This CAPEX consists of pre-FID, nominal investment, decommissioning, and post-closure monitoring costs, while the OPEX includes variable O&M and energy costs (Danish Energy Agency, 2021). Storage costs in Norway are expected to be cheaper, since they have larger storage fields than in the Netherlands.

Last, it is important to note that technical lifetimes are likely higher than economic lifetimes, Table 3.2 shows both. Due to high uncertainties surrounding CCS and the transitional nature of being a temporary solution for many industries, economic lifetimes for pipelines and storage are likely smaller. Operators want to recoup their investment faster to account for the uncertainty of future demand for CCS. Therefore, economic pipeline lifetime is assumed to be 25 years and economic pipeline lifetime 30 years. The sensitivity analysis in Chapter 5.1.5 shows the impact of this uncertainty.

Table 3.2: Techno-economic parameters excluding costs

Parameter	Value	Unit	Source
Discount rate	8	%	(Solomon et al., 2024)
Technical lifetime capture	25	years	(Danish Energy Agency, 2021)
Technical lifetime pipeline	50	years	(Solomon et al., 2024)
Technical lifetime injection	50	years	(Danish Energy Agency, 2021; Wildenborg et al., 2021)
Economic lifetime capture	25	years	(Danish Energy Agency, 2021; IEAGHG, 2025)
Economic lifetime pipeline	25	years	(Xodus Group, 2024)
Economic lifetime injection	30	years	(Xodus Group, 2024)
Pipeline capacity factor	0.9		(Solomon et al., 2024)

Table 3.3: Cost parameters for CCS infrastructure, recalculated to the units used in the model

Parameter	Value	Unit	Source
Offshore Pipelines			
CAPEX 20 Mtpa (180km)	1.4335	€/t/h/m	(Solomon et al., 2024; Wildenborg et al., 2021; ZEP, 2011)
CAPEX 10 Mtpa (180km)	2.2864	€/t/h/m	(Solomon et al., 2024; Wildenborg et al., 2021; ZEP, 2011)
CAPEX 2.5 Mtpa (180km)	6.7724	€/t/h/m	(Solomon et al., 2024; Wildenborg et al., 2021; ZEP, 2011)
Fixed O&M	4	% CAPEX/yr	(Solomon et al., 2024)
OPEX	0	€/t	(Danish Energy Agency, 2021)
Compression CAPEX	2.42	€/t	(Holm et al., 2025; Roussanaly et al., 2017)
Compression Fixed O&M	0.61	€/t	(Holm et al., 2025; Roussanaly et al., 2017)
Compression OPEX	8.27	€/t	(Holm et al., 2025; Roussanaly et al., 2017)
Onshore Pipelines			
CAPEX 20 Mtpa (180km)	0.9709	€/t/h/m	(IEAGHG, 2025; Simonsen et al., 2024; ZEP, 2011)
CAPEX 10 Mtpa (>150km)	1.5290	€/t/h/m	(IEAGHG, 2025; Simonsen et al., 2024; ZEP, 2011)
CAPEX 10 Mtpa (<150km)	1.8267	€/t/h/m	(IEAGHG, 2025; Simonsen et al., 2024; ZEP, 2011)
CAPEX 5 Mtpa (<100km)	3.994	€/t/h/m	(IEAGHG, 2025; Simonsen et al., 2024; ZEP, 2011)
CAPEX (<5 Mtpa) (in-cluster)	5.6019	€/t/h/m	(IEAGHG, 2025; Simonsen et al., 2024; ZEP, 2011)
Fixed O&M	4	% CAPEX/yr	(Solomon et al., 2024)
OPEX	0	€/t	(Danish Energy Agency, 2021)
Shipping			
Liquefaction CAPEX	5.45	€/t	(Roussanaly et al., 2021)
Liquefaction Fixed O&M	3.20	€/t	(Roussanaly et al., 2021)
Liquefaction OPEX	9.60	€/t	(Roussanaly et al., 2021)
Terminal	2.5	€/t	(Roussanaly et al., 2021; Sievert et al., 2025)
Ship transport (1000km), 5-10 Mtpa	23.71	€/t	(Roussanaly et al., 2021; Sievert et al., 2025)
Storage			
CAPEX (90 Mt)	5.09	€/t	(Danish Energy Agency, 2021)
OPEX (90 Mt)	11.11	€/t	(Danish Energy Agency, 2021)
Fixed O&M (90 Mt)	2.18	€/t	(Danish Energy Agency, 2021)
CAPEX (150 Mt)	5.20	€/t	(Danish Energy Agency, 2021)
OPEX (150 Mt)	9.68	€/t	(Danish Energy Agency, 2021)
Fixed O&M (150 Mt)	1.39	€/t	(Danish Energy Agency, 2021)
unitary cost for capture per sector			
Power	81	€/t	(IEA, 2021; Smith et al., 2013)
Chemical	32.5	€/t	(IEA, 2021)
Refinery	87	€/t	(IEA, 2021; Sydney Hughes & Alexander Zoelle, 2023; Tzimas & European Commission, 2009)
Steel	76	€/t	(IEA, 2021; Tzimas & European Commission, 2009)
Waste	90	€/t	(Bertone et al., 2024)

4

Results: System analysis and Model Definition

This chapter aims to answer the first research question: *What are the key characteristics and planned developments of the demand and supply of CCS in the Netherlands?* The current and planned capture, infrastructure, and storage facilities, as well as the main uncertainties and key actors within them are discussed here. The context in which the actors operate is set by the laws, regulations, and institutions in place. It is important to note, however, that these laws and regulations can be changed if they result in incorrect allocation of risks and costs or create barriers for the desired development of the system. Whether these allocations are incorrect depends on the goals or policy objectives of the CCS-system: i.e. what do we, as a society, want to achieve through the implementation of CCS, and what do we want to avoid. The Dutch policy objectives and public values in the context of the energy transition are discussed here to provide a context to measure the governance options to while answering sub-question 4.

4.1. Current and Planned CCS supply

The CCS system consists of the demand for CCS and the supply of CCS. The demand for CCS are the emitters in the industrial clusters, while the supply consists of the operators of transport and storage systems. Within these categories, multiple actors play diverse roles, have different objectives, and have varying uncertainties or concerns. The current and potential future actors on the supply side are discussed here.

4.1.1. Storage in The Netherlands

TNO (2025) estimates that the Netherlands possesses economically viable offshore storage of around 1260-1750 Mt. Onshore storage is not considered to be a viable option due to social acceptance and perceived risks. To reach the lower 1260 Mt capacity, 46 depleted gas fields are used, while the upper bound of 1750 Mt would need 126 fields and therefore smaller fields need to be utilized. The unitary costs of smaller fields are larger (Danish Energy Agency, 2021) and, therefore, it depends on the willingness to pay of the emitters which actual storage capacity is most realistic. Of the analysed fields, 310-440 Mt is not in areas with another designated surface activity, which means there is a substantial barrier in surface-use for CCS storage. This barrier can be lifted by repurposing the area to CCS storage or, where possible, double use of the area. The potential for both is still uncertain and depends on policy and the effects of double use (e.g. the consequences of injection-induced earthquakes on windfarms).

Another uncertainty of subsurface storage gathered from the interviews regards pressure communication between different injection fields. Injecting CO₂ into a depleted gas field increases the pressure in that field. This pressure can travel to the next when there is no fracture in the subsurface layer to prevent it. This leaves less room for CO₂ in neighbouring storage fields. How these fields communicate

is not yet fully known, since there are no large-scale CO₂ storage projects and it differs depending on subsurface characteristics. This pressure communication can influence both the available capacity and the business case of the storage fields. If a storage operator A injects CO₂ in its storage field the pressure communication between fields is large, operator A can inject more CO₂ than previously expected. If operator B then starts injecting later on in the neighbouring field, there is less capacity available. The injection pressure also has to be increased since the pressure in the field is higher already, which is more expensive. According to the interviewed expert, this could increase the risks and uncertainties for storage operators.

Even though there is some uncertainty in the total CO₂ storage capacity, the current projected projects could maintain their yearly injection capacities beyond 2050 (TNO, 2025). Although the Dutch government is legal owner of the gas fields, Shell and TotalEnergies hold 60% of the exploration permits for these gas fields (Mulder, 2024). When parties want to store CO₂, the storage permit becomes available for all parties to bid on ("Mijnbouwwet", 2025). However, because Shell and TotalEnergies already have the gas platforms and permits for gas exploration, they already possess the knowledge of the characteristics of the gas fields and can repurpose the old platforms. This gives them a strong advantage in the permitting process, even though they could sell off these platforms. Similarly, they also own large refineries, which means they are owners of both demand and supply of CCS. Therefore, there is asymmetric information between different parties in the value chain (Mulder, 2024). Currently, EBN (which is a state-owned company) is a non-operating partner in all gas exploration, owning 40%. They foresee a potentially similar role for future CO₂ storage projects (see the interview summaries in Appendix C)

The costs of CO₂ storage are driven by the site selection, deployment, and the technology advancement (David Kearns et al., 2025). The technology of CO₂ storage and monitoring is mostly mature and the advancements are assumed to be modest. Therefore, site selection has the largest impact on storage costs. This is influenced by:

- ease of access to the site.
- knowledge of the site, further strengthening the advantage for companies previously exploiting the gas fields.
- existing infrastructure: capital costs are lower if platforms can be repurposed.
- storage capacity/injectivity: if higher injection rates are possible, fewer wells are necessary to reach the desired injection rate, which decreases costs.
- the ease of monitoring leakage on-site.
- CO₂ volume and purity: injection efficiency increases with larger volumes and CO₂ purity, reiterating that the unitary costs of smaller fields is higher compared to larger fields. The CO₂ purity is currently negotiated in the contracts between the operator and the emitter.

The last uncertainty surrounding storage operation is the issue of liability, which was mentioned by two of the participants in the interviews. After the post-injection period, where the operator is responsible for monitoring and potential leakage (>20 years), responsibility is transferred to the state. This responsibility transfer is only initiated when "all available evidence indicates that the stored CO₂ will be completely and permanently contained" (Directive 2009/31/EC, 2018). The problem for the post-injection period is that operators have to actively monitor the site for at least 20 years, which could result in high costs. If leaks are detected, the costs of those leaks are highly uncertain: the leakage is treated as emissions and, therefore, the storage operator has to acquire ETS allowances at the current price. As will be further described in Section 4.3.1, future ETS prices are highly volatile but will likely rise significantly in the future. The long period of post-injection therefore leads to high uncertainty. After the transfer of responsibility, leakage is unlikely. However, this period is effectively indefinite and therefore still a potential risk for the government.

4.1.2. Transport

In order to connect the industrial clusters containing the emitters with the offshore storage fields, the CO₂ needs to be transported. As the literature review showed, pipelines are the most cost effective for large volumes, with ship transport becoming competitive over large distances (Becattini et al., 2022; d'Amore et al., 2021a). For this reason, domestic storage by ship is not considered in the Netherlands,

while long-distance transport to Norway is. Truck and rail connections are only cost-optimal for small volumes over short distances and are, therefore, not taken into account in this case study. The unitary distance-based cost (€/ton CO₂/km) of transporting CO₂ by pipeline decreases rapidly with an increase in capacity. The impact of distance on this unitary cost figure is less significant (Rubin et al., 2015), although it varies through the potential need of booster stations. For ship transport larger distances decrease the unitary shipping cost and an increase in capacity only slightly lowers the cost (d'Amore et al., 2021a). This means the preferred transportation method highly depends on the expected transport capacity and distance.

In the Netherlands, multiple transport projects are being developed as of 2026. The ones with a significant chance of succeeding are shown in Table 4.1. A visual representation of what a future transportation system might look like based on these projects was developed by Gasunie (n.d.) and is shown in Figure 4.1. The stakeholders in the offshore transport and storage project Porthos are EBN, Gasunie, and the PoR, while EBN and Gasunie are stakeholders in the Aramis trunk-line to the storages. They are all publicly owned companies. Onshore, the large-scale pipeline projects are all owned by Gasunie, although their (timely) realisation is more uncertain than the offshore projects.



Figure 4.1: Schematic representation of a future CCS network based on current planned and proposed projects (Gasunie, n.d.)

4.1.3. International Storage and transport

Internationally, there is more capacity available for storage. For Dutch CO₂, Norway, Denmark, and the UK are most interesting since they are relatively close and have a large storage capacities available. The first project for storage of CO₂ from the Netherlands to Norway will be completed in 2026. The Northern Lights company will transport 0.8 Mt CO₂ from Yara, a fertilizer producer, by ship towards Norway. Here, a pipeline will carry the CO₂ from the Norwegian terminal to a depleted gas field. Northern lights is owned by Equinor (a Norwegian, partly state-owned company), TotalEnergies, and Shell and will scale up from 1.5 Mtpa in 2025 to eventually 5 Mtpa.

Storage in the UK is currently not economically viable. Under the EU directive on the ETS (Directive 2003/87/EC, 2024), correct CO₂ storage is considered the same as not emitting CO₂ only if that CO₂ is from companies participating in the emissions trading system. This takes away the main incentive for capturing and storing CO₂. Especially for the North Netherlands (NN) cluster in the north of the Netherlands, storage in Denmark or Norway may be cheaper than domestic storage since pipelines

Table 4.1: Overview of CCS infrastructure projects including

Project	Location	Capacity (Mtpa)	Status & Description
OCAP	Amsterdam-Rotterdam	0.3-0.4	Already built, delivers CO ₂ to greenhouses, not used for storage at the moment
Porthos	Rotterdam-North Sea	2.5	Currently being build, completion expected in 2026, includes onshore compression and collection from industrial emitters in the port of Rotterdam. The capacity of the onshore collection pipeline is 10 Mtpa which can be used to later feed into Aramis or other projects.
CO ₂ Next	Rotterdam	15	CO ₂ Next is a compression and collection open-access terminal for ship transport. It will increase its capacity from 5.4 (2029) to 10 to 15 Mtpa.
Aramis	Rotterdam-North Sea	22.5	Aramis uses the CO ₂ next terminal and compression of Porthos to transport CO ₂ and store it in the North Sea. It will expand from 5 to 14 (2029/2030) to 22,5 Mtpa (2032). The permits have mostly been approved, but final investment decision (FID) still has to be taken.
Delta Rhine Corridor (DRC)	Germany-Venlo-Moerdijk-Rotterdam	~20	No FID has been taken yet. The project can be extended by connecting the Chemelot cluster and is expected to be in use in 2032.
Delta Schelde Corridor (DSC)	Antwerp-Moerdijk	10	No FID has been taken yet. The project can be extended by connecting the Chemelot cluster and is expected to be in use in 2032.
Northern Lights	Zeeland, Rotterdam	5 (initially)	A ship transport project offering transport as-a-service that can change loading locations depending on where terminals and liquefaction plans are built. They have 0.8 Mtpa contracted with the fertilizer producer Yara but can scale up to 5 Mtpa in the near-future and more later.

would have to stretch a large distance to gas fields currently considered for CO₂ storage (TNO, 2025).

4.2. Current and planned CCS demand

The demand side of the CCS network consists of the current emitters of CO₂ and potentially new demand for hydrogen production or carbon dioxide removal (CDR) technologies. The current industrial emitters have an incentive to reduce emissions because they have to buy emission rights to emit their CO₂. The industrial emitters are concentrated in the five industrial clusters in the Netherlands. The Dutch Emissions Authority (Nederlandse Emissieautoriteit, 2025) publishes the emitted CO₂ of all large emitters that fall under the EU ETS. They are therefore a good starting point to analyse the per-sector and per-emitter emissions. Looking at the 2024 emission data, 91% of the total emissions are from companies emitting more than 100 kt CO₂, which is generally considered the minimum for carbon capture to be viable (CE Delft, 2024; Martoriello et al., 2024). These are 60 out of the 334 companies in the data set.

4.2.1. Characteristics of the industrial clusters

Figure 4.2 shows the emissions and number of emitters per cluster for companies emitting more than 100 ktpa (kiloton per annum). 94% of these emissions are within the industrial clusters. The remaining

6% is scattered over the country in so-called "Cluster 6" companies. The scattered nature of relatively smaller emitters means these companies will benefit less from shared CO₂ infrastructure and it is more expensive to connect them. This fragmented nature means they are less likely to connect to large-scale shared infrastructure (in the early stages). Therefore, they are not taken into account in this analysis.

Figure 4.3 shows the number of emitters and the emissions per sector within the five clusters (excluding cluster 6). These sectors have different characteristics with different challenges. The demand potential and most important trade-offs are discussed below and a more detailed analysis of the sectors can be found in Appendix A.

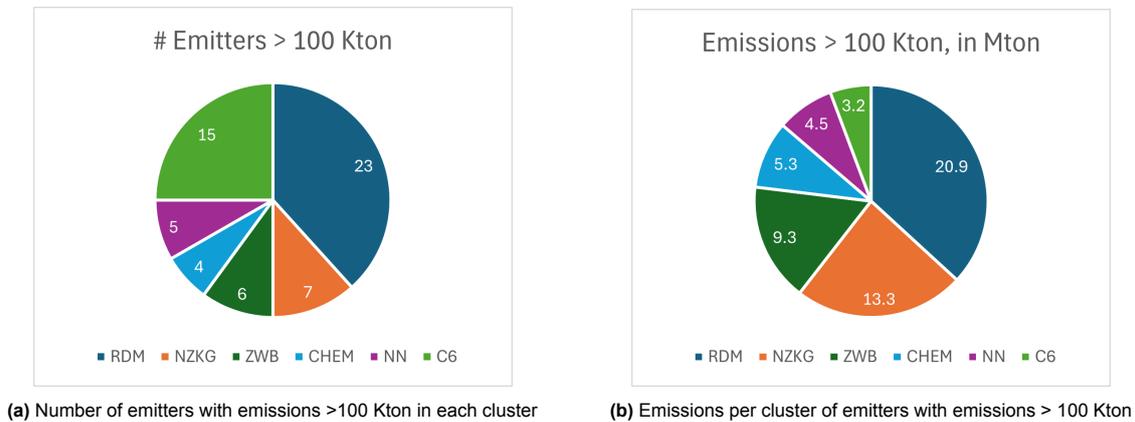


Figure 4.2: Number of emitters and emissions per cluster

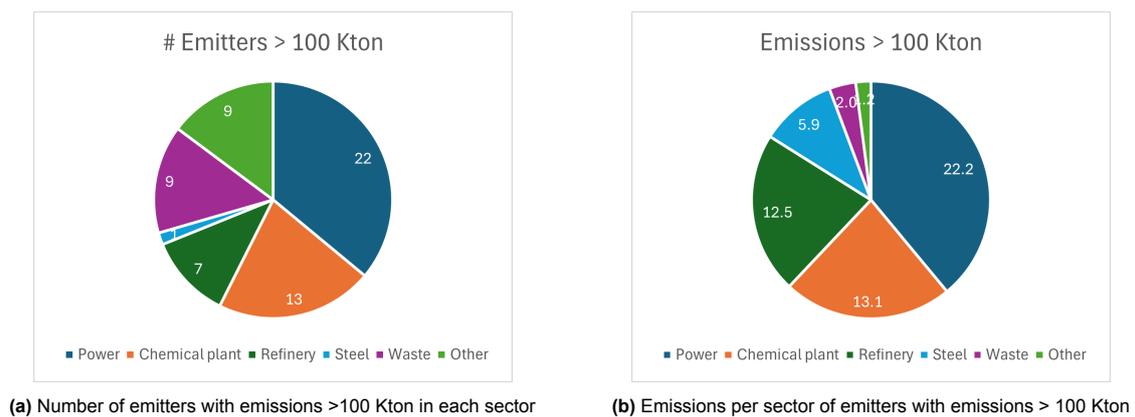


Figure 4.3: Number of emitters and emissions per sector (excluding cluster 6)

Electricity The largest share of current emissions comes from the electricity generation sector. However, most of the base load electricity generation using coal and gas will be phased out by renewable generation. The potential demand that remains is for CCS at gas turbines providing flexible generation when renewable production is low, or CCS at bio-energy generation plants (BECCS). This last technology delivers negative emissions through burning bio-fuels which have captured CO₂ from the atmosphere and storing that CO₂. While carbon capture at gas turbines has been proven viable, the low run-hours of flexible generation means the capital costs are often too high. Therefore, the utilized scenarios do not include capture at gas turbines (See Section 4.5.1). The uncertainty of a BECCS installation, which could in theory provide large amounts of CO₂, will be captured using negative emission variations.

Chemical Plants Chemical plants have a large potential for using CCS. 42% of their emissions are process emissions. Without innovation, CCS is the only CO₂ reduction route for this share of process emissions of the chemical industry. CCS also has a high potential in the remaining emissions of the

chemical industries, requiring 400 times less land and 10 than the usage of bio-fuel and 10 times less energy than re-use of CO₂ (Gabielli et al., 2020).

Refineries For refineries, CCS is an essential tool to reduce emissions (Concawe Review, 2018). No new refineries will be built in the EU and therefore, only the current refineries may have CCS demand. 70% of the emissions from the refinery processes is economically viable to reduce using CCS, limiting the potential demand (Sunny et al., 2022). Similarly to electricity production with biogenic fuels, refineries running on biomass can lead to net-negative emissions.

Steel There is only one steel producer in the Netherlands: Tata Steel. However, they produce 11% of all analysed emissions. Tata steel signed a joint letter of intent (JLoI) with the ministry of climate and green growth to both invest in emission reductions (KGG, 2025b). It is uncertain what emissions will be reduced using CCS, but the figure in Appendix A shows a potential. To show this uncertainty and the impact one large emitter in a smaller cluster can have on CCS potential, the model will include a Steel capture variation.

Waste Disposal Most of the waste incineration plants are in Cluster 6. Therefore, a large number of them are not taken into account. However, they have little alternatives for decarbonization and are therefore potentially first-movers, with potentials of 1-1.2 Mt reported (de Leeuw & Koelemeijer, 2022). This can be larger, however, depending on circularity and reuse of materials in the future. This shows the impact of the narrative surrounding the energy transition on future demand for CCS, which will be further discussed in Section 4.5.1.

Production of Blue Hydrogen Blue hydrogen the name for hydrogen produced using fossil fuels while capturing the CO₂. In the overview of the industrial sectors, the production of hydrogen is categorized in the chemical sector. Since there is only one producer of hydrogen and the future supply of blue hydrogen is uncertain, this categorization makes it possible to use the current chemical plant locations to estimate where hydrogen production will take place. Netbeheer Nederland (2025) estimate CCS from blue hydrogen to be around 2-8.5 Mtpa in 2050, further showing the volatility and uncertainty.

4.2.2. Carbon Dioxide Removal

The last potential source of CCS demand comes from carbon dioxide removal (CDR). CDR can be used to compensate the final remainder of emissions in 2050 to reach carbon neutrality and to realise negative emissions after 2050. This makes the development of CCS supply essential. Where CCS for (most) industrial processes is a transitional technology, negative emissions and the compensation of unavoidable emissions from, for example, land-use are a necessity from 2050 onwards. In the CDR roadmap, or "Routekaart Koolstofverwijdering" (KGG, 2025a), the Dutch government anticipates a total of 20-25 Mtpa CDR in 2040 and 2050. At the same time, the goal is to make the demand for CDR as little as possible through reducing CO₂ emissions elsewhere.

The options for permanent CDR are mineralization, BECCS, and DAC. Both BECCS and DAC need underground CO₂ storage (and therefore transportation). BECCS has the advantage that it can be used in synergy with producing fuels or chemical products from biofuels, but the cultivation of biomass requires large amounts of land, making biomass a scarce product. BECCS leads to both a reduction of emissions in industry where it is used and negative emissions. This means that the 20-25 Mtpa CDR demand cannot be simply added to the demand for CCS in the industry when analysing the total future demand potential. DAC on the other hand is a technology that could theoretically be placed anywhere. However, the technology has not been proven yet on a large scale and uses large amounts of energy, meaning it should be close to both CO₂ infrastructure and preferably electricity generation. With innovation and ample renewable electricity supply it may be a viable option in the future.

4.2.3. CCS supply chain

Combining the different parts of the supply chain analysis above, a schematic figure of the supply chain was created to show how the different stages parts of the system are connected. This concerns a possible CO₂ network lay-out. The CO₂ is first captured and conditioned for transport at the capture facility. This conditioning means that the CO₂ is purified to the specifications agreed with in the contract with the

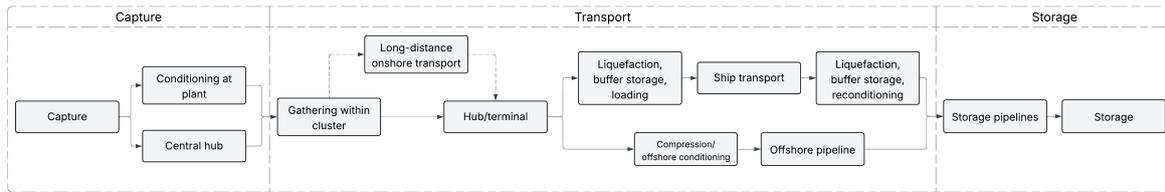


Figure 4.4: Overview of the supply chain of the CCS system

pipeline and storage operators. These specifications are not regulated (apart from safety regulations) and therefore could differ between operators (Brownsort, 2019). This could hinder interoperability or, as mentioned in the interviews, high specifications to reduce corrosion could lead to higher conditioning costs for the capture facility. While the transport and storage operators decide on the specifications, the user bears the costs. Conditioning could be done either at the capture facility or in shared facilities.

After the conditioning, CO₂ is gathered in pipelines in the industrial cluster before going to the hub/terminal (depending on pipeline or ship offshore transport). Long-distance onshore transport may be necessary depending on the location of the industrial cluster. For ship transport, liquefaction of the CO₂, buffer storage due to the intermittent nature of transport, and loading infrastructure is necessary. After the transport, the reverse process is conducted. For offshore transport, conditioning or compression is needed, increasing the pressure for the long-distance offshore transport and possibly improving purity for storage. From the offshore hub or shipping terminal, storage pipelines take the CO₂ to the store injection site.

