Bridging the Gap: Adoption of Carbon Capture Technologies in Dutch Industries

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by

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Foreword

The past few years have taught me the value of connecting knowledge, innovation, and practice. With this second thesis, I bring my academic master's journey to a close, four years after earning my first master's degree in nature conservation. Balancing this entire program alongside my office work, setting up a spin-off company, and my responsibilities at home has been both challenging and rewarding. Yet, my curiosity and determination drove me forward. It has been a privilege to explore carbon capture technology and gain deeper insight into the Dutch industries.

I am grateful to my supervisor, Dr. Mattijs Smits, for his guidance and constructive feedback, which consistently helped me refine my ideas and elevate this research. I also thank my second examiner, Maartje van der Knaap, for her engagement. My heartfelt thanks go to my family and my partner, Margret, for their unwavering support and understanding throughout this demanding period. To Oghenekaro and Ufuoma, for whom I have the honor of being a caregiver: thank you for your patience through the many days, evenings, and weekends I spent behind my desk. I am glad to now spend more time with my family. I also extend my gratitude to the experts and respondents who generously shared their time and insights. Their contributions defined the relevance and depth of this thesis and provided the data on which this thesis is built.

Exploring carbon capture technology has reaffirmed my interest in innovations that address societal challenges and embed them in public debates. The climate and energy transition are a shared responsibility that requires collective insights, creativity, and action. I hope this thesis serves as a source of inspiration and a call to continues collaboration.

Coen van den Brand

Abstract

Achieving climate neutrality by 2050 requires decarbonizing high-emission industries. Carbon capture and storage (CCS) is viewed essential for mitigating industrial emissions but faces barriers such as high costs, technical challenges, and limited societal and organizational acceptance. This study examines the innovation and behavioural factors influencing carbon capture adoption in the Netherlands, addressing gaps between early adopters and broader industry. A mixed-methods approach, combining surveys and interviews with 42 EU Emissions Trading System-regulated companies, explores how innovation attributes and behavioural factors shape adoption patterns. Findings show adoption is concentrated among large emitters, driven by regulatory pressures and strategic benefits, while smaller emitters face greater resource constraints and feasibility challenges. Key innovation attributes, such as reputational gains, market leadership, and technical expertise, enhance attitudes, external pressures, and perceived control, fostering adoption intentions. However, financial, logistical, and operational barriers remain significant. Scaling carbon capture adoption will require pilot projects, cost reductions, infrastructure expansion, and targeted support for smaller emitters. Aligning policy, industry, and society in a multi-level approach may bridge adoption gaps and accelerate decarbonization. By addressing these challenges, carbon capture can play a considerate role in reducing emissions and supporting climate goals, serving as both a transitional and long-term solution.

Table of contents

List of Tables

List of Figures

1. Introduction

The transition to climate neutrality is one of the most pressing global challenges. In line with the Paris Agreement (United Nations Framework Convention on Climate Change, 2015), the European Union (EU) has set ambitious climate targets: a 55% reduction in greenhouse gas emissions by 2030 (European Commission, 2021), a 90% reduction by 2040 (European Commission, 2024a), and full climate neutrality by 2050 (European Commission, 2018, 2019; European Parliament and Council, 2021). By 2023, EU emissions were 37% below 1990 levels (European Commission, 2024a), indicating progress but highlighting the need for accelerated efforts to meet upcoming goals. Achieving these targets requires transformative changes, especially in high-emission industries, where innovative technologies and shifts in organizational behaviour are essential.

Among decarbonization strategies, carbon capture and storage (CCS) are viewed critical for reducing industrial emissions (European Commission, 2023, 2024b; International Energy Agency, 2023 [IEA]). Unlike energy efficiency or renewable energy, CCS directly captures emissions at their source, making it indispensable for hard-to-abate sectors like cement, steel, and chemicals. CCS can also complement these mitigation strategies through addressing historical emissions with approaches such combining bioenergy with carbon capture and storage (BECCS) or direct air capture (DAC) both removing CO_2 from the atmosphere. Despite its potential, CCS adoption is limited by high costs, energy demands, infrastructure gaps, and societal concerns (Intergovernmental Panel on Climate Change, 2018; IEA, 2013).

Regulatory mechanisms such as the EU Emissions Trading System (EU ETS), the EU CCS Directive, and the Carbon Border Adjustment Mechanism (CBAM) aim to incentivize CCS deployment (European Parliament and Council, 2003, 2009, 2023). These frameworks have driven progress, yet scaling CCS to the required levels remains a challenge (European Commission, 2024b). This study investigates how innovation and behavioural factors shape CCS adoption patterns on a sectoral level, focusing on exploring the gap between early adopters and the broader industry.

As an EU member state, the Netherlands plays an important role in the EU's climate strategy, with national targets exceeding EU ambitions with a 60% emissions reduction by 2030 compared to 1990 levels, which stood at 228.1 megatonnes (Rijksoverheid, 2022). However, recent projections suggest reductions of only 44–52% by 2030 (Planbureau voor de

Leefomgeving, 2024b [PBL]), highlighting the urgency for action. In particular, NL ETS installations account for about 40% of the Dutch total emissions in 2023.

Achieving these targets is not only needed for national progress but also essential for contributing to the EU's broader ambition of capturing 50 megatonnes (Mt) of CO_2 annually by 2030 (European Commission, 2021). Looking further ahead, the EU envisions CCS storage capacities of 280 Mt per year by 2040 and up to 500 Mt annually by 2050 (European Commission, 2024a). Initiatives such as the Porthos CCS project and an additional CO_2 tax illustrate the Netherlands' commitment to innovation and decarbonization (Rijksoverheid, 2019), yet significant barriers remain (Akerboom et al., 2021). Further scaling CCS adoption in the Dutch industrial sector requires addressing barriers.

While CCS discussions often centre on cost and technical performance (IEA, 2020; Rubin et al., 2015), organizational attitudes and external pressures may be equally influential in shaping adoption (Gunderson et al., 2020). Innovation attributes like relative advantage, compatibility, and complexity could intersect with behavioural factors, such as attitudes, societal expectations, and external regulations, to determine organizational decision-making (Markusson et al., 2011; McLaughlin et al., 2023). This study contributes to understanding the interplay between these factors, providing insights into the adoption of CCS within Dutch industries. The central research question guiding this study is:

What are the main barriers and drivers for the adoption of carbon capture technologies in Dutch industries?

To address this question, the study draws on two complementary frameworks: Rogers' Diffusion of Innovations (DOI) and Ajzen's Theory of Planned Behaviour (TPB). DOI emphasizes innovation attributes, such as relative advantage, compatibility, and complexity, that influence perceptions of feasibility and adoption rates (Rogers, 1962). TPB focuses on behavioural factors, including attitudes, external pressures, and perceived behavioural control, which shape intentions and actions (Ajzen, 1991). Together, these frameworks provide an understanding of how innovation attributes and behavioural dynamics drive or hinder adoption. This approach also addresses the potential "chasm" between early adopters and the early majority (Moore, 1991), examining barriers to overcome this transitional phase.

This study examines two key aspects. First, how do the innovation attributes of carbon capture technologies influence adoption rates among Dutch industries? Second, how do behavioural

attributes shape decision-making regarding carbon capture adoption? The analysis explores the interactions between these factors, recognizing their potential to reinforce or conflict, such as when cost constraints clash with reputational benefits. By situating these questions within the Dutch context, this research captures the unique opportunities and challenges of CCS adoption in a country with progressive climate policies but limited implementation.

This thesis is organized into seven chapters. The introduction outlines the background, research objectives, and contextual relevance of CCS adoption in the Netherlands. The conceptual framework discusses innovation and behavioural theories, forming the basis for the study's hypotheses. The methodology chapter details the mixed-methods approach, integrating surveys and interviews. The findings are presented in two results chapters. One focuses on adoption patterns and behavioural drivers, while the other examines innovation attributes and key barriers. The discussion evaluates the implications, challenges, and opportunities for scaling CCS, alongside the study's strengths and limitations and recommendations for future research. The conclusion summarizes the contributions and implications.

In summary, this study aims to deepen understanding of the factors influencing CCS adoption by integrating innovation attributes and behavioural dynamics. By addressing these complexities within the Dutch context, the research aims to offer actionable insights for policymakers and industry leaders seeking to bridge the gap between early adopters and broader market diffusion, which may be equally relevant for other European countries and broader regions.

2. Conceptual Framework

This chapter outlines the theoretical framework used to examine the adoption of carbon capture technologies. As highlighted in the introduction, carbon capture is a vital component of the low-carbon transition in policies but faces persistent barriers to widespread adoption. To address these complexities, this study integrates technological and behavioural frameworks to offer a comprehensive understanding of adoption dynamics.

Existing literature often examines technological attributes, such as costs and infrastructure, separately from behavioural dynamics, or vice versa. This study bridges this gap by combining established theories to analyse the multi-level interplay between innovation and organizational behaviour towards carbon capture technologies. The Diffusion of Innovations theory (Rogers, 1962) and Crossing the Chasm (Moore, 1991) provide robust frameworks for understanding how innovation attributes, such as relative advantage, complexity, and compatibility, influence diffusion and adoption across adopter categories. Despite their origins decades ago, these theories remain widely relevant in innovation research (Lengyel et al., 2020; Paul et al., 2016; Valente & Vega Yon, 2020).

Complementing this innovation perspective are behavioural models such as the Theory of Reasoned Action (Fishbein & Ajzen, 1975) and the Theory of Planned Behaviour (Ajzen, 1991). These frameworks offer insights into how attitudes, subjective norms, and perceived control shape decisions and intentions. While extensively applied across fields, their use in addressing challenges like industrial decarbonization remains underexplored.

By integrating these frameworks, this study creates an approach to understanding the interdependence between technological attributes and behavioural factors. For instance, DOI can explain how complexity and relative advantage influence behavioural attitudes, while TPB addresses how external pressures and perceived control affect adoption decisions. This integrated framework is particularly relevant for understanding the complex organizational and strategic decision-making processes involved in adopting carbon capture technologies.

The mutual influence between these theoretical perspectives remains an area for further exploration, but their integration provides a nuanced lens for analysing the drivers and barriers of CCS adoption. By connecting innovation and behaviour, this study examines how these

factors accelerate or hinder carbon capture adoption, offering actionable insights for addressing the challenges of industrial decarbonization (Table 1).

Table 1. Theoretical Framework for Technology Adoption Analysis

Theory	**Application**	**Key Concepts**
Diffusion of Innovations (Rogers, 1962)	Explains how technologies spread within social systems	Relative advantage, compatibility, complexity, trialability, observability
Crossing the Chasm (Moore, 1991)	Analyses challenges in scaling technologies	Gap between early adopters and early majority
Theory of Reasoned Action (Fishbein & Ajzen, 1975)	Explains how intentions drive behaviour	Attitudes, subjective norms
Theory of Planned Behaviour (Ajzen, 1991)	Extends TRA by adding the perception of control	Perceived behavioural control

Note. This table outlines innovation and behavioural theories used to analyse technology adoption and organizational behaviour in this study.

2.1. Innovation Theories

2.1.1. Diffusion of Innovations

The *Diffusion of Innovations* theory, developed by Everett Rogers (1962), provides a framework for understanding how new technologies spread within social systems. It identifies five key attributes that influence adoption rates: relative advantage, compatibility, complexity, trialability, and observability. These attributes shape how potential adopters perceive an innovation, directly affecting their willingness to adopt it. For carbon capture and storage, these factors are particularly relevant, as the technology has yet to achieve large-scale implementation despite decades of recognized potential as a climate mitigation strategy (Braunreiter & Bennett, 2017; Bui et al., 2018).

Relative advantage refers to the perceived benefits of an innovation over existing alternatives, such as compliance with stricter environmental regulations, cost savings, or reputational gains from sustainability initiatives (Bui et al., 2018). Compatibility reflects the degree to which carbon capture aligns with organizational values, strategic goals, and operational workflows, influencing how seamlessly it can integrate into existing systems. Conversely, complexity acts as a barrier when carbon capture is perceived as difficult to understand or implement, a significant issue given its technical and infrastructural demands (Bahman et al., 2023). Trialability, the ability to test an innovation on a smaller scale through pilot projects, reduces

uncertainty and fosters trust in the technology (Plasynski et al., 2009). Observability, or the visibility of tangible results like emissions reductions or successful applications in similar industries, can serve as a catalyst for broader adoption. Together, these attributes help explain adoption patterns by influencing organizational perceptions of carbon capture and identifying opportunities to overcome challenges (Rogers, 1962).

While these attributes form the core of the diffusion process, Rogers' framework also incorporates broader factors such as decision-making processes, communication channels, social system characteristics, and the role of change agents (Figure 1). These variables offer a comprehensive view of how innovations spread, but this study focuses on the five key attributes as they most directly influence adoption behaviour and decision-making processes in organizational contexts.

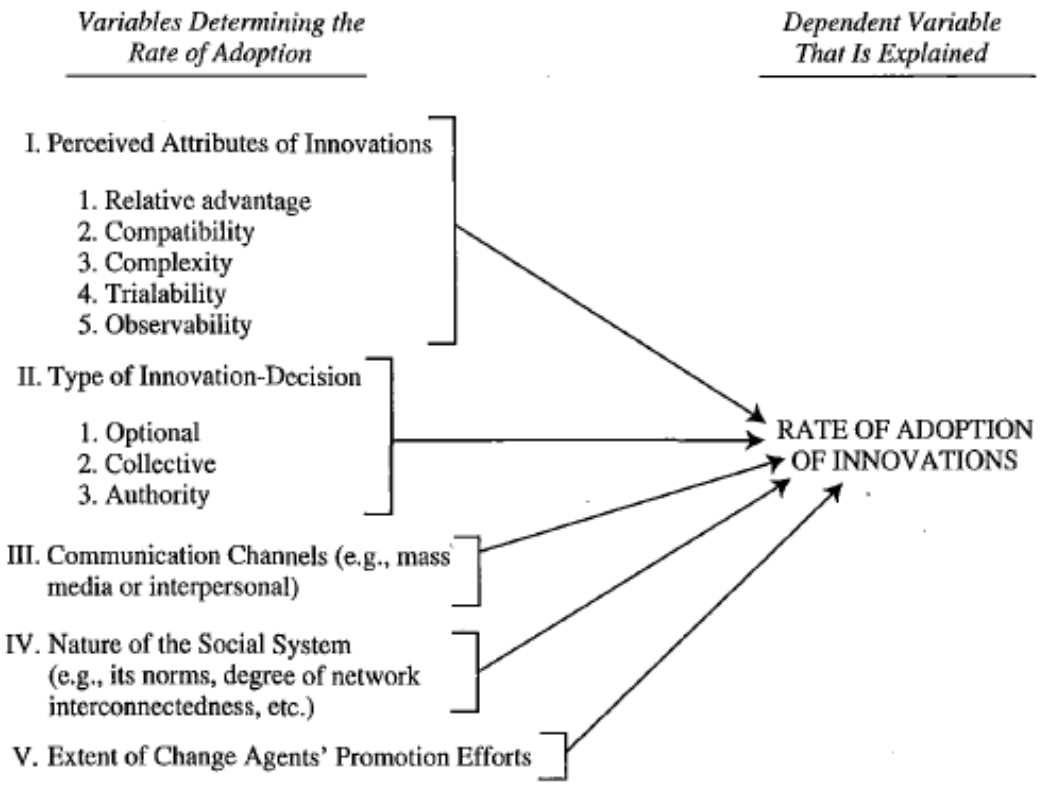

Figure 1. Variables Influencing the Adoption Rate of Innovation
Note. Based on Rogers' Diffusion of Innovations theory (1962), this figure highlights key variables influencing adoption, including innovation attributes (relative advantage, compatibility, complexity, trialability, observability) and contextual factors like decision-making, communication channels, social systems, and change agents.

In addition to innovation attributes, DOI categorizes adopters into five groups: Innovators (2.5%), Early Adopters (13.5%), Early Majority (34%), Late Majority (34%), and Laggards (16%). Innovators and Early Adopters initiate adoption by taking risks and embracing new

opportunities, while the Early and Late Majority represent the largest user segments and often require proven success and reduced risks before adopting. The segmentation, visualized in Figure 2, helps assess carbon capture's current position in its adoption lifecycle and informs strategies to address different adopter groups.

DOI also identifies five stages of the decision-making process: knowledge, persuasion, decision, implementation, and confirmation. These stages describe how adopters progress from learning about an innovation to evaluating its advantages and disadvantages, deciding to adopt, implementing the technology, and assessing its long-term value. Applied to CCS, these stages provide insights into how companies approach adoption internally and where they are in their decision-making stage, offering a framework that may help identify interventions that could accelerate diffusion.

2.1.2. Crossing the Chasm

The *Crossing the Chasm* theory, introduced by Geoffrey Moore (1991), builds on Diffusion of Innovation by addressing the critical gap between Early Adopters and the Early Majority (Figure 2). Early Adopters are often visionaries who embrace innovations despite uncertainties, driven by a belief in the long-term potential of the technology. The Early Majority, on the other hand, consists of pragmatists who require proven effectiveness, operational reliability, and economic feasibility before adopting. According to Moore, many technologies fail to scale because they cannot bridge this gap, leaving them confined to niche markets or early-stage applications (Moore, 1991).

Bridging the chasm requires a targeted strategy to meet the specific needs of the Early Majority. Moore emphasizes the importance of focusing on a well-defined niche within this group, tailoring solutions to their concerns, and delivering a "complete product." This means not only offering functional technology but also providing robust support, complementary services, and operational guarantees to reduce perceived risks. Building trust through credible references, such as successful Early Adopter case studies, is essential to reassure the more cautious Early Majority. Pragmatic communication should highlight tangible benefits, including reliability, cost-effectiveness, and risk reduction, to address their priorities. Collaborative efforts within ecosystems, such as fostering strong value chains and implementing mechanisms like pilot projects or risk-sharing agreements, can further lower barriers and create pathways to broader adoption.

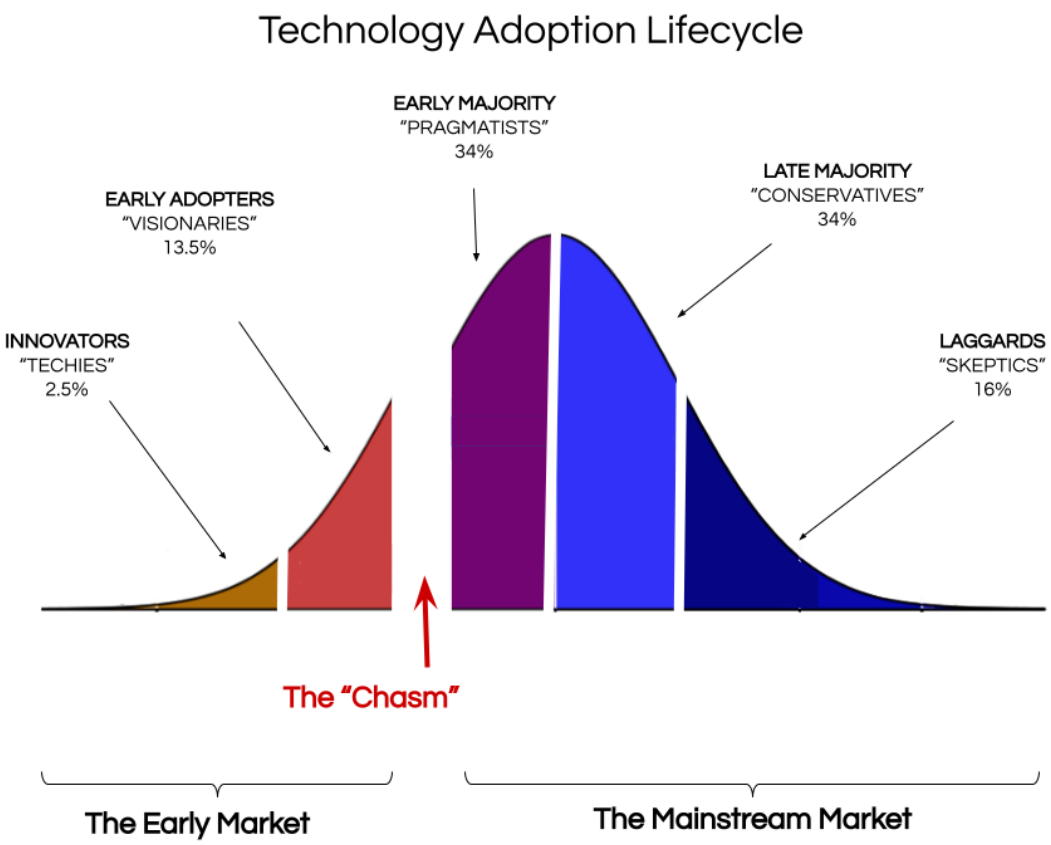

Figure 2. Adopter Categories and the Concept of the 'Chasm'
Note. Adapted from Rogers (1962) and Moore (1991), this figure illustrates the adopter categories and the "chasm" between Early Adopters and the Early Majority in the diffusion of innovations.

