THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Decision Making Beyond Models of Bioenergy with Carbon Capture and Storage

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Cover:
A bubble plot of CO_2 emissions from Swedish bioenergy actors. While such actors *could* deploy carbon capture and storage to align with scenarios of global climate mitigation models, only one actor has decided to deploy the technology as of 2025.

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Abstract

Although bioenergy with carbon capture and storage (BECCS) is a prominent CO_2 removal technology in global climate mitigation models, its deployment remains limited. To understand how BECCS could be scaled up beyond models, I identify key investment conditions for prospective BECCS actors in Sweden, including operators of combined heat and power (CHP) plants and pulp mills. Using robust decision making (RDM) methods, I combine the analytical strengths of models and actors to characterize investment decisions that are robust across uncertain scenarios. I find that actors need to exercise political power beyond their normal system boundaries to effectuate policies and discourse supportive of BECCS. Across most scenarios, the CHP actor Stockholm Exergi was found to require 151 EUR/tCO_2 from voluntary carbon markets. In practice, they may have secured higher market revenues plus subsidies at 160 EUR/tCO_2. Similarly, the CHP actor E.ON could require market revenues above 185 EUR/tCO_2 and subsidies at 160 EUR/tCO_2 to enable a robust investment. For CHP plants, incentives from the European Emissions Trading System could be insufficient unless allowance prices rise sharply or BECCS credits are integrated into the system through public procurement. Furthermore, actors should assess the capital costs of oxyfuel and chemical looping rigorously: If these capital costs are low, actors may regret opting for more mature capture technologies. Finally, BECCS actors need to utilize bioenergy responsibly, for example by recovering energy from industrial residues where biomass is sourced from biodiverse and net-negative forest. About 19 MtCO_2 p.a. could be captured from 113 existing bioenergy plants without sourcing any additional biomass, while the associated costs and CHP penalties could be constrained by efficient heat integration choices.

Keywords: *bioenergy, carbon capture and storage, BECCS, robust decision making*

List of Publications

This licentiate thesis is based on the research conducted in the following papers, which will be referred to by their Roman numerals:

(I) Stenström, O., Dilip Khatiwada, Levihn, F., Usher, W., and Rydén, M. (2024). A robust investment decision to deploy bioenergy carbon capture and storage—exploring the case of Stockholm Exergi. *Frontiers in Energy Research*, 11.

(II) Stenström, O., and Rydén, M. (under review). Regretting carbon capture from bioenergy – a case study. *International Journal of Greenhouse Gas Control.*

(III) Stenström, O., Kumar, T. R., and Rydén, M. (2025). A million scenarios to identify conditions for robust bioenergy carbon capture in Sweden. *International Journal of Greenhouse Gas Control*, 145, 104411–104411.

Oscar Stenström is the main author of and contributor to all appended papers. Significant contributions include study conceptualization, methodology, analysis, writing, and visualization. Magnus Rydén has contributed to all appended papers, mainly by supervising and reviewing the work, and by conceptualizing papers (II) and (III). Dilip Khatiwada and Fabian Levihn contributed by supervising and conceptualizing paper (I). Additionally, Dilip Khatiwada, Fabian Levihn, Will Usher, and Tharun Roshan Kumar have contributed to developing methodologies and by reviewing manuscripts. Detailed author contributions can be found in the appended papers.

Declaration of the Use of Generative AI

In papers (II) and (III), the generative AI ChatGPT was used to revise text originally written by the authors. Respectively, in papers (II) and (III), Claude Sonnet and ChatGPT were used to draft Python code. However, the text in this licentiate thesis is written without the use of AI.

Acknowledgments

I feel highly privileged to have collaborated with exceptional individuals during these initial years of my PhD. Similarly, I feel highly privileged knowing that a few years of continued collaboration lies ahead.

First and foremost, I want to thank my main supervisor Magnus Rydén. Your approach to supervision has undoubtedly kept me curious, challenged, and motivated. My ideas can be all over the place, yet you make serious efforts to engage with them. This engagement, underpinned by equal doses of skepticism and appreciation, contributes substantially to my sense of privilege.

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To my companions at the Division of Energy Technology, including Adam, Alice, Eliette, Iacopo, Judit, and Luis, and my comrades in the Graduate School of Energy Systems: Thank you for making these environments so engaging, inviting, and memorable—during and after office hours.

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Finally, I would like to thank my family for being such a varied constellation of deeply caring individuals, and Taalke, for being you and for being in my life.