4.3. Market Organization and Legal Framework

The current market organization and legal framework determine the context in which the actors in the CO₂ market is currently operating. However, this organization and legal framework can be changed by the regulator if their outcomes are considered deficient.

4.3.1. Current incentives and regulation

The current market organization is labelled as business-to-business (Hermans, 2025). However, this does not mean there is no Dutch and EU regulation: there are safety and market regulations as well as subsidies to support the development of the Dutch system. The market regulation is established in EU law (Directive 2009/31/EC, 2018) and adopted in the "Mijnbouwwet" ("Mijnbouwwet", 2025). Most important is the obligation for storage and transportation operators to provide reasonable, transparent, and non-discriminatory access to parties seeking storage of their CO₂. This access can be refused based on a lack of capacity, connection options, or incompatibility of technical specifications. For the projects that are currently operational this is not an issue. However, as the difference in conditioning requirements showed (Brownsort, 2019), subnetworks could become incompatible, hindering interconnectedness and a competitive market.

Another EU regulation in place is the Net-Zero Industry Act (NZIA) (Regulation 2024/1735, 2025). This regulation establishes a legally binding target to reach at least 50 Mtpa EU-wide CO₂ injection capacity by 2030 and obligates the biggest oil and gas producers to contribute to this capacity. The capacity obligation per company is based on the ratio of oil/gas they produced between 2020 and 2023. This has a large impact on storage capacity in the Netherlands, since oil and gas companies in the Netherlands need to realise the largest share of storage injection capacity: 13.32 Mtpa. Even though this capacity needs to be realised quickly, the question remains whether transportation and capture capacity can grow as much and as quickly, potentially undermining compliance (Foglia, 2025).

The largest incentive for implementing CCS is the cap-and-trade system EU ETS. How emitters predict the EU ETS price will develop determines their willingness to invest in CCS and alternatives. Pahle et al. (2025) describes the expected and predicted development of the ETS. From 2040 onwards, no new allowances will be issued for stationary installations and therefore, the total amount of available credits will steadily decline towards zero. Subsequently, the credit price will rise. Pahle et al. (2025) predicts that around 2050, the market price for the remainder of emissions will not be determined by the ETS

price, but by the cost of CDR offsetting hard to avoid emissions. The availability of CDR is therefore of great importance for the price. Pahle et al. (2025) further predicts that ETS allowance prices will reach approximately 185 EUR/tCO₂ in 2030 and increase to 456 EUR/t in 2050.

The Netherlands also has its own instrument to stimulate investment in renewable technologies and CCS. To reflect the transitional nature of CCS, the SDE++ will only include CCS until 2035. Furthermore, CCS projects only qualify for a subsidy when there are no cost-effective alternatives, which is decided based on the subsidy intensity (per kg avoided CO₂) which takes into account the avoided ETS costs. In 2025, no categories were excluded based on this criterion (CE Delft, 2024). Apart from the SDE++, the analysis above showed that state-owned companies also participate in CO₂ projects. Since they can accept smaller returns and take more risk (see interviews), this stimulates investment. However, in the B2B organisation, they have to participate conform market rules. It is therefore not a formal instrument the Dutch government is using to incentivize investment (Hermans, 2025). Last, the Netherlands has a CO₂ tax in addition to the ETS. This tax is based on a national emissions cap, which decreases until 2030, thus increasing the tax. The required ETS payment can be subtracted from this tax, effectively guaranteeing a minimal penalty for CO₂ emissions. However, to increase competitiveness with other EU countries, this tax is currently being phased out (Kabinet Schoof, 2024).

4.3.2. Characteristics of the CCS-system: institutional economics

The theories of institutional and transaction cost economics, as described in the literature review (Section 2.5), can be used to describe different components of the CCS chain. As explained in the interviews, the emitters currently need to pay for all parts of transport and storage and agreements themselves. From the emitter's perspective there are thus three main transactions: CO₂ to transport, CO₂ to storage injection, and/or CO₂ to ship transport. A fourth transaction is the transfer of liability between the storage operator and the state. Table 4.2 shows these transactions, along with how they score based on the characteristics of transactions described by Williamson (1998). This analysis can later be utilized when applying the possible forms of market organization to the CCS market.

Table 4.2: Characterization of transactions within the (Dutch) CCS system based on Transaction Cost Economics (TCE)

Transaction	Asset Specificity	Uncertainty	Frequency
1. Co₂ Transport pipeline emitter ↔ transport operator	High Site and physical specificity (capture facilities and pipelines)	High Volume and quality uncertainty, continuous flow needed	Continuous Continuous flow through the pipeline
2. CO₂ transport ship buffer ↔ shipping	Medium-high Shipping routes can vary more than pipelines, but terminals are site specific	Medium More flexibility and less asset specificity reduce some uncertainty	Recurrent (batch) Regular batches instead of continuous flow.
3. Storage Injection transport ↔ storage	High Limited number of suitable geological sites; platforms often tied to specific operators.	Medium Geological uncertainties but interviews show uncertainties are manageable	Recurrent Continuous injection required to maintain reservoir pressure and service levels.
4. Liability Transfer Storage operator ↔ State	Medium-High Specific to the unique geological characteristics of the stored site, but experience with multiple storage sites can reduce the asset specificity of the transfer	Medium Long-term leakage risks theoretically indefinite; financial impact uncertain; chance of leakage low	Low Occurs once after the post-injection monitoring phase (>20 years). For the state the transaction is somewhat recurrent.

4.4. Influence of public values on decision-making

The first layer of Williamson's social analysis framework describes the norms, customs, and traditions which influence decision-making and the selection of institutional arrangements (Williamson, 1998). These norms can be translated to specific goals for CCS: what are the goals for the development of the CCS system? These values are important in the decision-making on governance implementations, but are specific to the country implementing the governance, and are therefore discussed here. Mulder (2024) describes the following public values:

- CCS should contribute to reaching the climate goals
- Industry should stay in the Netherlands as much as possible
- CCS should not limit investment and innovation in alternatives for CO₂-reduction
- The development of the infrastructure should make negative emission technologies possible in the future
- All market parties should have non-discriminatory access to the infrastructure

These align with the public values in the National Energy System Plan or "Nationaal Plan Energiesysteem" (NPE). The NPE described the long-term vision for the transition towards a climate neutral energy system. Of the values in this policy document, sustainability, fair participation, reliability (through strategic autonomy and retention of industry), and transparency (EZK, 2023) correspond to the values of Mulder (2024). Affordability is mentioned as another important public value. Trade-offs between the values impact the (political) decision-making. An example of such a trade-off is the probability of reaching the climate goals and not limiting innovation and investment in alternatives. Through the development of CO₂ infrastructure, CCS is likely to become the cheapest abatement option for industry (Holz et al., 2021), possibly limiting the development of alternatives. At the same time, CCS may be essential to increase the probability of reaching climate targets.

4.5. Model parameters based on system analysis

The characteristics of the different parts of the value chain as identified in this system analysis are used as the basis for the model. The developed demand scenarios and variations are explained first. Next, the chosen capacities for infrastructure and storage supply are presented.

4.5.1. Demand Scenarios

The demand scenarios are taken from the energy scenarios of TNO (2024). These scenarios are based on two storylines for 2030-2050. In both scenarios, climate targets are met, meaning the total emissions in 2050 equals zero. In the ADAPT scenario, Dutch society strives to maintain its current lifestyle. Therefore, economic structure is preserved, fossil fuel use is limited but not fully phased out, and there is still a strong industrial sector. In TRANSFORM, citizens change their lifestyle, reducing demand for industrial and agricultural products. When comparing these scenarios with the system analysis and other scenario studies (Netbeheer Nederland, 2025), the TRANSFORM scenario provides the most plausible CCS demand figures. Since industry is responsible for more than 30% of greenhouse gas emissions, TNO (2024) have developed three different scenarios based on TRANSFORM, varying in level of the industry.

- Less Competitive (LC): a reduction of industry in the Netherlands, but products are still made from primary feedstocks
- Competitive & Import (C&I): competitive industry, but products are made from semi-manufactures
- Less Competitive & Import (LC&I): combining the two scenarios above

These scenarios contain figures for the amount of carbon capture per sector as well as the amount of storage. Since they show different future paths of the energy transition resulting in different CCS demand, they are ideal to show the impact of demand. They also correspond well with the system analysis above. Other variables which are missing in these demand scenarios can then be varied. The base TRANSFORM scenario and the LC&I variations are chosen as the base scenarios for this research, because the LC&I scenario shows a slower start-up of demand, representing the identified demand uncertainties in early stages.

Other variables that will be varied were chosen based on personal communication from interviews and the system analysis. They represent realistic and foreseen risks with a potentially large impact on investment decisions, including first- and late-mover (dis)advantages, utilization risks, and timing mismatches. This results in the variation of import from Germany and Belgium, shipping costs (representing subsidization from different countries), and future negative emissions. Figure 4.5 shows the capture per sector and the import for the two scenarios in the base case.

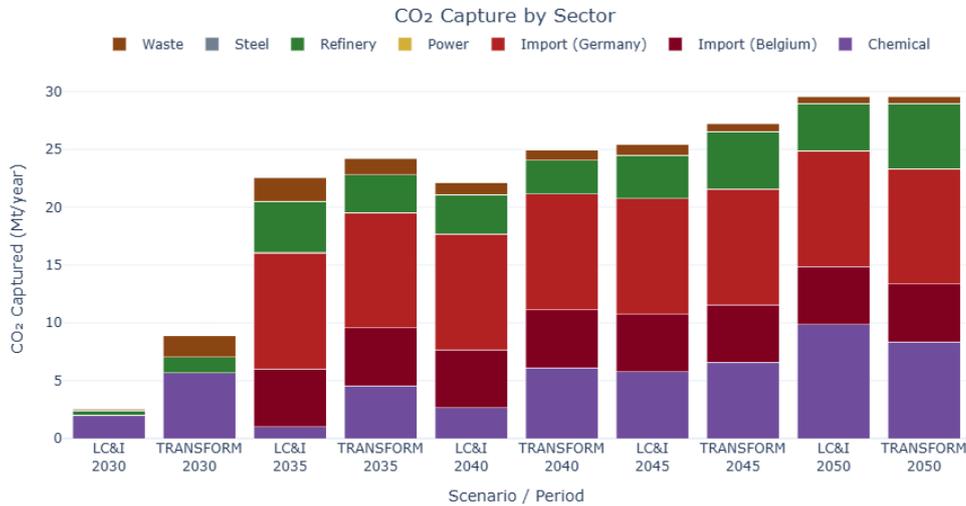


Figure 4.5: CO₂ capture by sector for TRANSFORM and LC&I base scenarios across investment periods. Scenarios are based on (TNO, 2024), with added import demand and hydrogen demand categorized under the chemical sector.

Table 4.3 presents the two base scenarios and their parameter variations. Each variation is applied to both base scenarios to assess sensitivity across different demand levels. While CDR in refineries or using BECCS may be part of the TNO (2024) scenarios, it is unclear how much of the CCS demand uses this combination of biofuels and capture. Therefore, CDR is varied in both scenarios on and below the figures mentioned in the "Routekaart Koolstofverwijdering" KGG (2025a).

Table 4.3: Overview of model scenarios and parameter variations. Parameter variations are applied to both base scenarios

Base Scenarios					
Scenario	Germany Import [Mtpa]	Belgium Import [Mtpa]	Steel Capture [Mtpa]	CDR [Mtpa]	Norway Ship Cost [% base]
TRANSFORM	10	5	0	0	100
LC&I	10	5	0	0	100
Parameter Variations					
Parameter	Values				
Germany Import	5, 10(base), 15, 20 Mtpa; from 2035 onwards				
Steel Capture	0 (base), 5.5 Mtpa; from 2040 onwards				
CDR	0 (base), 15, 20 Mtpa; increasing to 50, 75, 100% of total in years 2040, 2045, 2050				
Norway Ship Cost*	20, 60, 100% (base)				

*Excluding liquefaction

4.5.2. Supply of CCS in the Model

Based on the system analysis, the maximum infrastructure capacities are set as represented in Table 4.4. A second Aramis pipeline is added to increase the future transport capacity when demand

increases beyond the capacity of Aramis. This shows the trade-off between ship transport and building a second pipeline. Stores are added using the modularity constraint, with Porthos stores (which are smaller) being added in modules of 5 Mt and Aramis stores having a modularity of 30 Mt, which is chosen based on TNO (2025) and expected total demand.

Table 4.4: Minimum and maximum build capacities for major pipeline infrastructure. "inf" means no maximum and is used only where limited demand creates no unrealistic capacity optimization decisions

Onshore Pipelines			Offshore Pipelines		
Link	Min Cap. [Mtpa]	Max Cap. [Mtpa]	Link	Cap. [Mtpa]	Max Cap. [Mtpa]
Germany to Venlo (DRC)	20.0	inf	RDM to Aramis	22.0	22.0
Venlo to Moerdijk (DRC)	20.0	inf	RDM to Aramis2	10.0	20.0
Moerdijk to RDM (DRC)	20.0	30.0	RDM to Porthos	2.5	2.5
CHEM to Venlo	2.0	inf	NZKG to NZKG offshore	5.0	inf
Belgium to Moerdijk (DSC)	5.0	inf	RDM to Norway	0.0	20.0
ZWB to Moerdijk	2.0	inf	NN to Norway	0.0	10.0
Porthos collector pipeline	10.0	10.0			

4.5.3. Model Lay-out & Validation



Figure 4.6: All possible connections and buses. Bottom connection starting at RDM represents export to Norway

Figure 4.6 shows all possible links within the model. The buses in the figure show the emitters as analysed in Chapter 4 at representative locations. The links show the buses and subsequently storages. Their costs are per meter, except for the links representing export to Norway (from NN and RDM clusters). The emitters are automatically connected to the cluster they are added to as shown in the analysis. However, this leads to some illogical connections, for example around Moerdijk. Therefore, through analysing of the visual representations shown in Figure 4.6, some connections were changed to be closer to the bus, decreasing in-cluster pipeline costs. The pipelines from the emitters to the clusters are built when it is optimal for those emitters to capture CO₂, given the sectoral global constraints. The large projects identified in this system analysis are added in the year they are expected to be build.

4.5.4. Validation

Before analysing the results of different scenarios in Chapter 5, the base case model results were validated. The interviews and published costs of demonstration projects and (tariff) projections of future projects (Porthos, Aramis) can be used to verify the model results. Last, results of other optimization studies in Europe are used.

Case studies Since Porthos is included in the model, its projected tariffs provide a good sense of how accurate the model is. Cost figures for the project are not publicly available. Porthos tariffs are expected to be around 53.3 €/t, ranging from 44.7 (P10) to 62.4 (P90) €/t (Xodus Group, 2020). Potentially, with full utilization guaranteed, this could drop to 37.9 €/t. When dividing the yearly costs of the Porthos infrastructure by the stored capacity, the costs are 28.42 €/t, rising to 31.67 €/t including the over-dimensioned collector pipe. In the model, Porthos is fully utilized. This is a close approximation to the tariffs, with the tariff estimations being likely higher due to profit margins and uncertainties because of the first-of-a-kind nature of the Porthos project.

Projections of Aramis' tariffs are around 90.6 €/t for gaseous transport and 112.8 €/t for liquid transport when spreading all annualized costs over the 7.5 Mtpa required to start phase 1 (Xodus Group, 2024). The total costs in the model per ton for 7.5 Mt utilization are 61.53 €/t (62.61 €/t with the collector) when assuming similar storage to pipeline utilization, which includes conditioning, offshore transport, and storage. As the results will further elaborate on, this can be highly volatile to the assumed utilization for storage. With the volume uncertainties surrounding the Aramis project, which are greater than for Porthos, and inaccuracies in the tariff estimations of up to 30-40%, the costs are within range of the tariff estimation. It is also unclear what contingency and profit margins the Xodus Group (2024) estimations use. Last, looking at the first liquefaction project for shipping, the investment is 200 M€ for a total of 12Mt (Yara International, 2023). The total investment in the model would be around 195.6 M€, well within range.

Optimization studies Becattini et al. (2022) identifies a decreasing trend in levelised costs over time as more CO₂ is handled by the system. This same trend is observed in the model. The model results show the same trends. Furthermore, Becattini et al. (2022) note that the distance to storage has a large impact on costs. While Chapter 5 will elaborate more on this, the difference between Aramis and Porthos costs, even though Aramis benefits from economies of scale, shows this effect. The comparison between costs for Germany and emitter which are closer to storage shows the same relationship. d'Amore et al. (2021a) break down the cost of the CCS supply chain. They find that capture is good for around 60% of costs, while transport and storage take up 30 and 10% respectively. Figure 4.7 shows the cost breakdown for the TRANSFORM base scenario including the estimation of capture costs per sector from Table 3.3. While the ratios between the different components differ slightly, the basic build up of costs is similar to d'Amore et al. (2021a).

Expert interviews In the interview with the Port of Rotterdam (PoR), they indicated a *potential* of 12 Mt carbon capture at the port. The TRANSFORM scenario shows 8.11 Mt capture in the RDM cluster in 2050. For a medium carbon capture scenario this is a sensible amount of capture. Furthermore, the PoR expects a positive impact of import of CO₂ from the DRC. The scenario results show the same result for the model, with decreasing unitary costs when import is increased and vice versa (see Chapter 5).



Figure 4.7: Cost breakdown per component for multi-period optimization scenarios including average estimation of capture per sector

Multiple interviewed companies noted that publicly owned companies can, in some cases, accept a lower rate of return than private companies. Effectively, this means they can take more risk and a lower NPV. This is represented in the model by the discount rate. When lowering this discount rate, system costs decrease, confirming this expected behaviour.

The cost discrepancy between Aramis tariffs and the Aramis costs from the model was discussed in the interview with RVO. The participant recognized the discrepancy between costs in literature and projected (confidential) costs and tariffs to be around the identified amount. Likely, this difference results from high uncertainty mark-ups and possibly confidential and more up-to-date cost information, although the exact reason is unknown. The Porthos interview showed that the main cost drivers are distance and volume. The model reflects this in both the cost data and final results. The participant also reiterated that the Porthos project can offer relatively low tariffs compared to e.g. Aramis due to the short distance to storage and efficient coordination between stakeholders. This cost difference is also shown in the costs presented above.

5

Results: Identified Risks

This chapter aims to answer the second sub-question: *"What are the key risks in the development of the CCS network both over time and for different parties in the value chain?"*. The previous chapter explained the key characteristics of the developing Dutch CCS system. This sets the model constraints and potential connections as explained at the end of the chapter. First, the model results are presented with a focus on identifying risks in the system. Section 5.2 discusses the identified risks through the interviews. Last, section 5.3 concludes by combining these results to the final identified risks.

5.1. Model Results

The model results are presented in this section. First, the results of the base cases are presented, including infrastructure build-out and a cost comparison and analysis. Next, the variations are discussed. The scenarios and variations show the effects of import size, export costs, market position of large emitters, and the size of demand on costs. Some overarching results are discussed in Section 5.1.3 and 5.1.4. Section 5.1.5 presents the sensitivity results in more detail to further strengthen or nuance the results. The sensitivity analysis also provides a few useful insights for the risks and the later performance of the governance options under these risks.

5.1.1. Base Case Results

The results of the LC&I and TRANSFORM base scenarios are presented here. The total system costs include all capital costs and operational costs of the first year of each investment period discounted to €₂₀₂₄. This also applies to component costs. Note that, as shown in Chapter 3, shipping costs are defined in unitary costs for ship transport in €/t because of a lack of reliable CAPEX and OPEX data. However, since shipping is mainly included in the model to show its competitiveness and, therefore, the price for flexibility, this does not affect the results too much. Shipping costs itself are also driven by marginal costs more than pipeline transport and, therefore, this represents the relative flexibility of shipping.

Infrastructure Build-out

Figures 5.1 and 5.2 show the yearly capacities built in both scenarios along with the flows through the buses. The sizes of the buses and links represent the flows through them. Both scenarios end up with approximately the same structure, albeit with different flows and build-outs at different times. The TRANSFORM scenario build-out is discussed first.

The Porthos infrastructure is already built before the optimized periods, consisting of the offshore pipeline, storage pipeline (which represents the storage CAPEX), and the onshore collector pipeline which is over-dimensioned at 10 Mtpa to also be used for Aramis later on. In the first investment period, the optimizer decides to build the Aramis offshore infrastructure for storage. In order to reach the relatively high chemical capture rates in the TRANSFORM scenario, the ZWB cluster pipeline also has to be built, with a flow of 3.20 Mtpa. The Porthos pipeline is fully utilized and no infrastructure in other clusters is developed. In the second investment period (2035), the import constraint is added: 10 Mtpa

from Germany and 5 Mtpa from Belgium. Therefore, the DRC and DSC are built at the projected capacities, since those are the minimum constraints. This means the pipelines are underutilized. Starting from 2040, the ship transport is used, which shows that the Aramis trunk line is fully utilized for the first time. The model has the choice between a new pipeline of at least 10 Mtpa or ship, which can be flexibly built. It chooses ship transport because of this flexibility, even though it is more expensive, and builds 0.43 Mtpa of ship transport capacity. In the fourth and fifth investment period, 2045 and 2050, the flows increase but no large changes are seen. Most notably, ship transport increases to 2.74 and then 4.46 Mtpa. Both the Aramis and Porthos pipelines are fully utilized in these years.

The LC&I scenario starts off with a very small capture capacity of just 2.02 Mtpa only in chemical plants, representing a scenario where demand is only slowly ramping up and staying behind initial expectations. Therefore, only the Porthos infrastructure is used in the 2030-2035 investment period. Only the Porthos collector pipeline, and Porthos conditioning and storage infrastructure is built. Starting at 2035, when import from Germany and Belgium is introduced and inland demand increases, the DRC, DSC, and Aramis infrastructure is built. Interestingly, the model chooses to fully utilize the Aramis pipeline and reduce the flow through Porthos. Since storages are added in distinct chunks to represent the non-linear CAPEX investments, this saves developing new storages for Porthos and utilizing the Aramis storages more effectively. The CHEM and ZWB clusters are expanded in 2040, since chemical capture demand increases in this period. Starting in 2040, there is a small amount of ship transport (0.13 Mt). The Porthos infrastructure is not used in 2040, showing the advantage of more flexible ship transport compared to developing new storage sites with corresponding CAPEX investments. To save on the more expensive shipping costs, Porthos is fully utilized in 2045 and 2050, fully utilizing the stores and showing the impact of costs increasing non-linearly. Ship transport is used for the remainder of the demand in 2045 and 2050, increasing to 0.91 and 5.08 Mt respectively.

Overall, the flows are lower and delayed in the LC&I scenario. Since all large collector pipelines have a minimum build capacity and stores are added in chunks, this leads to lower utilization in the LC&I scenario. The associated costs will be analysed further in the next section.

Cost Analysis

The total CO₂ system cost are defined as the the sum of the annualised capital costs and the marginal costs of the modelled years in €₂₀₂₄. The NPV is different, since it is the value (or cost) of the investment and can be used to compare to alternatives. If the discounted avoided ETS price would be subtracted from the NPV, a negative NPV would generally mean that investing is cheaper than paying ETS and vice versa. The NPV values are presented here for reference, but the unitary costs (or levelised cost of transport (LCOT)) are the most valuable comparison tool, since it takes into account the varying levels of demand. In all cost analyses below, the capture costs are set to zero, which does not influence the decision-making because of the demand constraints per sector. Therefore, the discussed costs consist of all transport and storage components, excluding capture and the conditioning in the capture process. It does include conditioning for shipping transport (liquefaction) and conditioning and compression for offshore pipeline transport and subsequent storage.

The NPV of the TRANSFORM scenario are 9.61 B€, which is an average of 45.00 €₂₀₂₄/t. The NPV for the LC&I scenario are lower: 7.07 B€, or 42.96 €/t. This small difference in per ton capacity is because the LC&I scenario can postpone building Aramis to the second investment period, when the objective weighting is lower and the effect on the NPV smaller. This lowers underutilization and therefore lowers the difference between the two scenarios even though there is a large difference in demand. The unitary costs and total system costs in 2024 euros changes over time according to Figure 5.3. TRANSFORM starts with a high unit cost due to large underutilization of the Aramis infrastructure. A large chunk of storage capacity (30 Mt) and the full capacity transport infrastructure are built in 2030 to accommodate future demand. The total system costs of both scenarios ramp up over time. Note that these are annual costs in €₂₀₂₄, making the sum of them smaller than the total system costs which include investment period weightings to account for the full 5-year periods. Over time, shipping infrastructure is added to meet demand which the Aramis storage system cannot match. This increases total system costs and unitary costs. The increase in unitary costs even for small volumes of ship transport show the extra costs of ship transport.