For carbon capture technologies, Moore's strategies are particularly relevant. High upfront costs, complex infrastructure requirements, and technological uncertainties may create significant obstacles to scaling adoption. Demonstrating clear success stories and aligning CCS with the operational and economic needs of the Early Majority may be key to overcoming these challenges.

In the Dutch context, Crossing the Chasm provides valuable insights into the current adoption challenges facing CCS technologies. Despite their recognized potential, CCS projects in the Netherlands remain in the early adoption phase, with examples like waste processor initiatives and the upcoming Porthos project in the Port of Rotterdam (PBL, 2024a). These projects, driven by pioneering companies and stakeholders, demonstrate a willingness to take risks in pursuit of sustainability and innovation. However, scaling CCS adoption to reach the Early Majority may require clear demonstrations of operational success, proven reliability, and accessible infrastructure.

2.2. Behavioural Theories

2.2.1. Theory of Reasoned Action

The *Theory of Reasoned Action* (TRA), developed by Fishbein and Ajzen (1975), explains how intentions drive behaviour, making it a useful framework for understanding decision-making in organizations. Although originally designed to analyse individual behaviour, TRA is applied in this study to examine how companies and decision-makers approach innovation adoption. According to the model, intentions (the strongest predictors of behaviour) are influenced by two key factors: attitudes and subjective norms (Fishbein & Ajzen, 1975).

Attitudes reflect an organization's evaluation of a specific behaviour or technology, such as carbon capture, based on its perceived benefits, drawbacks, and expected impact. For example, if CCS is seen as an effective solution for reducing emissions and achieving economic benefits, such as subsidies or reputational gains, organizational attitudes toward adoption are likely to be positive (Wilberforce et al., 2019). Subjective norms involve perceptions of social pressure and expectations from stakeholders like governments, customers, and investors. These norms can largely influence organizational decisions. In highly regulated industries, positive attitudes toward CCS may align with external pressures, creating a strong intention to adopt the technology (van der Zwaan et al., 2022). Regulatory mandates, societal expectations, and investor demands may serve as powerful motivators for firms to pursue CCS adoption. For instance, firms subject to CO_2 taxes or emission reduction targets may adopt CCS as part of a broader strategy to achieve compliance and strengthen their market position and investor trust.

While TRA highlights the importance of intentions in driving behaviour, it also acknowledges that intentions do not always translate into action. Barriers such as limited financial resources, technical expertise, or infrastructure constraints can prevent implementation, even when intentions are strong. Additionally, external factors, such as market conditions or organizational culture, can influence adoption but fall outside TRA's scope. Despite these limitations, TRA provides a valuable lens for analysing how internal attitudes and external pressures shape organizational decisions about carbon capture technologies.

2.2.2. Theory of Planned Behaviour

The *Theory of Planned Behaviour* (TPB), introduced by Ajzen (1991), builds on the Theory of Reasoned Action by incorporating perceived behavioural control as a third dimension. While

attitudes and subjective norms influence an organization's intention to adopt technologies like CCS, perceived control determines whether these intentions can be translated into action. This dimension highlights the importance of internal factors, such as technical expertise and financial resources, alongside external enablers like supportive policies (Ajzen, 1991).

For CCS adoption, perceived behavioural control is particularly relevant due to the significant challenges organizations face, including high capital costs, technical complexity, infrastructure requirements, and societal concerns (Mulder, 2024). Even with positive attitudes and strong subjective pressure, such as CO_2 taxes, firms may fail to act if they perceive limited control over implementation (Rijksoverheid, 2019; van Alphen et al., 2007). This underscores the importance of addressing both internal capabilities and external constraints to facilitate adoption.

Targeted strategies can enhance perceived control by reducing barriers. Financial incentives, industrial knowledge-sharing, and pilot projects may help organizations overcome complexity and resource constraints. In the Netherlands, collaborative initiatives like shared CCS infrastructure in Rotterdam's industrial clusters demonstrate how pooling resources can alleviate financial and technical burdens, enabling adoption of CCS technologies.

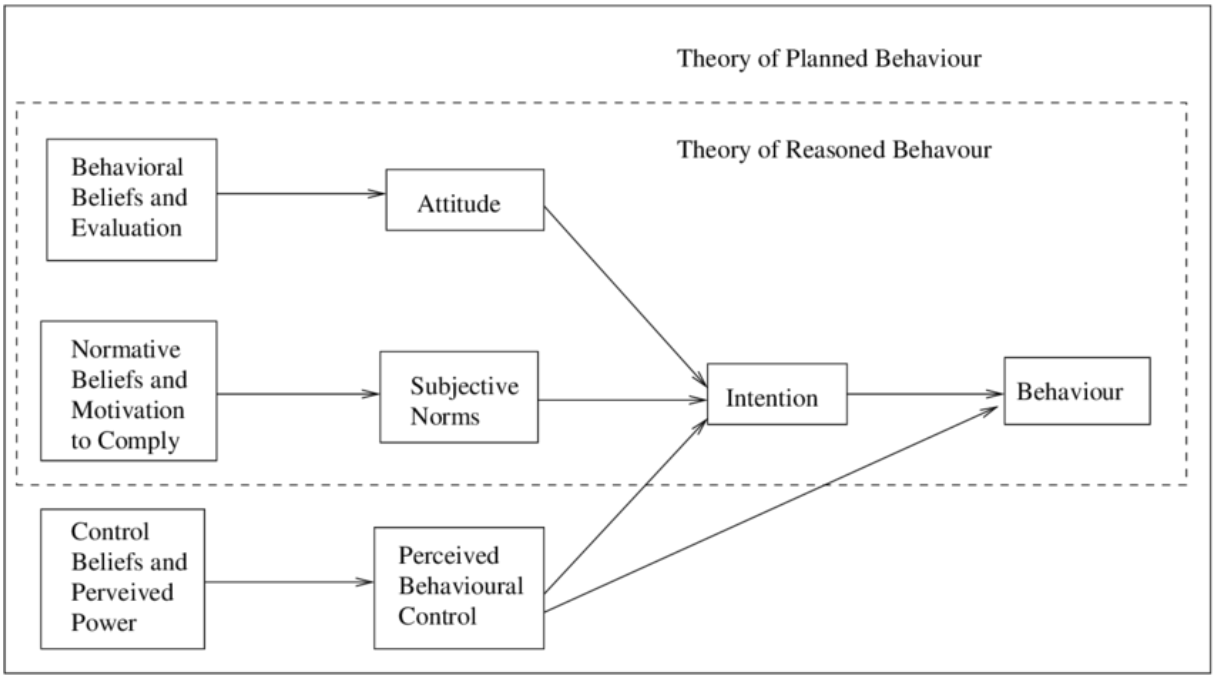

Figure 3. Theory of Planned Behaviour and Theory of Reasoned Action
Note. This figure illustrates how the Theory of Reasoned Action (Fishbein & Ajzen, 1975) evolved into the Theory of Planned Behaviour (Ajzen, 1991), showing how attitudes, subjective norms, and perceived behavioural control influence intentions and behaviour.

TPB is particularly effective for analysing gaps between intention and action, as well as the transition from early adopters to the early majority (Figure 3). By identifying the barriers hindering implementation, TPB provides a framework that may help develop strategies to enhance perceived control, ensuring organizations can move from intention to execution.

2.3. Integration of Innovation and Behavioural Theories

Building on the individual perspectives of the Diffusion of Innovations theory and the Theory of Planned Behaviour, this section examines how these frameworks complement and interact to provide a comprehensive understanding of carbon capture technology adoption. The integration of these theories highlights how technological attributes, and behavioural responses jointly shape organizational intentions and actions.

For example, relative advantage amplifies positive organizational attitudes by demonstrating tangible benefits such as regulatory compliance, reputational gains, and financial incentives. Compatibility with existing processes can enhance perceived behavioural control, as firms may view CCS as less disruptive and more feasible than alternatives. Conversely, high complexity may undermine favourable attitudes and erode confidence in implementation, even when external pressures and financial resources are present. These interdependencies indicate how adoption dynamics can be influenced by the interplay of innovation attributes and behavioural factors.

This integrated framework also helps address sector-specific challenges. In capital-intensive industries like energy and chemicals, high upfront costs, infrastructure demands, and limited trialability exacerbate uncertainty. Pilot projects can mitigate these concerns by increasing perceived control and building stakeholder trust, thereby enhancing both organizational attitudes and social norms. However, these dynamics may vary across sectors, as firms in other industries might prioritize different factors, such as immediate cost-effectiveness or visible benefits compared to alternatives.

Unexpected dynamics can also emerge within this framework. For instance, firms weighing reputational risks of inaction against cost constraints might find that collaboration within industrial clusters or public-private partnerships reduces financial and operational burdens, enhancing perceived control. Similarly, regulatory changes, such as targeted financial incentives, could shift the balance between relative advantage and social norms, encouraging adoption among hesitant firms.

By synthesizing these perspectives, this study offers a robust framework for analysing the multi-level factors influencing carbon capture adoption across industries. Table 2 summarizes the interactions between key innovation attributes and behavioural factors, highlighting their individual and potentially combined effects on adoption outcomes. This integrated approach not only bridges the gap between technological and behavioural theories but also ensures practical relevance by addressing industry-specific barriers and opportunities.

Table 2. Hypotheses on Factors Influencing CCS Adoption

Factor	**Effect on Adoption**	**Potential Interactions**
Relative Advantage	Encourages when benefits, such as compliance or cost savings, are clear	Enhances attitudes and amplifies external pressures
Compatibility	Facilitates when technology fits existing processes and values	Reduces complexity and increases perceived control
Complexity	Discourages if technical demands or costs are too high	Reduces perceived control and weakens attitudes,
Trialability	Increases likelihood by reducing uncertainty through testing	Builds trust and strengthens perceived control
Observability	Accelerates when results are visible and measurable	Reinforces relative advantage and external pressures.
Organizational Attitudes	Strengthens decisions when attitudes are positive	Offsets complexity and reinforces relative advantage
External Pressures	Encourages through regulations or societal demands	Enhances relative advantage and increases urgency.
Perceived Behavioural Control	Enables when resources and expertise are sufficient	Mitigates complexity and strengthens intentions

Note. This table summarizes hypotheses regarding key factors driving carbon capture and storage (CCS) adoption and potential interactions between these factors, including innovation attributes, organizational behaviour, and external pressures.

3. Methodology

This chapter details the methodological approach used to examine the adoption of carbon capture technologies in the Dutch industrial sector. A mixed-methods design, combining quantitative surveys and qualitative interviews, was used to identify adoption trends and explore underlying factors and contexts.

The study targeted industrial installations in the Netherlands regulated under the EU Emissions Trading Scheme (ETS). These installations were chosen for their significant contributions to national emissions and their exposure to ETS-driven regulatory measures and financial incentives. The Netherlands served as an ideal context due to its ambitious climate goals, robust industrial base, and supportive policies for emission reduction innovations.

Case selection relied on public data from the Netherlands Emissions Authority (NEa), encompassing 297 installations with CO_2 emissions data from 2021–2023. To avoid bias, no pre-selection was made based on CCS relevance. All companies were contacted in batches via email and online forms, targeting managers specializing in innovation, sustainability, or operations. Contact efforts spanned eight weeks, with up to three follow-up e-mails at two-week intervals. The final sample included a diverse range of sectors and emission levels, also capturing variations in organizational size, from companies with fewer than 50 employees to those exceeding 500.

The mixed approach provided a balance between breadth and depth. Surveys quantified adoption trends and assessed influencing factors, while interviews provided in-depth insights, enriching and validating the findings. While this study focuses on the Netherlands, its methodology and findings are applicable to other regions with similar industrial and policy contexts, offering a framework for understanding CCS adoption globally.

3.1. Surveys

To analyse factors influencing carbon capture adoption, a questionnaire (Appendix A) was designed based on Rogers' Diffusion of Innovations theory and Ajzen's Theory of Planned Behaviour. The survey evaluated key innovation attributes, such as relative advantage, compatibility, and complexity, alongside behavioural factors like attitudes, subjective norms, and perceived behavioural control. Open-ended questions were included to explore perceived challenges and gather closing remarks. Respondents also had the option to participate in follow-

up interviews. This approach enabled a systematic assessment of both technological and organizational attributes driving or hindering CCS adoption.

The survey received 45 responses, of which 42 were retained after data cleaning. The survey was completed by 45 managers involved in emission reduction programs, with 42 valid responses retained after data cleaning. Respondents represented a wide range of sectors, including agriculture (6 respondents), asphalt (2), ceramics (4), chemicals (3), food production (4), ICT (2), oil and gas (5), paper (5), energy production (2), and waste management (3), and other industries (6). Emission levels varied significantly, with installations emitting 1–10 kilotonnes (Kt) (6 respondents), 10–100 Kt (15), 100–1,000 Kt (13), and over 1,000 Kt CO_2 annually (8; Figure 4). This diversity ensured a representative sample of the Dutch industrial sector in terms of sectoral distribution and operational scale. However, key industries like steel, cement, and fertilizers were absent, representing a limitation in the sample.

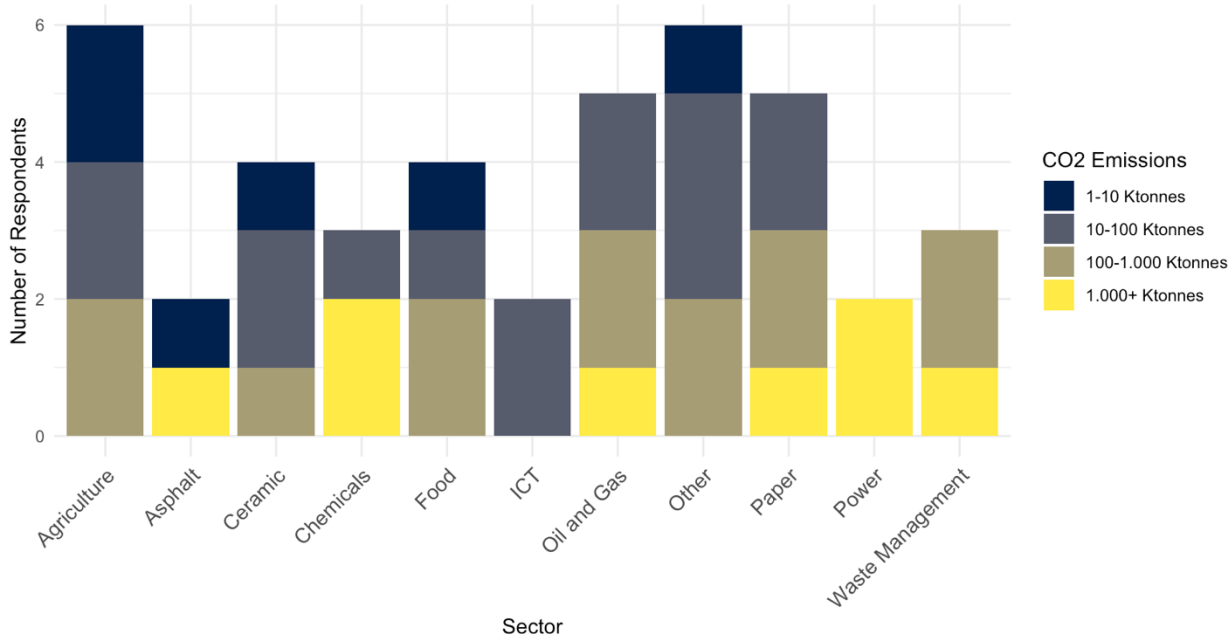

Figure 4. Respondent Distribution by Sector and CO_2 Emissions
Note. Stacked bar chart showing respondents by sector (n = 42), with bar segments representing CO_2 emissions categories.

Data analysis involved descriptive statistics and visualizations, including bar charts, regressions, and heatmaps, to identify trends and patterns. The adoption rate of CCS was calculated as the percentage of respondents reporting technology implementation. Analyses were conducted in R Studio (version 2024.09) using widely available packages for data

$$\text{Adoption Rate} = \left(\frac{\text{Number of New Adopters in the Time Period}}{\text{Total Number of Potential Adopters}} \right) \times 100\%$$

manipulation and correlation analysis. Significance tests were performed to examine group differences (e.g., sectoral representation and emission levels) and attribute correlations. While not the primary focus, and not reported in this study, these tests provided additional insights that supported and complemented the qualitative findings.

3.2. Interviews

Semi-structured interviews were conducted to gain deeper insights into the drivers and barriers influencing carbon capture adoption, complementing the survey findings with sector-specific contexts.

Fourteen survey respondents participated in follow-up interviews, representing diverse sectors: asphalt (1), chemicals (2), food production (1), ICT (1), oil and gas (3), energy production (2), waste management (1), building materials (2), and glass (1). Participants were primarily senior managers involved in emission reduction programs, with some engineers, executives, and mid-level professionals also included. Interviews were conducted online during and after the survey period, lasting between one and one and a half hours. To ensure privacy, no company or personal data are disclosed, and all participants provided explicit consent to being described at the sectoral level.

The semi-structured format allowed for in-depth exploration of carbon capture adoption in relation to innovation and behavioural attributes (Appendix B). Survey results were referenced during the interviews to verify or clarify findings. Transcripts were analysed using Atlas.ti (web version) through a combined thematic and framework approach. Key concepts, such as costs, technical complexity, and organizational intentions, were coded and structured within an analytical matrix. This matrix facilitated comparisons both within and across sectors, providing insights into factors shaping CCS adoption.

While the interviews provided valuable perspectives, some limitations should be noted. Voluntary participation may have led to an overrepresentation of companies with favourable views on emission reduction. Privacy constraints and a limited data collection timeframe may have influenced response rates, potentially affecting representativeness. Additionally, evolving policies and technologies could alter respondents' perspectives over time. Despite these

challenges, the diversity of sectors and emission levels represented offers a robust foundation for reliable insights into the current (2024) industrial landscape.

4. Adoption Patterns and Behavioural Factors in Carbon Capture

This chapter examines the adoption of carbon capture technologies among Dutch industrial sectors regulated under the EU Emissions Trading System. It explores adoption rates, sectoral differences, decision-making processes, and the behavioural factors influencing organizational choices, including attitudes, external pressures, and perceived control.

The findings reveal that large emitters, those exceeding 1,000 kilotonnes CO_2 annually, are leading in adoption. These companies often integrate carbon capture into long-term emission reduction strategies, reflecting greater alignment with strategic goals and available resources. In contrast, smaller emitters lag behind, highlighting financial and operational challenges that exacerbate disparities in adoption across sectors. While over half of surveyed companies are actively considering or implementing carbon capture, many remain in exploratory stages, and a notable portion has decided against adoption.

Behavioural intentions vary strongly across sectors. High-emission industries, such as waste management and energy, report strong intent to adopt CCS, driven by strategic benefits and alignment with climate goals. Conversely, sectors like ICT, paper, and ceramics demonstrate weaker intentions, often constrained by operational and technological uncertainties.

Positive attitudes toward CCS are frequently associated with active pilot projects, while cautious sectors delay adoption, anticipating greater clarity or policy support post-2030. External pressures, particularly from governments and shareholders, were found to play a crucial role in motivating adoption. Larger companies, benefiting from stronger resources and infrastructure, express higher perceived control and confidence in their ability to implement CCS. Smaller firms, facing limited resources and operational constraints, report lower perceived control, leading to delays or rejection of CCS adoption.

4.1. Adoption Patterns

4.1.1. Major Emitters as Early Adopters of Carbon Capture

Survey results show that 21.4% of companies (9 out of 42) in the Netherlands have implemented carbon capture technologies as of 2024. Adoption is concentrated in high-

emission sectors, including Chemicals (2 companies), Oil & Gas (2), Waste Management (2), Agriculture (2), and Energy (1). Larger emitters, particularly those emitting over 1,000 kilotonnes of CO_2 annually, are significantly overrepresented among adopters (n=5; Figure 5), suggesting that higher emissions create stronger incentives to adopt CCS. These incentives likely stem from regulatory pressures and large emission reduction targets.

Among the companies adopting carbon capture, 67% (6 out of 9) have been using the technology for more than five years, indicating substantial experience in integration and optimization. The remaining three companies are recent adopters, reflecting a growing interest in CCS among firms newer to the technology. While adoption rates remain low overall, large emitters are clearly leading the way, positioning themselves as early adopters of carbon capture technologies in the Dutch industrial sector.