List of Abbreviations

ASU	Air Separation Unit
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CART	Classification and Regression Tree
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CEO	Chief Executive Officer
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DACCS	Direct Air Carbon Capture and Storage
DR	Discount Rate
ESR	Effort Sharing Regulation
EU	European Union
ETS	Emissions Trading System
GHG	Greenhouse Gas
HHV	Higher Heating Value
HPC	Hot Potassium Carbonate
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LHV	Lower Heating Value
LULUCF	Land Use, Land-Use Change and Forestry
NPV	Net Present Value
OPEX	Operational Expenditure
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making
VCM	Voluntary Carbon Market

Table of Contents

List of Figures

List of Tables

1. Introduction

I became interested in carbon capture and storage (CCS) in 2023. At the time, I carried out a master's thesis project at Värtaverket, a Swedish combined heat and power (CHP) plant operated by Stockholm Exergi. Their plan was to couple an existing bioenergy combustion process with CCS (Levihn et al., 2019). Through CCS, the CO_2 generated from combustion would be captured, liquified, transported, and stored in bedrock. Such an integrated bioenergy conversion and CCS process is referred to as BECCS.

BECCS is a solution to a contested problem. On the one hand, BECCS could contribute to mitigating climate change by removing CO_2 from the atmosphere (CDR). On the other hand, powerful actors could rely on CDR to delay emissions reductions, thereby perpetuating our fossil-fueled energy system (Almqvist-Ingersoll, 2025). So what problem is BECCS solving? Although the reader can tentatively think of BECCS as a solution to atmospheric CO_2 removal, I will later define the problem in terms of both CO_2 imbalances and political power.

How BECCS achieves CDR is illustrated in Figure 1. First, biomass absorbs atmospheric CO_2 through photosynthesis. The biomass is then used as a feedstock for BECCS, where it is converted through combustion, gasification, or pyrolysis. The generated CO_2 is captured and stored underground, rather than re-emitted into the atmosphere. Note that some CO_2 is emitted during biomass harvest and processing and CO_2 transport and storage, indicated by the small arrows in Figure 1. The net flux of CO_2 removed from the atmosphere can thus be determined through life cycle assessment (Fajardy & Köberle, 2019). For example, in the Stockholm Exergi case, harvest and processing emissions amount to less than 2.5 % of the combustion emissions (cf. Hammar & Levihn, 2020).

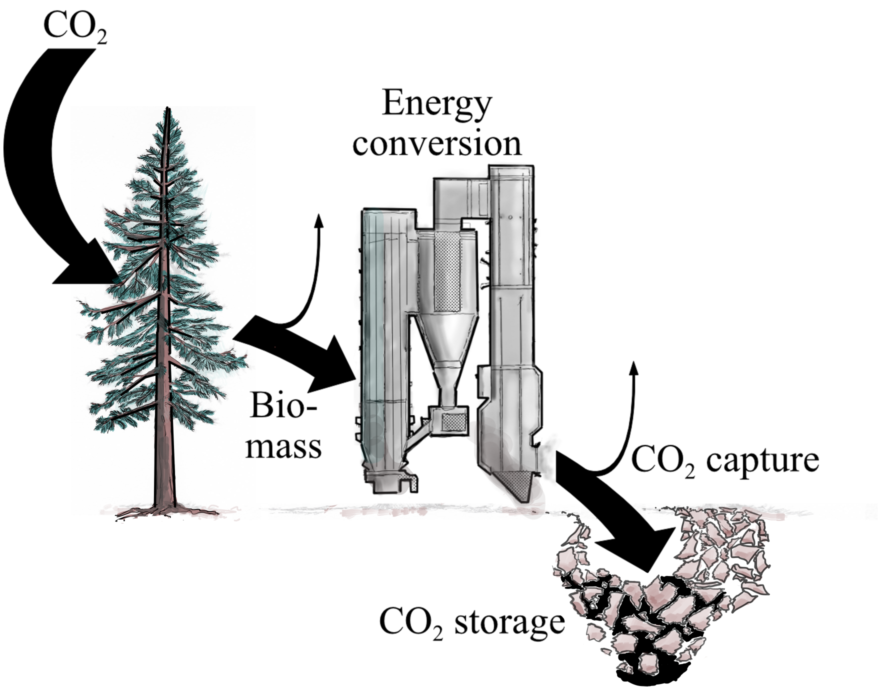

Figure 1: *Illustration of how BECCS achieves atmospheric CDR. Black arrows represent carbon in the form of CO_2 or biomass. Some CO_2 could be emitted during biomass harvest and processing, for example from machinery or decomposing biomass residues, or leaked during transport and storage. In Swedish applications, such emissions are generally low* (*in the order of a few percentages*) *relative to the captured combustion CO_2. The transportation step has been omitted from the illustration.*

CCS is not new: Across various commercial projects, CO_2 has been captured and stored in geological reservoirs for decades. One example is the Norwegian Sleipner project, which began operations in 1996 (Steen et al., 2024). However, commercial projects have mainly coupled CCS with fossil fuel systems, so bioenergy applications are relatively novel. The main difference is that fossil CCS prevents CO_2 emissions from geological-origin fossil fuels, while BECCS removes atmospheric CO_2 (Minx et al., 2018).