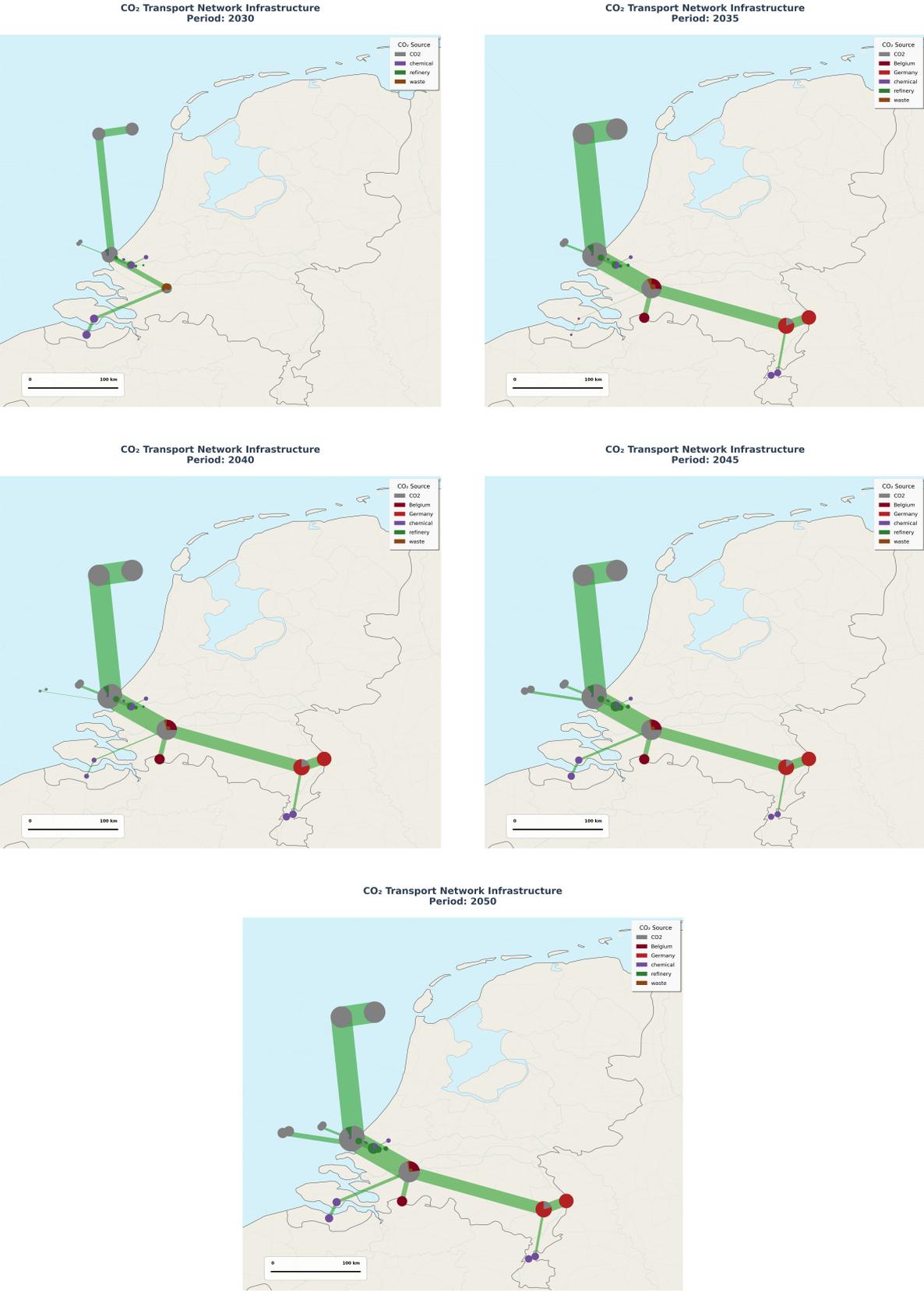


Figure 5.1: TRANSFORM scenario maps showing the development of the CCS network infrastructure across different years

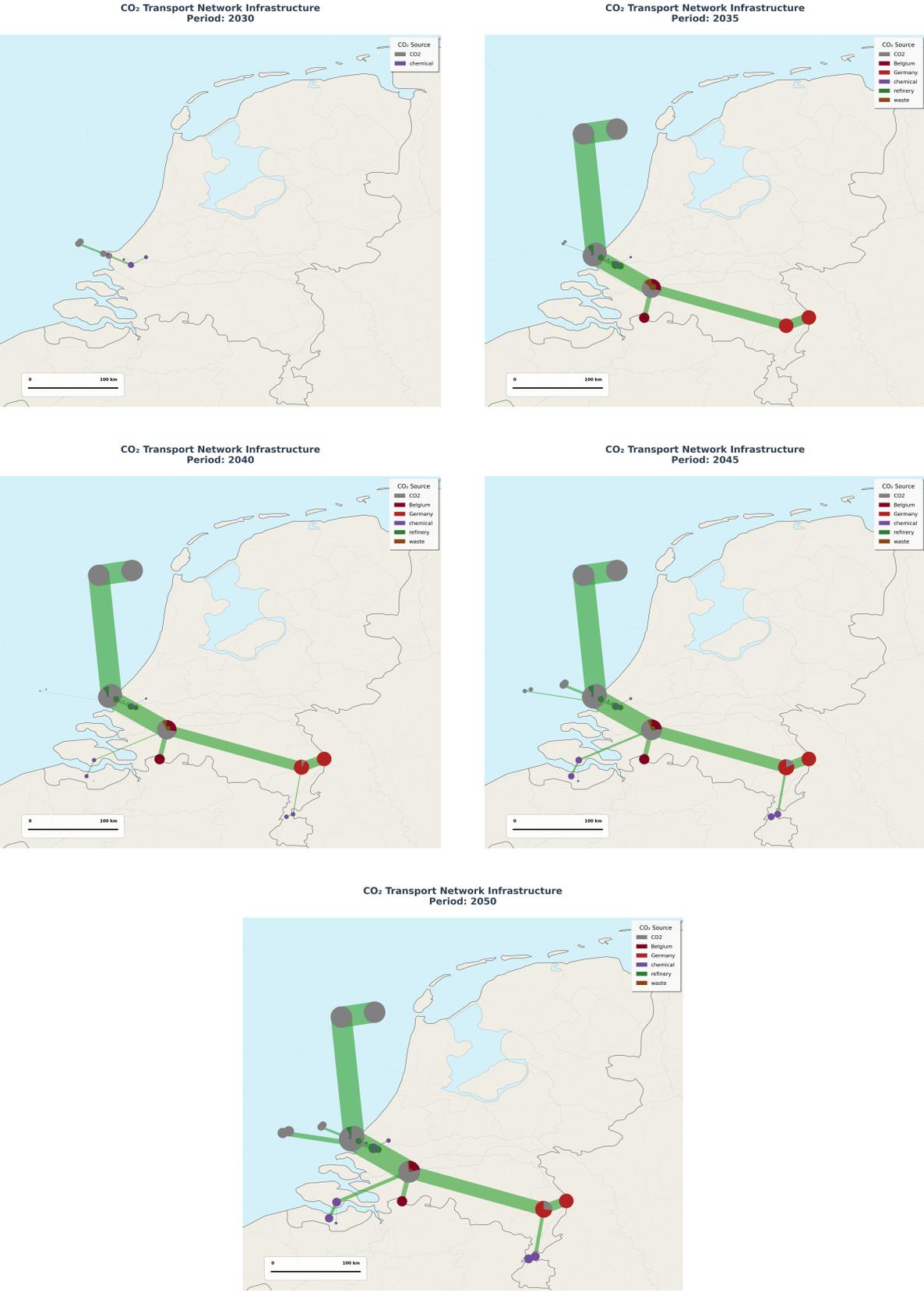
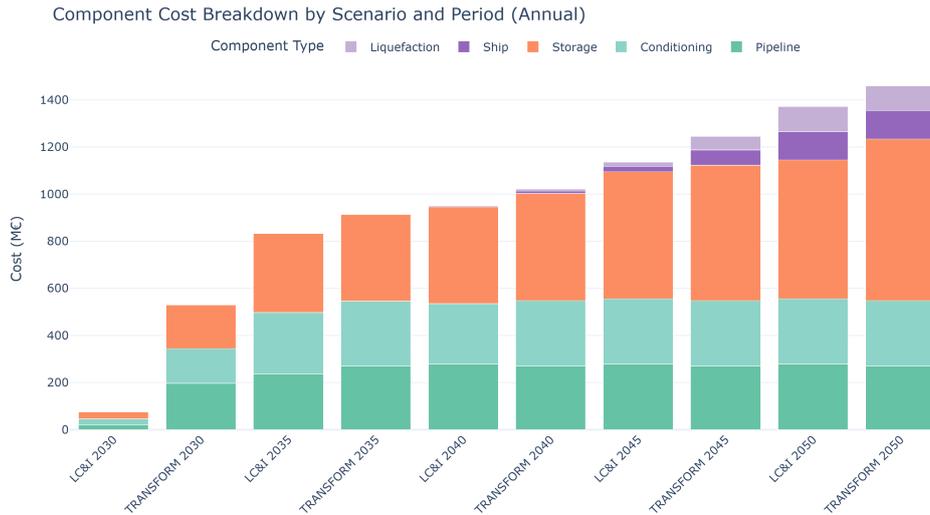
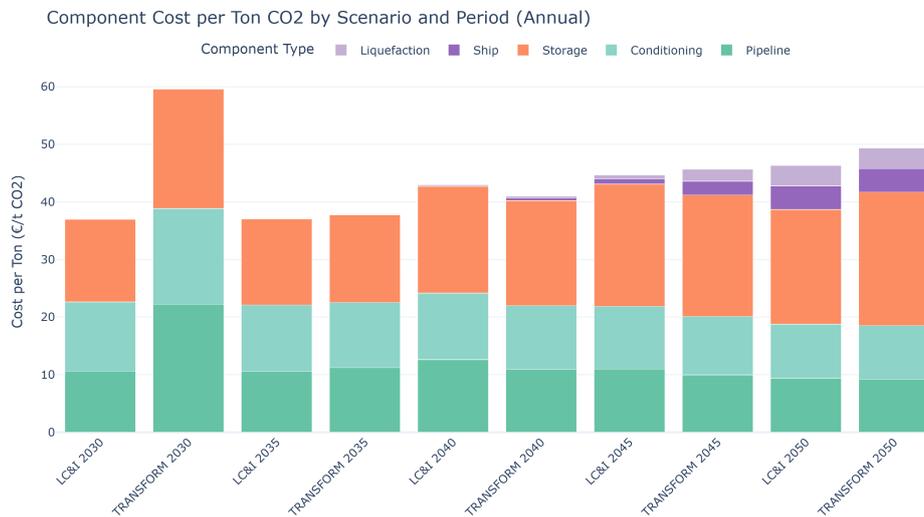


Figure 5.2: LC&I scenario maps showing the development of the CCS network infrastructure across different years



(a) Total yearly cost per component, does not consider objective weighting (yearly incurred cost in €₂₀₂₄)



(b) Costs per component per ton CO₂

Figure 5.3: Cost breakdown by component for TRANSFORM and LC&I base scenarios across investment periods

5.1.2. Parameter Variation Results

Below is the analysis of the variations. The import, steel capture, and shipping costs were varied with the goal of showing the impact of utilization, distance, total demand, and large companies on CO₂ infrastructure costs. Carbon Dioxide removal (CDR) shows the effects of large demand increases over time near the storage infrastructure. First, the development of the different variations are discussed after which they are compared and results are aggregated to show e.g. utilization patterns.

Germany Import Variation

When increasing the import from Germany to 15 Mtpa starting in 2035, the NPV increase to 8.69 and 11.29 B€ for the LC&I and TRANSFORM scenarios respectively. This is an 22.9 and 17.48% increase in NPV, close to the change in demand. For the 0 Mtpa scenario costs decrease to 4.95 (-30.0%) and 7.05 (-26.6%) B€. However, the actual drop in demand is higher (39.4 and 35.17 %), suggesting that costs do not scale linearly with demand. To support this, Figure 5.4 shows the average costs per ton of multiple TRANSFORM scenarios in all periods against the demand in those periods. This shows that higher flow through the system decreases costs per ton in the system. This effect is more pronounced in

the low-demand data points and decreases with increasing demand. The effect occurs due to increased utilization and larger pipelines benefitting from economies of scale. Since this is a linear optimization only taking into account incremental economies of scale, this effect should be even more pronounced for non-linear optimizations or actual costs. The cost of underutilization is further analysed in Section 5.1.3.

The spread in the figure is due to the different scenarios utilizing different infrastructure with varying cost structures. However, the fit, represented by R^2 , equals 0.952. Looking at the residual plot, the results are not biased with an even spread.

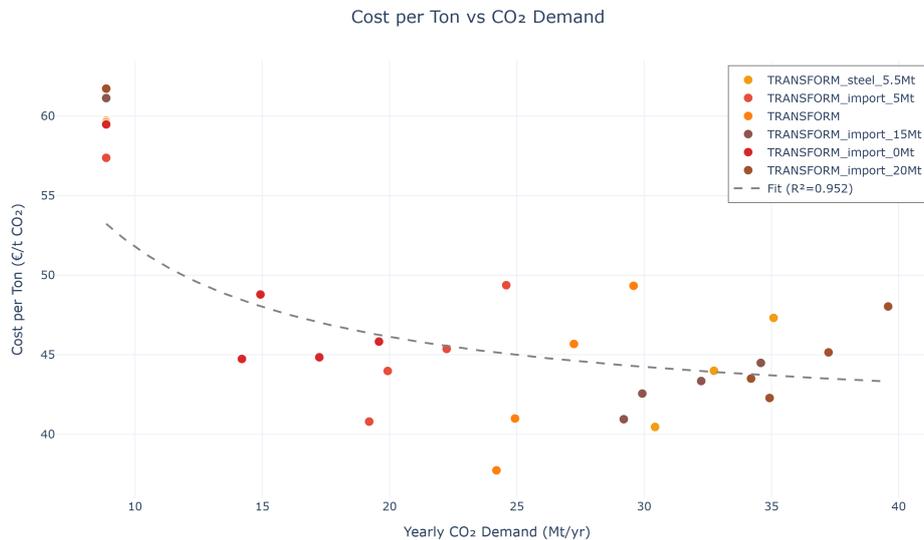


Figure 5.4: Average cost per ton versus total demand across all scenarios and investment periods, demonstrating economies of scale and the impact of system utilization on levelised costs

Steel Capture Variation

When introducing steel capture at Tata Steel in the NZKG cluster, NPV increases with around 900 M€ for both scenarios, which is the costs of developing the NZKG system. This is an increase of 9.16-12.72% which is small compared to the increase of demand of 14.5-16.2% or 16.5 Mt. This shows the advantage of perfect coordination and capacity planning. Being a small cluster with one large party, there is no underutilization in the cluster. Interestingly, part of the waste incineration capture demand for both the LC&I and TRANSFORM scenarios in 2040 are deferred to the NZKG cluster, meaning it is cheaper to capture there than in the Rotterdam area from a system perspective. In the LC&I scenario, the waste facility captures 2.45 Mt over the 3 years (2040, 2045, 2050), while this is 2.03 Mt in the TRANSFORM scenario. Adding this to the total capture of the steel capture facility, the costs per ton are approximately 38.50 €/t for the NZKG system in both scenarios. This shows the potential cost reduction for small systems when they can be fully optimized and utilization is 100%, even when accounting for economies of scale.

Norway Shipping Cost Variation

In the shipping cost variation, shipping and storage costs are reduced by 40 and 80%. Liquefaction costs stay similar however. This represents a case where transport and storage is subsidized heavily. Liquefaction is most likely done by the Dutch companies and not part of the transport on ship and, therefore, it is not decreased. The unitary costs barely vary with utilization for ship transport since the infrastructure can be flexibly built, representing the more flexible reality of shipping. For shipping, total shipping costs to Norway, including liquefaction, are 66.04 €/t. For the 40% and 80% reduction scenarios this is 47.92 and 30.58 €/t respectively. Therefore the cost reduction of the whole supply chain in both variations is 27.4 and 53.6%. To compare, the unitary costs of the Aramis storage at full utilization are 41.01 €/t. At full utilization, ship transport is therefore 37.9% more expensive than storage at Aramis. When the Aramis pipeline and storage are 50% utilized, this drops to 22.1%, with Aramis unitary costs increasing to 52.25 €/t.

Figure 5.5 shows a comparison of the different shipping costs variations with the LC&I and TRANSFORM scenarios. With the cost difference between Aramis and shipping in mind, the smaller reduction does not lead to significant changes in utilization of the routes. There is some unitary cost reduction, but not more volume. For the 53.6% reduction, the shipping route is preferred. This is the case especially in 2030. In 2030, the demand can be met with only the shipping route. However, this route is capped at 20 Mtpa which means that Aramis is needed when demand ramps up. Marginal costs of pipelines are non-existent and while storage marginal costs in the Netherlands are higher than in Norway due to smaller fields, this does not compete with the large marginal costs for shipping. Therefore, when Aramis is built, it is cheaper to use them. In reality, it will be hard to build the Aramis project when costs for shipping are subsidized heavily and therefore tariffs are lower.

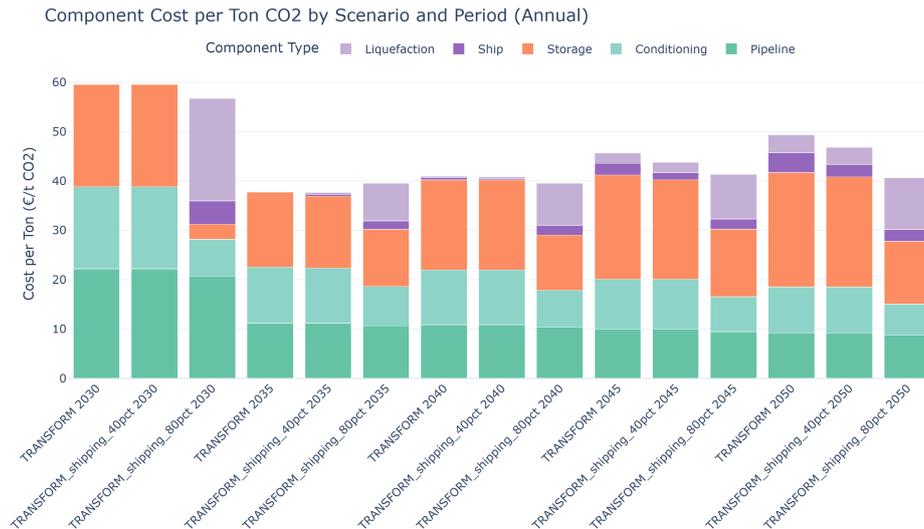


Figure 5.5: Cost breakdown by component for Norway shipping cost variation scenarios, showing the impact of shipping cost reductions on infrastructure utilization and component cost distribution

CDR variation

In the CDR variation, the CDR demand ramps up in equal increments from 50% to 75% to 100% of the variation value. This, along with its location (in the RDM cluster) makes it different from the import variation. The NPV in the variations are shown in Table 5.1. On average, only small changes in unitary costs are detected, with a year-by-year analysis showing the same small difference. What is happening in the CDR variation is the addition of a second pipeline to the Aramis storage with relatively high utilization from the start 50%. From this utilization level, variation in unitary costs is lower than at low utilization levels (see Section 5.1.3).

The extra demand decreases unitary costs in 2045 because there is enough demand to warrant the costs of this new pipeline, but increases the unitary costs in 2040 slightly because of low utilization of the pipeline. This shows that the current problem of reaching enough capacity to take FID for the Aramis project is not a one-off. Every large piece of infrastructure that needs high initial volumes could encounter the same potential coordination problem. From a system-perspective, it is clear that building a second pipeline to accommodate for CDR or other increases in demand is cheaper. However, this is with perfect foresight of demand and without this certainty, the more expensive shipping route may be chosen.

5.1.3. Utilization Analysis

Figure 5.6 shows the utilization of the Aramis, Porthos, and Aramis2 systems over time in all scenarios and variations. The figure does not include storage since the non-linear addition of storages means that the utilization of the storages is different than for the pipelines. The Aramis2 pipeline system is added in high demand scenarios and when shipping becomes cheaper since lower inland storage capacity is needed. Aramis2 has higher costs than the Aramis pipeline to account for the economies of scale

Table 5.1: Total NPV for the CDR variations. The scenarios ramp up in demand from 50-75-100% in 2040, 2045, and 2050 respectively.

Scenario	Ramping	Total Costs (B€)	Unitary Cost €/t
<i>TRANSFORM</i>			
10 Mtpa CDR	5-7.5-10 Mtpa	10.60	42.74
15 Mtpa CDR	7.5-11.25-15 Mtpa	11.33	43.26
20 Mtpa CDR	10-15-20 Mtpa	11.94	43.04
<i>LC&I</i>			
10 Mtpa CDR	5-7.5-10 Mtpa	8.21	41.95
15 Mtpa CDR	7.5-11.25-15 Mtpa	8.72	41.61
20 Mtpa CDR	10-15-20 Mtpa	9.38	-39.4% 41.94

with larger pipelines. Overall, utilization goes up and costs decrease when demand goes up. However, costs increase faster with lower utilization rates, showing the importance of initial capacity versus full utilization.

Low utilization is observed in two circumstances. First when there is a high demand just over the tipping point of building new infrastructure, showing that there is little flexibility when the base costs for shipping are considered. Second, utilization is low and unitary costs are high in variations and years where demand is low, showing the negative effects delayed demand has on costs. The effects here are mostly due to the pipelines, since their costs are almost fully driven by capital expenditures and fixed operational costs defined as a percentage of the CAPEX. However, conditioning facilities also have considerable capital and fixed operational costs, being almost half of the levelised costs when with full utilization.

Multi-Component Storage Systems: Utilization vs Cost

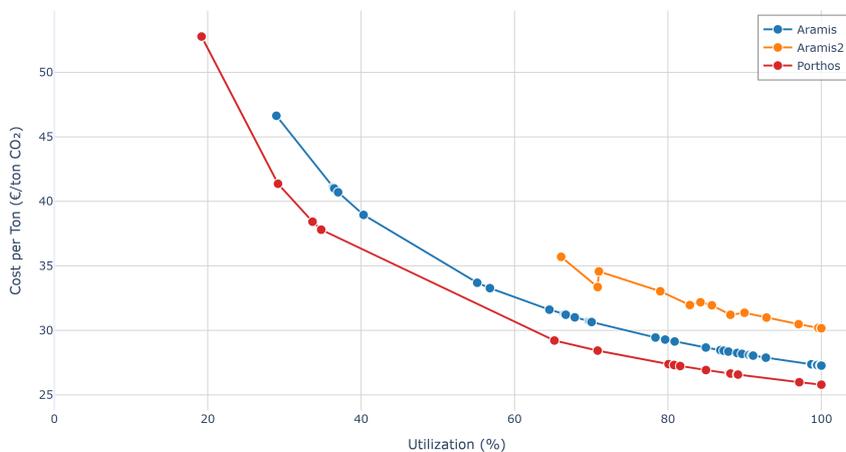


Figure 5.6: Cost per ton versus utilization rate for major storage systems across all scenarios, highlighting the non-linear relationship between capacity factor and unitary costs

Stores are also capital-intensive investments. However, they can be added to the offshore pipeline hub(s) more flexibly. In the model, this is represented by 30 Mt increases, taken as an average field size after the first few large fields are full (TNO, 2025). This is smaller for Porthos (5 Mt) because it is a smaller project with access to smaller storage fields. Figure 5.7 shows unitary costs of storage against utilization. This shows a similar relationship to the offshore transport systems. This shows the importance of initial capacity commitments before stores are developed. Store operators want to fill up their stores as quickly as possible to shorten the period in which they recoup their investment.

Figure 5.8 shows the utilization compared to the costs of large onshore and offshore pipelines. These show the same trend as the multi-component storage systems: costs per ton increase more when uti-

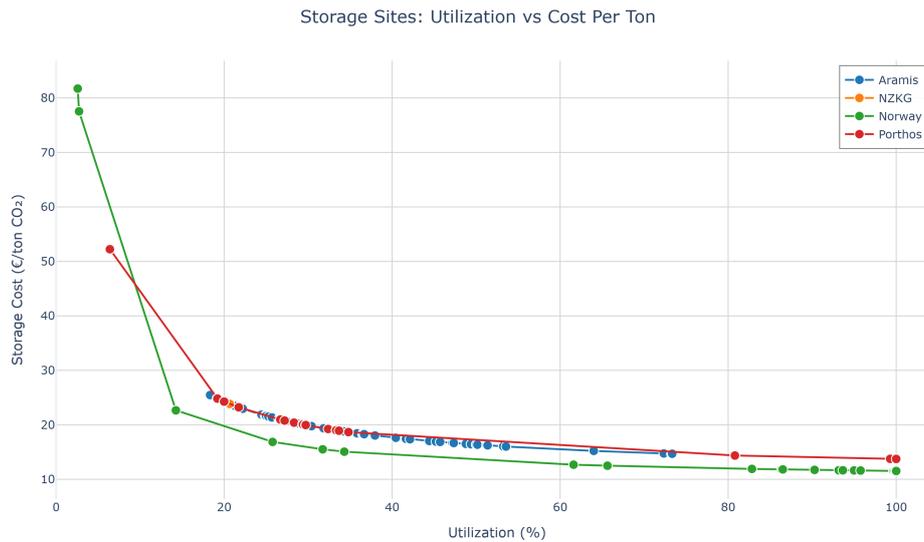


Figure 5.7: Unitary costs of storages with against utilization across all scenarios with unchanging costs.

Utilization is lower. Furthermore, offshore and long pipelines are, as expected, more expensive. However, this difference is relatively small since most long and offshore pipelines also have a higher capacity, again showing the impact of economies of scale. In general, both low demand scenarios and high demand scenarios just over the tipping point show the low utilization rates. The Porthos collector pipeline shows low utilization but the costs are less impacted than the other pipelines. Utilization is also in general between 18-58%. This is because some emitters are using the Moerdijk to RDM connection, which is part of the DRC, because they are closer to Moerdijk. The relatively small impact of low utilization confirms the decision of already overbuilding this capacity.