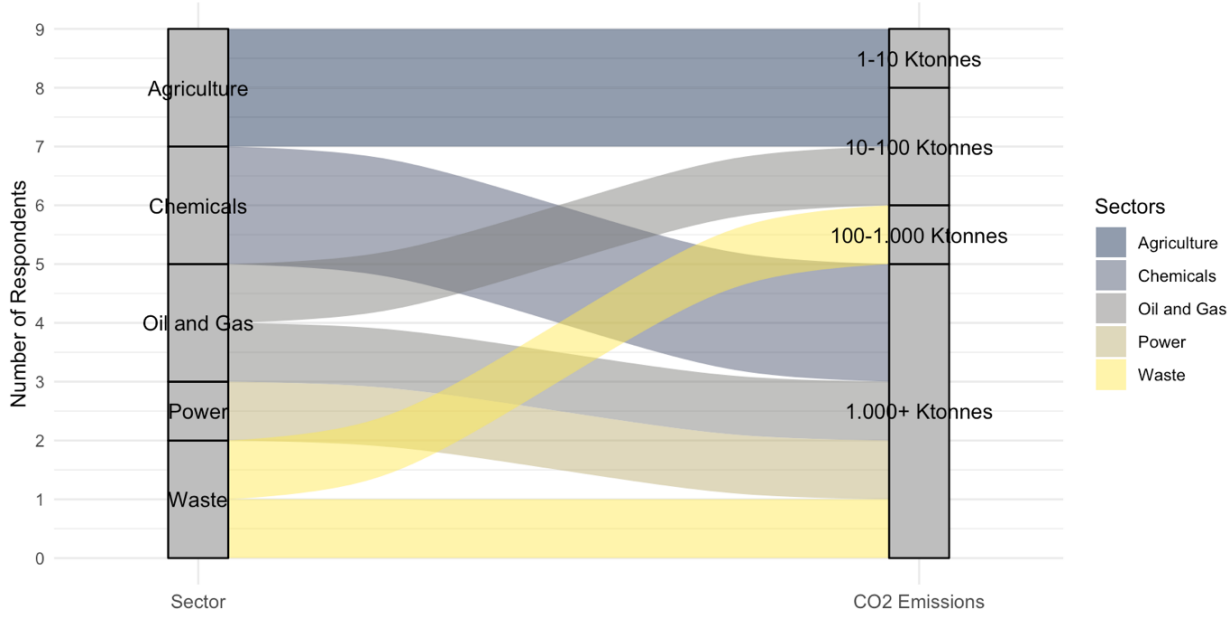

Figure 5. Implementation of Carbon Capture by Respondents
Note. Alluvial diagram showing 9 of 42 respondents adopting carbon capture technologies, categorized by sector (left) and CO_2 emission levels (right). Larger emitters appear more likely to implement these technologies.

4.1.2. Broader Sectoral Trends in Carbon Capture Adoption

A broader analysis of all ETS-regulated companies in the Netherlands reveals that 7.7% (23 out of 297) are actively involved in carbon capture projects, based on subsidy applications (e.g., SDE+ and TKI) and public commitments to CO_2 capture initiatives. While this percentage appears modest, these companies account for nearly half (46.9%) of the Netherlands' total CO_2 emissions in 2023, equivalent to 27.6 megatonnes of CO_2. Most are among the top 25 largest

emitters, underscoring the disproportionate role of major polluters in driving carbon capture adoption.

Sectoral trends show that adoption is most prevalent in Chemicals (5 companies), Energy (5), Waste Management (4), and Oil & Gas (4). Smaller contributions are noted from Industrial Gases (2), Steel (1), Fertilizers (1), and Glass (1), sectors absent from the survey but present in this broader analysis. These findings confirm that adoption remains concentrated among high-emission industries with substantial reduction potential.

This data aligns with survey results, reinforcing the conclusion that carbon capture technologies are primarily adopted by large-scale emitters. Despite limited overall adoption, this small group of major polluters has a significant impact on national emissions reduction efforts.

4.1.3. Saturation Among Major Emitters Signals Limited Growth

The survey's 21.4% adoption rate, the broader 7.7% adoption among ETS-regulated companies, and the 46.9% of national CO_2 emissions attributed to adopters reveal a nuanced picture of carbon capture adoption. While the survey suggests relatively high adoption among respondents, the broader analysis indicates that CCS adoption remains limited across the corporate landscape. However, the concentration of adoption among major emitters highlights their pivotal role in advancing national emissions reduction efforts.

The top 12 largest emitting installations, responsible for 60.5% of Scope 1 CO_2 emissions (equivalent to 35.6 megatonnes of the total NL-ETS of 58.8 Mt in 2023) are predominantly involved in carbon capture projects. This emphasizes the outsized contribution of these facilities to national climate goals. Yet, full CCS implementation is unlikely for all emission sources within these installations, as technical and economic constraints often limit the feasibility of carbon capture. Even partial CCS deployment, however, can significantly reduce emissions due to the sheer scale of these facilities' contributions.

Emerging trends suggest that adoption among major emitters may be nearing saturation. Decisions on whether to expand current projects or plateau will be critical in determining their short- and long-term contributions. Meanwhile, smaller emitters face substantial barriers, which hinder broader CCS implementation. Overcoming these obstacles will be essential for expanding CCS adoption across the Dutch industrial sector, although large emitters may contribute extensively themselves in achieving national climate goals.

4.2. Decision-Making and Reported Behaviour

4.2.1. Companies Show Growing Interest in Carbon Capture

Survey results show that 56.1% of respondents (23 out of 41; 1 nonresponse) are actively considering or implementing carbon capture technologies, indicating growing interest across industries. This percentage exceeds the current adoption rate discussed in the previous chapter, highlighting increasing recognition of carbon capture's potential.

Among respondents, 7.3% (3 companies) are in the confirmation phase, evaluating whether pilot projects meet expectations for full implementation, while 12.2% (5 companies) are in the implementation phase, testing the technology and requiring further evaluation. Another 7.3% (3 companies) are in the decision phase, assessing feasibility, and 4.9% (2 companies) are in the persuasion phase, weighing the pros and cons. Earlier in the process, 24.4% (10 companies) are in the knowledge phase, gathering information and familiarizing themselves with CCS. At the other end of the spectrum, 14.6% (6 companies) have not yet considered carbon capture, potentially reflecting a lack of urgency, while 29.3% (12 companies) have opted against adoption, possibly focusing on alternative emission reduction strategies.

These findings suggest that while many companies remain in the early stages of adoption, a significant proportion is progressing toward implementation, particularly in high-emission industries. This growing momentum underscores the importance of targeted strategies to address early-stage barriers and accelerate adoption across sectors.

4.2.2. High CO_2 Emitters Demonstrate Faster Decision-Making and Adoption

Survey results (Figure 6) show that companies emitting over 1,000 kilotonnes of CO_2 annually are more advanced in their decision-making processes, with many actively implementing or evaluating pilot projects. Companies emitting between 100 and 1,000 Kt follow closely, while smaller emitters often progress more slowly and remain hesitant to adopt carbon capture technologies.

The waste management and chemical sectors are at the forefront, with many respondents actively implementing or testing carbon capture, aligning with earlier findings on adoption rates. Sectors such as energy, agriculture, and oil & gas also demonstrate advanced decision-making stages, though many companies are still finalizing plans. In the oil & gas sector, a mixed

picture emerges. While some refineries are moving forward with carbon capture, others have delayed their plans, while transporters and platform operators in this sector are often not situated to apply CCS, contributing to this variation.

In contrast, industries such as ceramics, food processing, paper, and smaller emitters like ICT and asphalt remain in earlier exploratory phases. These companies frequently prioritize alternative sustainability strategies or have not seriously considered CCS adoption, highlighting a clear divide between high-emission industries under greater pressure to adopt CCS and smaller emitters, where adoption is less urgent.

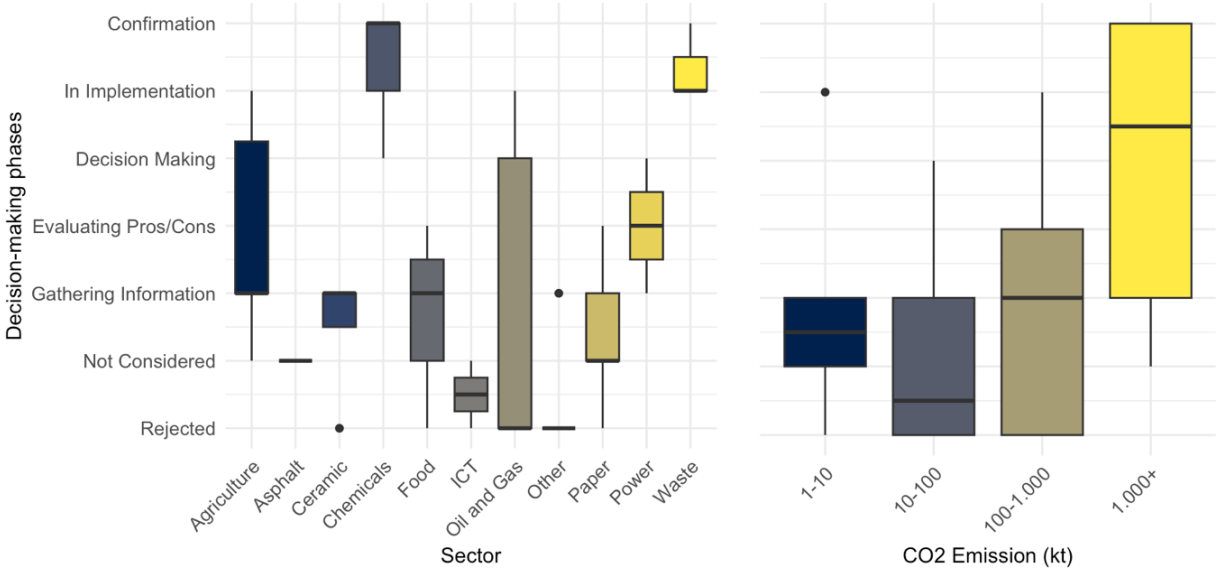

Figure 6. Decision-Making Stages for Carbon Capture Adoption

Note. The left panel illustrates decision-making stages by sector, with waste and chemical companies leading, while ceramics, food, and paper remain in earlier stages. Over a quarter of companies (n = 12) have rejected CCS, particularly in ICT and 'other' sectors, while one-sixth (n = 6) have not considered it, notably in asphalt. The right panel organizes decision-making stages by CO_2 emissions, showing companies emitting over 1,000 kilotonnes are furthest along.

4.3. Intentions to Adopt Carbon Capture

This section examines companies' intentions to implement carbon capture technologies, a key predictor of adoption as outlined in the Theory of Planned Behaviour (Ajzen, 1991). Intention, influenced by attitudes, external pressures, and perceived control, provides valuable insights into the likelihood of future adoption. Survey results indicate that intentions generally align with reported behaviour, though the average intention score across sectors is 2.2 out of 5, indicating moderate willingness to adopt. Logically, intention scores are lower than those of

their underlying factors, indicating that stacking barriers like reduced attitudes and perceived control reduce overall intent (Figure 7). This dynamic highlight the importance of addressing these inhibiting factors to strengthen adoption intentions.

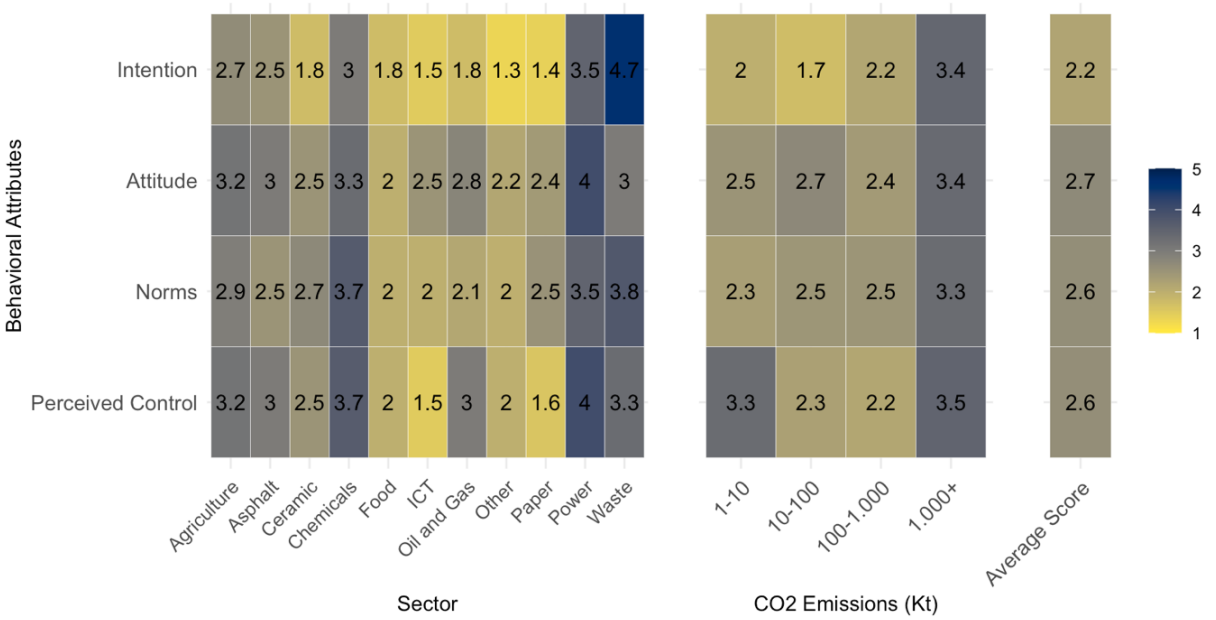

Figure 7. Perceptions of Behavioural Intention, Attitude, Norms, and Perceived Control
Note. Heatmap showing average scores (1–5) for behavioural intention and its factors (attitude, norms, perceived control) by sector (left) and CO_2 emissions (centre). Intention scores lower than individual factors, except in sectors emitting over 1,000 kilotonnes CO_2 and waste management. Positive intentions are also noted in agriculture, asphalt, chemicals, and power sectors.

4.3.1. Strong Intentions in Waste Management and Energy

Survey results highlight that the waste management (4.7) and energy (3.5) sectors exhibit the strongest intentions to adopt carbon capture technologies. Companies in these sectors often have concrete plans or are already engaged in pilot projects. In waste management, carbon capture is seen as essential for reducing emissions, driven by regulatory pressures and societal expectations. One respondent noted receiving SDE subsidies to expand a facility following successful pilot tests, demonstrating how external financial support strengthens adoption intentions (personal communication, waste sector, 2024).

In the energy sector, strong intentions stem similarly from the need for regulatory compliance and the lack of viable alternatives, but also from a potential business case. Companies are actively exploring innovative applications like Bio-Energy Carbon Capture and Storage (BECCS) to achieve net-negative emissions, and trade carbon credits on the voluntary market, although these efforts remain in early stages (personal communication, power sector, 2024).

Other high-emission industries, such as steel, cement, and fertilizers, are also identified as strong candidates for carbon capture due to their process-related emissions. For example, a respondent explained, “The process of making cement inherently produces CO_2, which is difficult to mitigate through other methods” (personal communication, oil and gas sector, 2024b). In these sectors, carbon capture is regarded as a practical and necessary long-term solution to address unavoidable emissions.

4.3.2. Mixed Intentions in Oil & Gas, Chemicals, Agriculture, Asphalt and Glass

The oil and gas sector exhibits mixed intentions for carbon capture adoption. While survey results show relatively low intent (1.75), interviews reveal a more nuanced picture, particularly among larger emitters. Companies involved in long-term projects, such as geological CO_2 storage, are actively participating in initiatives like the Porthos project, where oil and gas firms collaborate to scale carbon capture. One respondent described carbon capture as a cost-effective tool to “buy time by storing large amounts of CO_2 relatively cheaply,” while supporting broader climate goals (personal communication, oil and gas sector, 2024a). However, some refiners appear less advanced in their efforts, contributing to the sector’s overall low survey score. This reflects disparities in urgency and resource availability within the sector.

The chemical sector reports variable intentions, scoring moderately at 3.0. Some companies express strong interest in carbon capture, often driven by practical experience with pilot installations, but concerns about scalability and long-term costs remain. For others, carbon capture is seen as a temporary solution until more sustainable alternatives, like electrification, become feasible. One respondent noted: “We see CO_2 capture as temporary and will stop once electric furnaces are installed” (personal communication, chemical sector, 2024b). These differences highlight the sector’s complex configurations, diverse decarbonization solutions (including hydrogen), and competition to innovate while addressing emission reduction goals.

Intentions in agriculture (2.67), asphalt (2.5), and glass (1.75) sectors are moderate. In agriculture, carbon capture was viewed as a longer-term option, particularly in horticulture and dairy farming, but no interviews were conducted to provide deeper insights. In the asphalt sector, high costs deter adoption despite technical compatibility. A respondent explained: “It hasn’t really been looked at yet due to the significant investment required” (personal communication, asphalt sector, 2024). Similarly, the glass industry recognizes potential benefits but faces challenges in scaling the technology for smaller kilns. One respondent noted

receiving past subsidies for carbon capture, signalling interest in the future adoption once the technology becomes more cost-effective (personal communication, glass sector, 2024). Generally, these sectors currently lack immediate plans for widespread adoption but remain open to carbon capture as its cost-effectiveness and technical viability improve.

4.3.3. Low Intentions Among ICT, Paper, Ceramics, and Food

Sectors such as ICT (1.5), paper (1.4), ceramics (1.8), and food (1.8) report the lowest intentions to adopt carbon capture technologies. These industries often perceive CCS as too costly or unsuitable due to small-scale operations and the availability of alternative solutions. For instance, a respondent from the food sector explained: “We’re focusing on energy efficiency and electrification; carbon capture isn’t viable for our operations” (personal communication, food sector, 2024). Similarly, a representative from the building sector noted: “We are not working on carbon capture, nor do we intend to” (personal communication, building sector, 2024a). In the ICT sector, data centres prioritize simpler alternatives, such as HVO fuels, to meet sustainability targets (personal communication, ICT, 2024). This pattern reflects a broader preference among these industries for alternative strategies over CCS, some viewing it as a last-resort option. However, companies acknowledge that re-evaluation may occur if alternatives prove insufficient or regulatory requirements tighten, potentially increasing future interest in carbon capture.

4.4. Attitudes Toward Adoption

This section examines company attitudes toward carbon capture technology, defined as their evaluation of adoption based on perceived benefits and drawbacks (Ajzen, 1991). Survey results (n = 42) indicate an average attitude score of 2.7 out of 5, reflecting a moderate to cautious stance. Interviews provide deeper insights into this ambivalence. Positive attitudes focus on carbon capture’s role in achieving net-zero emissions and its contributions to sustainability and emission reductions. Conversely, negative attitudes arise from financial constraints, technical complexities, and concerns about the technology’s long-term feasibility. For many, carbon capture is seen as a necessary tool, but one often regarded as temporary or secondary compared to more sustainable alternatives.

4.4.1. Carbon Capture Often Seen as a Temporary or Secondary Solution

Many companies view carbon capture as a bridging or secondary solution, particularly when alternatives like electrification or hydrogen are not viable. As one respondent from the chemical sector noted, “You have to look for the easiest and most efficient way to reduce emissions. Carbon capture only comes into play when electrification isn’t enough” (personal communication, chemical sector, 2024b). This sentiment is echoed across sectors, with some organizations believing alternatives alone will suffice (personal communication, building materials sector, 2024ab; ICT sector, 2024a).

Smaller emitters, particularly those releasing less than 100 kilotonnes of CO_2 annually, often view carbon capture as a temporary measure until more sustainable solutions become accessible. A respondent from the oil and gas sector described it as part of their roadmap but emphasized a parallel focus on technologies that directly avoid emissions for other industries (personal communication, oil and gas sector, 2024a). The lack of immediate cost savings further contributes to the perception of carbon capture as a secondary option.

4.4.2. Financial and Technical Barriers Affect Attitudes

Financial and technical challenges strongly influence company attitudes toward carbon capture. Firms anticipating long-term economic benefits, such as reduced operational costs, tend to have more positive views. As one energy sector respondent noted, “While the initial costs are high, the operational expenses can become advantageous for larger installations” (personal communication, power sector, 2024b). In contrast, industries like asphalt and paper express caution due to perceived financial infeasibility and narrow commercial margins, which limit investment capacity (personal communication, asphalt sector, 2024a).

Technical challenges further discourage adoption, particularly for smaller installations or facilities less suited to carbon capture. Respondents from the building materials and glass sectors emphasized that the technology is primarily designed for large emission sites, making integration for smaller facilities impractical (personal communication, building materials sector, 2024a; glass sector, 2024a). These financial and technical barriers explain the cautious attitudes of many companies, though some foresee these challenges diminishing as conditions improve. Chapter 5 provides a detailed discussion of financial and technical obstacles.

4.4.3. Optimism About Carbon Capture in Emission Reduction

Despite financial and technical challenges, many companies remain optimistic about carbon capture's potential to reduce emissions, especially as economic and technological conditions evolve. Survey results indicate favourable attitudes in sectors like energy, chemicals, waste management, and oil and gas, with scores exceeding 2.5. Large emitters, particularly those releasing over 1,000 kilotonnes of CO_2 annually, exhibit the highest attitudes (3.4), driven by limited alternatives and a stronger business case for adoption (personal communication, oil and gas sector, 2024c; power sector, 2024b; waste management sector, 2024).

A respondent involved in a carbon capture and storage hub noted that increasing investments signal growing market confidence: "It's no longer just a good idea on paper" (personal communication, oil and gas sector, 2024c). Even large emitters not currently investing are closely monitoring advancements, viewing carbon capture as viable under improved conditions (personal communication, chemical sector, 2024b). This optimism underscores the long-term potential companies attribute to carbon capture, shaping their intention to adopt.