While BECCS holds mitigation potential, its upscaling has thus far been contentious and difficult. Studying a frontrunner like Stockholm Exergi was therefore a humbling experience. They required expertise and actions across many dimensions—technical, political, economic, and regulatory—to enable their final investment decision in 2025 (Stenström et al., 2024; Stockholm Exergi, 2025). Despite these actions, enabling conditions for other BECCS projects have not been fully realized. It is still uncertain whether or how enduring incentives can be established, and incumbent bioenergy actors can incorporate BECCS in their business models (Lefvert, 2024).

Similarly, it is uncertain how upscaling can occur without delaying emissions reductions, and while safeguarding sustainable biomass practices (Rodriguez, 2024). Indeed, when discussing BECCS, the challenge of upscaling is among the thorniest (cf. Fuss and Johnsson, 2021). Alternatively, this challenge can be defined more broadly as the challenge of scaling up all novel CDR methods, such as BECCS, biochar, direct air CCS (DACCS), and enhanced rock weathering. In global scenarios likely to limit global warming to 2°C or less, novel CDR is scaled up by an extraordinary factor of 260-4900 (median 1300) by 2050 relative to 2020 levels. This implies an increase from 0.002 to 0.52-9.8 $GtCO_2$ p.a. (Smith et al., 2023). Similarly, in the 6th assessment report by the Intergovernmental Panel on Climate Change (IPCC), below 2°C scenarios portray BECCS capacities between 0.52-9.45 $GtCO_2$ p.a. by 2050 (IPCC, 2023). If climate targets are to be met, strengthened scale-up efforts may be needed by researchers, industry, and policymakers (Smith et al., 2023; Lamb et al., 2024; Fridahl et al., 2023).

However, since the IPCC's 5th assessment cycle, large-scale BECCS has been hotly debated. Prominent issues include land and water constraints, carbon cycle responses, lifecycle emissions, costs and financing, social acceptance, institutional capacity, biodiversity impacts, and risks of delayed emissions reductions (Fuss, 2014; Fajardy and Köberle, 2019; Rodriguez, 2024). These issues have led researchers to question the feasibility of large-scale BECCS in climate scenarios, and in turn, the appropriateness and authority of the underpinning science. This critique has mainly targeted top-down research of integrated assessment models (IAMs) evaluated by the IPCC (Gambhir et al., 2019; Low and Schäfer, 2020; Haikola et al., 2019; Hansson et al., 2021). Similarly, concerns have been raised that BECCS mainly serves the interests of powerful incumbents reliant on fossil fuels (Lefstad et al., 2024; Carton et al., 2020).

Some of the critique against top-down models have motivated my bottom-up research. Bottom-up studies of prospective BECCS actors can provide insights into feasibility, enabling conditions, and wider societal impacts of BECCS from a real-world context (Rodriguez, 2024; Lefvert, 2024). Relatedly, calls have been made for more national cases studies on novel CDR (Smith et al., 2023). I have chosen to contribute to these research gaps by studying the decision making of prospective BECCS actors. If actors like Stockholm Exergi consider an investment decision (cf. Stenström et al., 2024) then their perspectives could reveal whether or how BECCS can be scaled up. Under this framing, BECCS is not only an abstraction in (contested) models, but a possible infrastructure commitment beyond models.

My focus on decision making beyond models is not a rejection of models. Rather, the idea is to research decision-making problems faced by humans, and to leverage the complementary strengths of models and humans to explore these problems. To systematize this methodology, I rely on the theoretical framework robust decision making (RDM) (Lempert, 2019). The framework supports robust decisions by letting stakeholders iteratively frame an uncertain decision and then evaluate this decision across a wide range of scenarios. The evaluation is based on stakeholder-defined performance criteria, for example energy efficiency, costs, or CO_2 mitigation. The RDM process requires models, but relies on these to support decision making rather than to make predictions (Lempert, 2019).

Like Rodriguez (2024) and Lefvert (2024), my work focuses on BECCS in Sweden. Sweden has an unusually large bioenergy sector, including centralized pulp and paper industries and biomass- and waste-fired CHP plants. Furthermore, Swedish bioenergy actors can apply for BECCS state aid via reversed auctioning (Fridahl et al., 2024), and CO_2 storage could be available on Norwegian or Danish territory (Anthonsen and Christensen, 2021). Along with a national net-negative climate target, these conditions have spurred interest in BECCS from other actors than Stockholm Exergi. For example, the energy utility E.ON is planning for BECCS in the city of Malmö (Ramboll, 2023), which is a case that I will detail later. Beyond Stockholm Exergi and E.ON, a range of CHP and pulp actors are at different stages of developing BECCS (Beiron and Johnsson, 2024), although most actors still lack enabling conditions (Lefvert, 2024). Given the increasing but contingent domestic interest in BECCS—and my own interest in BECCS at the intersection between science, industry, and policy—I consider Sweden a suitable focus. My scope and research aim are further specified below.