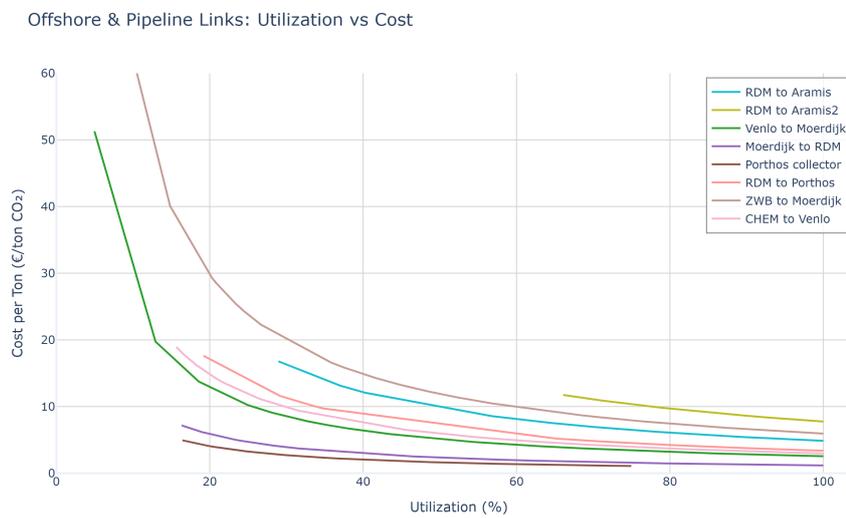


Figure 5.8: Cost per ton versus utilization rate for major onshore and offshore pipelines, showing the impact of distance, capacity, and economies of scale on transport costs across all scenario variations

5.1.4. Cost and Benefit Allocation

There are two dimensions in which the cost and benefit allocation varies: time and space. The time dimension relates to the allocation of costs for first-movers and late movers. Figures 5.3 and 5.6 show that when utilization is low, unitary costs can increase rapidly, which is especially the case in

the first investment periods. Note that the model has perfect foresight over future demand. Without perfect foresight and with uncertain demand, it is likely that either utilization will be lower or smaller pipelines will be built to mitigate some of the risk. If tariffs reflect the uncertainty and high unitary costs in the start-up phase, this shows a disadvantage for first-movers compared to waiting for investment. If infrastructure is built and not fully utilized yet, there does not seem to be a large disadvantage for late-movers. However, there is still a risk when low demand does not lead to FID for the projects needed for late movers, which is reflected in the LC&I scenario.

With large demand of both early and late movers, as reflected in the CDR variation, late movers could risk not getting access to initial storage and transport capacity. When there is a need for a second offshore transport system, the late movers become first movers to commit to the offshore infrastructure, again having a disadvantage. This is highly dependent on the development of demand, which is uncertain. The analysis shows that ship transport is not a cost-competitive alternative to pipeline transport (in the Netherlands) when pipelines are fully utilized, having 38% higher unitary costs.

The second dimension is space, referring to the extra costs for long-distance pipelines. Figure 5.9 shows the cost allocation in 2040 in the TRANSFORM scenario and import variations based on distance. It distinguishes between infrastructure with distance-dependent costs (onshore pipelines connecting individual emitters) and shared infrastructure with uniform costs (offshore pipelines, conditioning facilities, storage sites, and shipping). The total infrastructure cost per emitter C_i^{total} is calculated as:

$$C_i^{\text{total}} = C^{\text{shared}} + C_{\text{avg}}^{\text{onshore}} \times \frac{d_i}{\bar{d}} \quad (5.1)$$

where C^{shared} represents the unitary cost of offshore pipelines, conditioning, storage, and shipping infrastructure divided equally among all emitters; $C_{\text{avg}}^{\text{onshore}}$ is the average onshore pipeline cost per ton; d_i is the distance from emitter i to the nearest storage site; and \bar{d} is the average distance across all emitters.

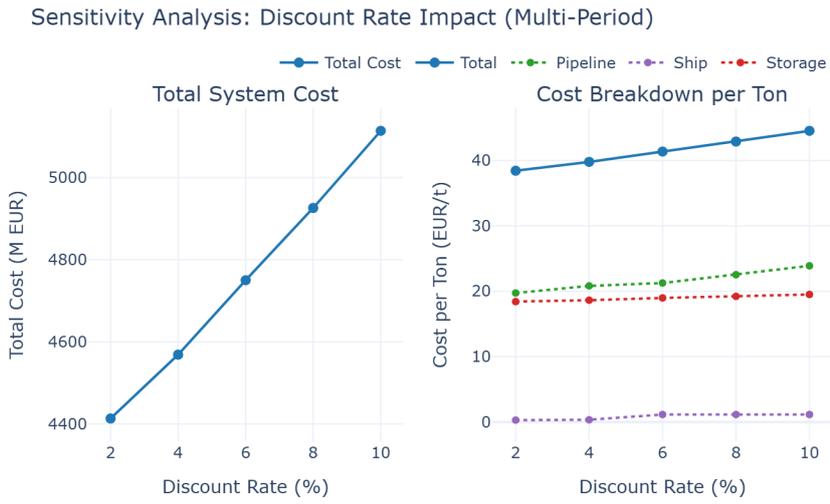
The figures show that average costs decrease when there is more import from Germany, following the trend that higher flow through the system decreases costs. However, the unfairness of cost allocation increases when Germany is added: Germany import and emitter3 (Chemelot) increase costs for other emitters. With increasing flow from 10-15 Mt, this effect decreases, showing again the advantage of increased system flow. All in all, the figures show that import decreases average unitary costs but increases per-emitter unitary costs if costs are shared over all emitters. Equal sharing of costs benefits emitters with a larger distance to storage sites, decreasing their unitary costs by up to 10.74 €/t, or 20.8 % compared to sharing costs based on distance.

5.1.5. Sensitivity Analysis

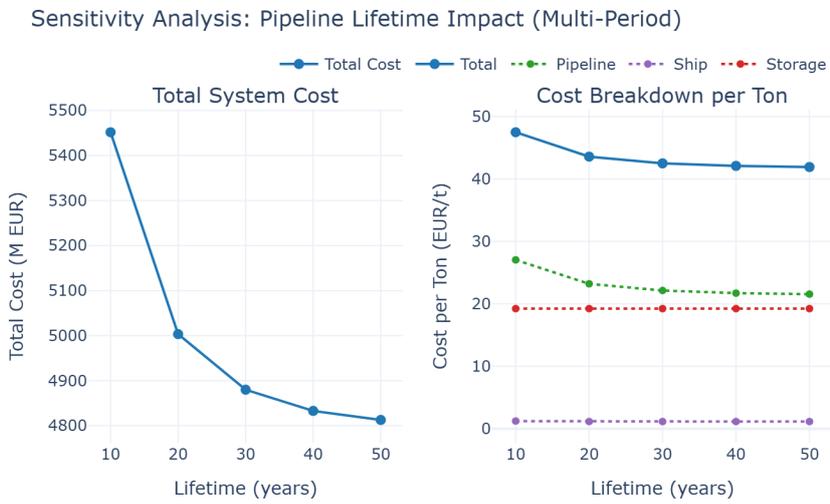
Figure 5.10 show the detailed sensitivity analysis results of discount rate, pipeline lifetime, and pipeline CAPEX on both system costs and unitary costs in the TRANSFORM base scenario. The system costs here are not the NPV, but the combined costs of the 5 years of operation and the annualized CAPEX in these years (i.e. they are not multiplied by the objective weightings). The component unitary costs are the effects the components have on total unitary cost.

Decreasing discount rates decreases both total system costs and unitary costs linearly, impacting the unitary costs of all components, but pipeline the most. The discount rate can be interpreted as the weighted cost of capital (WACC) and therefore has the highest impact on components with high capital investments. As mentioned by multiple participants in the interviews, publicly owned companies usually accept a lower WACC than private companies (3-4 vs 8+% depending on uncertainties). This shows the effect public financing can have on unitary costs, possibly decreasing unitary costs by 10 €/t.

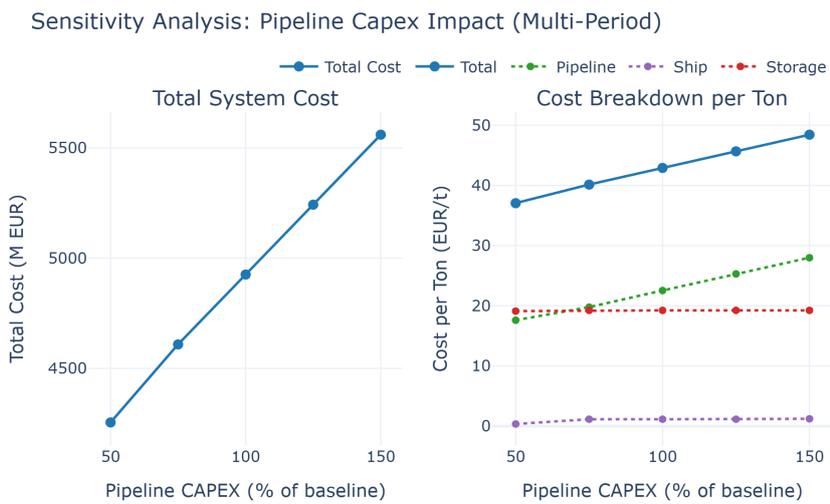
Reducing pipeline lifetime reduces total costs and pipeline unitary costs non-linearly, with low lifetimes quickly increasing costs. This shows the possible effects of both uncertainties and the transitional nature of CCS, both reducing the time companies want to recoup their investment. Xodus Group (2024) use 20 years for pipeline lifetime and the interview with Porthos showed their project lasts 15 years and is set to recoup investments in that period.



(a) Discount rate variation



(b) Pipeline lifetime variation



(c) Pipeline CAPEX variation

Figure 5.10: System cost sensitivity to discount rate and pipeline lifetimes in multi-period optimization.

to be a first-mover since the first-movers pay for part of the utilization risk (e.g. the full costs of the 22 Mtpa Aramis pipeline will be shared among the 7.5 Mtpa users (Xodus Group, 2024)).

Demand Uncertainty Demand uncertainty and the importance of the correct preconditions for emitters were mentioned in the EBN, Gasunie, PoR, RVO, and Porthos interviews. Three dimensioned were identified to influence demand: business-case, timing, and the investment/business climate. EBN, PoR, and Gasunie noted the importance and uncertainty of cross-border demand, specifically from Germany. This demand is important for the success of current projects and the increased flow through the system can lead to the realisation of economies of scale. Conversely, the uncertainty in tariffs which are not fully captured in the current SDE++ subsidy (interview PBL) currently lead to emitters postponing bidding for the SDE++ subsidy. If the tariff projections, which have almost doubled since the first inclusion of CCS (interview RVO), increase, the subsidy increases as well. This rewards waiting, possibly re-enforcing the first-mover disadvantage. The dichotomy of demand uncertainty and tariff uncertainty therefore strengthens the chicken-and-egg problem.

Market failure Both Porthos and EBN noted that it is evident that there is market failure in the currently developing CCS market. The asymmetric information due to the concurrent participation of Shell and TotalEnergies in storage injection and capture reduces trust in the system for other emitters (interview PoR). However, RVO noted that both the need for storage and the experience in such technologies does mean those parties take the initiative. Furthermore, the PoR noted an issue where storage operators compete for small initial volumes, which could lead to all (or some) of them not reaching the required volumes to start their project. The high barriers to entry due to the large investment costs and limited competition between certain parts of the value chain (interview Porthos) shows that the currently developing CCS market is an imperfect market.

5.3. Key Identified Risks

Combining the results from the literature and interviews, Table 5.2 shows the identified risks categorized. These are discussed further below.

Table 5.2: Synthesis of Key Risks in the Dutch CCS System: Combining Quantitative Model Results with Qualitative Interview Insights.

Risk Category	Quantitative Evidence (Model)	Qualitative Evidence (Interviews)
Coordination	Utilization risks; high capital costs; sensitivity to rising prices	Chicken-and-egg problem explicitly mentioned by almost all participants; demand, tariff, cost, liability, and business climate uncertainty
Market Power & Information Asymmetry	High capital costs; costly alternatives once pipelines are built; large sunk costs in multiple parts of the value chain	Lack of trust in storage parties because they are also customers; stores could outcompete one-another; market failure evident; interconnectability issues
Cross-Border Regulatory Risks	Import lowers overall unitary costs; export subsidization could impact cost competitiveness shipping; pipeline-based system cost-optimal from a systems perspective	Import important for current projects and economies of scale; currently relatively low export costs and more certainty due to foreign government support; long-term shipping contracts could reduce needed demand to lower unitary costs pipeline infrastructure
Temporal Risks	First-mover disadvantage; utilization risks for all new pipelines, also later on	First-mover disadvantage and late-mover advantage; competition stores may be possible in the future, but currently is not

Coordination Coordination came forward as one of the main barriers to investment in the interviews. This coordination problem has a few underlying causes. Low utilization results in high unitary costs for both pipelines and storages, with unitary costs doubling when utilization drops from 60-20% and storage and onshore pipelines showing an even steeper decline under 20% (see Figures 5.6, 5.7, and 5.8). The high asset specificity identified in Chapter 2.5.1 along with the high upfront capital costs shown in the model mean that parties need certainty before investing. However, the interviews identified large uncertainties surrounding future demand, liability, tariffs, costs, and the business climate (future of the industry). The model showed sensitivity to demand decreases through increasing unitary costs. Furthermore, uncertainty leads to infrastructure owners either reducing the capital recovery time or increasing returns on investment to compensate for the uncertainty. Figure 5.10 showed unitary costs and total system costs are sensitive to both variables.

Market power & information asymmetry Pipeline infrastructure exhibits natural monopoly characteristics due to high CAPEX and economies of scale. Market entry for new pipeline operators is difficult once the coordination problems have been solved. Ship transport, while possibly outcompeting pipeline transport due to increased flexibility and decreased coordination issues in the initial development stages, is up to 38% more expensive once pipeline infrastructure has been built. Even if shipping transport to stores would become more competitive, a monopolistic bottleneck still exists for long-distance onshore transport. Furthermore, the possible interconnectability issues could hinder competition, making investments even more relationship specific. The information asymmetry due to storage operators also being customers of the storages leads to distrust in the market. This was identified by Mulder (2024) and further strengthened by the analysis above.

Figure 5.11 shows the possibility of competition in the different parts of the value chain. The characteristics for identifying a monopolistic bottleneck are considerable sunk costs and a lack of substitutes. The model shows this is the case for the parts in the value chain coloured red. The blue parts show where competition may be possible in the future but there are considerable risks for market power. Close monitoring of those risks is therefore important.

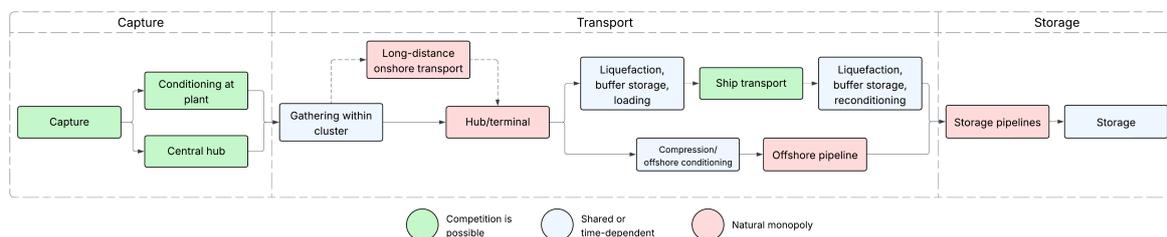


Figure 5.11: Overview of the supply chain of the CCS system including market power characteristics of each part of the supply chain.

Cross-border regulatory risks Both the model and interviews showed the positive impact import could have on the Dutch CCS system: even though cost sharing can become an issue due to the higher costs for e.g. Germany, the total increase in demand pushes down costs considerably (Figure 5.4). Without this demand, the CHEM cluster may not have the possibility to use CCS against acceptable costs. On the other hand, different cost compensation mechanisms in countries like Norway currently lead to lower prices and especially more certainty (interview, PBL), but could lead to sub-optimal outcomes from a systems perspective; where you would want multiple emitters to choose the same (less expensive route) to capitalize on the economies of scale (interview, Porthos). This can currently be observed with the ZWB cluster, where one company has chosen shipping, reducing the total demand potential for the cluster. Both the effects of import and export show the dependency on regulatory frameworks and decision-making in other countries.

Temporal risks The last dimension influencing the identified risks is time. The development of the CCS-system consists of two phases with different challenges, although they also share similarities. In the initial start-up phase, coordination risks dominate with parties hesitant to take FID. There is a large

first-mover disadvantage and the limited competition could hinder further development (as identified in both stores and between shipping and pipeline transport). In the second phase, when pipeline infrastructure and storages are built, pipeline transport has a clear monopoly and competition between stores may be possible, although still with large problems due to the non-linear addition of large stores as shown by the model. Even though first-movers enter long-term agreements with transport and storage operators, their natural monopoly and the high relation specific investments made by users would still reward opportunistic behaviour, increasing market power risks in this second phase.

However, if the large offshore infrastructure project is fully utilized during the second phase, a similar coordination problem could arise again, albeit with more trust in the market. New pipeline infrastructure (see Aramis2 utilization) needs a large commitment from capture facilities again which could be hesitant to provide it, having a first-mover disadvantage. In the model, this dynamic is observed when CDR demand is added, having to build the Aramis infrastructure. Therefore, although current installations have little disadvantage to be a late-mover, new demand entering the market at a later stage, may again be at a disadvantage. When designing interventions in the market using governance, it is therefore important to consider these changes over time. This will be further discussed in the next chapter.

6

Results: Governance Options Framework and Mitigation Performance

This chapter answers research questions 3 (Section 6.1) and 4 (6.2) by showing the governance and regulatory design options and showing how they perform under the identified risks of the previous chapter. Together, the chapters provide a governance framework consisting of the options and mitigation options under different risks.

6.1. Governance Options Analysis

This section aims to answer the research question *What are the different governance options to support the development of CCS networks?*. The governance options framework presented in Figure 6.1 presents all identified options from interviews and governance literature (see Chapter 2.5). The overarching categories, which are presented an options framework, are explained first after which the categories are further elaborated on including, expanding the options framework per category. The framework organizes governance options into three main governance categories: structural governance, network access, and economic regulation. Generally, the options further to the right are more disruptive to the market and the market incentives and necessitate more state control.

Structural governance addresses fundamental market conditions. This category encompasses ownership and unbundling of supply chain segments (CATF, 2024; Glachant, 2012). These structural choices directly shape the market's competitive landscape and, according to Transaction Cost Economics, help prevent opportunistic behaviour arising from incomplete contracts and high asset specificity (Williamson, 2005). *Network Access* focuses on operational mechanisms that minimize transaction costs and resolve coordination problems. Network access tools include the access regime (from interviews, Regulation 2024/1735 (2025)), deciding who has access and under what conditions, and capacity allocation mechanisms that set the rules determining whether infrastructure is built for current demand or future needs. *Economic Regulation* determines how financial risks and benefits are distributed among stakeholders, both between the state and market participants and between the market participants themselves. This category includes price regulation (Jaag & Trinkner, 2011) to potentially cap the tariffs, cost allocation determining the between-stakeholders cost sharing (from interviews), and volume risk allocation, determining whether the state or market participants take the volume risk (CATF, 2024).

6.1.1. Structural Governance

Figure 6.2 shows the structural governance category in more detail, showing only the market interventions and not the default market option. Ownership can be either private, or under market rules, hybrid (partial public ownership) or completely state-controlled. The interviews (EBN, Gasunie, PoR,

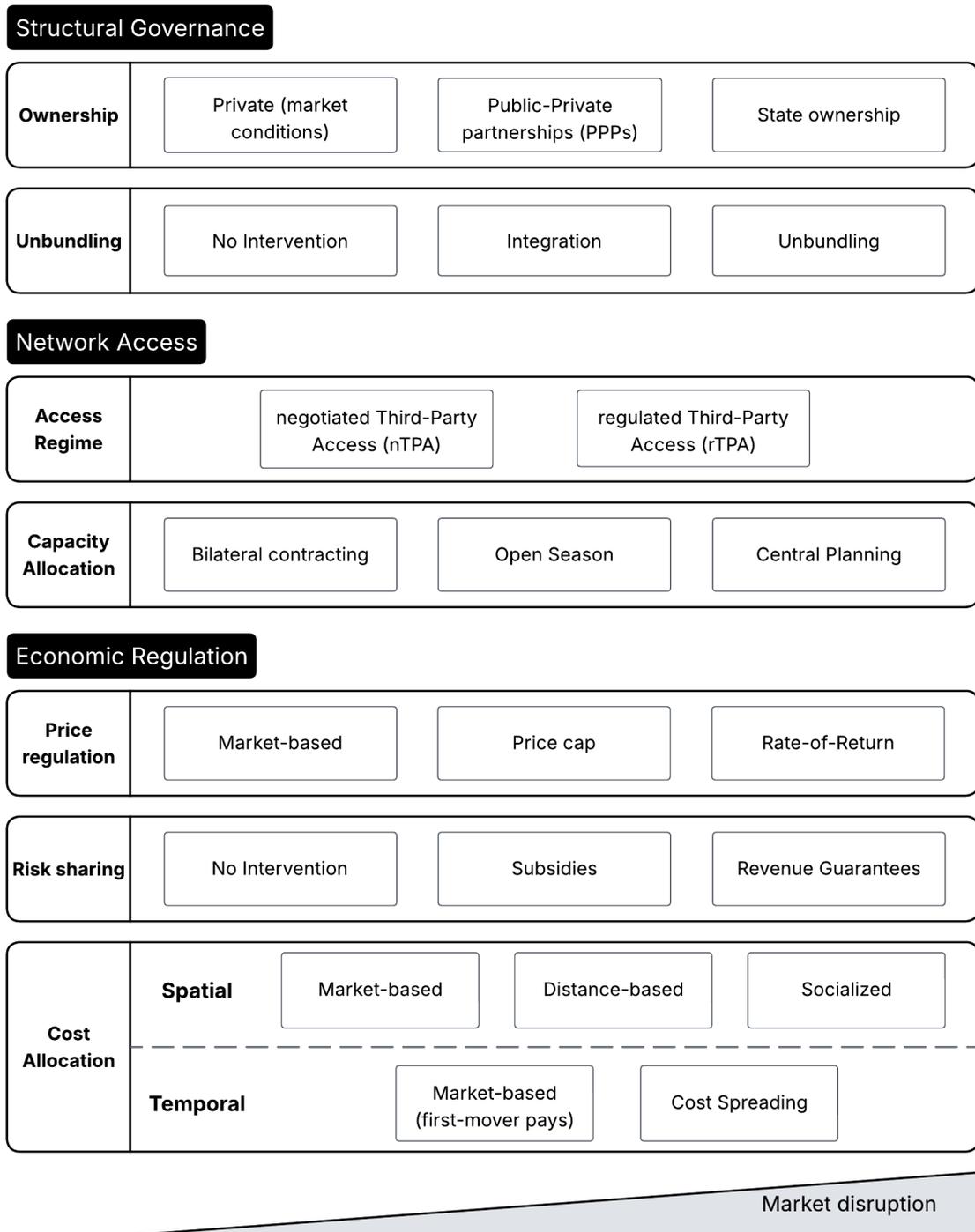


Figure 6.1: Governance options framework showing the identified governance options in CCS systems categorized in three main categories. The options framework is developed based on literature and interviews, but is developed by the author.

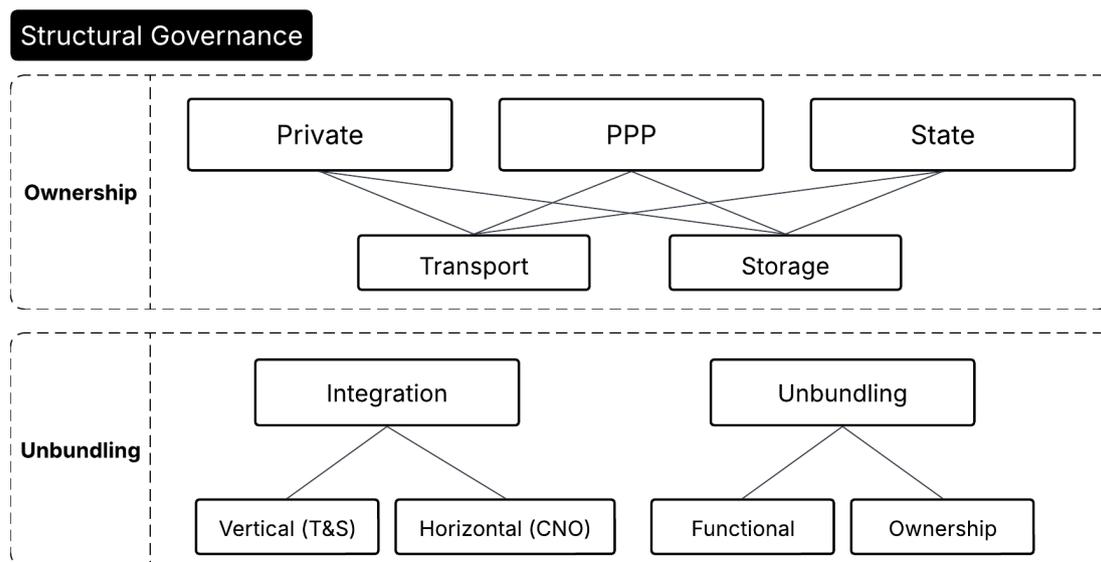


Figure 6.2: Options framework highlight showing the options within the Structural Governance category

Porthos) show that public companies can accept smaller margins and take higher risks than private companies. Therefore, public participation could de-risk investment. Furthermore, state ownership gives more control to the government, meaning they can take a larger central planning role and implement their public values. With ownership, the government takes the risks, but could also get the future profits directly. There are strict rules on government participation in the current regulatory framework, but market power and market failure in essential infrastructure are widely recognized to be a valid reason for state participation (Raad voor de leefomgeving en infrastructuur, 2025; Teulings et al., 2003). Full government control is considered to be the "last-resort" instrument to prevent market power abuse by Jaag and Trinkner (2011), heavily infringing on property rights and investment incentives. Figure 6.2 shows that the decision for market intervention could be made in two areas: transport and storage. For the CCS-system, state-ownership in capture facilities is not logical, since it is not part of essential and shared infrastructure.