4.5. Subjective Norms and External Pressures

This section explores how subjective norms, defined as social pressures from stakeholders, influence companies' decisions to adopt carbon capture technology (Ajzen, 1991). These norms shape organizational intentions by establishing what is perceived as socially acceptable. Survey results indicate a moderate average influence score of 2.6 out of 5 (Figure 7), suggesting that while external pressures are present, internal decision-making plays a more prominent role.

External pressures are highest in sectors like waste management (3.8), chemicals (3.7), and power generation (3.5). Companies emitting over 1,000 kilotonnes of CO_2 annually report elevated external pressure, averaging 3.3.

Governments and shareholders emerge as the most influential external stakeholders, driving adoption decisions through regulatory mandates and stock holdings. By contrast, customers, industry peers, and societal expectations exert less influence. Internally, board members hold the greatest influence, directly shaping strategic decisions on carbon capture.

4.5.1. Governments and Shareholders as Key External Influencers

Governments and shareholders emerge as the most influential external stakeholders driving carbon capture adoption. Governments were identified as highly influential by 26% of respondents (Figure 8), primarily through climate regulations, emission caps, and subsidies. A respondent from the oil and gas sector remarked, "Although carbon capture isn't financially attractive now, stricter regulations will likely force us to adopt it" (personal communication, oil and gas sector, 2024a). International agreements, such as the Paris Agreement, further intensify this pressure by requiring national emission reductions (personal communication, power sector, 2024b).

Shareholders also exert substantial influence, with 24% of respondents citing them as key drivers. Increasingly, they push companies to align with sustainability goals while maintaining profitability. One respondent noted, "Shareholders want sustainability but also financial returns," highlighting the dual pressure to balance environmental responsibility with market competitiveness (personal communication, glass sector, 2024).

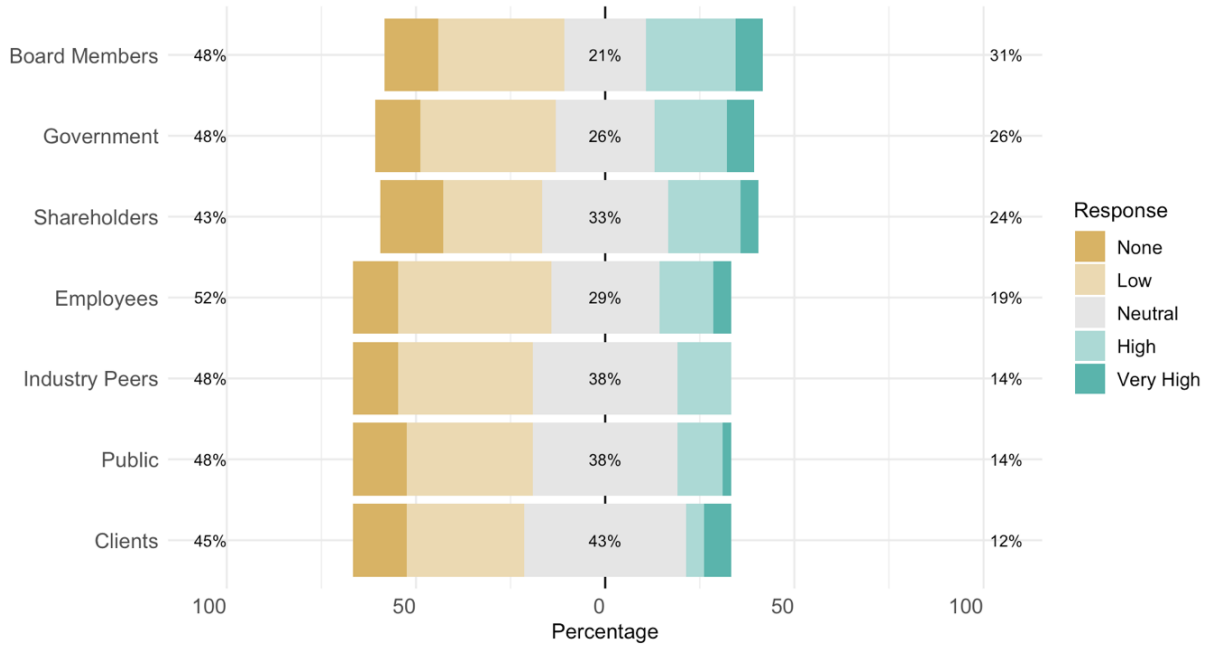

Figure 8. Stakeholder Influence on Carbon Capture Technology Adoption
Note. Diverging stacked bar chart showing stakeholder influence (low to very high) on carbon capture decisions. Board members have the greatest impact, followed by governments and shareholders. Employees, peers and society show moderate influence, while customers have the least impact, although the highest neutral score. Based on responses from 42 participants using a Likert scale.

Surprisingly, customers exert limited influence, with only 12% of respondents identifying them as key drivers, although having a high neutral score, which most likely will still be considered by companies. However, in sectors like waste management and food production, customer expectations play a more prominent role, reflecting sustainability as a competitive factor (personal communication, food sector, 2024; waste management sector, 2024). Industry peers and broader societal expectations also exert moderate influence (14%), often shaping decisions through competitive pressure and reputational considerations.

Societal pressures, including those from NGOs, public organizations, and citizens, indirectly influence adoption by shaping public opinion on corporate sustainability. While only 14% of respondents view this as significant, aligning with public sentiment can enhance a company's reputation and justify carbon capture investments. As one respondent observed, "If you look at Paris, we must try to stay under 1.5 degrees Celsius. Carbon capture is a way to buy time while we make the transition" (personal communication, oil and gas sector, 2024a).

4.5.2. Internal Norms Outweigh External Influence on Adoption

Internal norms, particularly the influence of board members, are the strongest drivers of carbon capture adoption decisions. Survey results indicate that 31% of respondents consider board members to have a high or very high level of influence, surpassing the impact of external stakeholders. As strategic leaders, board members make final decisions, often weighing profitability against ethical sustainability goals. One respondent observed, "Board members shape the strategic direction, including decisions on innovations like carbon capture" (personal communication, oil and gas sector, 2024a).

Employees also contribute to internal norms, with 19% of respondents citing their workforce as a significant influence. Sustainability-conscious employees can apply pressure through formal mechanisms like works councils or recruitment challenges. A respondent from the chemical sector noted, "Staff want to work for companies that at least have a sustainability plan" (personal communication, chemical sector, 2024b). This internal pressure complements external norms, collectively encouraging alignment with sustainable practices.

4.6. Perceived Control Over Implementation

Perceived control over carbon capture adoption reflects companies' assessment of the ease or difficulty of implementation (Ajzen, 1991). Survey results indicate a moderate average score

of 2.6 out of 5, highlighting significant perceived barriers. High costs, infrastructure limitations, regulatory uncertainty, and public acceptance challenges are the primary factors undermining control. Despite these obstacles, advancements in technology, expanded infrastructure, and favourable market conditions have the potential to improve feasibility perceptions and support broader adoption.

4.6.1. High Costs and Financial Risks Limit Perceived Control

Financial constraints pose the most significant barrier to carbon capture adoption, particularly for smaller companies. Respondents highlighted that high upfront costs and reliance on unpredictable subsidies undermine perceived control (personal communication, power sector, 2024a; building materials sector, 2024a). While subsidies can enhance feasibility, market uncertainty, such as fluctuating energy prices and unclear policies on negative emissions, deters short-term investment. Some companies plan to postpone adoption until after 2030, anticipating more stable financing mechanisms (personal communication, oil and gas sector, 2024a). These financial uncertainties compound the challenges of carbon capture adoption, as further discussed in Chapter 5.

4.6.2. Limited CO_2 Infrastructure as a Major Constraint

Access to CO_2 infrastructure remains a significant bottleneck for carbon capture adoption. Companies located far from hubs like the Port of Rotterdam face logistical and financial barriers, as reliance on pipelines or transport systems is often economically unfeasible (personal communication, glass sector, 2024). While large emitters near CCS hubs benefit from shared infrastructure, smaller companies and those outside the CO_2 backbone network struggle to participate, limiting their perceived control (personal communication, oil and gas sector, 2024a).

The Netherlands' prohibition of onshore CO_2 storage, unlike policies in the US and Canada, exacerbates these challenges by forcing reliance on offshore solutions, which add complexity and uncertainty (personal communication, chemical sector, 2024b). Planned storage hubs like Aramis may ease capacity constraints in the future, but their development remains uncertain. This interdependence between capture and storage creates a cycle of uncertainty: storage projects require guaranteed CO_2 supply, while capture projects depend on assured storage access (personal communication, oil and gas sector, 2024a). Additionally, the limited market

for CO_2 utilization offers little incentive for adoption, making storage the primary option for emissions processing and further increasing reliance on infrastructure.

4.6.3. Energy Grid Congestion Hinders Carbon Capture

Grid congestion poses a significant challenge in the Netherlands, where electricity infrastructure struggles to support energy-intensive processes like carbon capture. Companies often face delays while waiting for grid capacity expansions, limiting their control over project timelines. As one respondent explained, “We are in the queue, highly dependent on the capacity we will eventually receive” (personal communication, building materials sector, 2024). This uncertainty discourages adoption, particularly in regions already experiencing congestion, and also hinders the viability of alternatives such as electrification (personal communication, food sector, 2024).

4.6.4. Public Support as a Factor in Perceived Control

Public acceptance significantly influences perceived control over carbon capture adoption. While societal pressure drives demand for CO_2 reductions, companies risk reputational harm if carbon capture is viewed as inadequate or as prolonging fossil fuel reliance. One respondent noted concerns that societal resistance to carbon capture could shift focus to alternatives perceived as more acceptable (personal communication, oil and gas sector, 2024). Similarly, the use of biomass faces growing scrutiny, with a respondent stating, “We believe that biomass burning is no longer socially accepted” (personal communication, power sector, 2024a). Political support, closely tied to societal acceptance, further shapes perceived control. Without public backing, companies feel constrained in their decarbonization options, limiting their ability to adopt technologies like carbon capture.

Chapter Conclusions

This chapter examined the adoption of carbon capture technologies, revealing a divide between large and small emitters. Large emitters, particularly those exceeding 1,000 kilotonnes of CO_2 annually, lead adoption efforts by integrating carbon capture into long-term emission reduction strategies, thereby potentially contributing extensively to national emission targets. In contrast, smaller emitters exhibit lower adoption rates, posing a challenge to broader industry-wide implementation. While over half of surveyed companies are considering or implementing carbon capture, many others remain in early decision-making phases. Larger firms tend to be

more advanced, while smaller companies and those in less relevant sectors are still exploring options or have opted against adoption.

Behavioural intentions, influenced by attitudes, external pressures, and perceived control, emerged as strong predictors of adoption. Sectors with positive attitudes, such as waste management, energy, chemicals, and horticulture, showed higher adoption intentions. Conversely, smaller firms with limited perceived control over financial and technical feasibility, particularly in niche industrial sectors, reported weaker intentions to adopt.

5. Innovation Attributes Related to Carbon Capture Adoption

This chapter explores how the innovation attributes, like relative advantage, compatibility, complexity, trialability, and observability, influence carbon capture adoption within Dutch industrial sectors. These attributes shape decisions by highlighting perceived benefits, alignment with organizational goals, and implementation challenges. Sectoral differences, barriers, and opportunities are examined for each attribute.

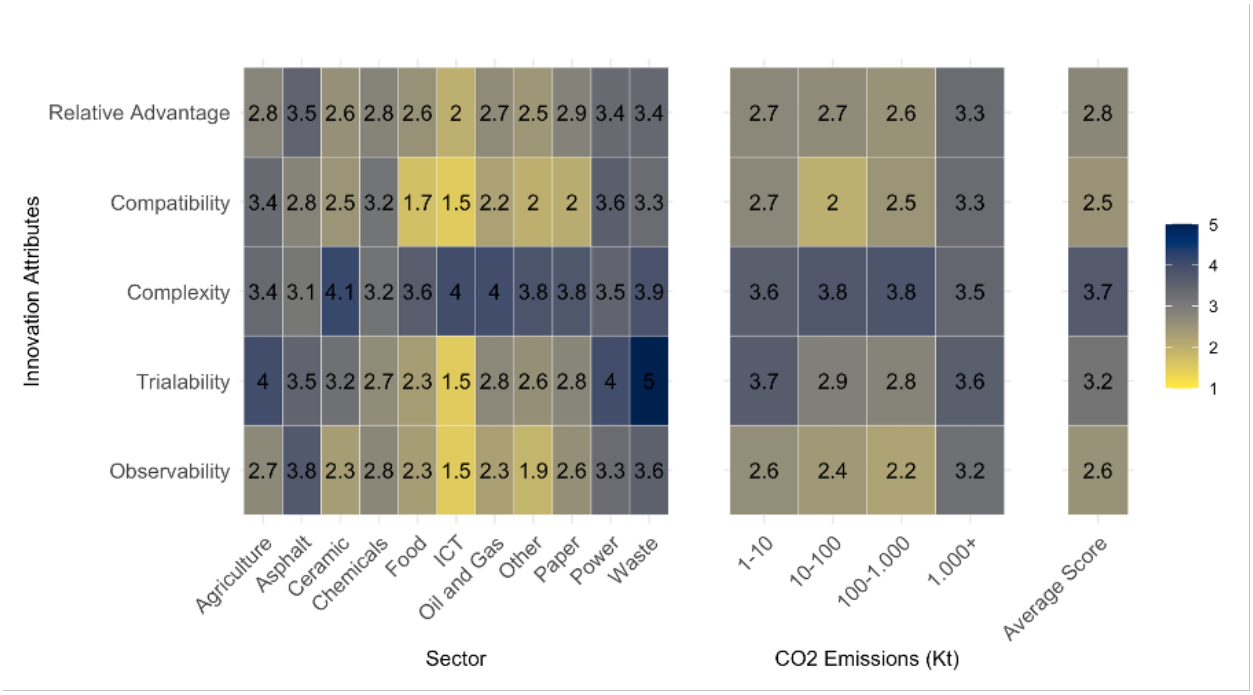

Figure 9. Heatmap of Innovation Attributes

Note. Heatmap showing average scores (1–5) for innovation attributes by sector (left), CO_2 emission category (middle), and overall averages (right), based on data from 42 respondents. Higher scores indicate positive values (e.g., relative advantage, compatibility), except for complexity, where higher scores represent barriers. High-emission sectors like energy, waste, and chemicals view relative advantage and compatibility as key drivers, with complexity as the consistent main barrier.

Survey results reveal significant variation in how sectors perceive these attributes. Relative advantage, scoring 2.8 out of 5, reflects moderate recognition of carbon capture's benefits, such as reputational gains and competitiveness. However, concerns about high costs and uncertain effectiveness hinder adoption. Compatibility, rated 2.5, underscores alignment challenges, particularly for smaller emitters, while larger emitters view carbon capture as more strategically compatible with their operations. Complexity, with a score of 3.8, emerges as the greatest barrier, driven by technical, financial, and regulatory hurdles that affect all sectors. Trialability, scoring 3.2, indicates a moderate possibility for pilot projects in reducing uncertainty and building confidence, particularly for resource-rich sectors. Observability, rated 2.6, shows that while environmental benefits are visible, financial and operational gains remain less tangible,

limiting broader adoption. Figure 9 summarizes these scores across sectors and emission categories, serving as a reference throughout the chapter to illustrate variations and trends.

5.1. Relative Advantage

Relative advantage refers to the perceived benefits of carbon capture compared to traditional emissions practices and alternative decarbonization strategies. As Rogers (1962) notes, stronger perceived benefits often accelerate adoption. This section explores how companies perceive the relative advantage of carbon capture technologies, focusing on sectoral and emission-level variations.

Survey results indicate a moderate average score reflecting mixed evaluations across four dimensions (Figure 10): reputation enhancement, competitive advantage, effectiveness compared to alternatives, and financial impact. Larger emitters, particularly those exceeding 1,000 kilotonnes CO_2 annually in sectors like waste management, power generation, and oil and gas, perceive greater relative advantage.

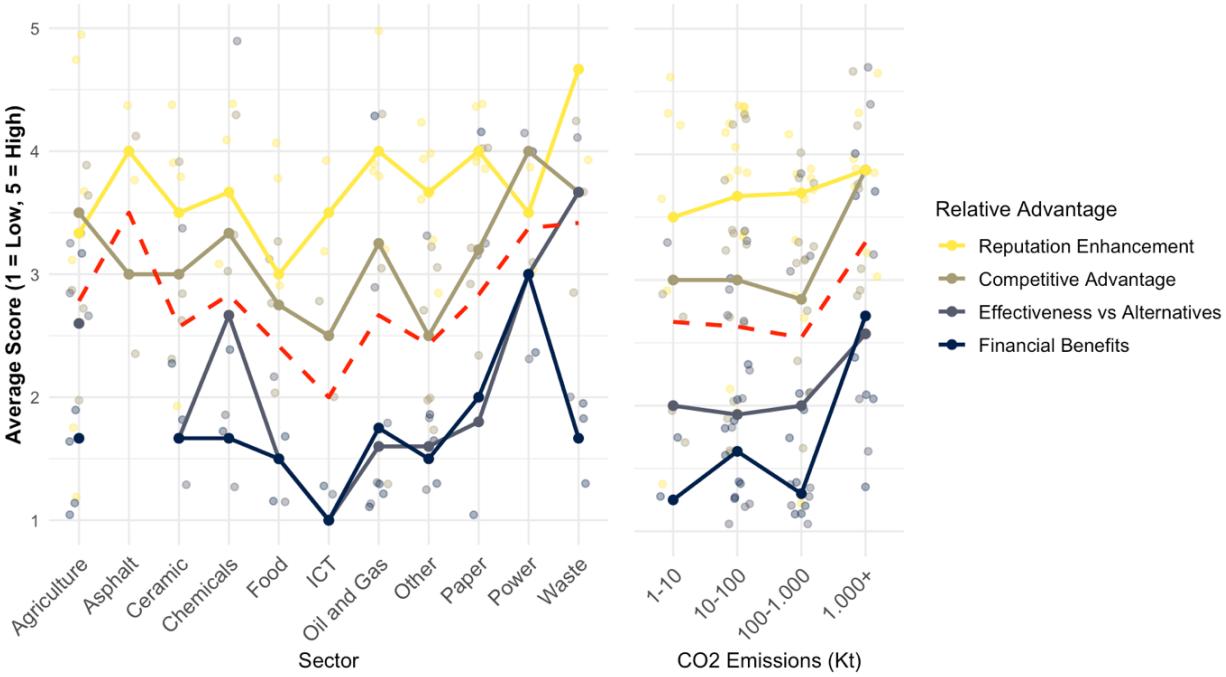

Figure 10. Perceived Relative Advantage of Carbon Capture
Note. This figure shows relative advantage scores (1–5) across sectors (left) and CO_2 emission groups (right), based on 42 responses. Sub-attributes include Reputational Benefits, Competitive Advantage, Effectiveness Compared to Alternatives, and Financial Viability. Jittered points represent individual responses, solid lines show category averages, and the red dashed line marks the overall average. Findings indicate moderate perceived

advantage, with strong reputational benefits across all sectors and higher scores for large emitters (>1,000 kilotonnes) driven by financial benefits.

Reputation enhancement scored highest at 3.7, highlighting public image and environmental responsibility as key motivators. Competitive advantage, rated 3.1, is significant in sectors where environmental innovation offers a market edge. However, effectiveness compared to alternatives scored lower at 2.1, while financial impact was rated the lowest at 1.7, underscoring concerns about high costs and uncertain returns. Larger emitters reported fewer financial barriers compared to smaller companies.

5.1.1 Carbon Capture Enhances Corporate Reputation

Carbon capture technology is widely recognized for its potential to enhance corporate reputation, achieving an average score of 3.7 out of 5 in the survey (Figure 10), with 72% of respondents highlighting its positive impact. By reducing CO_2 emissions, carbon capture aligns with growing stakeholder expectations for sustainability, demonstrating environmental responsibility and innovation. Adoption strengthens evaluations by international assessors and positions companies as pioneers in the low-carbon economy (personal communications, chemical sector, 2024a; oil and gas sector, 2024c). However, the reputational impact varies by industry, community perceptions, and the availability of alternative decarbonization strategies.

Carbon capture enhances reputation on both global and local levels. Globally, it establishes companies as forward-thinking sustainability leaders. Locally, small-scale projects improve public and political perceptions. For example, a waste management respondent stated, “We see ourselves as a public company with a political mandate to make waste processing as green as possible,” emphasizing carbon capture’s alignment with societal and political expectations (personal communication, waste management sector, 2024). Similarly, companies in chemicals and glass report reputational gains due to meeting consumer demand for sustainability (personal communications, chemical sector, 2024b; glass sector, 2024). However, in cost-sensitive industries like asphalt, carbon capture’s reputational appeal is often limited (personal communication, asphalt sector, 2024a).

Some respondents expressed reservations about carbon capture’s societal alignment. Social organizations and NGOs often advocate for technologies like electrification or hydrogen combustion, viewing these as more aligned with long-term environmental goals (personal communications, food sector, 2024; building materials sector, 2024a). This perception positions

carbon capture as a transitional measure rather than a definitive solution, tempering its reputational benefits.