1.1 Research Aim and Scope

My aim is to investigate the decision making of frontrunners and prospective operators of BECCS in Sweden. In pursuit of this aim, I apply RDM to answer the following question:

What conditions would enable Swedish decision makers to make robust, energy-efficient, and economic investments in BECCS?

By decision makers, I refer to actors operating biomass- and waste-fired CHP plants and pulp mills. Of these, I have studied two cases of BECCS coupled to biomass-fired CHP in greater detail. These cases concern Stockholm Exergi and E.ON, as introduced in Section 2.3.4.

The word robust refers to a robust decision, i.e., one that performs satisfactorily against stakeholder-derived performance criteria across a wide range of scenarios. When applying RDM, robust decisions are preferred over optimal decisions, since the latter can be vulnerable to uncertain scenarios (Lempert, 2019). RDM thus copes with the deep uncertainties facing (and deterring) decision makers. I am mainly focusing on investment decisions, implying that BECCS is paid for, built, and operated over a technological lifetime.

By energy efficient, I refer to a BECCS system that demands little additional biomass and grid power relative to a reference system without CCS. Furthermore, I refer to a system that converts biomass efficiently to useful heat and/or power. These efficiencies mainly depend on the level of heat integration and choice of CO_2 capture technology. The technologies discussed in this work include post-combustion capture using amines or hot potassium carbonate (HPC), oxyfuel combustion, and chemical-looping combustion.

By economic, I refer to an investment of low costs per ton of CO_2 captured and stored, or of positive net present value (NPV). NPV is a metric that summarizes the discounted costs and revenues of an investment over its economic lifetime, as described in Section 3.2.1. The revenues mainly depend on scenarios of energy prices and of policy support for BECCS and CDR.

Notably, my scope includes multiple models of BECCS deployment decisions. However, it also includes considerations of BECCS beyond models, such as actor perceptions of important BECCS conditions, Swedish and European Union (EU) policy and governance structures, scenarios of system shocks, and epistemological implications of BECCS modelling exercises. I believe these considerations are important to understand BECCS as a solution to the climate problem. While my aim is not to assess how BECCS can be a "solution" to delay emissions reductions (Almqvist-Ingersoll, 2025) the issue is recognized throughout this thesis.

After Section 1, i.e., this introduction, the rest of the thesis is structured as follows. Section 2 provides background. Here, I frame the climate problem as an imbalance of CO_2 emissions and political power, and I detail the potential for BECCS in Sweden. Section 3 describes my methodology. This includes my epistemological and ontological premises and my application of RDM and related algorithms. Section 4 covers analysis and discussions of my findings. Section 5 concludes.

2. Background

This section provides background based on a selection of literature that discuss BECCS. The selection is based on my judgment rather than systematic criteria, like those in literature reviews. A limitation of this approach is that it is selective, not fully representing any specific research field. A benefit is that it represents an integrated description of BECCS from diverse fields.

Below, I first draw from natural and social science to frame the climate problem as a carbon and power imbalance. I then describe key technology, governance, and investment conditions for Swedish BECCS.

2.1 The Carbon and Power Imbalance Problem

As implied, the role of BECCS depends on what problem it is envisaged to solve. I will therefore elaborate on my own problem definition, which is essentially a product of two streams of research that define the problem of climate change. Firstly, Allen et al. (2022) and related research (e.g. Allen et al., 2024; Fankhauser et al., 2022; Jenkins et al., 2022; Solomon et al., 2009) have defined the climate problem as an imbalance of greenhouse gas (GHG) emissions. The crucial solution to this problem is to balance emissions, thereby achieving net zero and halting global warming. Put differently, net zero is ”a balance between ongoing anthropogenic release of [GHGs] into the atmosphere and active GHG removal either through direct capture and disposal or anthropogenically enhanced natural removal processes: The term may be applied to an individual gas, such as CO_2, or a basket of gases combined using a GHG metric” (Allen et al., 2022).

Out of all GHG imbalances, the main problem is the carbon imbalance: CO_2 has induced most of global warming (Jenkins et al., 2022) and net zero requires radical reductions in CO_2 emissions from fossil fuels and land use (Fankhauser et al., 2022) which conflicts with fossil-based infrastructure, norms, and development strategies of most countries (Stoddard et al., 2021). Similarly, limiting global warming to 1.5 °C or 2 °C, in-line with the Paris Agreement

(UNFCCC, 2015), is contingent on limiting future cumulative CO_2 emissions and thereby staying within a so-called "carbon budget" (Kriegler et al., 2018). Notably, the relationship between carbon imbalance and global temperature increase can be approximated by Equation (1) (Allen et al., 2024).