The choice for unbundling is based on network regulation and transaction cost economics (Jaag & Trinkner, 2011; Williamson, 2005). First, there is a choice between unbundling or integration. Unbundling can be used to regulate monopolistic bottlenecks (Jaag & Trinkner, 2011). The goal is to assure non-discriminatory access conditions. Functional unbundling does not change ownership of bottleneck resources, but requires operations and management separation, where decisions need to be made independently by separated business units. An example here could be the creation of a network operator separate from the owner of the infrastructure (e.g. a "Carbon Network Operator (CNO)"). The operator is responsible for security of supply, safety, reliability, and environmental care of the infrastructure. Ownership regulation means an independent or government owned entity gets the monopolistic right to own and operate a certain part of the infrastructure. Since this creates a legal monopoly, this entity has to be regulated to prevent market power abuse, regulating third-party access and capping prices or allowed rate of return. These options will be explored in Sections 6.1.2 and 6.1.3.

The opposite of unbundling is integration. Integration could be used to solve coordination problems arising from high transactions costs (Williamson, 2005) but (as an opposite of unbundling) could lead to higher market power for one company. According to TCE, transactions characterized by high asset specificity and a recurrent frequency can reduce transaction costs through integration (hierarchical governance). High transaction costs are one of the causes for the coordination problem (interview, RVO). For integration there are two options: vertical integration and horizontal integration. Vertical integration is the integration of e.g. transport with storage, as is the case in the Porthos project. Horizontal

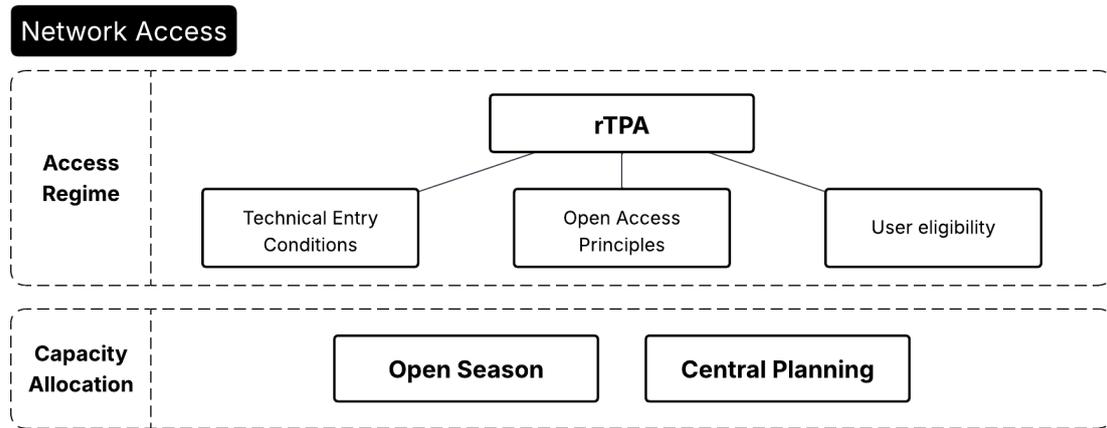


Figure 6.3: Options framework highlight showing the options within the Network Access category

integration is the integration of, for example, conditioning activities with pipeline transport activities, or onshore pipelines with offshore pipelines. Integration can be combined with unbundling to set the market conditions. For example, if a CNO operates all onshore and offshore pipelines and a separated entity within the same company owns the infrastructure (and no-one else is allowed to own or operate them), that is horizontal integration combined with both functional and ownership unbundling.

6.1.2. Network Access

Figure 6.3 highlights the network access options in more detail. The governance choice here is regulated Third-Party Access (rTPA). This means that access rules are established ex-ante by the regulator rather than negotiated confidentially. This can be used to restrict market power (Jaag & Trinkner, 2011) and is essential when unbundling creates a legal monopoly, although it can also be implemented separately from unbundling. There are three options. Technical entry conditions can be used to define physical and chemical parameters, such as CO₂ purity, pressure, and temperature. This includes essential safety regulations but setting specific or minimum requirements can also ensure interoperability. Open Access principles mandates fair, reasonable, and non-discriminatory access. The goal is to prevent discrimination to give all users a fair chance to entry and prevent market power. However, it is less effective than structural changes to the market (Vickers, 1995). Last, user eligibility establishes who is permitted to access the market. In early stages or when alternatives are available, users could get priorities. The current SDE++ instrument effectively implements this although without hard rules, removing eligibility for the subsidy if alternatives are available (CE Delft, 2024). User eligibility can also create less restrictive rules, i.e. the (regulated) operator needs to provide capacity to all demand in all locations. This is especially an option for essential infrastructures like the electricity network.

Capacity allocation refers to how capacities are set and how they are distributed among emitters. Apart from bilateral contracting, where the market decides the optimal capacities to build, there are two options: a mandatory open season and a central planning. With an open season, the operator aggregates non-binding or binding interest from multiple emitters during a specific window to determine the capacity before FID. This reduces the risk of under-dimensioning while maintaining market signals (Pickl & Wirl, 2011). However, upcoming sectors which are under-represented currently (like CDR or blue hydrogen production) would not have the chance to enter in the open-season, which could result in high costs later on when new infrastructure needs to be built for the late-movers. To accommodate for this, a central planning could provide a solution. Here, the government or a central planner determines the optimal capacity based on long-term climate targets rather than immediate commercial interest, ensuring economies of scale are realized. This is a large market intervention and, therefore, requires state guarantees to ensure parties can manage the mandated capacities. Whether intervention is necessary largely depends on whether the market currently results in building (clearly) sub-optimal capacities.

6.1.3. Economic Regulation

The last category of the governance options framework is economic regulation. This includes the cap-and-floor mechanisms for market power and to reduce volume risks as implemented in the UK for example (CATF, 2024) and the allocation of costs both over time and space.

Price regulation is one of the least invasive methods for reducing market power, apart from access rTPA (Jaag & Trinkner, 2011). With price regulation, the regulator caps the price the operator can charge. The options here are an allowed Rate-of-Return (RoR) or a price cap. RoR, or cost-plus regulation, sets an allowed maximum return on investments and operating costs. This allowed return is often combined with state guarantees for that allowed return, as is the case with the Regulated Asset Base (RAB) model in the UK (CATF, 2024). An allowed RoR does not incentivize cost efficiency, especially when it is combined with state guarantee, since higher spendings lead to the same returns. A price cap can be implemented to protect users, setting a maximum tariff. It incentivises operational efficiency since returns can increase when costs decrease. However, it carries the risk of under-investment or no investment if the cap is too low and prices rise rapidly. A price cap can also be combined with a credit guarantee, capping prices but saving the company when a certain floor is reached (providing them with a minimum revenue). The combination of guarantees and price regulation is often called a cap & floor mechanism.

Risk sharing includes the governance mechanisms used to distribute financial exposure between the private sector and the state. Subsidies are the currently used tool by the Dutch government to take on part of the risk. The SDE++ (CE Delft, 2024) focusses on demand-side subsidies by covering the unprofitable margin of CCS capture installations. This subsequently also increases demand certainty for the T&S operators. Supply-side subsidies directly support either store or transport operators (or both). This could be through an instrument like the SDE++, but the more incidental nature of these projects also creates the possibility for customized agreements. While this reduces uncertainty, they are just one-time payments and not guarantees. State guarantees create more certainty than subsidies with two options: a minimum revenue guarantee or loan guarantees. A minimum revenue guarantee is the floor part of the cap & floor mechanism. It de-risks a large part of the investment, especially when flows and utilization are low. Loan guarantees reduce the cost of capital (WACC) since the state guarantees that loans will be paid back, reducing interest rates. Both the minimum revenue guarantee and loan guarantee are used in the UK (CATF, 2024).

Cost allocation determines how infrastructure costs are allocated over users, determining the tariff structure. There are two dimensions: spatial and temporal. Spatial allocation determines who pays for the infrastructure for far-away emitters, and temporal allocation determines who, over time, pays for low utilization.

Spatial cost allocation can be either distance-based or socialized. The default in the market is currently distance-based, where emitters need to have contracts with all infrastructure operators from their facility to the storage (interview, Gasunie). However, it is not regulated, with the Porthos project sharing costs among all users (interview, Porthos) although they are all relatively close to one another, making cost sharing not particularly unfair. When regulating tariff structure, the options could be distance-based or socialized. Distance-based tariffs are fair to all users, since they only pay for the parts of the infrastructure they use. Distance-based tariffs could be socialized per cluster, simplifying the tariff structure. This is what the UK has implemented (CATF, 2024). The advantage of fully socialized costs across all users could be the realisation of cost reductions across the board due to volume increases. To implement socialized cost allocation, it is necessary to have one operator, or at least one party offering contracts (interview, Gasunie).

Temporal cost allocation can be front-loaded, or deferred. Front-loaded tariffs mean that the first-mover users pay for initial low utilization by sharing the full infrastructure costs over the initial users. This de-risks investment for the infrastructure operator, but increases tariffs for first-users. This is the default currently seen in the Dutch CCS market, but could be mandated, which is why it is included here. To reduce the first-mover disadvantage, costs can be deferred to the late-movers through temporal cost-sharing. This was brought up as a possible governance option in the interview with EBN. There is a significant role for the government here, since it increases risks for the infrastructure operator. The government could implement a Revenue Support Agreement (RSA), where the state compensates the operator for the shortfall between the artificially lowered entry tariffs and the actual allowed or required

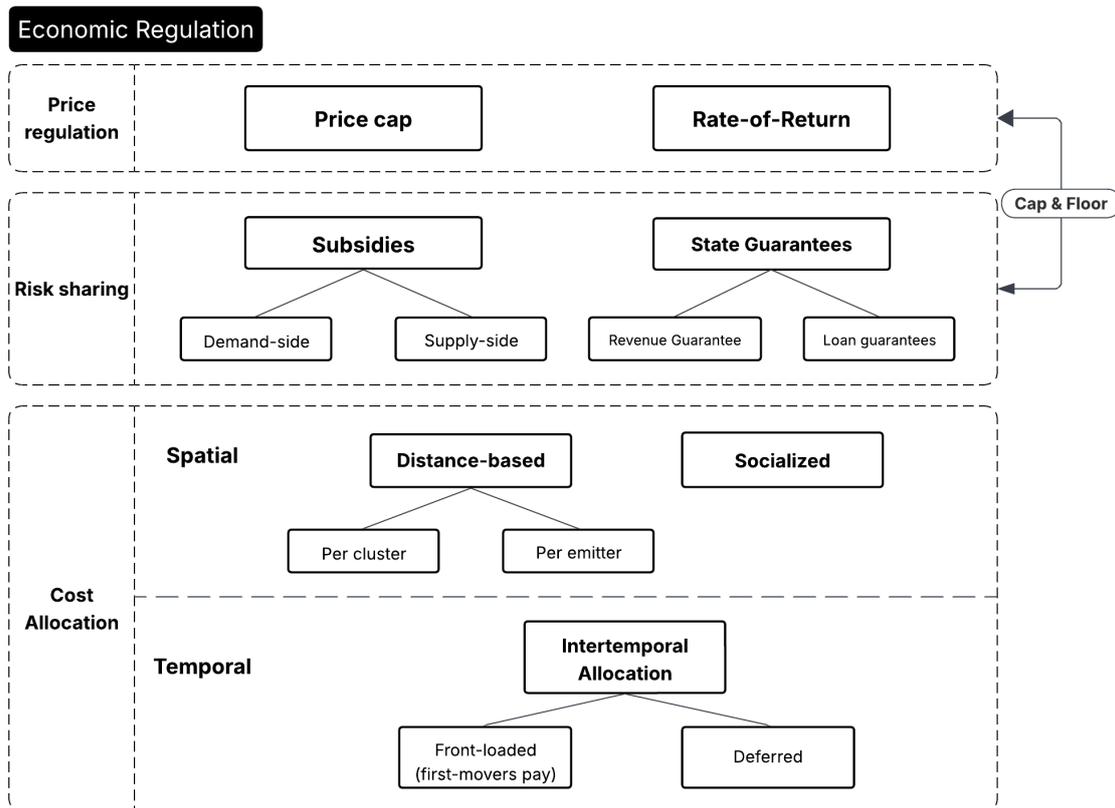


Figure 6.4: Options framework highlight showing the options within the Economic Regulation category.

revenue required to cover capital costs (CATF, 2024). This decoupling ensures the project remains bankable for the operator while protecting first-mover users from prohibitive fees.

6.2. Performance of Governance Options

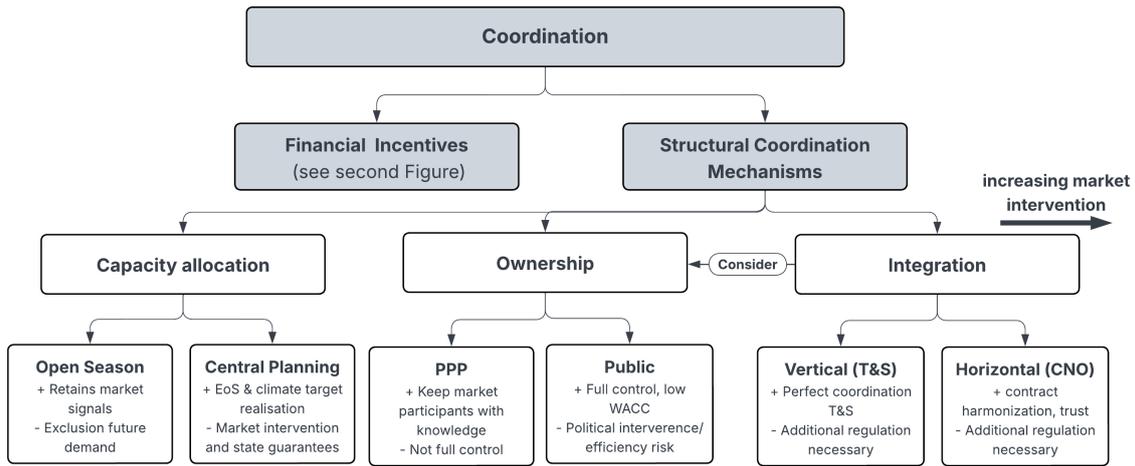
This section combines the risks identified in Chapter 5 with the governance options framework developed above. The goal is to answer sub-question 4: *How do different governance options perform in mitigating the identified risks in CCS networks?* To achieve this, decision trees have been developed for the coordination and market power risks showing the governance options along with their main performance considerations and trade-offs. These are further elaborated on in Sections 6.2.1, and 6.2.2. The Cross-border regulatory risks (6.2.3) determine the decision-making regarding on what level the governance should be implemented, i.e., for the Netherlands, state-level, bilateral agreements, or EU-level. The temporal risks (6.2.4) relate to the transitional nature of CCS and therefore reflects on the governance decision framework in the two identified phases.

6.2.1. Coordination

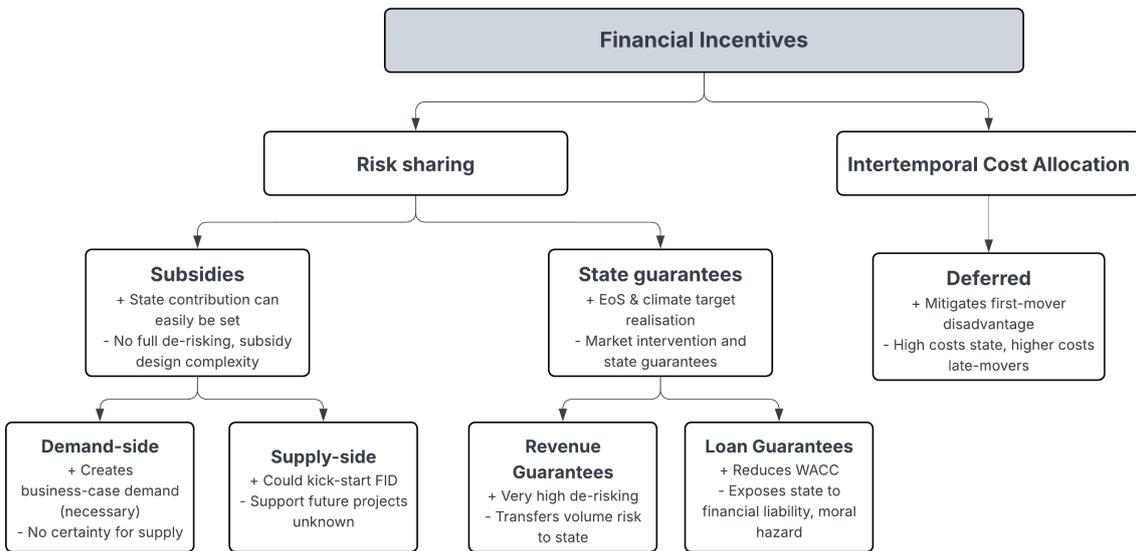
To mitigate the identified coordination risks, there are two governance instruments available: Financial Incentives, covering the utilization risks at the heart of the coordination problem, and Structural Coordination mechanisms, drawing from TCE (Williamson, 2005) and capacity allocation literature (Pickl & Wirl, 2011). First, the Structural Coordination mechanisms are discussed.

Structural Coordination

From the governance options framework, three options can be identified which structurally mitigate the coordination problem. Capacity allocation through an open season or central planning could decrease future undercapacity (Pickl & Wirl, 2011). Such an instrument is only necessary if the market does



(a) Market Coordination Governance tree addressing coordination failures in the CCS value chain. Structural coordination mechanisms are shown more closely, while figure 6.5b elaborates on the Financial Incentives



(b) Financial Risk Governance tree detailing instruments for managing financial uncertainty, which is part of the coordination risk.

Figure 6.5: Governance frameworks addressing Coordination risks developed by the author based on the risks and governance options framework

not provide the right incentives for optimal capacities. With the first large-scale planned projects in the Netherlands (Aramis, DRC, DSC), overcapacity to serve future demand is incorporated. Therefore, unless high utilization risks will outweigh potential economies of scale in the future, capacity allocation seems to be unnecessary in the future.

Ownership can help mitigate the market coordination problem. Mandatory public-private partnerships (PPPs) in stores particularly could mitigate issues of store interaction and take away underlying liability and monitoring concerns (interview, EBN). This creates trust in the market, reducing the chicken-and-egg hold-up problem. Full public ownership of certain parts of the CCS value chain shows market parties that the state fully supports CCS, which was named as an important enabling factor in multiple interviews.

Integration is the most intrusive way to solve the coordination problem by minimizing transaction costs (Williamson, 2005). Vertical integration can lead to perfect coordination between transport and storage, one of the success factors of Porthos (interview, Porthos). This could be compiled with state participation through PPPs in both storages and transport as a hybrid partial integration form improving coordination (interview, EBN). Horizontal integration, for example by integrating pipeline segments leads to better coordination between those segments and contract harmonization (interview, Gasunie), reducing complexity for the users, reducing the coordination problem. There is a trade-off here with market power, where legally integrated systems have a higher market-power, especially because there is limited competition possible. When choosing integration, it is therefore important to also unbundle it from other activities and regulate the market power (Jaag & Trinkner, 2011) (see Section 6.2.2)

Financial Incentives

Financial Incentives reduce the utilization risk and risks from high upfront investments identified at the heart of the coordination problem. Without these risks, coordination would not be an issue since there would not be a risk of large stranded assets. The goal with financial incentives is to incentivize and de-risk investment in such a way that parties can take the first step, increasing trust for others.

Risk sharing, where the governance takes on part of the utilization and stranded asset risk, directly impacts the risk. Tools like the SDE++ create demand through reducing investment risk and supply-side subsidies do the same for the transport and storages. In the interview with Porthos, storage was noted to be the "crux": if injection capacity is realised, there is trust in the market that their captured CO₂ can go underground eventually. On the other hand, a sound business-case for emitters and demand creation have been mentioned in multiple interviews as essential and currently, without the SDE++, lacking. Therefore, demand-side incentives seem to be persistent in all chosen governance forms.

Subsidies have the down-side that they are mostly one-time or fixed payments. In a developing system, quickly rising costs can therefore make subsidies less effective. State guarantees create more de-risking, guaranteeing that the state will take a large part of the risk, even with rising costs. However, this decreases incentives if not set properly and transfers a large part of the risk to the state, possibly being expensive. Especially loan guarantees could create a moral hazard, where operators might take excessive risks because they know the state will bail out their debt.

An important underlying reason for the coordination issue is the first-mover disadvantage and late-mover advantage (interview PoR, model results) creating a hold-up problem. Inter-temporal cost allocation could solve this issue by deferring the costs to later generations. This does create higher risks for the operator, especially if volumes (which are highly uncertain) are lower than predicted. The state could step in here with guarantees under the conditions that costs are deferred and the state will pay if demand is lower than expected. In that case, tariff regulation may be necessary to ensure tariffs are set correctly. This could lead to high risks in the beginning phases of the transport projects. In the first investment period of the TRANSFORM scenario, unitary costs are 59.60 €/t with 8.7 Mtpa demand. The average unitary costs over all investment periods is 45.00 €/t. Deferring costs would transfer the risks to the operator or state (or a combination), costing in this scenario 391.5 M€/y, without full certainty that this will all be compensated for later.

6.2.2. Market Power & Information Asymmetry

Figure 6.6 shows the options to reduce the identified Market Power and Information Asymmetry risks, increasing in the effect they have on property-rights and investment incentives.

rTPA is a logical first step towards reducing market power. Open Access Principles have already been implemented in both the EU and the Netherlands ("Mijnbouwwet", 2025; Regulation 2024/1735, 2025). Ensuring this non-discriminatory access is important in the CCS market, as identified by Gasunie in the interviews and the discussion of public values by Mulder (2024). However, these principles are only behavioural constraints and do not structurally limit market power, being less effective and having high regulatory costs (Vickers, 1995). It is therefore essential, but may not be enough. In addition, technical entry conditions could promote competition by ensuring interconnectability (interview, TNO), although this could reduce technical efficiency for specific supply chain components.

Tariff regulation limits market power by capping the monopolistic price setter. In the current phase of development, tariffs likely represent costs accurately because demand is lower than the projected

capacities. However, when demand exceeds the supply capacities, the operator can increase tariffs because of limited competitive alternatives. Furthermore, the SDE++ mechanisms takes into account current projected tariffs (interview, PBL). While currently set by an independent party (Xodus Group, 2024), this lowers the incentive for operators to decrease tariffs or built cost-efficient infrastructure since demand is less elastic to the price (the government takes the risk).

Last, unbundling restricts market power and asymmetric information (Jaag & Trinkner, 2011). This unbundling could decrease distrust the users currently have to parties operating in both storage and users (interview, PoR). State ownership when choosing ownership unbundling could be a logical choice because of the public interest surrounding CCS (interview, Gasunie). If CCS is seen as an essential infrastructure by the state, it could implement its public values (reaching climate goals, affordability, keeping industry, realising future CDR) more effectively. The identification of a natural monopoly as a large risk in the future CCS system indicates, according to network regulation frameworks (Jaag & Trinkner, 2011), that unbundling and subsequently tariff regulation may be necessary. Especially given that the alternative when prices are high is the reduction of industry, which is against the public values in the Netherlands particularly.

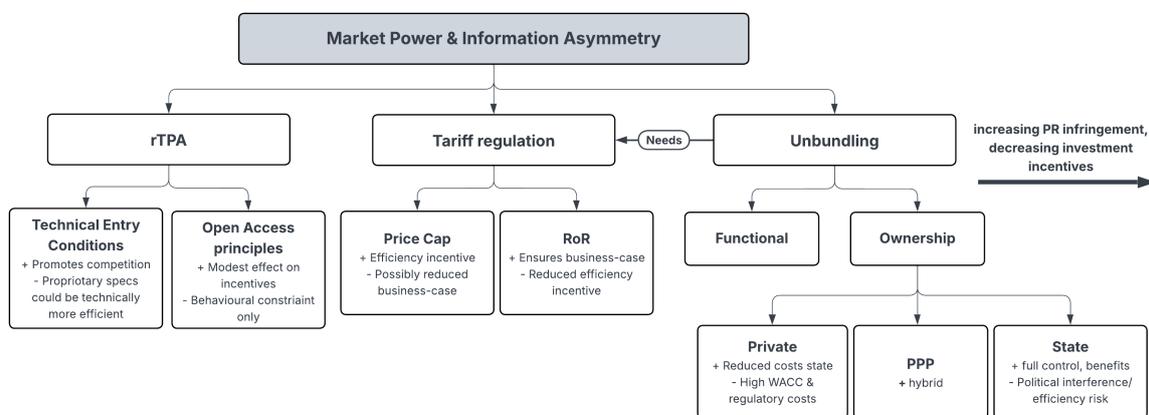


Figure 6.6: Governance framework for mitigating Market Power & Information Asymmetry developed by the author based on the risks and governance options framework

6.2.3. Cross-Border Regulatory Risks

Cross-border risks influence where the governance should be implemented and includes spatial cost allocation. The model showed that socializing costs can be unfair to emitters close to storage, who have to pay for infrastructure they do not use. On the other hand, socializing costs does give everyone an equal chance to use CCS and could lead to average unitary cost reductions. The decision-making surrounding this governance choice boils down to explaining the non-discriminatory access and fair participation identified as a public value (EZK, 2023; Mulder, 2024). On a European level, spatial socialization of costs could result in more opportunities for emission reductions through CCS in parts of the EU without storage capacity.

EU-level governance is best suited for harmonization of technical standards (e.g., CO₂ stream composition) to ensure interoperability between countries. Open Access principles (like Regulation 2024/1735 (2025)) and regulatory principles (e.g., unbundling) could ensure a level playing field between countries and prevent market power in one country to worsen the position of another. However, Financial Incentives, such as subsidies and Revenue Support Agreements, should primarily remain at the National level, as these instruments rely on domestic tax revenues and countries have different public values influencing their decision-making on CCS. Consequently, the connection between these distinct national regimes requires Bilateral governance. Bilateral agreements could create demand certainty, of which the sensitivity of the Dutch market to German imports is a good example.

6.2.4. Temporal Risks

Chapter 5.3 identified two, not strictly separate phases in the development of CCS-systems: the phase to FID of large projects and initial commitment, and the more mature phase, which eventually could exhibit the same risks as in phase 1 again. This creates governance trade-offs, which are discussed below.