While carbon capture significantly enhances corporate reputation by visibly contributing to environmental goals, companies must balance its advantages against evolving stakeholder expectations and the growing preference for fossil-free solutions.

5.1.2 Early Adoption Provides Advantages and Challenges

Carbon capture offers strategic benefits for sectors such as horticulture, chemicals, oil and gas, glass, power generation, and waste management. Early adoption helps companies comply with stringent environmental regulations, improve market positioning, and explore new revenue streams. Survey results indicate a moderate appeal, with an average score of 3.1 out of 5 (Figure 10), and significant variation across sectors.

Regulatory compliance is a key driver. Early adopters align with the EU Emissions Trading System and national carbon taxes, avoiding penalties and exposure to volatile carbon prices. A respondent from the energy sector explained, “Carbon capture allows us to proactively meet future regulations and CO_2 reduction requirements, giving us an edge over less-prepared competitors” (personal communication, power sector, 2024b).

Early adoption also enhances customer and investor appeal. Companies working with sustainability-focused partners gain a competitive edge. For instance, a glass sector respondent noted, “By implementing carbon capture, we help customers achieve their CO_2 reduction goals, strengthening our position as a preferred supplier and creating new business opportunities” (personal communication, glass sector, 2024a). Additionally, sustainability leadership attracts talent, as environmentally conscious employees seek responsible employers (personal communication, chemical sector, 2024b).

Revenue opportunities from carbon credit trading and biogenic CO_2 utilization appeal to early adopters, especially under the ETS or voluntary markets. However, financial viability depends on stable markets and consistent regulatory support. Smaller emitters, such as those in the food sector, view alternatives like electrification or biogas as more feasible due to carbon capture’s high costs (personal communication, food sector, 2024). Even larger emitters remain cautious, considering hydrogen and electrification as potentially more cost-effective future solutions (personal communications, building materials sector, 2024b; waste management sector, 2024).

Market dynamics create additional complexity. Intense competition may pressure companies to adopt underdeveloped technologies, increasing risks of technical and financial setbacks (personal communication, oil and gas sector, 2024b). Dependence on government subsidies exacerbates uncertainty, as reduced public support in the future may threaten project viability on the long-term (personal communication, building materials sector, 2024a). Carbon capture certification also competes with alternative decarbonization strategies, diminishing its distinctiveness as a competitive advantage.

Fragmented industry approaches and international policy disparities limit economies of scale and complicate adoption. Collaborative frameworks are helpful to address these challenges (personal communications, waste management sector, 2024; glass sector, 2024a). Additionally, customers' unwillingness to pay premiums for sustainable products reduces investment capacity, for example low margin sectors like asphalt (personal communication, asphalt sector, 2024a).

While carbon capture offers clear competitive advantages, it also presents significant challenges. Companies must balance these benefits against financial and technical risks. Strategic planning, robust regulatory frameworks, and collaboration seems essential to leverage the technology effectively and navigate its complexities.

5.1.3 Carbon Capture Viewed as End-of-Pipeline Solution Compared with Alternatives

Industries are increasingly exploring decarbonization strategies like electrification, hydrogen, biofuels, and energy efficiency alongside carbon capture. Survey results give carbon capture a relatively low score of 2.1 out of 5 compared to these alternatives (Figure 10), due to perceptions of high costs, complexity, and uncertain long-term viability. While essential for high-emission sectors, many companies prioritize alternatives seen as more cost-effective and flexible. Larger emitters (1,000+ kilotonnes CO_2 annually) regard carbon capture as critical, while smaller emitters favour less resource-intensive approaches (personal communications, building materials sector, 2024b; oil and gas sector, 2024a).

Carbon capture is often seen as a temporary or fallback solution, possibly deployed while industries adopt other strategies. This reflects the limited scalability of alternatives, slowing progress in reducing emissions (personal communications, chemical sector, 2024b; waste management sector, 2024). This section evaluates how industries weigh various decarbonization strategies and the role carbon capture plays in sustainability goals.

Energy-saving measures are often the first step, offering cost-effective solutions without major infrastructure investments. Process optimization, insulation upgrades, and energy-efficient machinery are common examples. For instance, building materials companies have reduced emissions through product redesign and modernization (personal communication, building materials sector, 2024b). However, these measures are finite, and further reductions often require more complex solutions like carbon capture (personal communication, chemical sector, 2024a).

Electrification is seen as practical, mostly for smaller emitters. Technologies like electric ovens, heat pumps, but also chemical crackers, drastically reduce CO_2 emissions. For example, a building materials company fully electrified its operations, eliminating the need for carbon capture (personal communication, building materials sector, 2024a). However, electrification faces challenges in the Netherlands, such as high upfront costs and grid congestion, with around 10,000 companies awaiting grid capacity upgrades (personal communication, chemical sector, 2024b).

Hydrogen offers potential for decarbonizing energy-intensive industries like refineries and chemical plants by replacing fossil fuels for combustion processes. Some companies view hydrogen as a viable alternative to carbon capture, particularly for multiple emission sources (personal communication, oil and gas sector, 2024b). However, high production costs and underdeveloped infrastructure make hydrogen a long-term rather than immediate solution (personal communications, asphalt sector, 2024a; oil and gas sector, 2024b).

Biofuels and biogas are promising renewable options, especially when paired with carbon capture. Capturing biogenic CO_2 can achieve carbon-negative outcomes and actively remove CO_2 from the atmosphere (personal communication, food sector, 2024). Integrating steam from nearby facilities, such as waste incinerators, also improves energy efficiency. However, competition for renewable resources and limited availability constrain short-term scalability.

For large emitters, like waste management, steel, energy, and cement, carbon capture is often the only viable option for significant emissions reductions. A waste management respondent stated, “We are typically an industry where there is no other way to go green” (personal communication, waste management sector, 2024). Similarly, oil and gas companies reliant on combustion processes often see carbon capture as indispensable and as opportunity to sell

technology (personal communication, oil and gas sector, 2024c). These industries benefit from integrating carbon capture into existing infrastructure, minimizing redesign costs.

In contrast, smaller emitters often favour alternatives like electrification and hydrogen due to lower costs and reduced infrastructure demands. A respondent from the chemical sector noted, “We prefer fossil-free solutions, yet we are dependent on the availability of alternatives” (personal communication, chemical sector, 2024b). Choosing a decarbonization strategy requires careful evaluation, as substantial investments lock industries into long-term commitments. Companies must balance current feasibility with future innovation to ensure their strategies align with immediate needs and long-term sustainability goals.

5.1.4 Financial Costs and Limited Benefits are Key Barriers in Adoption Decisions

The high costs of carbon capture technologies significantly hinder adoption, with survey results revealing a low financial benefits score of 1.7 out of 5 (Figure 10). While large emitters (scoring 2.7) benefit from economies of scale, smaller companies face major barriers due to limited resources and tight profit margins, making financial viability a critical factor in decision-making.

Carbon capture requires substantial capital (CAPEX) and operational (OPEX) investments. Installation costs can reach from tens to hundreds of millions of euros, compounded by energy-intensive processes and CO_2 transport and storage expenses (personal communications, oil and gas sector, 2024c; waste management sector, 2024). Smaller emitters, in particular, struggle to justify these investments. As one asphalt sector respondent stated, "There is very little room to make large financial investments in things we cannot guarantee will pay off" (personal communication, asphalt sector, 2024a). Similarly, a food industry representative noted, "Without substantial subsidies, the costs of carbon capture cannot be justified" (personal communication, food sector, 2024).

Many companies prioritize alternatives like electrification, seen as more predictable in terms of costs. A chemical sector respondent explained, "Electrification also comes with high costs, but we have a better understanding of its financial impact, making it preferable over carbon capture" (personal communication, chemical sector, 2024a). Financial constraints also limit the scope for pilot projects, which are essential for scaling carbon capture technologies. One power sector respondent described the difficulty of justifying pilot projects without immediate returns, slowing innovation and adoption (personal communication, power sector, 2024b).

Despite these challenges, large emitters see long-term financial benefits. These include reduced carbon credit costs, avoided fines, and revenue from negative emission credits. Early adopters also mitigate exposure to fluctuating carbon prices by accumulating credits that can be retained or sold as prices rise. As one oil and gas sector respondent noted, "By implementing carbon capture, we can achieve significant savings on emission rights and fines" (personal communication, oil and gas sector, 2024c).

While future revenue from negative emission credits enhances carbon capture's financial potential, this market remains underdeveloped and poorly regulated (personal communications, power sector, 2024b; waste management sector, 2024). Addressing these uncertainties through stable market conditions and supportive policies may be essential to improving this financial feasibility and encouraging broader adoption.

5.2. Compatibility with Corporate Frameworks

Compatibility measures how well carbon capture aligns with an organization's values, processes, and needs. Technologies that integrate seamlessly into existing operations are adopted faster, while those requiring significant adjustments face delays (Rogers, 2003).

Carbon capture compatibility varies widely across sectors. Waste management and energy report higher alignment due to established CO_2 infrastructure, while building materials and food industries encounter greater challenges. The overall compatibility score is a moderate 2.5 out of 5 (Figure 9), driven by differences in strategic fit, operational integration, and carbon management goals.

Operational integration poses the greatest challenge, scoring lowest across sectors. Industries with robust infrastructure, face fewer disruptions, while others struggle with misaligned workflows and infrastructure deficits (Figure 11). These variations and their impact on adoption will be explored in the following sections.

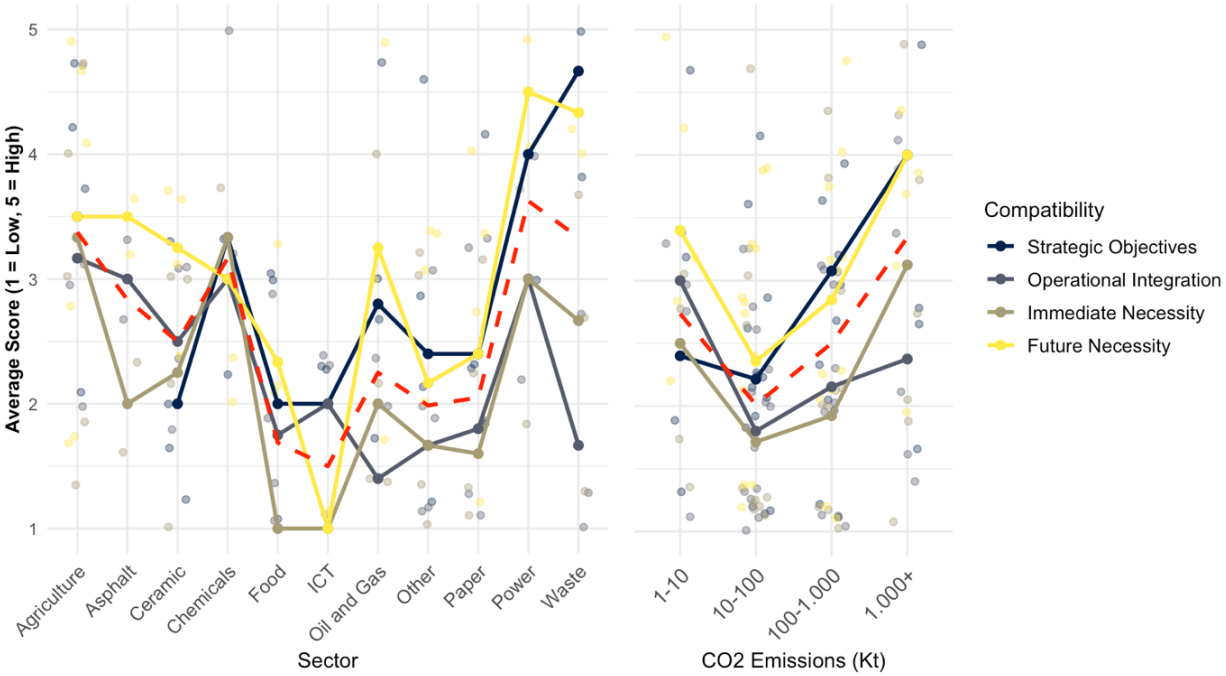

Figure 11. Compatibility of Carbon Capture Technology

Note. This figure shows compatibility scores across sectors (left) and CO_2 emission groups (right) based on 42 responses. Sub-attributes include Strategic Fit, Operational Integration, and Immediate and Future Needs. Jittered points represent individual responses, solid lines show average scores, and a red dashed line marks the overall average. Findings indicate neutral compatibility overall, with higher alignment in power and waste sectors and greater immediate need perceived by larger emitters.

5.2.1. Alignment with Growth Strategies and Sustainability Goals

Carbon capture's alignment with industry strategies varies widely, with an average score of 2.9 out of 5 (Figure 11). High-emission sectors like waste management, energy, oil and gas, and chemicals view carbon capture as essential to their sustainability and growth strategies. In contrast, industries like food production and data centres prioritize alternatives that better fit their operations.

For high emitters, carbon capture is integral to long-term CO_2 reduction goals. In the oil and gas sector, respondents emphasized active investments in carbon capture projects as part of their strategic frameworks (personal communication, oil and gas sector, 2024c). Similarly, waste management and energy sectors consider carbon capture critical to achieving sustainability targets, incorporating pilot projects to comply with stringent regulations (personal communication, waste management sector, 2024; power sector, 2024b). In the chemical industry, strategies increasingly include advanced carbon applications, though its application varies, like pre-combustion capture for hydrogen production and oxy-fuel combustion, showcasing innovation in emissions reduction (personal communication, chemical sector,

2024b). Some industries see carbon capture not only as a regulatory necessity but also as a strategic opportunity to reinforce their environmental leadership and operational sustainability.

In contrast, sectors like food production and building materials find carbon capture misaligned with their sustainability and financial goals, favouring electrification or industrial heat pumps as more feasible options (personal communication, building materials sector, 2024a; food sector, 2024). Data centres dismiss carbon capture as irrelevant, given their low emissions from backup generators, and instead focus on energy efficiency and renewable energy integration (like HVO; personal communication, ICT sector, 2024a). These sectors' view carbon capture as prohibitively expensive and ill-suited to their operations, prioritizing fossil-free solutions that better align with their sustainability and financial objectives.

5.2.2. Operational Integration Faces Process Challenges

Operational integration of carbon capture technology remains challenging, with an average survey score of 2.2 out of 5 (Figure 11), reflecting its perceived complexity. Integration issues stem from compatibility with existing infrastructure, sector-specific processes, and the need for careful planning to minimize disruptions. While pilot projects in some sectors have provided initial insights, the feasibility of broader implementation varies significantly.

Carbon capture systems are typically designed for combustion-related processes, such as gas boilers and combustion furnaces. However, integration depends on sector-specific setups. Common challenges include spatial constraints for equipment installation and the necessity of temporary shutdowns during implementation.

Refineries show relatively straightforward integration due to their existing infrastructure and expertise, such as distillation columns and nearby depleted gas fields for CO_2 storage. Carbon capture also aligns well with hydrogen production, enhancing sustainability. However, variability in operations limits the effectiveness of standardized solutions (personal communication, oil and gas sector, 2024a, 2024b, 2024c).

In the chemical sector, integration is more complex. Facilities with multiple steam crackers require separate capture units for each furnace, significantly increasing costs and inefficiencies. Additionally, emissions with diverse chemical compositions, often poorly monitored, can interfere with capture processes (personal communication, chemical sector, 2024b). A respondent explained, "The downside of a cracker is that you need a separate capture unit for

each furnace, which is very expensive and inefficient" (personal communication, chemical sector, 2024b).

The waste management sector encounters challenges in scaling carbon capture for large volumes of flue gases from incinerators. While pilot projects have shown potential, scaling requires significant modifications to core processes (personal communication, waste management sector, 2024). Similarly, in the energy sector, existing systems must be adapted, and scaling operations adds further complexity (personal communication, power sector, 2024b).

Smaller emitters, such as asphalt plants and food processors, often deprioritize carbon capture due to simpler alternative solutions. One asphalt industry respondent noted explained their emissions pass through a fabric filter, making carbon capture relatively easy to be attached, although not likely given the costs (personal communication, asphalt sector, 2024a).

Successful integration requires long-term planning to align installation with maintenance schedules and minimize disruptions. Factories often shut down operations during scheduled maintenance, typically planned years in advance, limiting opportunities for carbon capture implementation (personal communication, chemical sector, 2024b; power sector, 2024b). Moreover, carbon capture investments, which typically span a 15-year horizon, pose challenges for older facilities nearing the end of their operational life, complicating long-term viability (personal communication, oil and gas sector, 2024b).

5.2.3. Immediate and Future Carbon Management

The adoption of carbon capture technology reflects the interplay between immediate regulatory demands and long-term sustainability goals. Immediate needs focus on current CO_2 reduction pressures, driven by regulatory requirements and corporate sustainability targets, while future needs anticipate stricter emissions regulations, market trends, and evolving technologies. Together, these dynamics influence industries as they integrate carbon capture into their decarbonization strategies.

Survey results show a relatively low perceived urgency for immediate adoption, with a score of 2.2 out of 5 (Figure 11). Smaller emitters often prioritize alternative solutions, whereas larger emitters, exceeding 1,000 kilotonnes of CO_2 annually, report a stronger immediate need due to regulatory and reputational pressures. In contrast, future needs scored higher at 3.0 out of 5,

reflecting an expectation that carbon capture will gain importance as stricter CO_2 regulations and technological advancements make the technology more accessible and cost-effective.

As advancements improve efficiency and reduce costs, and as other carbon reduction methods may face other limitations, carbon capture is reported to become increasingly part of industrial decarbonization strategies.

5.2.4. The Oil and Gas Supply Chain's Role in Carbon Capture

The oil and gas sector plays a pivotal role in carbon capture adoption, addressing both immediate emissions reduction needs and future sustainability goals. As a major contributor to CO_2 emissions, the sector spans the entire supply chain: extraction, refining, transportation, and storage. The sector's supply chain shows how urgency, regulatory pressure, and emerging opportunities shape the integration of carbon capture technology.

Offshore platforms, as the starting point of the supply chain, extract hydrocarbons, such as fossil fuels. Many platforms are strategically located near depleted gas fields, positioning them as key sites for future CO_2 storage projects. This proximity offers a cost-effective and scalable storage solution for the industry (personal communication, oil and gas sector, 2024a).

Refineries serve as central hubs for integrating carbon capture, viewing it as both a regulatory requirement and a business opportunity. By incorporating capture systems, refineries can reduce emissions and may generate revenue from emission credits (personal communication, oil and gas sector, 2024c), although smaller or specialized refineries may delay adoption, waiting for technologies to mature and become more cost-effective. One respondent explained: "We'll re-evaluate carbon capture in the next operational cycle when costs and efficiencies improve" (personal communication, oil and gas sector, 2024b).

The transportation and storage stages of the supply chain are equally important. Developing infrastructure to transport large volumes of CO_2, via pipelines, marine vessels, or road transport, requires managing pressure conditions, preventing leaks, and mitigating corrosion, in which the oil and gas sector is well experienced. Their offshore platforms, which are in some cases owned by oil companies, are well-suited for CO_2 storage due to the existing infrastructure. However, the technical complexity of CO2 storage differs from that of hydrocarbon extraction, but the industry expects to overcome it and is already building knowledge to that end with CO2 storage projects. Furthermore, initiatives like the Porthos project underscore the sector's dedication to

advancing carbon capture technology and to be part of the early adopters (personal communication, oil and gas sector, 2024a).

Despite logistical and technical hurdles, the oil and gas sector demonstrate a collective commitment to carbon capture. From offshore platforms to refineries and storage projects, each stage contributes to integrating this critical technology into the industry's sustainability strategy. As one respondent stated, "Yes, we are very busy with carbon capture and find it important to convey the message and explain what it is" (personal communication, oil and gas sector, 2024a). This unified approach positions the sector as a leader in immediate action and potentially long-term decarbonization efforts.

5.3. Complexity of Implementation

Complexity, defined as the perceived difficulty of understanding, implementing, and using an innovation, is a major barrier to carbon capture technology adoption. Scoring 3.7 out of 5 in the survey (Figure 9), complexity spans technical integration, financial feasibility, and regulatory compliance. Larger emitters often possess the resources and expertise to manage these challenges, while smaller companies struggle due to limited infrastructure and technical capabilities. Financial risks, including uncertain returns and high upfront costs, further amplify the complexity, especially for smaller sectors. Larger emitters also face hesitation due to unclear business cases. Regulatory hurdles, such as prolonged permitting processes and shifting policies, compound these challenges, causing delays. Scaling up after pilot projects adds logistical difficulties, particularly in transport and storage. The following sections explores these dimensions, highlighting their impact on adoption.