$$dT_{CO_2} = \kappa_E[E_{GEO} + E_{LUC} + (\rho_F - \rho_E)G]\Delta t \tag{1}$$

Here, ΔT_{CO_2} is the CO_2-induced warming over a multi-decade time interval Δt, while the total warming comprises ΔT_{CO_2} plus non-CO_2 warming. ΔT_{CO_2} is induced by E_{GEO}, the net rate of CO_2 emissions from fossil fuels and industrial processes, by E_{LUC}, the net rate of biogenic CO_2 emissions from anthropogenic land-use change, and by G, the cumulative net CO_2 emissions from human activities from pre-industrial times up to the mid-point of Δt. Furthermore, the constant κ_E has been assessed to 0.45(±0.18) °C per trillion tonnes of CO_2 emitted, while the difference $(\rho_F - \rho_E)$ could be approximately zero if key climate-stabilizing systems—like the biosphere CO_2 sink and the deep ocean's overturning cycle—remain intact (Allen et al., 2022).

While this carbon imbalance equation should be considered a reductionistic approximation of complex climate dynamics, Allen et al. (2024) note that "Equation (1) reproduces, within uncertainties owing to internal climate variability, the response of coupled climate–carbon-cycle models to a broad range of emissions scenarios up to the time of peak warming". To provide an example, if $E_{GEO} + E_{LUC}$ equals 36.3 $GtCO_2$ like current annual emissions (Deng et al., 2025), then Equation (1) yields a CO_2-induced warming of +0.4°C between 2025–2050.

The carbon imbalance problem could be solved, in part, through BECCS. In the short term, BECCS and other CDR can reduce net emissions and thus the induced warming from E_{GEO} and E_{LUC}. Furthermore, some emissions may be hard to abate due to costs or lack of abatement options, such as from aviation, cement, or waste-to-energy. Rather than eliminated, these residual emissions could be compensated for by BECCS to ensure $E_{GEO} = 0$. Finally, in case of temperature overshoot, BECCS and other CDR could enable net-negative CO_2 emissions ($E_{GEO} + E_{LUC} < 0$), which may reverse temperatures. These are three commonly imagined roles that BECCS could play in solving the climate problem (IPCC, 2023).

The second stream of research that influences my problem definition is that of Stoddard et al. (2021), who synthesize findings from, e.g., Ekberg et a. (2022), Nasiritousi (2017), Stirling

(2014), and Carton et al. (2020). Based on nine diverse perspectives, they describe why the carbon imbalance has persisted, and identify power as a common explanation. This includes entrenched and institutionalized power, like that of the fossil fuel industry; instrumental forms of power, like reductionistic economic and mitigation modelling; and the power of ideas, like the inability of low-carbon imaginaries to challenge high-carbon lifestyles. Note that this definition of power is broad: It encompasses diverse ways through which human relationships inhibit or facilitate system changes. I refer to this problem framing as a power imbalance, since the solutions supposedly lie in disrupting dominant power structures (Stoddard et al., 2021).

In Table 1, I draw on the nine perspectives to exemplify how power sustains the carbon imbalance (i.e. net CO_2 emissions). My ambition is not to provide an exhaustive analysis of the relationship between power and climate change. Rather, the idea is to illustrate that the climate problem can be considered an integrated carbon and power imbalance: If power structures like the fossil fuel industry or high-carbon norms were disrupted, the carbon imbalance would be easier to solve (cf. Gheels, 2014). For more details, the reader may refer to Stoddard et al. (2021).

If Table 1 illustrates our problem, then BECCS is not an obvious solution. Conversely, BECCS has been criticized since it could be relied upon to perpetuate the fossil status quo (Markusson et al., 2024; Rodriguez, 2024; Carton et al., 2020; 2023; Almqvist-Ingersoll, 2025). For example, the Stockholm Exergi project could lead to overall reduced emissions reduction efforts depending on what emissions it ends up offsetting (Olsson et al., 2024; Dufour et al., 2024). More broadly, the inclusion of large-scale BECCS in IAM scenarios has reconciled stringent climate targes with relaxed emission reduction ambitions (Obersteiner et al., 2018), emphasized mitigation pathways that are non-disruptive to society while framing out others (Hansson et al., 2021), and enabled the conception of (potentially infeasible) temperature overshoot and return pathways (Reisinger et al., 2025).

Both power and carbon imbalances are therefore important when thinking of BECCS as a solution to the climate problem. Similarly, both aspects are important for decision makers deploying BECCS. For example, decision makers may want to contribute to carbon balance, or ($E_{\text{GEO}} + E_{\text{LUC}} = 0$), but may have limited power to do so, due to lacking agency or incentives. Essentially, this dual problem definition provides dual perspectives on how BECCS functions as a “solution”.

Table 1: Stoddard et al. (2021) described how power sustains the global carbon imbalance (net CO_2 emissions) through nine perspectives. Here, I provide examples based on these perspectives.