The primary governance trade-off arises from the conflicting needs of these two development phases. The early phase (pre-FID) is characterized by acute coordination failures and high capital risk, necessitating state intervention, such as vertical integration, or heavy subsidization as we see now, to secure initial volumes and a sound business-case for all participants. However, these same mechanisms can become liabilities in the mature phase, where they may entrench monopolies, reduce competition, and inflate costs. Consequently, the governance options should be evaluated while keeping in mind that establishing a rigid governance framework to solve early-stage risks may block the later transition to a competitive, market-based regime and may lock-in carbon capture as the preferred mitigation method (Akerboom et al., 2021). It is therefore important to create a governance framework that is adaptive (interview, TU Delft).

At the same time, the pre-FID phase could arise again with new infrastructure transport. The question that then remains is whether the CCS market could eventually be a mature market without subsidization, although driven by the ETS price. Conflicting with the views of Mulder (2024), the results of this research have shown that certain parts of the CCS value chain, particularly pipeline transport, inherently possess natural monopoly risks which should be mitigated. Also in the long-term towards a mature market. Asymmetric information and the non-linear addition of large stores raise the question whether competition between stores will be feasible in a future market. Interviews confirmed that multiple stakeholders have concerns about the notion of effective storage competition will eventually emerge.

To conclude taking into account the temporal considerations inherent in the CCS-market while designing governance interventions is essential to a good governance design. The governance choices as well as how they are linked and perform under the different risks have been analysed in this chapter. It shows the many trade-offs policymakers should consider.

7

Discussion

This chapter discusses the results and put them into the context of the broader energy transition, other countries, networked infrastructure, and the current theoretical framework surrounding CCS and governance. Next, the chapter reflects on the methodological choices and presents the limitations and future research.

7.1. Integration with Broader Energy Transition

The broader context of the energy transition and energy system provides a good insight in the trade-offs and impact of decision-making for governance in the context of CCS.

A lock-in to fossil fuels and less investment in alternatives has been identified as a potential issue for the use of CCS technology by Akerboom et al. (2021) and preventing this lock-in is identified as one of the public values. The model, literature (Durmaz, 2018; Holz et al., 2021), and interviews showed clear advantages of increasing volumes in the system due to economies of scale. The goal in the broader energy transition of prioritizing alternatives compared to CCS therefore contradicts with a pure optimization of CCS systems. CCS competes with alternatives on resources (both public and private) and space, showing the importance of striking a balance in the decision-making on governance. CCS is hugely important for reaching climate targets and limiting global warming (Grant et al., 2025; IPCC, 2023), but the lock-in of fossil fuels that may accompany it should be carefully considered. The first step in decision-making for CCS-systems is therefore to identify clear energy system and CCS goals as it influences the extent to which risks should be mitigated and which risks are acceptable.

At the same time, the decision to support CCS infrastructure is inextricably linked to the public value of retaining industrial activity within the country and EU in general. High CO₂ infrastructure prices can lead to the risk of carbon leakage rather than abatement. If the policy maker is too hesitant due to lock-in concerns, energy-intensive industries may relocate rather than transition. The strong dependency on cross-border flows from Germany identified in the results suggest that this 'anchor' function is regional, not just national, requiring bilateral governance alignment to prevent the stranding of assets in both the port of Rotterdam Germany.

7.2. Applicability to Other Countries

The Netherlands has a unique position, having both inland demand and being a hub for export and domestic storage. The developed governance framework is also highly relevant for other countries which have the potential to become a hub with the same characteristics, particularly the UK and Norway in the EU. However, Norway for example relies more on import from ships, which reduces (but not eliminates) the risks of stranded assets for import due to differing regulatory frameworks in other countries.

For countries without storage capacity (like Belgium and Germany), the governance framework is still a useful tool, although with some changes. The coordination problem is reduced to coordination between transport operators and users. However, this could increase the market power of transport companies

even more, since they only rely on a connection to another country and do not have to coordinate with the more complex storage operators. This is likely why Belgium has chosen for a CNO governance model (Fluxys, 2025). For countries with other characteristics that want to implement CCS as a network, the governance options framework provides a good first step to identify all possibilities. The risk assessment for that specific country should show which risks need mitigation and subsequently which governance forms could be combined and chosen.

For countries where CCS will play a small role and will not become a networked infrastructure, this governance framework is largely not applicable. The issues it solves are inherent to the networked nature. This is illustrated by the Steel variation in the model. When there is a small cluster with just one or maybe a few parties, utilization risks are very low and coordination is relatively easy due to the limited number of actors involved. In such cases, if it is not desirable or likely that other emitters want to connect to the infrastructure, only financial support structures to realise the emission reductions may be necessary.

7.3. Comparison with Energy Infrastructure Networks

The risks, and governance discussed in this report could also apply to other infrastructure developments. However, there are some key differences.

The natural gas and electricity markets are already mature. Both have seen a shift towards unbundling and market power regulation. As an essential infrastructure (which could be said of CCS as well) many of the governance options discussed in the framework are applied in those networks as well. However, a large difference are the users: a general household or consumer will not use the CO₂ network. Therefore, consumer protection plays a less significant role in the CCS governance; the reason to prevent it is to keep prices to such a level that energy-intensive industry does not leave. This distinction means that the primary market failure to address is not the exploitation of captive households, but rather the hold-up problem where infrastructure operators might exploit the high switching costs of industrial emitters once they are locked into a pipeline connection. Therefore, governance interventions such as price regulation should be designed not to micromanage end-user tariffs, but to provide the long-term price stability required for industries to commit to decarbonization without losing their competitive edge in the global market.

Another logical comparison to the CCS market is with the also developing hydrogen market. Apart from the similarities, such as their main use being in energy-intensive industries, there exist synergies between the markets. This is observed in the DRC project, which exists of both CO₂ pipelines and hydrogen pipelines. If blue hydrogen is considered as an essential transitional step towards green hydrogen and therefore CCS demand increases, they are linked even more. To capitalize on these synergies, similar governance in both markets could be preferred. There are two large differences however: CO₂ is a waste product, while hydrogen inherently has value, and CCS for fossil fuel use is a transitional technology, not future-proof like hydrogen. Therefore, investment de-risking in the hydrogen market may be prioritized over CCS if necessary. The developed framework can be applied to the governance of the hydrogen network with these differences, impacting the observed risks, in mind.

7.4. Reflection on the Theoretical Framework

Williamson (2005) posits that transactions characterized by high asset specificity and deep uncertainty are ill-suited for standard market governance due to the risk of opportunistic behaviour (the "hold-up" problem). The model results explicitly quantify this risk. The utilization analysis (Figure 5.4) demonstrates that unitary costs for pipeline infrastructure can double when utilization drops from 60% to 20%. This confirms that CCS infrastructure represents a high-risk, specific asset with little alternative value if the intended transaction fails. Consequently, the "chicken-and-egg" coordination failure identified in the interviews is a sign of a rational response by actors protecting themselves against the hold-up risk inherent to specific assets. As predicted by the framework of Williamson (2005), vertical integration has been shown to alleviate this problem, being an essential reason for the success of Porthos.

The research confirms the applicability of Network Regulation theory (Jaag & Trinkner, 2011) to CCS. The model results regarding economies of scale (Figure 5.2) and the cost disparity between pipeline

and ship transport (shipping being 38% more expensive for large volumes) confirm that the pipeline backbone exhibits the characteristics of a natural monopoly, effectively locking users in. The identification of this characteristic refutes the notion that CCS can function as a purely competitive market in the long run. Instead, it supports the theoretical necessity of the "Unbundling" and "Regulated Third-Party Access" (rTPA) interventions proposed in the governance framework to prevent market foreclosure and ensure the public value of fair access.

However, both TCE and the network Regulation Theory do not take into account the time dimension which greatly impacts the CCS market. In developing markets like CCS, the disparity between the initial start-up phase (characterized by coordination problems) and the subsequent mature phase (characterized by market power risks) may require different approaches. The framework developed in this research begins to unveil this difference: combining governance solutions of both theories and practical examples into one and exploring synergies and trade-offs between the choices (e.g. state participation reduces market power and the coordination problem). The combination of both theories creates a more complete picture of the possibilities and improves the use of the theories through different phases of a developing market.

Furthermore, the combination of an optimization model quantifying the risks and interviews qualifying risks and concerns from stakeholders has been effective. This gap was identified in literature and this work is the first step towards closing this gap. While the options are identified and related to the risks, future research should focus on refining, further quantifying and testing, and elaborating on the presented results. The limitations and future research are discussed in the next section.

7.5. Limitations and Future Research

The limitations of the research and research approach are presented below. These are divided in limitations of the model and limitations of the interviews and system analysis.

7.5.1. Model limitations

The optimization model is a MILP model. This means that costs are scaled linearly. While economies of scale were introduced through implementing different costs for differently scaled infrastructure, this does not fully do justice to the actual economies of scale, which can be large and are a driving factor for costs. In order to correctly quantify effects of increased volumes, which are important in the decision-making on the future CCS-system, future research should focus on better optimization or simulation of these effects. While the model gives some insight into the effects of utilization, demand, and import and export, it should be noted that most costs are largely uncertain. Other research has the same limitations (IEAGHG, 2025), with uncertainties of up to 50% for certain estimations. Bottom-up cost estimations are rather old and future research should aim to improve on these. Only then it is possible to accurately estimate the costs of different governance options, without which the decision-making is difficult and has large uncertainties.

The top-down demand scenario approach of the model can also be problematic. While giving a good insight into non-optimal situations where demand has to be met, it does not show the actual optimal development given alternatives. Furthermore, due to the aim of this research and time constraints, the effects of different policy options are not measured in the model. Future research should focus on implementing the options presented in the governance framework in models including alternatives to see the effects on public values better quantify the trade-offs.

Another limitation of the model is the assumption of perfect foresight, where all investment decisions across the 2030-2050 planning horizon are made simultaneously with complete knowledge of future costs, demands, and technological developments. This contrasts with real-world decision-making, where infrastructure investments are sequential and irreversible decisions made under deep uncertainty. The model cannot capture strategic behaviour such as waiting for information revelation before committing capital, nor does it account for learning effects and behavioural responses to policy signals over time. For instance, the LC&I scenario's optimal delay of Aramis investment is only identifiable with perfect foresight: actual investors facing 2030 decisions must rely on probabilistic forecasts and risk assessments. Furthermore, the model does not incorporate technology learning curves or cost reductions from deployment experience, particularly for emerging technologies like ship-based CO₂ transport

where TRL uncertainties suggest costs could decrease substantially with scale-up. The static treatment of technology costs means the model may underestimate the value of flexible, modular approaches that allow for technology substitution as innovations mature. Additionally, by not explicitly modelling alternative decarbonization pathways such as electrification, hydrogen production, or demand reduction, the model cannot fully assess the lock-in risks identified in the governance analysis. Future research should develop dynamic models incorporating real options theory to value flexibility under uncertainty and explicitly model the competition between CCS and alternative mitigation technologies to better quantify the transitional versus permanent role of CCS infrastructure in the energy system.

7.5.2. Interviews and System Analysis

An inherent risk for doing interviews, literature reviews, and a system analysis is the inclusion of certain stakeholders, experts, and data, while excluding others. For example, interviews with capture emitters are missing, giving only the point of view of transport and storage operators. While personal conversations with some emitters have been used for checking certain lines of reasoning, confidentiality has prevented the information from being used and further explored. While the system analysis tried to include many different stakeholders and future projects, it cannot be exhaustive. In a fast changing environment as the energy transitions, period updates to the information along with the effects they may have can be important for future decision-making.

The governance framework presented in this research is derived primarily from network industry theory and generic regulatory economics literature, with limited empirical validation from operational CCS systems since the system is in the beginning stages. While the UK and Norway provide valuable reference points, fundamental differences in market structure, industrial composition, and political economy limit direct transferability of lessons. Furthermore, the analysis does not explicitly consider coordination requirements with adjacent energy system governance structures for electricity, hydrogen, and heat networks, which may create institutional constraints or opportunities for integrated approaches. Future research should undertake comparative case studies of emerging CCS regimes across multiple jurisdictions and explore integrated energy infrastructure governance to reduce regulatory complexity and transaction costs.

Last, future research should focus on rigorous testing and adjustment of the presented frameworks in this research. Given the importance of CCS and lack of specific CCS governance literature, expanding upon this literature can be greatly beneficial. Quantitative tests can be designed to show the effects of different governance choices to measure the performance and costs of the identified governance options, measured against the identified risks. The presented options framework and the extension to the identified risks is a good starting point for this future research as well as an exploration of governance options for regulators.



Conclusion

The objective of this thesis was to provide insight in the risks and governance options within CCS-systems by studying the (unique) case of the Dutch CCS-system. The formulated sub-questions from the introduction are revisited and answered below, after which the main research question is answered and policy advice for the Dutch government and regulator is given, considering the trade-offs presented in the previous chapter.

8.1. Answering the Research Questions

The sub-questions are answered first, after which the main research question is answered.

8.1.1. SQ1: Key Characteristics and Planned Developments

What are the key characteristics and planned developments of the demand and supply of CCS in the Netherlands?

The system analysis in Chapter 4 has provided a clear overview of the different sectors, transportation modes, and planned projects. The large supply projects for the Netherlands are Aramis, Porthos, Northern Lights, and onshore projects such as the DRC, and DSC. Many of the involved parties were found to be active in multiple parts of the supply chain. The possible supply for CCS consists of refinery, chemical plants, waste industry, and possibly steel, each with a different potential and different characteristics to take into account. Additional demand may come from hydrogen plants and CDR, where the size depends on future regulatory choices. The impact of public values on the CCS system as well as unique characteristics of the CCS system (in the Netherlands) have been identified. Key public values impacting decision-making are non-discriminatory access, not limiting investment and innovation in alternatives, keeping energy-intensive industry, and contributing to climate goals. In the current regulatory framework, the EU ETS is the driving factor for the CCS market, while the SDE++ attempts to ensure the large CAPEX investments are partly de-risked. Incentives for storage capacity through the NZIA are available, while there were no specific transport incentives identified. These are all organized in customized agreements.

8.1.2. SQ2: Key Risks in the CCS Network

What are the key risks in the development of the CCS network both over time and for different parties in the value chain?

The qualitative results from the interviews and the quantitative insights from the model were combined to identify the key risks in the development of the CCS-system. Four key risks were identified: coordination, market power & information asymmetry, cross-border regulatory risks, and temporal risks. The coordination problem stems from high utilization risks and upfront capital expenditures, creating a hold-up, or chicken-and-egg problem, where all parties wait for the others to invest. Uncertainties surrounding demand, liability, tariffs, costs, and the business climate lead to no emitter wanting to be

first-mover. Without this commitment transport and storage operator do not want to take FID and start building.

Market power & information asymmetry was identified as the second risk. Pipeline infrastructure exhibits natural monopoly characteristics due to high CAPEX and economies of scale. Once pipelines are built, shipping is not competitive with pipeline transport, solidifying the monopolistic bottleneck pipelines create. At the same time, concurrent ownership of storage injection and capture facilities (being both a user and an operator) for certain users lower trust in the market for other users.

The third identified risk, cross-border regulatory risks, show the reliance of the Dutch CCS-system on regulatory choices made in other countries. Import could reduce overall unitary costs while subsidized export could increase utilization risks and therefore the coordination problem Dutch projects, despite these projects being cheaper in the long-run.

Last, temporal risks highlight that the risks change over time. The initial start-up phase towards FID is mostly driven by coordination risks, while the second phase, after FID and during operation, mainly exhibits market power risks. However, if the pipelines are fully utilized and new infrastructure needs to be built, the same coordination problem could arise again. The same characteristics creating the coordination problem are still in place, although the problem would be smaller due to increased market trust after the first large-scale project.

8.1.3. SQ3: Governance

What are the different governance options to support the development of CCS networks?

To answer this question, a Governance Options Framework was developed based on transaction costs economics, network regulation frameworks, and current CCS governance. This was substantiated by interviews. The framework showed three main categories including the governance options: structural governance, network access, and economic regulation.

Structural Governance considers structural changes to the market: changing ownership of market segments either to a specific private party, the state, a hybrid option (public-private partnerships). In addition, unbundling considers the separation or integration of market segments. Integration can be vertical (between transport and storage) or horizontal (within transport, e.g. integrating pipelines). For unbundling, the choices are between functional unbundling, where legally separated parts of one company control the unbundled segment, or ownership unbundling, where ownership changes.

Network Access considers who has access and under what conditions. Access can be regulated, setting the technical entry conditions, open access principles, or deciding who is eligible to enter (e.g. what sector). This can ensure fair and non-discriminatory access although only being based on behavioural constraints, which can be less effective than structural changes. Next to the access regime, capacity allocation can be used to ensure sufficient capacities are built. Apart from bilateral contracting, which is the default of the market, a mandatory open season could ensure enough capacity is built for the currently interested parties. Assigning a central planner could ensure capacity for new demand.

Economic Regulation determines how financial risks and benefits are distributed amongst stakeholders, both between the state and market participants as well as operators and users. Price regulation can cap the allowed return or allowed tariffs of the operator, limiting the price-setting power of a natural monopoly. The state can take a larger share of the risks by utilizing subsidies or implementing state guarantees. Subsidies (for demand or supply) generally only partly de-risk investment, but for the state it is exactly clear how much risk they take. With full guarantees, the state takes the full risk by guaranteeing a minimum revenue or by reducing the cost of capital through loan guarantees, paying back the loans if the project fails. Last, cost allocation determines how costs are divided over users. Spatially, this can be distance-based, where all users pay for the infrastructure they use, or socialized, all users share all costs. Temporal cost allocation determines how costs are spread over time. Deferred cost allocation could reduce costs for first-movers but increases risks for the the operator or state, depending on who takes the risk.

8.1.4. SQ4: Performance of Governance Design Options

How do different governance options perform in mitigating the identified risks in CCS networks?

The performance of governance options was evaluated against the specific risks identified in SQ2, revealing that no single instrument is optimal across all dimensions. Instead, a combination of structural governance, market rules, and economic regulation mechanisms are required to address the distinct challenges of CC.

To mitigate coordination risks in the start-up phase, purely market-based mechanisms were found to be insufficient due to the high asset specificity and utilization risks. Financial incentives, specifically state guarantees or supply-side subsidies, perform best in covering the utilization risk that currently stalls Final Investment Decisions (FID). Structurally, Public-Private Partnerships (PPPs) in storage and vertical coordination (facilitated by state participation) are the most effective measures to bridge the trust gap between emitters and operators, effectively solving the hold-up problem by aligning incentives.

Regarding market power and information asymmetry, particularly for the pipeline backbone, the analysis indicates that behavioural constraints alone (such as negotiated access) are inadequate to prevent foreclosure. Legal unbundling of transport and storage from capture activities is a structural option that could eliminate information asymmetry and ensure trust for third-party users. This must be complemented by Regulated Third-Party Access (rTPA) and tariff regulation. While this combination effectively mitigates the natural monopoly risks inherent to pipeline infrastructure, it could worsen the coordination problem. Therefore, it is important to address both risks simultaneously.

Concerning cross-border regulatory risks, the analysis shows that national governance alone is insufficient given the dependency of the Dutch CCS system on German import volumes and competition with Norwegian storage. While harmonized technical standards can be pursued at the EU level to ensure interoperability, financial and utilization risks for international flows are best mitigated through bilateral agreements.

Finally, the performance of these options is heavily time-dependent. The research demonstrates that governance must be adaptive: mechanisms that perform well in the start-up phase (such as public ownership and heavy subsidization) are necessary to trigger initial volumes but may need to transition towards regulatory oversight (unbundling and tariff regulation) as the market matures. While choices regarding cost allocation and risk sharing depend on the political prioritization of public values, (legal) unbundling, rTPA, and minimum technical standardization emerge as robust governance choices that perform positively across all scenarios.

8.1.5. Main Research Question: Governance design for risk mitigation in the Netherlands

Temporal phasing: different governance for different development stages

How can governance be designed to mitigate risks in the developing Dutch CCS network?

While there is no "best" governance design, the research laid out all options in the context of CCS, identified trade-offs, and provided a basis for decision-making on governance design. By utilizing the presented frameworks while carefully weighing the public values, costs, and impact on alternatives, governance can be designed in such a way that the identified risks, in particular coordination and market power risks, are mitigated. Dependency on regulatory frameworks for import and export show the importance cross-border agreements and coupling of governance. Finally, the governance design can only be successful when the changes of the risks over time are accounted for. Practically, to break the initial coordination problem ("chicken-and-egg"), the government must actively intervene through financial de-risking (state guarantees) and structural coordination (PPPs or state participation). However, this creates a trade-off: while these measures effectively mitigate utilization risks, they risk establishing the market power of early incumbents. Therefore, the governance design must couple different support mechanisms with ex-ante regulatory safeguards, specifically legal unbundling and regulated Third-Party Access (rTPA).

8.2. Policy Recommendations

While the research objective and answers to the research questions showed the risks, governance design choices and trade-offs, actionable next steps for policy are presented here. Three have been prioritized.

Act quickly This research has shown that, at a minimum, the current business-to-business governance should be carefully reconsidered. With the first large-scale CCS projects about to be built and take FID in the upcoming years, there is momentum in the market, boosted by Porthos likely starting operation this (2026) or next year. However, without solving the coordination problem, the next projects could be postponed or cancelled entirely. To reconsider the current governance model, the government should: identify their goals of the CCS system, confirm and elaborate on the risks presented in this research, and then formalize the governance choice.

Define an Exit Strategy To address the temporal risks identified in the analysis, where governance needs shift from resolving coordination failures in the start-up phase to managing market power in the mature phase, support mechanisms must be designed with explicit evolutionary paths. Governance instruments should incorporate clear 'sunset clauses' or periodic review points contingent on market maturity indicators. This research has shown that a fully competitive market can, also in time, not be expected. However, the government should recognize the evolving goals of the CCS system and evolve with it accordingly while accepting the permanent role of government participation.

Institutionalize Cross-Border Interdependencies The government must recognize that the viability of the Dutch CCS backbone is contingent on international flows and should therefore couple national governance with active foreign policy. First, the government should prioritize binding bilateral agreements with Germany and Belgium to secure the import volumes required for economies of scale, effectively underwriting the 'hub' function that domestic subsidies cannot cover alone. Second, the Netherlands must actively drive EU-level collaboration to harmonize technical standards (such as CO₂ purity specifications) and liability frameworks. The Netherlands should make their position as a hub clear, ensuring that European guidelines in the upcoming regulatory packages do not inadvertently hinder the development of CCS in the Netherlands.

8.3. Societal and CoSEM relevance

To conclude, this master thesis exhibits both societal relevance and is relevant for the Complex Systems Engineering and Management (CoSEM) masters programme. This research was explicitly about managing a complex system, identifying (governance) interventions for a wicked problem under large uncertainties, which is in large part the goal of the CoSEM programme. The thesis incorporates interests and behaviour of different actors as well as existing regulatory frameworks and considers them in the social-technical design to alleviate the identified risks.

As explored in this research, CCS is a necessary solution for realising quick emission reductions as well as future negative emissions to limit global warming to manageable levels. It is a way to keep industry in the Netherlands, which applies to other countries as well, countering carbon leakage. However, this research also explored that this goal may not be reached if essential risks are not mitigated. These risks are not technical, but regulatory, with governance offering solutions. Global warming is an inherent societal problem with CCS playing an essential role in the solution and therefore, solving the CCS governance challenges is crucial.

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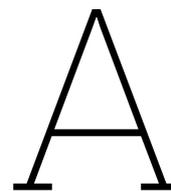
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Sector-specific demand analysis

A.1. Electricity Production

The largest share of current emissions comes from the electricity generation sector. These are either base load electricity production installations or flexible generators which only produce during peak demand hours. As the energy transition continues, the base load capacity will be replaced by renewable generation to an increasing extent. Renewable generators, like wind and solar pv, have lower variable cost than generators using fuel and are therefore first up in the merit order when they bid into the electricity market. This means that flexible generators using more expensive fuels will be used less often. However, for security of supply, they remain essential: in the few hours with high demand and low renewable generation (e.g. when the sun does not shine), generators using fuels that can be quickly ramped up or down are still necessary. This does mean that these flexible generators have less hours in which they need to recoup their investment. At the same time, emitting CO₂ becomes more expensive with rising CO₂ prices, making their business case increasingly uncertain. For the CCS demand from these generators this has the following consequences:

1. The base-load fossil generators will be phased out in the future, decreasing the potential demand of CCS from electricity generators and leaving only generators producing relatively few hours a week.
2. The intermittent production of CO₂ leads to operational challenges for the CO₂ pipeline infrastructure which should already be accounted for in the planning of the infrastructure. Compared to a constant stream of supply, an intermittent source needs a higher pipeline capacity for the same yearly supply or needs intermittent storage, both of which increase the investment costs of the infrastructure.
3. The challenging business case for flexible generation in combination with its importance creates policy uncertainty: it is likely the government has to intervene, but uncertain how they will do that. This, along with uncertain hydrogen and bio-fuel prices and availability, leads to an uncertain demand potential. The demand depends on whether the flexible generators will use hydrogen, bio-fuels, or fossil-fuels with CCS in the midterm.