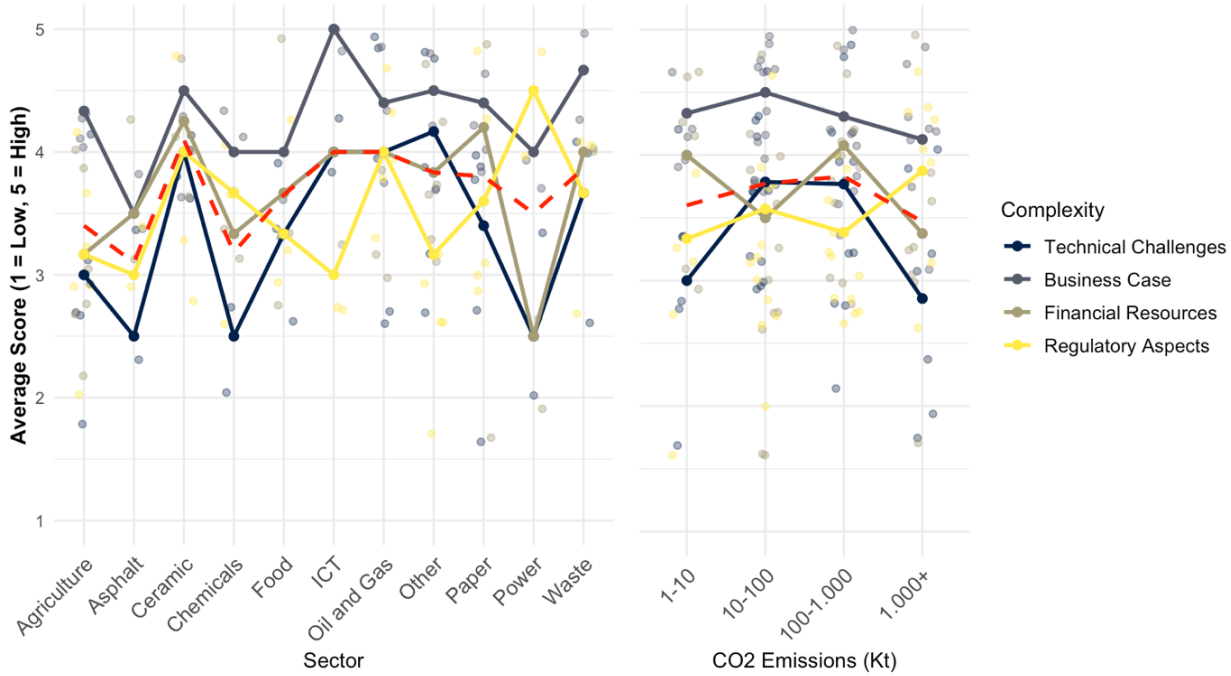

Figure 12. Complexity of Carbon Capture Implementation

Note. Figure showing complexity scores across sectors (left) and CO_2 emission groups (right; n=42). Sub-attributes include Technical Challenges, Business Case Viability, Financial Resources, and Regulatory Aspects. Jittered points represent individual responses, solid lines show average scores, and a red dashed line marks the overall average. Implementation is perceived as highly complex, with business viability being the greatest challenge. Larger emitters face more regulatory complexity but fewer technical challenges.

5.3.1. Technical Challenges and Lack of Expertise Increase Complexity

Implementing carbon capture technology involves significant technical challenges, rated 3.5 out of 5 in complexity (Figure 12). These challenges stem from sector-specific variations in expertise, evolving technology maturity, and intricate supply chains for transport and storage. While sectors with robust technical infrastructure navigate these challenges more easily, others face substantial barriers due to knowledge gaps and reliance on external expertise.

Technical complexity varies across industries, shaped by familiarity with chemical processes and new technology integration. Experienced sectors, such as oil refining and chemicals, often manage carbon capture effectively due to their established expertise (personal communication, chemical sector, 2024b). A respondent from the oil and gas sector explained, “The technology itself is relatively simple, especially at a refinery where they are accustomed to complex technologies” (personal communication, oil and gas sector, 2024c). These industries benefit from in-house capabilities and infrastructure, enabling smoother adoption.

In contrast, sectors like waste management and power generation face steeper learning curves, relying on external providers to design and operate systems. This dependence raises risks and

costs, especially when adapting to emissions with low CO_2 concentrations or mixed compositions. A respondent from the building materials sector highlighted, “Even monitoring emissions in chimneys is challenging, let alone maintaining a constant air balance during the carbon capture process” (personal communication, building materials sector, 2024a). A shortage of skilled workers further complicates operations for high-capacity systems requiring 24/7 monitoring and maintenance (personal communication, oil and gas sector, 2024c).

Concerns about technology readiness also hinder adoption. Many companies doubt the maturity of available solutions, especially in sectors less experienced with chemical systems. Few technologies have reached proven readiness levels (TRL 9), while many others remain in development. Emerging solutions like cryogenic and membrane-based systems show promise but are commercially unviable, reinforcing uncertainty (personal communication, chemical sector, 2024b). As a respondent from the agricultural energy sector remarked, “It is not a proven technology. So, you don’t know. It’s said that one device can capture a lot of CO_2, but we need to see it first” (personal communication, power sector, 2024a). Even established solutions, such as amine-based systems, present operational hurdles, including frequent chemical replacements and energy-intensive processes (personal communication, waste management sector, 2024). Overpromising by start-ups further erodes confidence, leading to hesitation among potential adopters (personal communication, building materials sector, 2024a).

Challenges extend across the supply chain, including emissions capture, transport, and storage. Transportation remains a bottleneck, particularly for companies far from industrial hubs like the Port of Rotterdam. Without access to pipelines, these companies face higher costs relying on trucked liquid CO_2. Moreover, large pipeline projects, such as the 270 km North Rhine Corridor connecting Dutch and German clusters, are often delayed by technical and administrative challenges, impeding broader adoption (Ministerie van Klimaat en Energie, 2024).

CO_2 storage poses additional complexities. In the Netherlands, legal restrictions confine storage to offshore fields, increasing transportation needs compared to onshore options. Injection into depleted gas fields requires precise control of pressure and temperature, often involving reverse-direction injection in a supercritical state. Advanced monitoring and safety protocols are essential. As one respondent noted, “There is already experience with small-scale injection projects, but scaling up to larger projects is still uncharted territory and brings uncertainties”

(personal communication, oil and gas sector, 2024a). Without cohesive and efficient transport and storage networks, the potential of carbon capture remains constrained.

5.3.2. High Costs and Uncertain Returns Complicate Economic Feasibility

High costs, market uncertainties, and reliance on subsidies significantly hinder the economic feasibility of carbon capture technology. With a complexity score of 4.3 out of 5 (Figure 12), survey respondents emphasized these economic barriers. While larger emitters find more viable return-on-investment (ROI) pathways, smaller firms struggle to justify costs without substantial government support. Achieving economic feasibility will require stable CO_2 pricing, streamlined regulations for negative emissions, and sustained financial incentives to de-risk investments. Although evolving policies and technological advancements may improve viability, significant hurdles persist.

Market volatility and regulatory ambiguity undermine financial planning for carbon capture. Stable CO_2 prices are crucial for estimating costs and potential revenues from emission rights trading. However, the combined impact of the Dutch CO_2 levy and the European Emissions Trading System creates an unpredictable financial environment. Under current legislation, the Dutch levy will rise from €30 per ton in 2021 to €150 per ton by 2030 (PBL, 2024c). Meanwhile, volatile EU-ETS prices complicate financial planning, particularly when they drop below the national levy, resulting in additional taxation. A respondent from the food sector explained, “The investment is simply too expensive, and the unpredictability of CO_2 prices makes it even riskier” (personal communication, food sector, 2024). Similarly, energy price volatility and grid congestion in the Netherlands restrict access to affordable power for energy-intensive carbon capture systems, further increasing uncertainty (personal communication, building materials sector, 2024a).

Political inconsistency regarding biogenic carbon capture adds complexity. Respondents noted unequal treatment of CO_2 sources: “If I capture CO_2 with my bioenergy plant, I don’t get extra rights... but if I capture CO_2 with a gas-fired plant, I don’t have to buy rights for the part I capture” (personal communication, waste management sector, 2024). Such inconsistencies discourage investment in biogenic capture and limit market development for negative emissions, which remain confined to voluntary trading markets (personal communication, power sector, 2024b).

The ROI for carbon capture investments often fails to justify high costs, leading to hesitancy among companies. Without clear revenue pathways, such as CO_2 utilization or storage credits, many firms struggle to achieve acceptable returns. A refining sector respondent stated, "A project must yield x% return, or we won't do it. The higher the risk, the higher the required returns, which is hard to achieve with carbon capture" (personal communication, oil and gas sector, 2024c). For most industries, captured CO_2 is seen as a liability requiring storage, with limited value creation. Exceptions exist in the agricultural sector, where captured CO_2 enhances greenhouse yields, demonstrating niche applications with direct benefits (personal communication, power sector, 2024a). However, the lack of widespread CO_2 applications beyond storage exacerbates financial challenges (personal communication, oil and gas sector, 2024b).

Storage options add to these difficulties. The Porthos project, scheduled to begin operations in 2026, is already fully booked (37 megatonnes of CO_2), while the larger Aramis project (over 400 Mt) remains uncertain (personal communication, oil and gas sector, 2024a). Companies increasingly recognize the need to develop capture and storage projects in parallel to ensure feasibility. As one respondent noted, "A CO_2 storage or usage option must be developed in parallel with the capture project" (personal communication, power sector, 2024b).

Funding carbon capture projects is another widespread challenge. While some companies benefit from financial liquidity or bank financing, most rely heavily on subsidies to offset costs and de-risk investments. As one respondent put it, "Without long-term subsidies and a guarantee of stable CO_2 prices, it is a financially very risky investment" (personal communication, power sector, 2024b). Programs like SDE++ help make projects viable by reducing financial risk. However, this reliance on subsidies introduces vulnerabilities, as policy shifts could destabilize financial plans. Some companies aim to reduce dependence on subsidies, but alternative funding remains limited (personal communication, building materials sector, 2024a). Innovative subsidy models, such as those in the Porthos project, provide some stability. Porthos includes provisions to adjust subsidies if EU-ETS prices drop, ensuring financial viability for participants (personal communication, oil and gas sector, 2024c).

Uncertainty about financial returns and the risk of better alternatives emerging discourage companies from committing to carbon capture. As one respondent explained, "There's a risk of investing in carbon capture now, only to find that a better alternative emerges later" (personal

communication, building materials sector, 2024b). This hesitation delays investments and slows progress toward decarbonization goals.

5.3.3. Regulatory Uncertainty and Policy Delays Create Barriers to Implementation

Regulatory frameworks strongly influence the adoption of carbon capture technology, serving as both enablers and barriers. Survey respondents rated the complexity of navigating regulations at 3.6 out of 5, highlighting challenges such as permitting delays, cross-border policy inconsistencies, and unclear market standards (Figure 12). While mechanisms like the EU Emissions Trading System and the Dutch CO_2 tax incentivize adoption, regulatory ambiguities and delays hinder progress. As one respondent noted, "Current policies and future regulations will strongly determine the feasibility and timing of carbon capture implementation and must align with rapidly changing technologies" (personal communication, power sector, 2024b).

The EU ETS and Dutch CO_2 tax encourage emission reductions through penalties and tradable allowances, with the ETS Market Stability Reserve (MSR) ensuring credit supply stability. However, respondents cited CO_2 price volatility within the ETS system as a major investment barrier (personal communication, food and oil and gas sectors, 2024). Regulatory developments like the inclusion of waste incineration plants under the EU ETS by 2028, which will require these facilities to report emissions and purchase allowances, are increasing pressure to adopt carbon capture technologies (personal communication, waste management sector, 2024).

Permitting is one of the largest obstacles, with respondents emphasizing the lengthy, complex approval processes that inflate costs and disrupt timelines. One respondent explained, "The complexity of complying with regulations and certifications is often underestimated" (personal communication, power sector, 2024b). Nitrogen regulations further complicate matters, for example, a chemical sector respondent reported a three-to-four-year delay caused by unexpected nitrogen rules, requiring costly project reassessments (personal communication, chemical sector, 2024b). Despite frustrations, some companies view permitting as an opportunity to advance sustainability goals and align projects with long-term strategies (personal communication, building materials sector, 2024a).

Beyond government regulations, market standards and customer expectations increasingly drive adoption. Pressure to align with initiatives like the Science Based Targets Initiative (SBTI) pushes companies to meet stricter climate goals. As one respondent noted, "Our customers expect us to commit to SBTI, which suddenly makes the Greenhouse Gas Protocol's

stance on carbon capture very important" (personal communication, food sector, 2024). While such expectations can spur innovation, they also create tensions with existing regulatory frameworks.

Cross-border regulatory differences complicate scaling carbon capture projects. Post-Brexit uncertainties have disrupted EU-UK collaboration on shared North Sea storage fields (personal communication, oil and gas sector, 2024a). Similarly, delays in projects like the North-Rhine Corridor pipeline underscore the need for stronger European coordination to advance large-scale initiatives. The EU's Carbon Border Adjustment Mechanism, which imposes carbon-based import taxes, offers some relief by levelling the playing field for European producers and mitigating carbon leakage risks (European Parliament and Council, 2023). Respondents welcomed CBAM's potential to drive global carbon reductions.

Negative emissions policies remain underdeveloped, especially for biogenic CO_2 capture. The inconsistent treatment of biogenic emissions under the EU ETS creates financial uncertainties for biomass and fermentation projects (personal communication, waste management sector, 2024). Voluntary markets for negative emissions also lack stability, further complicating their business case. Additionally, debates over biomass sustainability, such as allocating biomass to e-fuels versus energy production, temporary stall progress in this area (PBL, 2024c). Without clearer integration of regulatory frameworks, long-term planning and investment remain constrained.

5.4. Trialability

Trialability is critical to the adoption of innovations like carbon capture technology, allowing organizations to test on a small scale before full implementation. Pilot projects reduce uncertainty, build confidence, and provide practical insights into the technology's benefits and challenges (Rogers, 1962). Successful trials not only mitigate risks but also serve as case studies to encourage wider adoption. Survey respondents rated trialability at 3.2 out of 5 (Figure 9), reflecting both opportunities and obstacles.

Figure 13 illustrates sectoral differences in trialability. Sectors such as agriculture, power, and waste management benefit from greater capacity to conduct trials, enabling progress toward adoption. Conversely, sectors like ceramics and food report limited ability to pilot or scale the technology, hindering adoption. Scaling up after pilot projects presents additional challenges,

including technical complexity, infrastructure requirements, and significant financial investments. Sectors with lower trialability face difficulties at both trial and scaling stages.

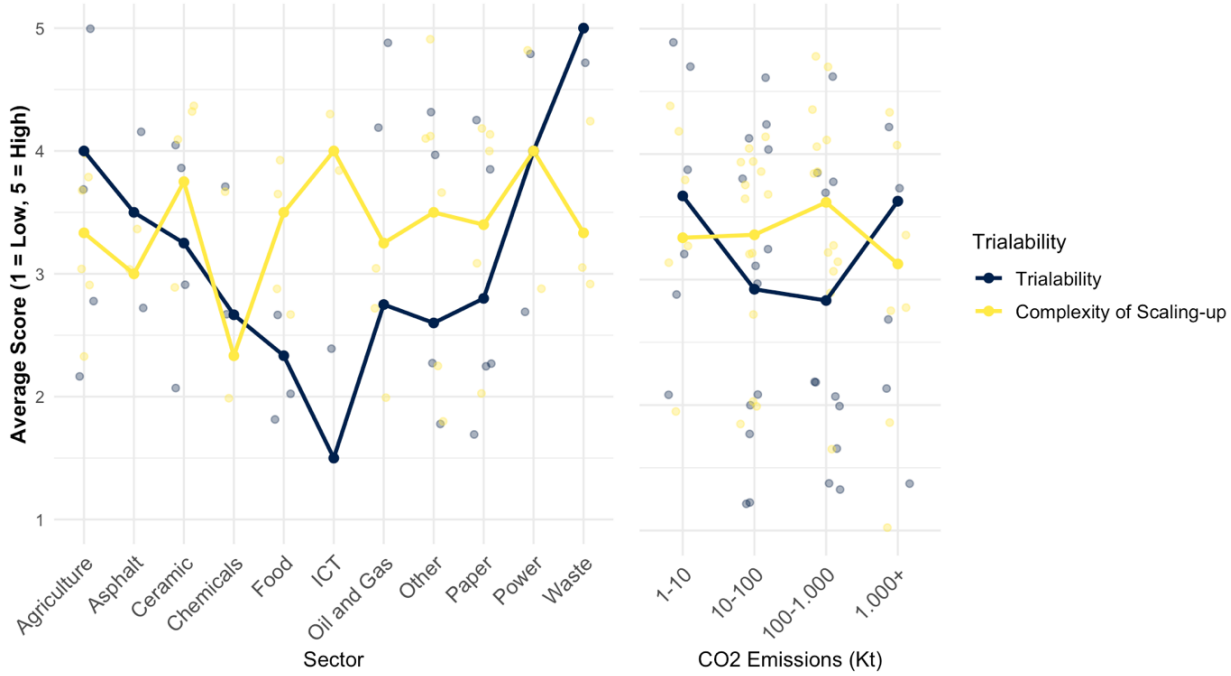

Figure 13. Trialability and Scaling Complexity of Carbon Capture
Note. This figure shows trialability and scaling complexity scores across sectors (left) and CO_2 emission groups (right; n=42). The y-axis represents scores (1 = Low, 5 = High) for pilot project feasibility and scaling challenges. Jittered points represent individual responses, with solid lines showing average values. Sectors with stronger resources and infrastructure score higher on trialability and lower on scaling complexity, while low trialability is linked to greater scaling challenges.

5.4.1. Availability of Resources and Strategic Alignment Enhances Trialability

Trialability, the ability to test carbon capture technologies through pilot projects, is essential for reducing risks and refining implementation strategies. This section explores key factors influencing trialability, including resource availability, strategic alignment, and preliminary research. Sectors with robust infrastructure and financial capacity demonstrate higher trialability, while others face barriers due to funding gaps and logistical challenges.

Infrastructure and operational fit are critical to successful pilot projects. Sectors such as waste management, energy, and agriculture achieve high trialability scores of 5.0, 4.5, and 4.5, respectively (Figure 13), as they can adapt existing processes. Pilot projects range from small-scale installations capturing a few kilotonnes of CO_2 annually to near-complete systems. A respondent from the oil and gas sector noted, “Pilots can be conducted on many different scales. Starting small, just a few sea containers, is often useful” (personal communication, oil and gas sector, 2024c).

While subsidies like SDE and DEI provide critical support, they rarely cover full pilot costs, forcing companies to rely on internal investments. A respondent from the energy sector explained, “We’re looking at a pilot at two locations, but what we call a pilot is actually a complete installation” (personal communication, power sector, 2024b). These financial demands underscore the significant commitment required to advance carbon capture technologies.

Strategic alignment with long-term sustainability goals also enhances trialability. Companies use small-scale trials to refine strategies, mitigate risks, and ensure alignment with broader decarbonization plans. A respondent from the energy sector shared, “We are installing a small unit and expect it to be ready early next year. This will allow us to test its heat and electricity usage and assess performance” (personal communication, power sector, 2024a). These early investments reflect foresight, building a foundation for site specific implementation.

Feasibility studies are also critical for assessing the technical and commercial viability of pilot projects. Companies that invest in these early steps gain critical insights, reduce risks, and design more effective trials. However, resource-intensive feasibility studies can deter smaller companies, slowing their adoption of carbon capture technologies. Investing in robust preliminary research helps identify challenges, align strategies, and set the stage for scalable implementation.

5.4.2. Scaling Up Pilot Projects Faces Multiple Challenges

Scaling up carbon capture technologies faces barriers such as technological immaturity, logistical hurdles, and economic challenges. Addressing these issues requires strategic collaboration, targeted investments, and sustained policy support.

Technological immaturity is a key barrier. Many companies hesitate to invest in pilots due to concerns about reliability and readiness. A respondent from the oil and gas sector explained, “Pilot plants are often done by researchers and smaller startups... If we go for it, we will immediately move forward” (personal communication, oil and gas sector, 2024b). Some technologies remain at low technology readiness levels (TRLs). A chemical sector respondent noted, “We are working on a pilot and demo scale, but we still need a few years to develop it” (personal communication, chemical sector, 2024b). Emerging technologies hold promises but are years from commercialization, creating uncertainty and slowing adoption (personal communication, power sector, 2024a).

Integrating pilot projects into operations presents significant logistical challenges. Carbon capture systems often require customization to address unique emission sources. For example, a respondent from the building materials sector shared, “We have four chimneys, and we can't link them. So, you would need four separate units” (personal communication, building materials sector, 2024a). Refineries and chemical plants face similar complexities, as emissions from multiple furnaces require separate capture units (personal communication, chemical sector, 2024b). These logistical issues increase costs and extend project timelines, complicating pilot projects.

The financial burden of pilot projects further hinders scaling efforts. While sectors with higher trialability, such as chemicals and asphalt (average score of 3.5), are more willing to conduct pilots, many remain cautious without clear financial benefits. A respondent from the energy sector noted, “There are SDE and DEI subsidies, but they don’t cover the entire demonstration” (personal communication, power sector, 2024b). Without strong financial incentives or profitability pathways, some companies favour alternatives or wait for more favourable times. A respondent from the asphalt sector explained, “We currently see better alternatives, so we don’t need CCS in principle” (personal communication, asphalt sector, 2024a).