Perspective	Examples of how power sustains CO_2 emissions
International Climate Governance	*The international climate response regime, organized under the United Nations Framework Convention on Climate Change (UNFCCC), cannot enforce (sufficiently ambitious) national CO_2 mitigation commitments (Nasiritousi et al.,* 2024).
The Fossil Fuel Industry	*The industry is systematically obstructing progress on climate action, e.g., by discrediting science, lobbying, or silencing opponents (Ekberg et al.,* 2022).
Geopolitics and Militarianism	*Geopolitical competition drives resource extraction and control of, e.g., oil and gas, and is often enabled by military forces (Kaldor,* 2007).
Imaginaries	*The dominant imaginary that industrial activities and economic growth should be sustained prioritizes CCS as an emissions reduction solution, while alternative development imaginaries and emissions reduction opportunities are framed out (Lefstad et al.,* 2024).
High-carbon Lifestyles	*High-carbon activities, like commuting by car, are often routinized and embedded in culture, norms, and expectations, and are therefore difficult to change into low-carbon activities (cf. Kurz et al.,* 2015).
Inequity	*Collective climate action is undermined by responsibility principles that are perceived as unfair: For example, they do not fully reflect that developed nations have caused most of climate change while developing nations are more vulnerable to it (cf. Winkler et al.,* 2018).
Economics and Financialization	*The union of neoclassical economics and neoliberal ideology enforces a narrow, monetized, and market-based definition of (and approach to) development, rendering climate externalities deprioritized and GDP growth prioritized (Raworth,* 2017).
Mitigation Modelling	*The scope for climate policy is mainly dictated by IAM research, as communicated through IPCC assessments, which tends to filter out more diverse representations of possible climate transition pathways and fundamental criticisms (towards BECCS) and risk legitimizing relatively relaxed decarbonization efforts (Hansson et al.,* 2021).
Energy Supply Systems	*Policies that reduce fossil fuel usage are necessary—since new energy infrastructure tends to be additional to (rather than replace) incumbent energy infrastructure—but must overcome the energy–economic growth paradigm including its vested fossil fuel interests (York and Bell,* 2019).

2.2 The Potential for BECCS in Sweden

The previous critical discussion of BECCS as a solution to the climate problem will now be followed by a more descriptive discussion of Swedish BECCS potentials. Below, I describe centralized bioenergy conversion systems, BECCS technologies, policy and governance structures, and key investment conditions.

2.2.1 Centralized Bioenergy Conversion

Compared to other countries, Sweden has advantageous conditions for BECCS owing to its well-developed forestry industry and centralized bioenergy conversion infrastructure (Fuss and Johnsson, 2021). Around 120 TWh of forestry biomass is energy converted annually. Major bioenergy consumers include CHP plants and pulp mills, of which the latter combust around 40 TWh to recover pulping chemicals (Energiforsk, 2021). The biomass is typically combusted in boilers, where the generated heat is transferred to steam cycles and converted into electricity and process heat. The annual CO_2 emissions from CHP and pulp mill boilers are respectively visualized in the left and right maps of Figure 2. Here, pulp mills that produce paper products in addition to pulp are referred to as integrated. Although most of the CO_2 originates from biomass (36 Mt) a fraction originates from fossil sources (3.4 Mt), mainly fossil plastic in waste-fired CHP plants.