Given these characteristics, it is likely that flexible generation plants in the Netherlands will not use CCS (without specific interventions from the government) due to a lack of a business case. This is reflected in the used scenarios of the model described in section

A.2. Chemical plants

Of the current emissions potentially being eligible for the use of CCS, 24% is from chemical plants. This share consists of diverse companies, but they can all be considered hard-to-abate and need access to all available technologies to address emissions from combustions and most notably unavoidable process emissions (Cefic, 2024). In 2021, the process emissions accounted for 42% of the total emissions in chemical plants. Without innovations in these chemical processes or demand reduction, this shows

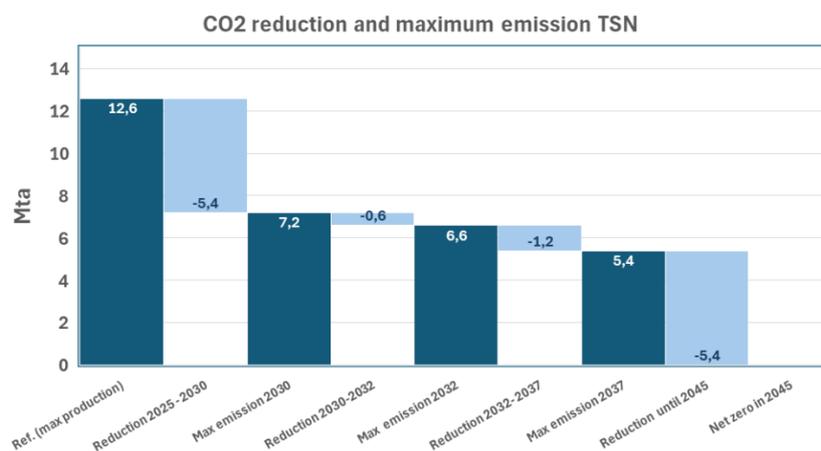


Figure A.1: Planned emission reductions of Tata Steel until 2050 (KGG, 2025b)

a potential need for carbon capture and storage. To support this claim, Gabrielli et al. (2020) emphasize that it is important to talk about defossilization in the chemical industry instead of decarbonization, since carbon is a necessary building block for for example plastics. They compare CCS to the use of bio-fuel and utilization of carbon (CCU), where carbon from other processes or direct air capture (DAC) is used in the chemical process. For chemical plants, CCS has a high potential, requiring 400 times less land than the bio-fuels route and using at least 10 times less energy than CCU. However, they foresee challenges surrounding the support of continued fossil use, and the need for a CO₂ network and its financing. This all shows that CCS will most likely play a critical role in the decarbonization (or defossilization) of the chemical industry.

A.3. Refineries

For refineries, CCS is an essential tool to reduce emissions (Concawe Review, 2018). No new refineries are expected to be built in the future in the EU, making the costs for retrofitting essential. Due to the heterogeneity of emission sources in the refinery process, only around 70% of the process is eligible for CCS. For the other 30% fuel switching (hydrogen or biomass) is considered the best option, since capture besides the point sources is not cost-effective (Sunny et al., 2022). Fuel switching is considered less expensive in general, but the limited availability of hydrogen and biofuels will likely drive up prices and necessitates strategic choices on their use. Furthermore, 80-90% of emissions from refineries are scope 3 emissions, meaning they occur when the refined products are burned. Therefore, refineries will eventually need to transition towards alternative feedstocks, such as biomass or synthetic fuels, which can deliver near-zero emissions over the entire lifecycle (Sunny et al., 2022). Combining biogenic feedstocks with CCS (BECCS) could even allow refineries to generate negative emissions, effectively removing CO₂ from the atmosphere to offset emissions elsewhere. However, there are significant hurdles for these implementations.

A.4. Steel

In the Netherlands, there is only one company producing steel: Tata Steel. However, emit 11% of the CO₂ of the analysed emitters (see Figure 4.3b). In September 2025, the government and Tata Steel signed a joint letter of intent (JLoI) (KGG, 2025b), where both the state and Tata Steel will invest to reduce emissions of the plant. This will lead to the reduction of emissions as shown in Figure A.1. First, the coal-fuel installations are replaced by gas before 2030. The JLoI states that CCS infrastructure will be built, but it does not state the amount of CCS. This will again depend on the availability and estimated prices of hydrogen and bio-fuels as well as CCS itself. However, from the letter, it is evident that part of the emissions remaining after 2030 will be reduced using CCS.

Waste Disposal The Netherlands has 12 waste incineration plants. 4 of which are included in this analysis of the ETS companies above 100 kt emissions in the clusters, since many of these incineration

plants are in cluster 6 (9 above 100 kt emission). However, even though they are in cluster 6, Twence and AVR Duiven have already captured CO₂, which was 30 kt and 3.6 kt respectively using post-combustion techniques. These relatively small volumes at a large distance from the planned central infrastructure have a very limited effect on the infrastructure development. They do show the potential for usage of CCS for emission reductions in waste disposal. de Leeuw and Koelemeijer (2022) report a potential of 1-1.2 Mt for CCS from waste incineration. However, they emphasize that CCS is a bridging technology, confirming the current view of CCS for most industrial processes. Last, CCS for waste incineration is relatively expensive since the emissions only have a carbon content of 36%, which makes the installation three times more expensive compared to emissions with a carbon content of 100%. On the other hand, they also have little realistic alternatives. This, along with their public ownership structure means that waste disposal companies are among the first-movers for CCS.

A.5. Production of blue hydrogen

Blue hydrogen is created using fossil fuels and CCS. Blue hydrogen is seen as a transition technology and, eventually, green hydrogen is the preferred way of production. However, blue hydrogen is more affordable and therefore necessary for the scaling of the hydrogen market and decarbonization of some of the industry. In the current selection of industrial companies with emissions above 100 kt, one company produces (grey) hydrogen, they are categorized as a chemical plant in Figure 4.2. Starting in 2026, they will capture and store their CO₂ via the Porthos infrastructure. Depending on the scenario, Netbeheer Nederland (2025) estimates around 2-8.5 Mtpa of CO₂ coming from the production of blue hydrogen in 2050 (which needs to be captured). It can be assumed that this blue hydrogen will be produced close to future hydrogen demand and infrastructure and CCS infrastructure and supply, which comes together in the industrial clusters. Particularly in the Rotterdam industrial cluster, looking at the planned projects (Aramis and Porthos).

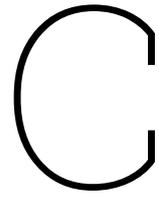
B

AI Statement

AI was used as a complementary tool in this research. Two main tools were utilized: The Google Gemini 3.0 Pro model (Google, 2025) for writing purposes and GitHub copilot (GitHub, 2025), and specifically Claude Sonnet 4.5 (Anthropic, 2025) for coding and creating the model.

Gemini 3.0 was used during the writing process to brainstorm on content and report structure, and refine specific paragraphs. However, all text included in this thesis is the author's original work. The AI model was used primarily for grammar checks and stylistic refinements. Specific text segments were submitted with targeted prompts to solicit feedback or phrasing suggestions. While the model served as a conversational partner for brainstorming, no text generated during these sessions was directly incorporated into the final report. Furthermore, any literature or references discussed with the AI were manually verified in the original source material to ensure accuracy. Throughout the project, the full report was periodically uploaded to Gemini 3.0 to review consistency and identify formatting or textual errors.

GitHub Copilot, integrated within Visual Studio Code, was utilized to accelerate the coding process. To ensure correct implantation of the design choices made by the author, the initial model framework was created independently by the author. The AI agent was then used iteratively to build out specific code blocks via targeted prompts. All AI-generated code was rigorously tested and verified by the author before acceptance to ensure the intended outcome was achieved. This way, crucial model design choices were made by the author while the AI agent assisted with the specific code implementations. this sped up the code implementation significantly, leaving more time for the author to focus on the conceptual work and design choices.



Interview Summaries

This appendix includes all summaries of the interviews. Since the stakeholders and the researcher are Dutch, the interviews and subsequently the summaries are as well. All participants signed a consent form for the inclusion of the summaries and all participants received the summaries well before publication for final checks. The summaries start on the next page.

C.1. Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek (TNO)

Interview met een medewerker van TNO

Ervaring

Lang in het CCS veld (nu generalist), aardwetenschappen achtergrond, research activiteiten gericht op transport en opslag. Ook internationaal in CCS context actief.

Problemen in het verleden (vergelijking met nu)

- 2010: te weinig politieke ondersteuning, wel interesse industrie. Dat was het probleem.
 - Gebrek aan financiële ondersteuning vanuit de overheid (niet voldoende)
 - Europees probleem: alle projecten zijn omgevallen hierdoor.
- Nu wel duidelijke politieke steun en financiële steun, daarom is het deze keer anders. Dit kan wel altijd beter.
 - Porthos: risico's liggen bij de staat, want EBN, HBR, Gasunie
 - Aramis: minder overheidsrol, daar kan de overheid meer van de risico's absorberen. Vooral long-term liability: iemand moet aansprakelijk zijn voor na de post-injectie (die ongeveer 20j duurt). Als het daarna mis gaat heb je hele hoge kosten en op dit moment blijft de operator in enige zin, ook na de overdracht aan de overheid, nog verantwoordelijk. De kans is heel klein, maar periode in principe oneindig en dus ontstaat er een onbegrensd risico. De Staat zou deze liability moeten omarmen om risico's te verminderen

Risico's van CCS

- Technisch: issues zijn niet van technische aard, we kunnen het. Hoe het operationeel moet gaan we uitvinden, maar is nog niet opgelost. Geen fundamentele problemen.
 - Opslagkant: capaciteit kan vrij snel limiet bereiken, dan zijn aquifer-opslagen wellicht mogelijk, maar die zijn nog heel onzeker. In Engeland, Noorwegen zijn er gigatonnen aan opslagcapaciteit, meer dan in Nederland.
- Economisch: Lastig om klanten te vinden, commitment is hier een issue. Dit is een kip-ei situatie. Iemand zou misschien dat risico op zich moeten nemen, welke economische risico's dit precies zijn nog niet volledig duidelijk.
- Politiek/beleidsmatig: Aanvragen voor vergunning opslag zijn ingediend, projecten kunnen pas verder als dit echt is afgegeven. FID Aramis: moet gelijktijdig van 20tal bedrijven instemming krijgen door de grote afhankelijkheden. Deze afhankelijkheden zijn een groot risico.

Samenwerking met het buitenland

- Samenwerking met buurlanden is snel van belang door gelimiteerde capaciteit in Nederland
 - Compatibility is hierin belangrijk, vooral de kwaliteit van CO2 kan invloed hebben, er zitten verschillen in specificaties. Wellicht wordt dit lastig te koppelen, want CO2 door het buitenland is al anders dan wat door Porthos en Aramis stroomt. Nu lijkt dat wel goed te gaan in de marges.
 - Barrière voor samenwerking zit vooral in de long-term liability, als er buitenlandse CO2 in de systemen en onder de grond zit, wie is er dan verantwoordelijk?
 - Moet op regeringsniveau iets geregeld worden
 - Bijvoorbeeld: potje (fonds) voor eventualiteiten in de verre toekomst, dit moet internationaal
 - Hier moet je vroeg mee beginnen

Lock-in

- CCS is een transitietechnologie die heel lang blijft
- Eerste doel emissiereductie tot net zero, CO2 afvang en DAC of bio-CCS
 - Maar dan begint het tweede doel: permanent verwijderen, negatieve emissies in totaal
 - Hier doet men wat makkelijk over soms, maar we hebben nu al 2 graden opwarming, dus alles wat we nu uitstoten is al te veel en moeten we later compenseren

- De enige manier die op de benodigde schaal de CO₂ permanent van de atmosfeer kan isoleren is het ondergronds opslaan van de CO₂
 - 2 graden wereldwijde opwarming houden is geen optie
- Gascentrale is wel snel te schakelen, BECCS minder: nu heb je deze technologieën nog nodig in het systeem. Ontwikkelen nieuwe technologieën duurt 20-30 jaar, tot die tijd moeten we iets. Dit geeft de onmisbaarheid van CCS aan, het is nodig om tijd te kopen voor die nieuwe processen.
- Als CCS community moeten we dit soort dingen duidelijk uitleggen, verhaal tegenover lock-in dat het gewoon moet en we weinig keuze hebben.

Verdere mogelijke issues met CCS in de toekomst

- Als er straks allemaal offshore projecten zijn:
 - De capaciteit afhankelijk van de druk, de drukruimte bepaald de opslagcapaciteit. De berekeningen gaan uit van de ruimte die je onder druk zet
 - Sommige gasvelden staan in verbinding, het drukverschil is daardoor te meten in het nabijgelegen veld
 - De drukruimte van veld 1 beïnvloed de business case van het andere veld, van de eerste verbeterd de business case (druk gaat deels naar ander veld) en het verslechtert in volgende.
 - Die cumulatieve drukruimte moet zo goed mogelijk gebruikt worden (door de overheid), wat er nog niet is een oplossing voor de impact van drukcommunicatie
 - Governance is hier nodig
 - Dit heb je ook met gasvelden over een grens, maar voor opslag is dit nog niet te meten, de drukverdeling weet je pas later.
- Grotere opslag-gerelateerde issues:
 - Kwaliteit CO₂: welke specificaties wil je gebruiken? Wil je deze specificaties juist liberaler of strenger hebben?
 - Drukcommunicatie, de drukruimte moeten we zo goed mogelijk benutten. Je wil ook niet de business case hier ineens door verslechterd door het verminderen van de capaciteit en het verlagen van de duur van injectie.
 - Europees denken we dat we genoeg opslagcapaciteit hebben, maar het grootste deel hiervan is heel onzeker, we kennen de eigenschappen van de ondergrond niet precies, je moet boren om dit te meten en de grootte van het drukvolume in te schatten: dit kost geld en tijd.
 - Er is behoefte om dit te testen, er is ook budget Europees voor testinjecties en boringen.
 - Member States zouden hier meer geld voor opzij moeten zetten, Nederland is hierin wel redelijk actief al, heeft al vrij veel kennis.
 - Bewijzen van bestaan van opslagcapaciteit
 - De opslagcapaciteit in Europa begint vorm te krijgen. Opslagprojecten in NO, NL, DK, IT en UK zullen naar verwachting in 2030 operationeel zijn. Er zijn echter onvoldoende opslagprojecten in ontwikkeling om industrieën die CCS willen toepassen in heel Europa te bedienen
 - Ruimtegebruik offshore is een groot punt, er is 1-1.5 Gt aan opslag mogelijk, maar dit moet dan niet bedekt worden met bijvoorbeeld windparken.
 - Die 1-1.5 Gt geldt voor de gasvelden in NL. 1.5 Gt is een getal dat door Gasunie-EBN is gepubliceerd, in 2018. TNO heeft enkele maanden geleden ook een studie gedaan en gepubliceerd over opslagcapaciteit van onze gasvelden offshore. Of we die 1.5 Gt ook gaan halen, hangt af van de geschiktheid van elk veld afzonderlijk, van ruimtegebruik offshore, en uiteindelijk natuurlijk van de kosten van het ombouwen van elk afzonderlijk veld ('geschiktheid' is meestal een ander woord voor 'kosten').
 - Hier moeten keuzes gemaakt worden, die zijn politiek.

C.2. Technische Universiteit (TU) Delft

Interview met een researcher aan de TU Delft

- Achtergrond: verstand van huidige CCS-systeem, de ambities op dit gebied, en het technische vergunningsverlening verhaal
- Grote probleem: in het opbouwen van het systeem moet je grote investeringen doen. De vraag is wie die grote investeringen gaat doen en daarmee ook wat de Governance en regulering gaat worden hiervan. Dit is zowel voor de infrastructuur als de velden. De vraag is ook of dezelfde partij de aanleg van de pijpleidingen moet doen die ook de opslag doet.
 - Hoe gaat deze partij de investeringen terugverdienen? Wat is het business model? Of is die er misschien niet en zou uiteindelijk een overheidspartij dit op zich moeten nemen?
 - Hoe meer risico's er zijn, hoe hoger de vergoeding die nodig is om de risico's te dekken voor private partijen. Hiermee gaan ook de kosten van de energietransitie omhoog.
- Een lastige uitdaging is ook wie er controleert als de velden eenmaal vol zitten.
- Het systeem wordt complex door de vele compartimenten waarin het uiteen valt: velden die eigendom zijn van olie- en gasmaatschappijen, pijpleidingen op land en zee, en emitters.
 - Deze hebben allemaal een ander risicoprofiel
 - Kan of moet je dit scheiden?
- De puzzelstukken van het systeem zijn van een afstand wel overzichtelijk, als je gaat inzoomen zit er veel politieke, bestuurlijke, en business complexiteit in verstopt.
- Het is belangrijk om een onderscheid te maken in het soort risico dat bestaat en dat je ziet. Technisch, geopolitiek, economisch/investeringen, beleidsrisico's (policy risk)
 - Beleidsrisico's zijn hier een grote factor
 - Hier valt onder: vergunningskeuzes, beloningsstructuren (ROIs), capaciteitsprognoses en hoe het systeem eruit zou (moeten) zien, veiligheid, monitoring, verantwoordelijkheid
 - Beleid heeft hier een grote invloed op en kan dit vastleggen
 - Hier zouden verschillende Governance structuren een uitweg kunnen bieden. Afhankelijkheden en samenhang tussen leidingen is hier belangrijk, net als de monitoring en wie betaald als er lekkage is.
 - Veel van deze risico's vertalen zich uiteindelijk in investeringsrisico's en kosten, maar komen dus voort uit andere risico's
- Wat als er CO₂ ontsnapt? Boete voor bedrijven? Wie neemt het risico? Wie controleert dit? Wie is verantwoordelijk? Wat als er een overname is?
 - Is dynamiek in eigendomsverhoudingen offshore gasvelden
- Facetten hierboven zijn allemaal van invloed op het business model dat geschikt is voor zowel publieke en private partijen?
 - Ook: Waar zijn de winstmarges van afhankelijk?
- In hoeverre de waardering van de CO₂ vooraf is vastgelegd? Dat vertaald zich ook in inkomsten en kosten stromen die op een bepaalde manier geordend moeten worden met regulering
- Institutionele economie zou een goede perspectief zijn om dit probleem te benaderen.
 - Het probleem is niet een efficiëntie probleem, maar een probleem van hoe bepaalde maatschappelijke waarden vertaald worden in een systeem van ordening en van regulering. De kosten en risico's zijn belangrijk, maar worden gedreven door een serie van maatschappelijke eisen. Dit brengt een bepaalde governance, ordening en een structuur van het systeem met zich mee.
 - Transactiekostenperspectief belangrijk: wie betaald de kosten van het ordenen, in kaart brengen, definiëren van maatschappelijke waarden, lange termijn veiligheid, timing van aansluitingen, aansluiting op andere delen van de energietransitie.
- Hoe omgaan met de balans van het stimuleren van CCS om snelle reducties te realiseren en het tegelijkertijd niet té veel stimuleren om zo investeringen in alternatieven te verminderen?
 - Adaptieve scenario's: niet uitgaan van de meest ideale toekomst alleen, maar ook situaties waarbij CCS minder snel gaat of minder wordt.
 - Wat is dan de keuze hoe we omgaan met bestaande industrie?
 - Politiek: hoe gaan we in Nederland ons geld verdienen?
 - Scenario's nodig zeker als het gaat over het beheer van het systeem

- Wat vaak mis gaat in Den Haag: Uiteindelijke doeleinden van het energiesysteem worden geprojecteerd op de huidige organisatie infrastructuur en de instrumentatie daar van, maar vervolgens gebeurt er dan niks. Voor bedrijven is er geen logica om daar iets mee te doen.
 - Een gelijksoortige discussie zie je ook bij warmtenetten, streven naar een ideale markt en die richten we nu pas in, maar dat werkt niet als je allerlei bedrijven moet overhalen met grote risico's
 - Lange termijnperspectief van dat je er uiteindelijk vanaf moet werkt niet voor het uitzicht van een bedrijf. Je moet de investeringstermijn van een bedrijf als uitgangpunt nemen, of je moet als overheid het risico op je gaan nemen. Als de overheid in staat zou zijn om dit beter te doen.
- Internationaal en hoeveel capaciteit overal is: scenario analyse loslaten op hoe dit zich ontwikkeld is de beste manier om daar mee om te gaan.
 - Vraag is wel hoeveel je van het buitenland afhankelijk wil zijn. Ligt ook weer aan schaal en infrastructuurkosten
- De governance keuze is sterk afhankelijk van waar de transactiekosten terecht komen. Tegelijk is de governance keuze ook weer van invloed op waar de transactiekosten terecht komen, dit is een soort cirkelredenering.

C.3. Energie Beheer Nederland B.V. (EBN)

Hieronder is de samenvatting van een interview met een medewerker van EBN

- Wat doet EBN?
 - 40% staatsdeelneming in gaswinning
 - Mandaat voor gaswinning en warmte: taken zijn per wet geregeld, deelneming in joint ventures
 - Non-operating ventures, zowel de baten als lasten worden gedeeld
 - Nog geen mandaat voor CCS zoals voor gaswinning en warmte. Op dit moment moet EBN per projectfase en per project instemming vragen aan de minister via artikel 82 lid 4 uit de Mijnbouwwet.
 - Bij CCS-projecten moet EBN voor de eerste drie fasen : pre-FEED, FEED en FID, instemming vragen. De realisatiefase en monitoring zitten bij het FID moment in
 - Porthos: is een apart project, volledig vanuit staatsbedrijven. Er is 50/50 eigenaarschap voor het transport offshore voor Gasunie en EBN en ook 50/50 in opslag tussen Gasunie en EBN
- De markt vraagt ook om 40% participatie in CO2 opslagprojecten, of wellicht zelfs meer dan dit
 - Het is vanuit het verleden niet gebruikelijk dat EBN meer dan 50% in handen heeft, mogelijk zou dit wel kunnen helpen in de opstartfase van CCS.
- Aramis zit nu in de feed fase en gaat richting FID. De intentie is 50/50 eigenaarschap met Gasunie voor de offshore trunkline
 - Er is een systeemintegratie voordeel om zowel in Porthos als Aramis te participeren, deze gebruiken namelijk hetzelfde compressorstation
 - Dit gaat fragmentatie tegen waardoor tijdige realisatie makkelijker is
- 2^e risico naast coördinatie en het tegelijk nemen van FID: het volume aanbod vanuit emitters. Dit is de grootste potentiële dealbreaker. Theoretisch is er veel aanbod, in de praktijk is het nog de vraag hoe dit aanbod op gang komt.
 - Weinig partijen zijn bereid om zich nu al te committeren, ze willen hun opties openhouden en er is ook risico dat ze naar het buitenland kijken
 - EBN zit zowel in transport als in de opslagen en zou daarmee een coördinerende rol kunnen spelen om beide tijdig te realiseren.
 - Er zijn 3 dingen die erg bepalend zijn voor het opkomen van aanbodvolume: Business-case, timing, en investeringsklimaat
 - Op dit moment is er een zekere mate van “gaming” in de markt: partijen zijn aan het afwachten op beste opties
- Liability/monitoring:
 - Kamerbrief 2023: rol als operator of last-resort voor EBN + lange termijn beheersrol en monitoring
 - EBN ziet dat ook zo voor zich, hoe dat er concreet uit ziet wordt nog uitgewerkt.
- EBN moet op basis van de mijnbouwwet deelnemen op marktconforme voorwaarden
- Het is evident dat er sprake is van marktfalen
- Vraag: Gaat deze markt überhaupt op gang komen zonder hoog overheidsingrijpen?
- Aramis is over-gedimensioneerd
 - Het wordt gebouwd met volumes van DRC en België in gedachte
 - Als DRC niet op gang komt, is het de vraag of Aramis haar volledige capaciteit kan benutten. Met volumes uit Duitsland wordt dat makkelijker
- Door de hoge investeringskosten drukken de uitgaven erg op de business case: lasten spreiding over generaties zou dus een goed idee kunnen zijn
 - Voorinvesteringen zijn hoog en terugverdientijd is langer dan bij traditionele olie- en gasprojecten.
 - Nu starten is wel erg belangrijk en het verdienvermogen is er wel daadwerkelijk; de vraag is daarom, wil je dit als Nederland ook zien als een mogelijk verdienmodel
 - In de huidige situatie heb je marktfalen. Een grotere rol voor EBN kan daarbij belangrijk zijn om de markt op gang te brengen. Hiervoor heeft EBN wel een bepaalde omvang nodig. Als de rol te klein is voor EBN dan wordt het lastiger om een organisatie te financieren die monitoring doet.