Even after successful pilots, scaling up introduces additional hurdles. Large-scale implementation demands significant capital investments, infrastructure modifications, and careful integration planning. A respondent from the power sector remarked, “Scaling up means going a thousand times bigger. That’s a serious investment” (personal communication, power sector, 2024b). Spatial constraints further complicate scaling, especially for facilities with limited space for new equipment. A respondent asked, “Where do you put that container?” (personal communication, ICT sector, 2024a). Additionally, scaling requires rigorous testing and ongoing development to ensure reliability across diverse industrial applications. These challenges lead many companies to delay scaling until technologies mature and funding becomes more accessible.

5.4.3. Pilot Projects as Catalysts for Industry Confidence and Adoption

Pilot projects are pivotal in driving the adoption of carbon capture technologies by offering real-world demonstrations of their feasibility and benefits. These initiatives provide industries with actionable insights into the operational, technological, and financial aspects of carbon capture, fostering confidence and accelerating large-scale adoption. Acting as proof-of-concept,

pilot projects gain visibility through industry engagement, conferences, and publications, amplifying their impact.

Successful pilot projects showcase carbon capture's capabilities and dispel doubts about its viability. High-profile examples, such as initiatives in refineries and waste incineration facilities, have bolstered industry confidence (personal communication, oil and gas sector, 2024c; waste sector, 2024). The Porthos project stands out as a transformative initiative, capturing CO_2 from multiple industrial sources and storing it in depleted North Sea gas fields. Cited frequently by respondents, Porthos has become a benchmark for collaborative, scalable carbon capture and storage solutions. As one participant observed, “Projects like Porthos not only showcase what’s possible but also inspire others to take similar steps” (personal communication, waste sector, 2024). These projects serve as vital case studies, offering clear evidence of carbon capture’s scalability and impact to both industry and public stakeholders.

The flexibility of pilot projects enables testing in diverse contexts, from fossil-based emissions to biogenic CO_2 sources. Waste management companies, for example, have piloted systems targeting incineration emissions, while agricultural sectors explore using captured CO_2 to enhance greenhouse productivity (personal communication, waste sector, 2024). Other pilots integrate capture with storage or utilization technologies, such as testing mineralization processes or evaluating CO_2 injection into depleted gas fields. These efforts address critical challenges, including managing CO_2's physical and chemical properties during transport and storage, ensuring adaptability to various industrial processes (personal communication, oil and gas sector, 2024a). By tackling these challenges, pilot projects refine technologies, identify best practices, and build sector-specific expertise to support broader implementation.

Although limited in scale, pilot projects bridge the gap between theoretical potential and practical application, laying the groundwork for large-scale deployments. As one respondent noted, “A few more deployments would be useful to gain the market's confidence and solidify the case for broader adoption” (personal communication, oil and gas sector, 2024c). While scaling these projects remains challenging, their contributions to emission reduction strategies are indispensable. By refining technologies, addressing operational barriers, and sharing findings, pilot projects strengthen stakeholder trust and advance the development of carbon capture ecosystems. These efforts not only support industry-specific goals but also play an important role in meeting national and global climate targets.

5.5. Observability

Observability influences the adoption of new technologies, as stakeholders are more likely to embrace innovations with visible and easily understood benefits (Rogers, 2003). For carbon capture, showcasing tangible outcomes like emissions reductions or operational improvements helps build visibility and drive adoption. However, the large-scale, technical nature of carbon capture systems makes demonstrating their value challenging. Survey respondents rated observability at 2.6 out of 5 (Figure 9), highlighting mixed perceptions of carbon capture's visibility.

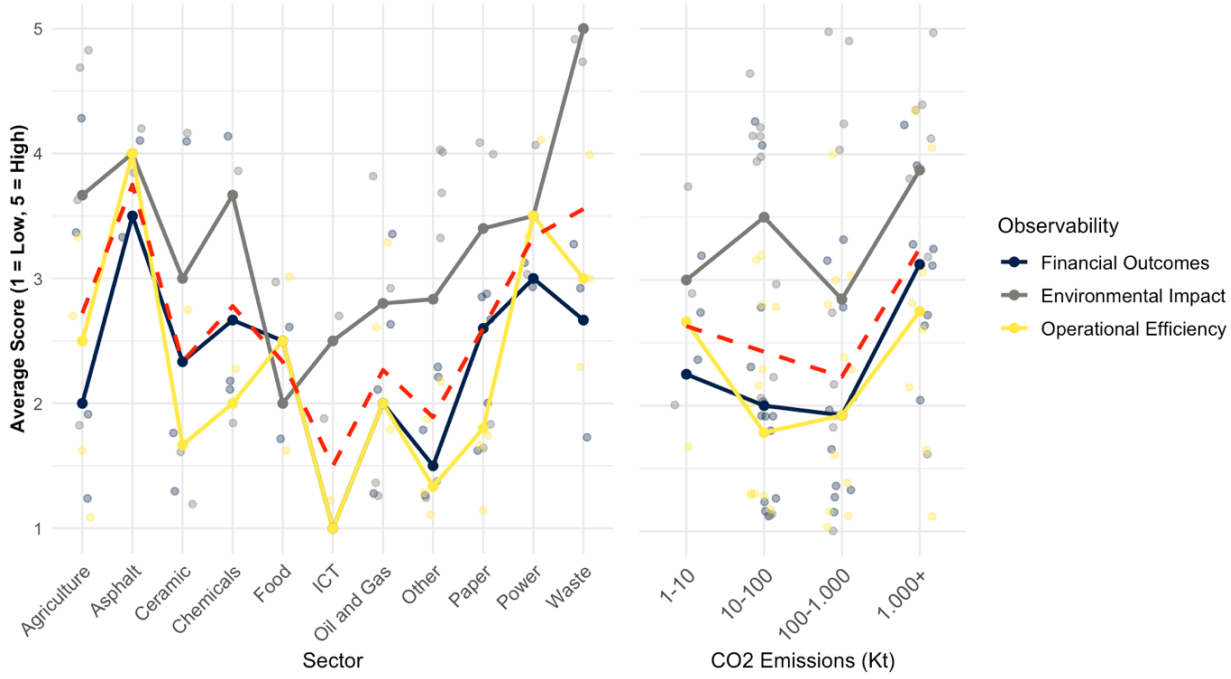

Figure 14. Observability of Carbon Capture Technology

Note. Figure showing observability scores (1 = Low, 5 = High) across sectors (left) and CO_2 emission groups (right; n=42), focusing on environmental, financial, and operational visibility. Jittered points represent individual responses, with solid lines showing averages. Higher CO_2-emitting sectors score higher on observability possibly due to greater feasibility and visibility of installations, while lower-emission sectors with complex financial and operational contexts score lower.

Environmental visibility scored highest (3.3), as benefits like emissions reductions are often emphasized in sustainability reports and media coverage (Figure 14). In contrast, financial visibility was rated much lower (2.2), with stakeholders frequently lacking clear data on cost-effectiveness or profitability. Operational visibility received the lowest score (2.1), reflecting the internal, technical nature of these improvements, which are rarely communicated externally.

Sectoral differences reveal that larger emitters (1,000+ kilotonnes CO_2 annually) achieve higher observability scores (3.3), primarily due to their capacity to showcase significant environmental

impacts. These companies also tend to have more resources to promote their initiatives, further enhancing the visibility of their carbon capture efforts.

5.5.1. Environmental Benefits are Recognized but Also Contested

The observability of carbon capture technology is closely tied to its environmental benefits. As the urgency to address climate change grows, stakeholders such as clients, environmental organizations, regulators, and competitors focus on the visibility of CO_2 reduction efforts. Sectors like waste management (5), asphalt (4), chemicals (3.7), agriculture (3.7), energy (3.5), and paper (3.4) report higher visibility of these benefits (Figure 14). Public recognition and sustainability certifications enhance this observability, while regulatory compliance plays a complementary role. However, perceptions of carbon capture's environmental impact vary, influencing its broader adoption.

Carbon capture offers measurable environmental benefits, particularly in CO_2 reduction. These achievements are well-documented in sustainability reports, emissions databases, and media coverage. For example, a waste management professional noted, "Carbon capture contributes directly to reducing our CO_2 emissions, which is positive for the environment" (personal communication, waste management sector, 2024). However, in sectors less reliant on carbon capture, its relevance is contested. A respondent from the food sector stated, "Even though carbon capture reduces emissions, we prefer to focus on fossil-free solutions. Relying on it may harm our reputation among stakeholders who value complete sustainability transitions" (personal communication, food sector, 2024). This divergence underscores the importance of achieving measurable reductions and communicating them effectively.

Certifications and regulatory compliance further enhance the visibility of environmental benefits. Programs like EcoVadis and the Science-Based Targets Initiative validate top-tier sustainability performance, boosting stakeholder trust and industry reputation (personal communication, building materials sector, 2024b; chemical sector, 2024a). A chemical industry respondent highlighted how their carbon capture efforts placed their company in the top 5% of sustainability performers, enhancing its influence (personal communication, chemical sector, 2024a). Compliance with CO_2 reduction standards and permits reinforces environmental leadership and is often highlighted in sustainability reports and press releases. As one respondent observed, "Regulations influence the speed and direction of technology adoption,

making compliance and strategic choices highly visible" (personal communication, chemical sector, 2024b). Such alignment improves stakeholder perceptions and encourages adoption.

Public perception and political support are critical to the success of carbon capture. In the Netherlands, media outlets and sustainability platforms like Energeia highlight both the potential and limitations of the technology. While positive coverage generates interest and bolsters adoption, negative narratives can foster scepticism. Companies mitigate these challenges by engaging stakeholders like NGOs and policymakers to align on sustainability goals. A respondent from the chemical sector noted, "We often discuss our sustainability initiatives with NGOs and policymakers to ensure alignment and build trust" (personal communication, chemical sector, 2024b). Carbon capture's alignment with the Paris Agreement objectives further enhances its appeal to environmental organizations and policymakers (personal communication, power sector, 2024a).

Securing public and political support remains a challenge, especially when controversies surrounding the technology are spotlighted. A respondent from the oil and gas sector emphasized, "Positive public perception is critical for generating political backing, which enables subsidies and other incentives" (personal communication, oil and gas sector, 2024a). To address these concerns, companies increasingly prioritize strategic communication, focusing on carbon capture's role in reducing CO_2 emissions and its necessity in sectors lacking viable alternatives. This approach aims to improve public sentiment, attract political support, and secure the incentives needed for successful adoption.

5.5.2. Financial Observability as a Barrier to Adoption

Financial observability is relevant for the adoption of carbon capture technologies, as stakeholders, such as investors, shareholders, CFOs, and financial institutions, require clear financial benefits. However, it remains a significant barrier, with a survey score of 2.2 out of 5 (Figure 14). Cost uncertainties and debates over who bears the financial burden (companies, governments, or society) exacerbate investment hesitancy and slow adoption.

A major challenge is the lack of transparent financial data. Companies often hesitate to disclose sensitive details, making it difficult to demonstrate financial benefits. This, combined with unpredictable regulations and market dynamics, complicates the public financial case for carbon capture. As one respondent explained, "Potential savings often depend on future regulations and market conditions, complicating predictability" (personal communication,

waste management sector, 2024). Larger emitters (1,000+ kilotonnes CO_2 annually) report higher financial observability (3.1), potentially benefiting from greater insights across their market segments.

The costs of inaction, such as regulatory fines, rising carbon taxes, and reputational damage, pose significant financial risks. A chemical sector respondent noted, "The costs of doing nothing are also there, which makes the discussion about who bears the costs important" (personal communication, chemical sector, 2024b). While these costs have long-term implications, they are less immediately visible, complicating their quantification and decision-making.

Improving financial observability requires companies to share success stories through reports, investor briefings, and media. Transparent communication about financial benefits can build stakeholder trust and attract sustainable financing, while building momentum across industries. As one energy sector respondent observed, "The visibility of sustainable projects can facilitate additional financing streams, as banks have interests in sustainable projects" (personal communication, energy sector, 2024a).

Regulatory support, such as subsidies and tax incentives, can further enhance financial visibility and reduce cost uncertainties. Aligning private-sector transparency with public-sector incentives strengthens the financial observability for carbon capture, fostering adoption. By demonstrating clear economic benefits and addressing cost uncertainties, companies can build stakeholder confidence and accelerate implementation.

5.5.3. Operational Benefits Have Low Visibility, Slowing Adoption

Operational observability, the ability to monitor and showcase the operational advantages of carbon capture, remains limited, slowing adoption across industries. With a survey score of 2.1 out of 5 (Figure 14), operational benefits are the least visible observability attribute. These benefits are often recognized only internally by technical staff and production teams, with minimal external visibility. Addressing this gap could enhance stakeholder confidence.

The lack of operational observability stems from several interconnected issues. First, implementing carbon capture requires significant, site-specific infrastructure modifications that are complex and highly specialized. Companies often withhold proprietary details, further reducing visibility to external stakeholders and limiting opportunities for cross-sector

collaboration. As a respondent from the chemical sector noted, this reluctance reduces learning opportunities for other industries (personal communication, chemical sector, 2024b).

Second, the technological complexity of carbon capture creates adoption barriers. Companies unfamiliar with emission-reduction technologies often view operational changes as daunting. A waste management sector respondent explained, “Implementing carbon capture requires significant operational changes and is therefore less attractive” (personal communication, waste management sector, 2024). This perception discourages adoption, especially when challenges are emphasized over potential benefits.

Third, operational outcomes are rarely shared public due to competition. While companies track metrics like efficiency improvements and emissions reductions internally, specific operational insights are seldom communicated externally. Without visible proof of operational success, stakeholder confidence in carbon capture remains low, further slowing its diffusion.

To address these challenges, companies may adopt proactive strategies to showcase operational benefits. Sharing successful integration efforts, such as optimized ovens or increased power plant efficiency, could provide tangible proof of carbon capture’s value. For example, a respondent from the energy sector observed, “Carbon capture can offer operational benefits by making power plants more flexible and efficient” (personal communication, energy sector, 2024).

Companies can foster broader interest by sharing case studies and lessons learned through conferences and industry platforms. Highlighting how specific operational challenges were resolved can inspire confidence and serve as benchmarks for others. Successful companies can act as role models, demonstrating practical benefits and easing concerns about complexity. Including metrics in sustainability reports and annual reviews allows companies to communicate tangible outcomes, such as reduced emissions or enhanced efficiencies, to a wider audience. Clear, operational results may build credibility and foster trust, helping benefits become more relatable to external stakeholders.

Chapter Conclusions

This chapter examined how innovation attributes influence the adoption of carbon capture technologies in Dutch industrial sectors. The findings reveal that relative advantage, compatibility, complexity, trialability, and observability interact to shape adoption outcomes.

While high-emission sectors with technical expertise, infrastructure, and strong CO_2 reduction priorities adopt faster, smaller emitters and resource-constrained industries face significant barriers.

In high-emission sectors like chemicals, oil and gas, and waste management, alignment among these attributes fosters adoption. Regulatory pressures, reputational benefits, and existing infrastructure enhance the relative advantage of carbon capture, making it a strategic priority. Compatibility with sustainability goals, paired with technical expertise, reduces complexity and supports integration. Trialability through pilot projects mitigates risks and builds confidence, while visible environmental gains strengthen stakeholder trust and accelerate adoption.

Conversely, in sectors like food production, ceramics and paper misaligned attributes hinder progress. High complexity, low trialability, and poor observability of financial and operational benefits create significant obstacles. For these industries, carbon capture often appears incompatible with their decarbonization strategies, delaying investments or shifting focus to alternative solutions.

A persistent challenge across sectors is the lack of financial observability. High upfront costs, uncertain returns, and fragmented infrastructure weaken stakeholder confidence, particularly for smaller emitters. Financial incentives, such as subsidies and carbon tax credits, combined with improved infrastructure access and pilot projects, are needed to overcome these barriers.

To broaden adoption, fostering alignment among innovation attributes is critical. Transparent reporting and public communication of environmental and financial benefits can build stakeholder confidence. Collaborative efforts, including shared infrastructure and cross-sector pilot projects, can address economic and technical uncertainties. Tailored support for each sector's unique challenges may enable Dutch industries to scale carbon capture technologies, contributing to national and global decarbonization goals.

6. Discussion

This study explored the factors influencing carbon capture adoption in Dutch industrial sectors regulated by the EU Emissions Trading Scheme. By examining adoption rates, motivations, and barriers, the research provides a detailed understanding of the current landscape.

The findings reveal significant sectoral differences. Large emitters are progressing faster than smaller ones, leveraging resources and aligning carbon capture with strategic emission reduction goals. Innovation attributes, such as relative advantage, compatibility, and complexity, strongly influence adoption intentions. Positive attributes drive adoption, while barriers like technological complexity and limited access to pilot projects reduce perceived control and slow implementation. This interplay underscores the connection between behavioural factors and technological attributes in shaping adoption outcomes.

This chapter situates these findings within existing literature and complementary frameworks, highlighting their implications for policy, industry practice, and the broader adoption of carbon capture technologies in the Netherlands.

6.1. Adoption Cycle of Carbon Capture

Carbon capture technology is widely recognized as being in the early stages of adoption, primarily driven by "innovators" in hard-to-abate or energy intensive sectors like cement, steel, fertilizers, and chemicals (Bahman et al., 2023; Ma et al., 2022; Psarras et al., 2017). These industries adopt carbon capture out of necessity, as few viable decarbonization alternatives exist. Benefits such as economies of scale, access to technical expertise, enhanced competitiveness, and reputational gains further incentivize adoption (Ashkanani et al., 2021; Bui et al., 2018; Pires et al., 2011). In some cases, the potential for CO_2 reuse in fuels or chemicals adds economic appeal (Ghiat & Al-Ansari, 2021; Huo et al., 2022). However, challenges like financial constraints, public opposition, and dependency on CO_2 infrastructure continue to slow broader adoption (Ministerie van Economische Zaken en Klimaat, 2024 [EZK]; PBL, 2024c; VNO-NCW, 2024)

This study aligns with the literature but reveals nuances in the Dutch landscape. Large emitters, those producing over 1,000 kilotonnes of CO_2 annually in sectors such as waste processing, energy, oil and gas, and chemicals, are further along in the adoption cycle than previously assumed. Many are actively involved in feasibility studies, pilot projects, and early

implementations, driven by market leadership, reputational benefits, policy and investor pressure, and access to resources. Smaller emitters, by contrast, face slower adoption due to limited resources, lower economies of scale, and reduced perceived control. Exceptions exist in innovative sectors like horticulture and dairy, where proactive adoption may be supported by opportunities for CO_2 reuse in greenhouse operations and export-driven markets.

h the findings and the literature highlight carbon capture's transitional role in reducing emissions while allowing time to develop sustainable alternatives. Combined with energy conservation and renewable energy, carbon capture can contribute to decarbonization strategies (Lechtenböhmer et al., 2015; McLaughlin et al., 2023; PBL, 2024b; Wilberforce et al., 2019). Pilot and demonstration projects are critical for reducing technical and financial uncertainties, building confidence, and scaling commercialization (Plasynski et al., 2009). However, investments in carbon capture risk locking in fossil fuel reliance, diverting resources from renewable energy. Integrating carbon capture into broader decarbonization strategies can mitigate this risk, positioning it as a transitional tool for the next 20–30 years rather than a permanent solution. In specific sectors, like those with process emissions, long-term carbon capture may remain essential.

The adoption of carbon capture in the Netherlands appears more advanced than expected, particularly among large emitters. Recent projections by VNO-NCW suggest that over 100 projects could reduce annual emissions by 20 megatonnes, with 10 Mt targeted by 2030 (VNO-NCW, 2024). The Dutch Climate Plan envisions 20–25 Mt of annual storage by 2040, aligned with a 90% emissions reduction compared to 1990 levels (EZK, 2024). Among the 297 ETS-regulated companies studied, 50 emit over 100 kilotonnes of CO_2 annually, with 25 exceeding 1,000 Kt. Of these large emitters, nearly half (n = 23) are actively considering carbon capture in 2024. Their participation will be critical for meeting national CO_2 reduction targets, yet achieving these goals will require overcoming high costs, regulatory barriers, and infrastructure challenges.

6.2. Drivers and Barriers of Carbon Capture Adoption

The adoption of carbon capture technology in the Netherlands is driven by a complex mix of innovative and behavioural factors. Although the technology is vital for achieving CO_2 reduction targets, barriers such as high costs, infrastructure gaps, and public concerns continue to hinder progress. At the same time, innovations in technology, collaborative infrastructure,

and strategic public engagement present significant opportunities. This section explores the barriers and opportunities identified in this study, situating the findings within the broader context of existing literature.

6.2.1. High Costs and Financial Challenges

High investment and operational costs remain major barriers to carbon capture adoption. Initial investments often exceed tens of millions of euros, with capture systems comprising up to 80% of total project costs (Li et al., 2018; Psarras et al., 2017). Current capture costs range from €40 to €110 per ton of CO_2, with storage adding €10–€20 per ton, but can rise significantly for First-of-a-Kind projects due to higher financial and technological risks (Skagestad et al., 2014). This financial burden particularly affects smaller emitters and less-resourced sectors.