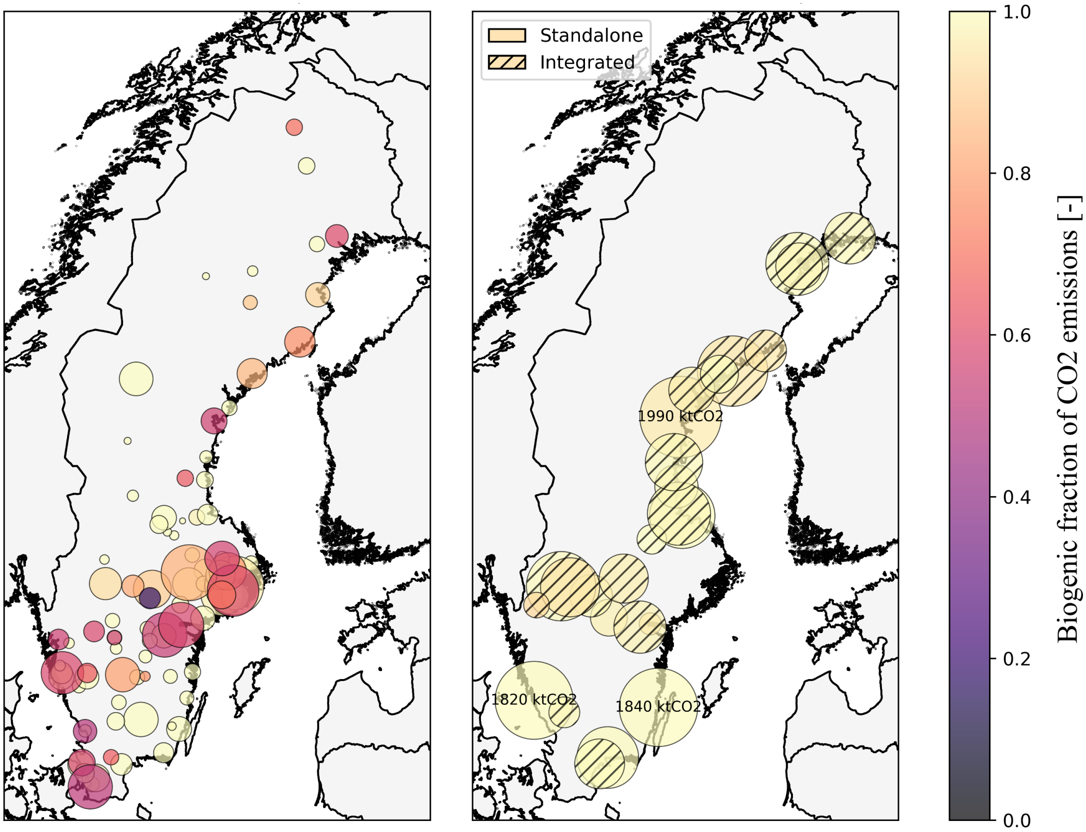

Figure 2: CO_2 emissions of CHP plants (left) and integrated and standalone pulp mills (right). Darker color indicates a greater fraction of fossil emissions, which is often the case for waste-fired CHP plants.

In biomass-fired CHP plants, boilers are often designed for fluidized bed combustion. Fluidization of solid biomass and bed material is enabled by large fans, and is advantageous since fuels of variable, high-ash, and high-moisture compositions can be reliably and efficiently converted (Störner et al., 2021). Waste-fired plants also rely on fluidized bed boilers, or grate-fired ones. Generally, CHP boilers supply heat to steam cycles, in which steam is expanded through turbines and condensed to generate power and district heating. District heating systems are common in Sweden. These are underground piping networks that distribute heated water at around 78-100 °C to meet building heat demands. Such CHP setups can be highly efficient, especially if boiler flue gases are condensed for additional district heating. For the fluidized bed boiler at Värtaverket, the total CHP output divided by the fuel input can reach 90 % based on the higher heating value (HHV) of the fuel, or 112 %, based on the lower (LHV) (Gustafsson et al., 2021).

Considering pulp and paper mills, these consume around 52 TWh of bioenergy annually, which is significant relative to the total industrial energy demand (all energy carriers) of 136 TWh (Energimyndigheten, 2025a). Most mills rely on the Kraft process, in which the largest CO_2 emission source is the recovery boiler (Lefvert, 2024). This boiler is used to recover process chemicals by combusting so-called black liquor, a byproduct from Kraft pulp cooking. Steam is generated by the combustion heat, expanded in turbines, and condensed to supply various process heat demands. To improve efficiencies, process waste heat could be recovered but it is typically of low grade (temperature). Available heat above 60 °C often corresponds to less than 15 % of bioenergy inputs (Cruz et al., 2021). For integrated mills, the availability of low-grade waste heat and high-grade steam is especially constrained, since these mills also supply energy demands for paper production (cf. Lacaze-Masmonteil, 2024).

Integrating BECCS into CHP plants or pulp mills entails different technological challenges and opportunities. One prominent challenge is the substantial energy penalty of capturing and compressing CO_2 from flue gases—as is often required in retrofit cases—before subsequent transport and storage. Opportunities for reducing energy penalties depend on the bioenergy conversion system, since CHP plants and pulp mills have different constraints on boiler designs and heat integration. Opportunities also depend on the chosen CO_2 capture technology.

2.2.2 BECCS technology

This section briefly describes CO_2 capture, conditioning, transport, and storage technologies. For details, the reader may refer to Bui et al. (2018). My focus is on capture technologies, since these affect the on-site operations of the studied decision makers. The CO_2 capture problem can be usefully understood by considering the stoichiometric air-oxidized combustion reaction in Equation (2).

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right)(O_2 + 3.77N_2) \rightarrow \left(\frac{y}{2}\right) H_2O + xCO_2 + 3.77\left(x + \frac{y}{4} - \frac{z}{2}\right) N_2 \qquad (2)$$

Here, complete combustion of a hydrocarbon fuel of composition x, y and z would require $(x + \frac{y}{4} - \frac{z}{2})$ units of oxygen. Oxygen is typically supplied by air, containing around 3.77 moles of inert nitrogen per mole of oxygen, implying that the mixed flue gas is diluted by $3.77(x + \frac{y}{4} - \frac{z}{2})$ units of nitrogen. In practice, more air than the stoichiometric air demand is usually supplied to ensure complete combustion, further diluting the flue gases. Work is then required to separate CO_2 from the diluted gas mix. The specific work increases as the CO_2 concentration (and partial pressure) decreases (Capocelli and De Falco, 2022).