C.4. Port of Rotterdam (PoR) / Havenbedrijf Rotterdam (HBR)

Interview met Port of Rotterdam (PoR)

- De rol van havenbedrijf binnen de CCS waardeketen is als aanjager, mede investeerder in lokale infrastructuur (landlijn Porthos), en begeleider van de ruimtelijke inpassing van CCS projecten binnen het havengebied
- Welke policy enablers zijn er?
 - Voor klanten: nu geen business case en geen incentive om first-mover te zijn
 - Verleidelijk om af te wachten
 - Toekomst onzeker maar ze moeten wel een lange termijn contract aangaan van rond de 15 jaar
 - Onzekerheid in regelgeving mbt grote investeringen
 - SDE++ dekt niet de daadwerkelijke delta tussen ETS en kosten
 - Biogeen: de relatie met SDE++ en geld verdienen met negatieve emissies is onzeker
 - De gehele marktontwikkeling van negatieve emissies is erg onzeker
 - Voor afvalverwerking is de toekomstbestendigheid van de gehele industrie onzeker
 - Blauwe waterstof: afzetmarkt Rotterdam is mogelijk te klein voor de benodigde schaalgrootte van sommige partijen en onzeker, de DRC is nodig om dit te vergroten, maar die is pas op zijn vroegst rond 2032/2033 klaar
 - Afwachtend op de DRC
- Wat zou kunnen helpen om het afwachtende gedrag te verlagen is demand creation in low carbon producten samen met het verhogen van de SDE++ compensatie
 - Je zou mogelijk een voordeel/beloning voor de eerste klanten willen, maar door non-discriminatory TPA is dit moeilijk
 - Nu is het tarief hoger voor de first-movers, ze betalen mee aan het volloop risico
- Inschattingen CO2 afvang in de haven: uit plannen met variërende vordering
 - Potentie van 12 Mt CO2-afvang zonder al 2,5 van Porthos
 - Nieuwe blauwe waterstof productie en ook productie uit restgassen als mogelijke opkomende CO2 aanbod onder deze 12 Mt
- CO2 leiding DRC impact
 - Positief effect op tarieven aan de offshore zijde door bundeling van volume: hoeveel precies wordt nog uitgerekend
 - Schaalvoordelen reden voor DRC
 - Belangrijkste: waarde industrie Rotterdam wordt gecreëerd door oa de Duitse industrie (en het gehele ARRRR cluster), dus wil je die industrie helpen
 - Voor ARRRR is de meest kosteneffectieve route voor CO2 naar Rotterdam
 - Afhankelijk van hoeveel CCS we nodig hebben en hoeveel van de industrie in Rotterdam afhankelijk is van ARRRR
- Is Nederland de juiste exit point voor Duitsland? Wil je doorvoerland zijn (economisch gezien)?
 - Volumes bundelen levert de laagste maatschappelijke kosten op Europees, maar ook voor Nederland (het Rotterdamse deel)
 - Vanuit Rotterdam kan je ook naar VK velden: ook vanaf de Aramis leidingen
 - Het zou logisch zijn als Duitsland een deel mee betaald, of misschien zou dat uit de EU subsidie kunnen
 - Cost-sharing is een lastige discussie
 - Investeren in het CO2-netwerk voor Belgische/Duitse klanten dmv staatsdeelname kan voor de staat rendement opleveren
 - Neveneffecten zoals behoud en aantrekken van industrie, werkgelegenheid, kennis en innovatie, export, etc. zijn erg lastig te kwantificeren, hoewel ze een belangrijke positieve impact kunnen hebben
- Pijpleiding duurt lang en is onzeker, schip is dit alleen net zo goed door terminal ontwikkelen
 - Minder flexibiliteit nu het nog geen volwassen markt is
 - Zelfde issues in opstartfase: daarin dus geen competitie
- Impact van Porthos op de activiteit in de Rotterdamse haven: Vestigingsklimaat Rotterdam staat onder druk door hoge energiekosten etc. De bouw van Porthos geeft vertrouwen in de verdere ontwikkeling van CCS in de haven en geeft dus een driver om hier te blijven
- Centrale ATR voor afvang: is dat/kan dat voordeliger zijn dan individuele afvang?
 - Aantrekkingskracht voor bedrijven, schaal kan tot voordelen leiden

- Maar ook lastig om de leidinginfra aan te leggen, regulatie hierin ook nog niet op orde: bijvoorbeeld dubbele belastingen door het heen en weer sturen van gassen/CO₂
- Wel potentieel en logica hiervoor, makkelijker om contracten te sluiten
 - Meer volume en dus ook meer macht in de onderhandeling van de voorwaarden van contracten
- Marktordening
 - In hoe je er naar kijkt zou je transport en opslag van elkaar moeten (in pijpleiding transport)
 - Marktwerking en concurrentie werkt niet in pijpleiding transport, je wil een grote leiding door schaalvoordelen en ruimtegebruik
 - Als er sprake is van een monopolie positie wil je partijen beschermen tegen macht, regulering hierin en aanwijzen de monopolie positie mag hebben is dan logisch
 - Wil wel voorkomen dat tarief regulatie leidt tot hogere tarieven voor de eerste bedrijven, het leidt namelijk niet altijd tot een aantrekkelijk aanbod in begin
 - De regulatie zou moeten in combinatie met het risico afdekken
 - Opslag: marktwerking kan in theorie
 - Verschil in fase naar FID met tenminste 1 partij en als het transport er al is en er meer opslagpartijen komen
 - Nu wel wat concurrentie, maar doordat ze concurreren voor een klein volume krijgen alle opslagpartijen een klein deel. Zo concurreren ze elkaar mogelijk uit de markt.
 - Stapsgewijs marktwerking toevoegen zou wellicht kunnen werken
 - Logisch dat Shell en Total niet meer aandeelhouder gaan zijn in Aramis (de leiding), er ontstond bij sommige emitters veel wantrouwen hierdoor → je kan de staatsdeelnemingen in transport zien als monopolie, dan zouden doeltreffende maatregelen nodig kunnen zijn
- Rol van PoR als staatsdeelneming
 - Zit in de landleiding van Porthos
 - Heeft goed inzicht in vraag en kan in sommige gevallen een lager rendement accepteren dan private partijen vanuit het grotere belang van de verduurzaming van de industrie in de haven
 - Geen ambities voor operationele deelneming
- Hoe ga je om met de simultane vraag van bedrijven naar meerdere alternatieven? Dit kan namelijk leiden tot overschatting
 - Bij CES moeten bedrijven aangeven of het de keuze is of additioneel, dus kan je zo checken met wat bedrijven aangeven
- Ruimte probleem: Kan ook daarom niet zomaar extra leidingen aanleggen
- DRC en CO₂Next sluiten los aan op Aramis. Samen met de Porthos landlijn capaciteit kom je dan richting de 22Mt invoer capaciteit van Aramis

C.5. Planbureau voor de Leefomgeving (PBL)

Interview met een medewerker van PBL

- De meest relevante categorieën zijn grotendeels gecoverd in de huidige categorieën
 - Hoe omgaan met negatieve emissies is nog niet volledig gedekt, dit is afhankelijk van ander beleid. Hetzelfde geldt voor het corrigeren van heffingen voor biogene emissies en vrijwillige CO2 handel
- Kosteninschatting DAC vs mitigeren bij industriële processen
 - In de SDE staan nu alleen vermeden kosten bij de tuinder door CCU, dit valt dus niet onder koolstofverwijdering
 - Alleen goedkoper dan gedeeltelijke CO2 opslag vloeibaar, als er dus geen vollast CO2 afvang is
 - Bijvoorbeeld bij elektriciteitssector of combinatie CCU en CCS
 - Dit is nu de duurste CCS techniek die in de SDE zit
 - Voordeel is dat het een simpele unit is die je kan neer zetten, op den duur kán het daardoor goedkoper worden dan CCS bij industriële toepassingen door het vermijden van de inpassingskosten
- Ontwikkelingen in aanmeldingen voor CCS categorieën
 - Data ligt bij RVO en de CCS data wordt niet gepubliceerd
- Missende afdekking SDE/ander soort beleid
 - Kosten transport en opslag zijn meegenomen in de SDE, maar hier is niet heel goed zicht. Daarom zijn er externe Xodus reviews voor tarieven voor een indicatie.
 - Die waarden worden genomen, maar deze kunnen sterk stijgen en zijn onzeker
 - Ander beleid voor het dekken van kosten van infrastructuur kán hier verbetering in aanbrengen door de tarieven zekerder te maken of te verlagen
- Signalen uit de markt zijn nu dat opslag in het buitenland goedkoper kan in Nederland (lagere tarieven voor vragers van CO2 opslag en transport)
 - Dit komt waarschijnlijk door andere kostencompensatiestructuren in het buitenland
- In de KEV is er geen differentiering tussen verschillende CCS categorieën
- Het uitgangspunt van de SDE is dat categorieën niet sectorspecifiek zijn
 - Er moet een technisch verschil zijn om een aparte categorie te maken
- Blijven kijken of CCS kosteneffectiever is dan andere verduurzamingsroutes is een logisch uitgangspunt om vast te houden in beleid en de SDE specifiek.

C.6. Gasunie

Samenvatting interview met twee medewerkers van Gasunie

- Wat is de huidige rol van Gasunie in de CCS-keten?
 - Ontwikkeling van het transport netwerk is de focus van Gasunie.
 - Bij het Porthos project is Gasunie ook mede-eigenaar van de opslag, dit is een uniek project. Gasunie heeft geen wens om verder in opslag te zitten bij andere projecten.
 - Het doel van de activiteiten op CCS: is het versnellen van de transitie
 - Gasunie gaat bij het toekomstbeeld van het Nederlandse energiesysteem uit van 50% moleculen (incl. CO₂ en dus CCS) en 50% elektriciteit
 - Verdere lopende CCS projecten zijn het ontwikkelen van de Aramis trunkline, de DRC en DSC en de terminal CO₂Next (waarbij de terminal een gezamenlijk project is met Shell, TotalEnergies, en Vopak)
 - Anders dan in de gasmarkt valt de tijdelijke overslag en opslag bij transport in de CCS-keten (zoals gedefinieerd in Art. 3 lid 29, verordening 2024/1735 van de EU)
 - De verordening definieert terminals, compressorstations, liquificatie en tijdelijke opslag ook als onderdeel van het vervoer van CO₂. Dit is nieuw tov de oude regelgeving
 - Hierdoor en doordat deze activiteiten veel te maken hebben met het transport is het voor Gasunie logisch om ook in deze onderdelen van de keten te zitten.

- Wat is volgens Gasunie de rol van het CCS-systeem in het (energie)systeem van de toekomst?
 - Het is niet aan Gasunie om die politieke keuze te maken, maar Gasunie levert wel input dmv oa scenariostudies
 - Zowel negatieve emissies in de toekomst als afvang bij industriële processen is van belang
 - De hoop is dat het CCS systeem is het bijdragen aan industriële de-carbonisatie doordat het een verduurzamingsroute is met relatief lage maatschappelijke kosten (tov alternatieven); vooralsnog heeft CCS voor meerdere toepassingen de laagste kosten per vermeden ton CO₂
 - CCS is een noodzakelijke transitietechnologie waarvan het belang is toegenomen in de afgelopen jaren, er is meer vraag naar en er zijn meer projecten die opkomen
 - CCS staat nu ook hoger op de agenda in Brussel
 - Er is hier een parallel met waterstoftransport: CCS wordt gezien als een onmisbare technologie (essentiële infrastructuur) voor verschillende factoren om concurrerend te kunnen blijven, daarom is het volgens Gasunie belangrijk dat (net als bij het waterstofnetwerk) toegang op min of meer gelijke voorwaarden mogelijk is
 - Gasunie ziet zijn eigen rol om dit te realiseren als faciliterend dmv het aanleggen van de infrastructuur
 - Om dit publieke belang te dienen is het ook van belang dat een publieke partij dit aanlegt netwerk aanlegt

- Wat zijn belangrijke voorwaarden voor een toekomstig systeem en wat zijn factoren die de ontwikkeling tegenhouden?
 - Het zetten van de juiste randvoorwaarden voor de industrie om te investeren is belangrijk, deze moeten gezet worden door de overheid
 - Niet-discriminatoire toegang tot transport en opslag is hierin voor Gasunie heel belangrijk, de precieze invulling hiervan is aan de overheid
 - Gasunie is van mening dat 1 publieke partij dit zou moeten regelen, dit mag dan gereguleerd worden. Voordat dit mogelijk is moet de afvang kant (randvoorwaarden voor de industrie) eert op orde te zijn om risico's te verkleinen. Dit komt er op neer dat het volloopriscio in zekere mate afgedekt moet worden
 - Contractharmonisatie is ook belangrijk om de complexiteit voor afvangers te verminderen. In de gasmarkt stapelen tarieven als je verder weg zit van waar het gas gewonnen wordt door de extra infrastructuur die nodig is. Als je de infrastructuur als essentiële infrastructuur ziet moet je het ook interessant houden voor buitenlandse partijen en partijen die verder van opslag zitten om de tarieven betaalbaar te houden.

- Het doel van contractharmonisatie is het ontzorgen van afvangers door voor hen de contractenketen te versimpelen.

- Wat is het voordeel van het verbinden van Nederland met het buitenland:
 - Het is van publiek belang om andere EU landen te verbinden met Nederland om zo Europees emissiereducties te realiseren.
 - Het vergroten van volumes verkleint de per-ton kosten, dit houdt de infrastructuur betaalbaar

C.7. Rijksdienst voor Ondernemend Nederland (RVO)

Samenvatting het interview met een medewerker van RVO

Antwoord op vragen

- Wat doet RVO met CCS?
 - RVO is het uitvoeringsorgaan van het ministerie; onderdeel van het ministerie in zekere zin
 - Voert opdrachten uit voor verschillende ministeries
 - Uitvoeringszaken en publieke dienstverlening: voor CCS is dat vrij breed
 - Innovatiesubsidieregelingen: projectbeoordelingen en regelingen
 - Voor CCS specifiek is RVO zwaarder betrokken bij de algemene ontwikkelingen. RVO volgt de ontwikkeling van CCS meer geeft als daarnaar gevraagd wordt expert advies
 - Er is een specifiek team bij RVO die CCS, CCU, en CDR op zich neemt. Dit team ziet dus veel dwarsverbanden binnen de markt (synergien)
 - Een voorbeeld hiervan het gebruik van DAC bij glastuinbouw ipv DAC voor koolstofverwijdering in de beginnende fase. Zo ziet het team dus niet alleen de meer voordehandliggende opties, maar kan het meer ook over sectoren heen kijken. Binnen het ministerie van KGG is dit bijvoorbeeld meer verspreid.
- Welke trends zie je in de SDE-rondes over de jaren heen?
 - De kosten van CCS zijn enorm gestegen, basisbedragen voor transport en opslag waren eerst 60 EUR/t, nu zijn deze al ongeveer het dubbele
 - Dit komt zowel door inflatie (wat bijzonder hoog is geweest) als de grote onzekerheden die ingeprijsd worden in de tarieven. Dit laatste (wat je zou kunnen beschouwen als transactiekosten) zou kunnen dalen als er FID is genomen en de bouw is begonnen.
 - Dat het rijk achter de ontwikkeling van Aramis staat blijkt dus nog niet voldoende te zijn om deze onzekerheidsmarges te drukken.
 - Je ziet in de huidige aanvragen dat er vooral afwachting van Aramis is. Aramis heeft hoge startvolumes nodig en kan nog geen FID nemen
 - Animo is er maar dit wordt niet volledig gerepresenteerd nog in de SDE aanvragen
 - Het was een van de goedkopere opties en nu komen er ook andere categorieën die concurreren
- Waarom stellen verschillende bedrijven investeringen uit?
 - Vestigingsbeleid: het is de vraag of bedrijven zelf nog een lange toekomst in Nederland zien, dan zijn grote investeringen in CCS niet logisch.
 - Bijvoorbeeld voor Chemelot, hoge energie en gas prijzen in Nederland maken verslechteren het vestigingsklimaat.
 - Geopolitiek: veel onzekerheid over oa de samenwerking tussen landen
 - Onzekerheden over het terugverdienvermogen van de investeringen over 15 jaar
 - Gestegen kosten jaar op jaar halen de rationale van CCS onderuit. Het is minder duidelijk een goede/de meest goedkope optie
 - Alternatieven komen dichterbij; dit is op zich goed mits die alternatieven ook daadwerkelijk mogelijk worden en niet te lang duren. De beschikbaarheid van deze alternatieven is ook erg onzeker waardoor de zeef in de SDE nog niet laat zien dat deze alternatieven heel dichtbij zijn.
- Welke verschillen zie je tussen de industrieën?
 - Petrochemie: dubbelrol, zijn vaak ook zelf eigenaren van gasassets en operator van gasproductie, waardoor ze vaak ook in CO2 opslag zitten (Shell, ExxonMobil, etc)
 - Die nemen al veel initiatieven en zullen daarom ook snel langer hier in blijven investeren en dit als verduurzamingsoptie zien
 - Partijen die meer afhankelijk zijn van deze partijen zullen eerder terugtrekken (bijvoorbeeld chemie bedrijven)
 - Bij Aramis door de onduidelijkheid wie wel/niet aanluiten in het project kan deze asymmetrische informatie het vertrouwen verminderen
 - Bij Porthos was deze mentaliteit anders, de wil was er om gezamenlijk het project van de grond te krijgen. Het was duidelijk wie de investerende partijen waren gedurende het proces.
- Welke verschillen zie je nog meer tussen Porthos en Aramis?

- Afdelingpartijen konden bij Porthos allemaal tegelijk door één SDE ronde heen. Alle stappen in het proces naar realisatie konden tegelijk genomen te worden, wat het coördinatieprobleem voorkomt die we bij Aramis wel zien
- Het kip-ei probleem/de cross-chain risks dat bepaalde delen eerder klaar zijn dan anderen bij Porthos daardoor veel minder dan bij Aramis
- Kan je reflecteren op de huidige werking van de SDE en wat voor tools of opties mogelijk nodig zijn?
 - De SDE is voor opschaling van technieken en wordt gebruikt om CCS in de markt te zetten. Bij Porthos ging dit goed, maar CCS is anders dan zon, pv, wind etc.
 - Bij CCS zijn er grotere projecten maar minder, dat past misschien iets minder in de SDE doordat de concurrentie wat minder natuurlijk gaat
 - Bij de SDE laat je wie de subsidie krijgt over aan de markt maar toch heb je een belang bij een bepaalde uitkomst. Er is geen zekerheid wie gaat aanvragen en wie de subsidie krijgt.
 - Mogelijke opties in de toekomst:
 - Als het niet de vraag is of je CCS wil zou je ook een aparte tool kunnen maken, bijvoorbeeld met tenders zoals bij WOZ (aan de hoogsteieder). Zo kan je bijvoorbeeld een opslagproject in een keer aanbieden

Overige besproken onderwerpen

- CCS bij gascentrales
 - Veel studies maar als Nederland nooit zo naar gekeken, vooral internationaal zijn hier uitgebreid studies naar gedaan
 - Er zijn verschillende mogelijkheden voor technologieën (post-combustion, pre-combustion, ALLAM cycle)
 - In de VS draaien deze al redelijk veel
- Kostendata
 - Wetenschappelijke studies komen uit op orde-groottes als 40 EUR/t voor transport en opslag, maar zoals eerder genoemd worden deze getallen in de praktijk hoger ingeschat.
 - Ergens zit dus een risico inprijzing of commerciële mark-up waardoor de tarieven en uiteindelijke kosten hoger zijn
 - Wat het valideren lastiger maakt is dat veel data niet publiek is (bijv break-down kosten Northern Lights of Aramis)
- Als je netwerken op elkaar wil aansluiten moet je voldoen aan de specs van dat netwerk
 - Deze specs worden vanuit transport en opslag operators strak gezet om heel veilig te houden terwijl die kosten dan komen op afvangers
 - Hierom wordt het afstemmen van specs internationaal ook wel geopperd
 - Dit kan voornamelijk van belang zijn bij gasvormige CO2
 - Het is ook de vraag wie dan die kosten moet betalen, nu komen deze vooral terecht bij de afdang
- In het verleden is de keuze gemaakt voor een B2B markt en niet om bijvoorbeeld een netwerk operator aan te wijzen, die keuze heeft een grote impact in de huidige ontwikkeling van het CCS-systeem.

C.8. Porthos

Interview met een medewerker van Porthos

(schuingedrukte tekst zijn vragen van de interviewer)

- *Kan je wat achtergrond geven over Porthos, hoe het project tot stand is gekomen, de stakeholders, etc.?*
 - Porthos bestaat uit drie 100% staatsbedrijven die een gezamenlijke transport en opslag infrastructuur aanleggen
 - Porthos is een onderdeel van de gehele de-carbonisatie strategie van de haven van Rotterdam, met het uitgangspunt dat het kan, maar dat CCS nodig is
 - Geen enkel individueel bedrijf zou een gezamenlijke infra structuur aanleggen, die zouden dan kiezen voor het ontwikkelen van hun eigen infrastructuur.
 - 2.5 Mtpa transport en opslag voor 15 jaar (fase 1)
 - Collector pijplijn van 10 Mtpa, deze extra 7.5 Mtpa is bedoeld om Aramis op gang te brengen
 - Die extra 7.5 Mtpa wil Porthos ook nog verkopen en benutten, dat is nog een rol die overeind blijft naast de 2.5 Mtpa voor Porthos

- Porthos is een first-of-a-kind project: hiervoor waren CCS projecten losse fabrieken met 1 pijpleiding en opslag direct daaraan gekoppeld, maar geen netwerken; een verzamel pijpleiding voor CO2 bestond nog niet en bestaat nog steeds nergens (hoewel er wel plannen voor zijn)
 - CO2 transport en opslag was ook hiervoor alleen voor EOR
 - CCS zoals bij Porthos komt vanuit een ander uitgangspunt: de klimaatdoelen en minder ETS betalen in plaats van het vergroten van de winst door EOR

- *Welke problemen zijn er in de opstartfase van Porthos geweest en hoe zijn deze opgelost?*
 - 2 aan van het begin geïdentificeerd en geprioriteerd
 - Geld: het was nog goedkoper om uit te stoten en dus zat er een gat in de business case
 - Integratie van CCS in de SDE++ opgezet voor het versterken van deze business-case.
 - Gebrek aan politiek en maatschappelijk draagvlak
 - Wie is er aansprakelijk voor mogelijke lekkage en welke kosten zijn er aan verbonden?
 - Opslagvergunningen waren nog niet eerder door de EU uitgegeven.
 - Ingewikkeld project om van de grond te krijgen doordat 8 FID's nodig waren met hoge risico's
 - Wat het iets minder ingewikkeld maakte is dat er nog weinig regulering was, daardoor was er meer vrijheid

- Het is belangrijk om niet alleen op de risico's te focussen, maar om ook de positieve redenen van het uitvoeren van het project te benadrukken
 - *Waarom is Porthos dan geslaagd?* Er was een grote wil bij de aangesloten partijen, iedereen voelde zich geïnteresseerd aan de klimaatdoelen. Het was een goede samenwerking van private partijen, publieke partijen en de overheid

- *Welke risico's zitten er nog in de vervolgfases van het Porthos project, wanneer het project operationeel wordt? Bijvoorbeeld technische risico's?*
 - Het is nog spannend nog hoe het gaat in de ondergrond: de drukopbouw in de opslag. Dit is uitvoerig gemodelleerd, maar een project als Porthos is nog niet eerder gedaan.
 - Er is geen reden om aan te nemen dat dit niet goed gaat
 - Technische risico's worden niet zo gezien, alle onderdelen van de keten zijn los van elkaar bewezen
 - Wel moeten alle klanten op tijd klaar zijn om CO2 te leveren en af te vangen
 - De afvangers zijn volop bezig met het bouwen van installaties dus lijkt dit groot risico meer

- *Hoe verhoudt het Porthos project en de risico's en lessen die hieruit zijn geleerd zich tot opschaling naar en realisatie van grotere projecten zoals Aramis?*

- Aramis kan voortbouwen op het Porthos compressor station en de collector pijpleiding
 - Ook is er nu meer draagvlak nu dan er was voor CCS, politiek en maatschappelijk
 - De opstartproblemen rond regulering die nog niet duidelijk waren toen Porthos begon zijn nu opgelost
 - De visie van de participant op basis van ervaringen is dat het een fout was om te zeggen dat de verdere ontwikkeling van het CCS-netwerk nu volledig aan de markt is
 - De eigenaarsconstructie zoals deze bij Porthos is gekozen is goedkoper dan private partijen door een lager rendement dat overheidsinstanties kunnen accepteren.
 - Het zou verstandiger zijn om Porthos in de volgende opschalingsfase verder in te zetten
 - Private partijen die hogere rendementen nodig hebben, hebben dan ook hogere subsidiering nodig. Zolang deze subsidiering nodig is, is het inzetten van publieke partijen een logische stap.
 - Zo kan je ook de kennis benutten die je met Porthos op doet
 - Ook voor de klant is het logischer om een partij aan te wijzen: nu zie je dat de contractenketen erg ingewikkeld wordt. Dit verhindert de keten.
 - Klanten zijn ontevreden over opslagpartijen en tarieven, Porthos heeft nu eindelijk wat vertrouwen opgebouwd en zou dit kunnen gebruiken.
 - Het is eenvoudig om te laten zien dat er marktfalen is
- *Wat zijn de grootste cost-drivers en onzekerheden in projecten zoals Porthos?*
 - Er zijn grote kostenstijgingen die na het sluiten van de contracten niet meer verrekend kunnen worden. Deze kostenstijgingen komen vooral door materieel en personeel
 - Afstand en volume bepalen de kosten het meest.
 - Porthos is behoorlijk efficiënt, alle klanten zitten dichtbij en de opslag is ook dichtbij. Door deze afstanden maakt het voor klanten ook niet uit als een andere partij een paar kilometer verder op zit. Deze extra kosten vallen weg in de marge. Bij bijvoorbeeld een klant uit Duitsland en een klant uit Rotterdam is het de vraag of de klant in Rotterdam wil meebetalen aan het transport voor de klant uit Duitsland.
 - De ontwikkeling van de ETS is een grote onzekerheid
 - Aan de afvang kant is er ook een grote stijging aan kosten te zien
 - Vanuit klantperspectief heeft een grote impact welke rendementen er worden verwacht door de transport en opslag partijen? Dit wordt sterk beïnvloed door de eigenaarschap van de infrastructuur (publiek of privaat)
 - De ontwikkeling in het industriecluster in Zeeland is interessant: 1 partij kiest voor schepen omdat ze niet langer willen wachten op de ontwikkeling van buisleidingen, terwijl voor het hele cluster het delen van een buisleiding efficiënter kan zijn.
 - Dit verhoogt uiteindelijk voor iedereen in het cluster de prijzen en is suboptimaal vanuit een systeemperspectief.
 - *Zijn er verder nog extra punten die je aan de hand van dit gesprek zou willen toevoegen?*
 - Er is geen vlekkeloze samenwerking tussen de 3 staatsbedrijven van het Porthos project, maar komt wel steeds beter op gang. Als dat vertrouwen er is en de rollen goed verdeeld worden is er dit een sterk instrument voor Nederland om een hub en netwerk aan te leggen
 - De rol van regulering
 - Oppassen met te veel regulering, het reguleren van tarieven en aanwijzen netbeheerder kan wellicht te veel zijn. Dit omdat er geen land vol met CO2 pijpleidingen komt. De leidingen komen niet bij consumenten.
 - Je hoeft ook niet verplicht te stellen dat publieke partijen de ontwikkeling moeten doen
 - De crux zit op opslag, alles draait daarom; zonder opslag heb je geen transport

- Opslag bepaald technisch je hele project
 - EU en NL onderschat dat het ontwikkelen van opslagprojecten door de markt vanzelf zou gaan. De staat zou opslagprojecten meer naar zich toe moeten trekken.
 - In principe is competitie op termijn misschien mogelijk, maar dan moet het niet een gesubsidieerde markt zijn. Daar moet dus eerst een doorbraak komen
- Porthos is een goed voorbeeld van een succesvol project dat door 3 overheidsbedrijven is geïnitieerd