In the Netherlands, high electricity prices exacerbate these challenges. Energy-intensive processes, such as CO_2 compression, increase electricity demand by 25%, making operations less competitive compared to countries with lower energy costs, such as Germany (2 times lower) and the United States (4 times lower; (Draghi, 2024; Shen et al., 2022; Wilberforce et al., 2019). Combined with capital expenses, these costs risk creating "excess inertia," where high upfront investments slow adoption even in sectors with urgent decarbonization needs (Golombek et al., 2023). Findings consistently emphasize the need for public-private partnerships to mitigate these financial risks and accelerate investments (Berenblyum et al., 2021; Draghi, 2024).

Despite these barriers, advancements in carbon capture technologies offer pathways to cost reductions. Innovations like amine-based systems, membranes, and cryogenic capture, along with process optimizations, have the potential to improve cost efficiency (Bui et al., 2018; Liu et al., 2017; Martin et al., 2021). Process optimizations, such as increasing CO_2 concentrations and stream purity, further improve the cost-effectiveness of carbon capture systems (Brandl et al., 2021; Psarras et al., 2017). Collaboration within industrial clusters further reduces costs by enabling shared infrastructure for capture, transport, and storage (Bains et al., 2017). However, emitters outside these clusters face higher transport costs, emphasizing the need for equitable infrastructure investments.

CO_2 utilization (CCU) also presents economic opportunities. Applications such as greenhouse enrichment, beverage carbonation, and emerging markets for polymers and construction materials can generate supplementary revenues (Bruhn et al., 2016; Ghiat & Al-Ansari, 2021;

Mikulčić et al., 2019). However, limited demand for CCU products restricts its short-term impact, requiring coordinated policies to stimulate markets and align CCU technologies with decarbonization goals (Schmid & Hahn, 2021).

Encouragingly, CCS costs are declining. Capture costs have fallen from €200–€250 per ton of CO_2 in the early 2000s to projected levels of €30–€50 per ton by 2030, supported by rising ETS prices expected to reach €150 per ton (Anderson & Newell, 2004; Peres et al., 2022; PBL, 2024c). This trend signals CCS's potential to transition from a high-cost niche solution to a scalable decarbonization technology.

Addressing financial barriers may require public-private partnerships, financial incentives, and robust policy frameworks. Subsidies, tax credits, and carbon pricing can mitigate risks and accelerate deployment. Combined with innovation and industrial collaboration, these measures can help carbon capture realize a global decarbonization strategy.

6.2.2. Infrastructure Gaps and Logistical Complexities

The lack of shared infrastructure, particularly CO_2 transport networks and storage facilities, remains a major barrier to carbon capture adoption in the Netherlands. Smaller emitters located outside industrial clusters face disproportionately high transport costs and logistical challenges, with geographically dispersed sectors like ceramics and paper being especially disadvantaged (Shogenova et al., 2021). In contrast, industrial clusters benefit from shared infrastructure, enabling economies of scale and reducing costs (Bains et al., 2017; Turgut et al., 2021).

Without a national CO_2 transport network, emitters outside clusters rely on costly and inefficient transport chains, further strained by the Netherlands' high energy prices, which increase compression and transport costs (Pires et al., 2011). Offshore storage projects like Porthos and Aramis are critical for scaling carbon capture, but their limited or uncertain capacity often prioritizes large emitters, leaving smaller companies at a disadvantage. This imbalance has led to calls for public oversight to ensure equitable access and prevent monopolistic practices in CO_2 storage markets (Mulder, 2024; Staten-Generaal, 2024). The Dutch ban on onshore storage exacerbates this issue, heightening dependence on offshore solutions and creating uncertainty about long-term capacity. International partnerships with countries like Norway and the UK, which offer significant offshore storage resources, present an opportunity to address these challenges but require coordinated strategies to align national priorities with international efforts (Teir et al., 2010).

Strategic public investments, transparent governance, and pricing mechanisms may be essential to expanding infrastructure access. More demonstration projects and early successes are also critical for building confidence among businesses and encouraging broader participation in carbon capture initiatives. Future research could explore ways to optimize infrastructure for dispersed emitters and strengthen the economic case for CO_2 utilization could also support broader adoption, ensuring carbon capture's role as part of a sustainable energy transition.

6.2.3. Public Perception and Acceptance

Public acceptance is vital for the success of carbon capture technology but faces significant challenges. Concerns about safety, CO_2 leaks, property damage, and fossil fuel dependency, along with the "Not in My Backyard" mindset, drive resistance (Berenblyum et al., 2021; Van Der Zwaan & Smekens, 2009). Offshore storage, though generally preferred, raises environmental concerns like ocean acidification (Ashworth et al., 2015; Federico et al., 2020). Scepticism is further fuelled by fossil fuel company involvement, with critics arguing that carbon capture may delay the transition to renewable energy and risk fossil lock-in (Bui et al., 2018). Subsidies for fossil-based carbon capture under schemes like SDE++ intensify these concerns, diverting resources from cleaner energy alternatives (Staten-Generaal, 2024).

In response, the Dutch government plans to phase out subsidies for fossil carbon capture by 2035, redirecting focus to renewable energy and sustainable alternatives (Mulder, 2024). Clear communication and consistent policies are essential to address conceptions and public expectations with decarbonization goals. Public awareness of carbon capture remains low, with fewer than 10% of respondents in countries like Canada and the UK familiar with the technology, while 60% oppose new projects (Boyd et al., 2017; Perdan et al., 2017). Similar trends in South Korea and China underscore the correlation between low awareness and resistance (Koh et al., 2019; Wang et al., 2021). In contrast, three-quarters of European energy experts view carbon capture as essential, revealing a disconnect between expert opinion and public sentiment (Shackley et al., 2007).

To build public trust, framing carbon capture as a transitional tool within broader decarbonization strategies may contribute. Transparent communication and campaigns can highlight carbon capture's role in reducing emissions while complementing renewable energy investments (Berenblyum et al., 2021; van der Zwaan et al., 2022). Engaging public concerns in policymaking, such as prioritizing biogenic CO_2 sources over fossil-derived CO_2, could

bridge gaps between societal priorities and policy objectives (Duetschke et al., 2014). A sector-specific approach can address localized concerns (van der Zwaan et al., 2022), while international collaboration on best practices may further improve acceptance. Future research could investigate the drivers of resistance, the role of trust in government and industry, and effective citizen engagement strategies.

6.3. Integrating Behavioural and Innovation Theories

This study integrates Rogers' Diffusion of Innovations (1962) and Ajzen's Theory of Planned Behaviour (1991) to analyse the adoption of carbon capture technology within organizations. Together, these frameworks explain how behavioural, technological, and social factors influence decision-making, highlighting the interplay between innovation attributes and adoption intentions.

Innovation attributes like relative advantages (e.g., emissions reductions, competitiveness) and compatibility strengthen attitudes toward carbon capture adoption. Trialability (e.g., pilot projects) and complexity influence perceived control, while high observability amplifies external pressures through subjective norms, as early adopters and opinion leaders have roles in shaping industry standards. Conversely, high complexity and low visibility reduce perceived control, hindering adoption intentions. TPB also complements DOI by explicitly addressing external pressures, such as those from investors, governments, or society, which Rogers' broader concept of the "social system" only partially captures. This integration provides a more comprehensive understanding of how external influences drive adoption decisions.

Building on Moore's concept of "crossing the chasm," carbon capture adoption may require more than technological innovation to appeal to the Early Majority. This group prioritizes proven solutions with low risk. For caron capture, this may means developing integrated strategies that include operational guarantees, risk-sharing mechanisms, and robust infrastructure. These measures can reduce perceived risks, enhance confidence, and overcome barriers to broader adoption.

By addressing the specific needs of the Early Majority through behavioural and innovation-focused strategies, policymakers and industry leaders may help transition carbon capture from a niche innovation to a mainstream decarbonization technology.

6.4. Theoretical Extensions

The Theory of Planned Behaviour (Ajzen, 1991) and Diffusion of Innovations (Rogers, 1962) provide valuable insights into carbon capture adoption by highlighting decision-making processes and innovation characteristics. However, these models have limitations when applied to system-dependent technologies like CCS. TPB's focus on individual behaviour may oversimplify organizational adoption, where external factors such as regulations, market dynamics, and industry standards are critical (Al-Mamary et al., 2016). Similarly, DOI's linear diffusion model may underrepresent the iterative and context-specific dynamics of CCS adoption, including leadership roles, organizational culture, and industrial collaboration (Axsen & Kurani, 2012). These gaps highlight the need for complementary frameworks that address systemic and socio-technical dimensions.

The Technological Innovation Systems (TIS) framework focuses on systemic functions such as market formation, resource mobilization, and knowledge development (Hekkert et al., 2007). Projects like Porthos in Rotterdam demonstrate how shared infrastructure, and industrial collaboration can mobilize resources and foster knowledge exchange. Similarly, the project highlights the importance of early government investment in addressing systemic barriers. Unlike DOI, which centres on adopter categories and innovation attributes, TIS emphasizes the structural and institutional changes necessary to scale carbon capture technologies.

The Multi-Level Perspective (MLP) situates carbon capture adoption within socio-technical transitions, exploring the interplay between niche innovations, dominant regimes, and landscape pressures (Geels, 2002). In the context of CCS, landscape pressures such as decarbonization targets and public demand for sustainability create opportunities for pilot projects to emerge in protected niches. Pilot projects illustrate how these innovations can scale and challenge entrenched fossil fuel regimes when supported by external pressures and aligned with policy incentives. MLP expands on DOI by framing innovation as part of a dynamic and multi-layered transition, rather than a linear process.

Network theory builds on TPB by focusing on social structures and relationships that drive carbon capture adoption (Granovetter, 1978; Valente, 1996). Industrial clusters like Rotterdam-Moerdijk illustrate how collaboration and knowledge-sharing reduce risks and creates momentum for broader adoption. A key dynamic within these networks is the concept of thresholds, where organizations are more likely to adopt carbon capture technologies once a

critical number of their peers have done so. Crossing these thresholds creates legitimacy and lowers perceived risks, further accelerating diffusion (Granovetter, 1978). Therefore, early adopters within the Rotterdam-Moerdijk cluster may serve as benchmarks for other industrial clusters, demonstrating the feasibility of CCS and reducing uncertainty for later adopters.

Within these networks, opinion leaders, such as industry consortia or early adopters, catalyse adoption cascades by demonstrating feasibility and influencing others (Iyengar et al., 2011). These dynamics occur when organizations cross adoption thresholds, gradually building momentum. For CCS, achieving critical mass is essential. As the number of adopters grows, network effects amplify legitimacy, adoption accelerates, and the technology becomes self-sustaining (Katz & Shapiro, 1985). These dynamics extend beyond the behavioural focus of TPB and linear assumptions of DOI, offering a broader perspective on adoption pathways.

Future research could develop diffusion models that integrate internal and external factors influencing technology adoption, such as leadership, institutional structures, policy environments, and market readiness (Meade & Islam, 2006; Taherdoost, 2018). Exploring iterative processes, network structures like hubs and clusters, and the role of critical mass could provide further insights into scaling carbon capture technologies. Research on cognitive factors, such as risk perception and willingness to invest, and the evolution of successive technology generations, could refine diffusion models and inform adoption strategies.

6.5. Strengths and Limitations

This research combined surveys and interviews to explore how Dutch industrial companies adopt carbon capture technology. By linking research questions to theoretical attributes, the study provided a clear framework for analysis, identifying broad trends and uncovering sector-specific insights into the behavioural and technological factors shaping adoption.

Focusing on Dutch ETS companies proved effective, as these organizations are key players in national carbon capture policies and account for a large share of CO_2 emissions. Including both large and small emitters ensured diverse perspectives, validated through desk research. However, sectors like cement, steel, and fertilizers were underrepresented, leaving some important dynamics unexplored. While the findings apply beyond the Netherlands, sectoral and regional nuances require further study.

The combination of structured surveys and semi-structured interviews worked well. The surveys offered measurable insights into behavioural and innovation drivers, while the interviews added depth and context. However, the structured format of the survey made it harder to capture unexpected themes, and the smaller interview sample limited the range of perspectives. Companies already involved in carbon capture were more likely to participate, ensuring detailed and informed responses but reducing input from less-engaged organizations. Additionally, respondents unfamiliar with carbon capture found some survey questions challenging, leading to incomplete responses that had to be removed during data cleaning.

The study coincided with key developments in the energy transition, such as the publication of the Climate Plan 2025–2035 and ongoing parliamentary debates, increasing the relevance of its findings. Despite its strengths, the methodology had some limitations. Frameworks like TPB and DOI effectively addressed behavioural and technological factors but limited a systemic approach. The exclusion of non-ETS companies further narrowed the focus to regulated industries, leaving the dynamics of non-regulated emitters unexplored.

Future research can tackle these gaps by including more sectors, adding non-ETS companies, or using longitudinal methods to examine how policies and markets evolve over time. Focus groups and case studies could delve deeper into sector-specific challenges, and more flexible approaches could help uncover emerging themes.

7. Conclusion

This study explored the adoption and diffusion of carbon capture technologies within the Dutch industrial sector, focusing on companies regulated under the EU Emissions Trading Scheme. Using a mixed-methods approach of surveys and semi-structured interviews, it explored key drivers, barriers, and sector-specific dynamics influencing adoption. Grounded in Rogers' Diffusion of Innovations and Ajzen's Theory of Planned Behaviour, the research highlighted how behavioural, technological, and contextual factors shape decision-making processes.

The findings show that large emitters (over 1,000 kilotonnes CO_2 annually) are leading adoption, with the potential to capture 10 megatonnes annually by 2030 and 25 Mt by 2040. These companies have lesser alternatives and may act as catalysts for broader adoption, demonstrating feasibility through increased pilot projects and shared infrastructure, helping to bridge Moore's "chasm" to the early majority. Smaller emitters face greater challenges, including limited economies of scale, restricted infrastructure access, and financial constraints, often making alternatives like electrification more attractive.

Adoption is shaped by a complex interplay of drivers and barriers. Economic incentives (e.g., reputational gains and competitive advantages) and operational capabilities (e.g., technical expertise and access to infrastructure) drive adoption intentions, while external pressures from regulations and societal expectations provide additional incentives. Barriers like high costs, infrastructure gaps, uncertain alternatives, and societal concerns (regarding safety and fossil fuel dependence) lower adoption intentions. Furthermore, smaller emitters, which are often reliant on infrastructure shared with larger companies, face additional logistical and economic hurdles, though having more alternative options available.

Scaling adoption will require an increase in pilot projects and innovations to drive down costs, improve CO_2 utilization, and reinforce the effectiveness of ETS price mechanisms. Key priorities include investments in CO_2 transport networks, enhanced accessibility to offshore storage facilities, and transparent sectoral regulatory frameworks. Equally important is fostering public engagement to build societal trust. The Netherlands, with its strong regulatory environment and access to offshore storage, is well-positioned for large-scale carbon capture. However, addressing equity in infrastructure access and mitigating competitive imbalances may be needed to ensure widespread adoption.

This research emphasizes carbon capture's role as a transitional technology, particularly in hard-to-abate sectors. Beyond the Netherlands, the findings offer insights for industrialized nations integrating carbon capture into decarbonization strategies. Future research could explore underrepresented sectors, examine longitudinal impacts of adoption, and develop strategies to align public perceptions with policy goals. These efforts are essential for advancing carbon capture as a cornerstone of the energy transition.

A successful transition may require a cross-sectoral approach that balances technological innovation, economic feasibility, and societal acceptance. A clear, long-term roadmap towards and beyond 2050 may guide further decarbonization efforts while addressing both challenges and opportunities.

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Appendices

Appendix A: Survey Questionnaire

Thank you for participating in this research. Please be assured that all responses will be kept confidential and used exclusively for academic research purposes, ensuring your anonymity. The survey is expected to take approximately 10-15 minutes to complete.

1. **Demographics:** In which sector does your organization operate? [Open answer]
2. **Demographics:** What is the size of your company? [Multiple choice]
3. **Demographics:** What is your position within the company? [Multiple choice]
4. **Demographics:** How actively are you involved in the innovation process within your organization? [Rating 1–5]
5. **Demographics:** What is your organization's approximate direct (scope 1) carbon footprint? [Multiple choice]
6. **Decision-making / Actual Behaviour:** Please select the stage that best describes your organization's status regarding carbon capture technology adoption. [Multiple choice]
7. **Adoption-rate:** If your organization has adopted carbon capture, when did your company start using this technology? [Multiple choice]
8. **Compatibility:** How well does carbon capture technology fit within your organization's growth strategies and sustainability goals? [Multiple choice]
9. **Compatibility:** To what extent does carbon capture technology integrate with your current operational processes without significant changes? [Multiple choice]
10. **Complexity:** Please rate the complexity of implementing carbon capture technology in your organization from the following perspectives: technical challenges, business case, financial resources, regulatory aspects. [Likert]
11. **Compatibility:** To what extent does your organization need carbon capture technology to address immediate and future needs for carbon management? [Likert]
12. **Perceived Behavioural Control:** How confident is your organization in its ability to successfully implement and manage carbon capture technology? [Rating 1–5]
13. **Relative Advantage:** To what extent does adopting carbon capture technology provide your organization a competitive advantage over others who have not adopted it? [Rating 1–5]
14. **Relative Advantage:** Does carbon capture technology offer a more comprehensive solution compared to other decarbonization options available to your organization? [Multiple choice]
15. **Relative Advantage:** Do the financial benefits outweigh the initial and operational costs of implementing carbon capture technology in your organization? [Multiple choice]

16. **Attitude:** What is your overall assessment of carbon capture technology in terms of its benefits and drawbacks for your organization? [Rating 1–5]

17. **Norms:** Please rate the level of expectations to adopt carbon capture technology for the following stakeholders on your organization's decision: board members, shareholders, clients, employees, government, public, industry peers. [Likert]

18. **Observability:** How visible would the benefits and outcomes of applying carbon capture technology be to your organization's key stakeholders: financial outcomes, environmental impact, operational efficiency. [Likert]

19. **Relative Advantage:** How do you anticipate adopting carbon capture technology will influence your organization's reputation in terms of innovation and environmental responsibility? [Multiple choice]

20. **Trialability:** To what extent can your organization conduct small-scale pilot tests or trial runs with carbon capture technology before full-scale implementation? [Multiple choice]

21. **Complexity:** Please rate the level of complexity your organization faces when scaling up carbon capture technology after initial trials. [Multiple choice]

22. **Perceived Behavioural Control:** What are the main challenges your organization faces in adopting carbon capture technology? [Open question]

23. **Intention:** How likely is your organization to adopt carbon capture technology within the next year(s)? [Rating 1–5]

24. **Closing:** Are there any other comments, concerns, or suggestions you would like to share about adopting carbon capture technology in your organization? [Open question]

25. **Follow-up:** Would you like to engage further with our research? Please select all options that apply to you. If interested, please leave your e-mail below. [Multiple choice]

Appendix B: Interview Questions

The following questions served as guidelines for interviews conducted to explore the adoption of carbon capture technologies within Dutch industries under the EU Emissions Trading System (ETS). These questions were adaptable, and the conversation could deviate depending on the context and responses from the interviewee.

Introductory

a. Brief introduction of the interviewer and the study.

b. What is your role within the company?

c. Could you briefly describe the emitting processes in your organization?

Core Questions

1. **Relative Advantage**: Can you describe why carbon capture offers more, or fewer benefits compared to other solutions, such as in terms of efficiency, cost savings, or ease of use?
2. **Compatibility**: How does carbon capture align with the existing values and practices of your organization?
3. **Complexity**: What challenges do you foresee in implementing this innovation, such as technical, financial, or operational barriers?
4. **Trialability**: Is it possible to test carbon capture on a small scale before committing to full implementation? If so, how would you approach this?
5. **Observability**: How visible are the benefits of carbon capture to others within or outside your organization?
6. **Adoption Rate:** What factors influence the speed and extent of carbon capture implementation? When did your organization begin considering this technology?
7. **Decision-making Process:** What steps and considerations are your organization currently taking when deciding on this technology?
8. **Attitude**: What is the general attitude of your organization toward implementing carbon capture?
9. **Norms**: What expectations or external pressures from stakeholders influence your organization's decision to adopt carbon capture technology?
10. **Control**: How easy or difficult is it to implement carbon capture technology in terms of available resources and external factors?
11. **Behavioural Intention:** How likely is it that your organization will adopt carbon capture technology in the future?
12. **Actual Behaviour:** What concrete steps has your organization taken toward adopting carbon capture technology?

Supplementary Questions

- What do you see as the key bottlenecks in your business model for carbon capture and storage?
- What changes do you think are necessary to make carbon capture and storage more accessible and feasible?
- Under what conditions do you think implementing a pilot plant would be feasible, and when would it not be?
- In what timeframe do you see the necessity for CO_2 reduction and the adoption of carbon capture technologies?
- What are your expectations regarding carbon capture and storage initiatives?
- Why do you think alternatives might be considered better than carbon capture and storage?
- At what stage in your process would you consider applying carbon capture, and which specific technologies are you exploring?