This CO_2 separation problem can be solved in four distinct ways, illustrated in Figure 3. Through post-combustion capture processes, CO_2 is absorbed or adsorbed from the nitrogen-diluted flue gases. Amine-based absorbents are commonly used but require heat to release the absorbed CO_2, around 2-4 GJ/t (Bui et al., 2018). Alternatively, in pre-combustion processes, the fuel is first gasified or reformed and purified at elevated pressures, for example 30 bar. CO_2 separation then occurs before the fuel gas is combusted. Because separation occurs at high partial CO_2 pressure and low concentrations (or near-absence) of nitrogen, the separation work is small (Voldsund et al., 2016). An example of suitable absorbent in such applications is HPC, since it relies on a pressurized flue gas (cf. Gustafsson et al., 2021).

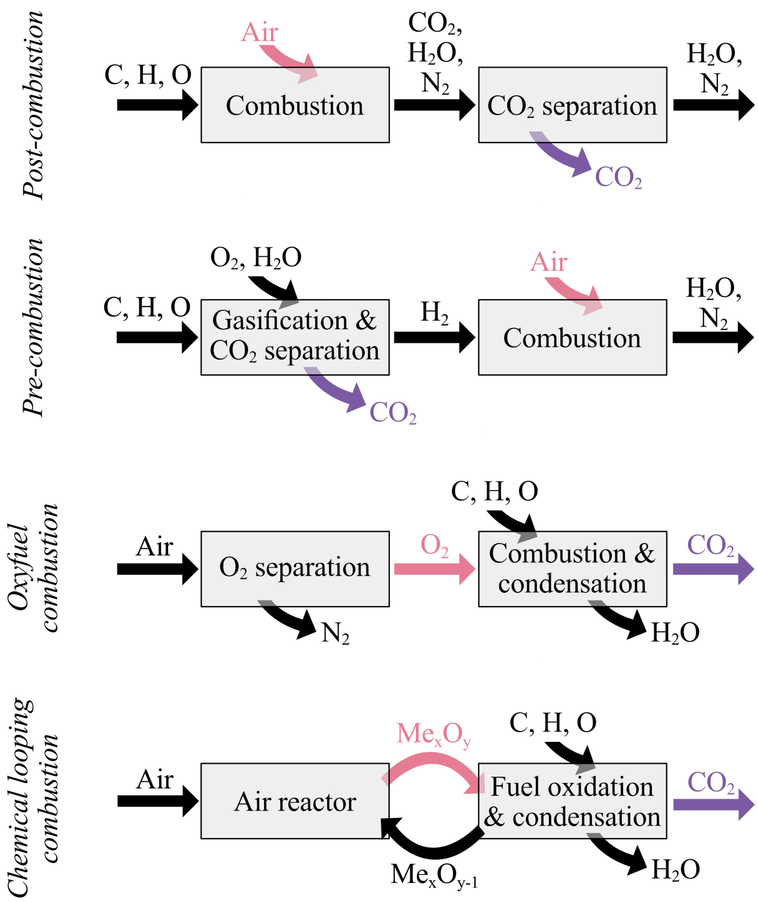

Figure 3: Four common capture technology families, including post- and pre-combustion capture, and oxyfuel and chemical looping combustion. Separated CO_2 is marked in purple and the oxygen supply in pink.

Oxyfuel and chemical looping combustion are two alternative capture technologies. Both supply the combustion reaction of Equation (2) with pure oxygen instead of air, thereby avoiding nitrogen in the flue gases. During oxyfuel, the oxygen is generated by an air separation unit (ASU), which requires a substantial power input of 230 kWh/tO_2 (Farajollahi and Hossainpour, 2022). During chemical looping, the oxygen is instead supplied by oxygen carriers. These are chemically active metal oxides (Me_xO_y) that function like bed material in fluidized bed combustion. The oxygen carriers are circulated between a fluidized bed fuel reactor, where the carriers are reduced and the fuel oxidized, and an air reactor, where the carriers are re-oxidized by input air. This oxygen carrier loop ensures that fuel and air never mix, and that oxygen is supplied to the fuel reactor without any significant energy penalty (Lyngfelt, 2020). Chemical looping has only been operated at around 3 MWth, although a 30-50 MWth plant is planned for in China (Haugen et al., 2023).

The present work mainly considers post-combustion capture using amines or HPC, oxyfuel, and chemical looping combustion.

Notably, energy efficiencies of CO_2 capture processes can often be improved by site-specific heat integration. For example, high-grade waste heat from an amine capture plant can be transferred to district heating systems using heat exchangers, while low-grade heat can be upgraded to higher (and useful) temperatures using heat pumps (Roshan Kumar et al., 2023). Equation (3) illustrates the heat transfer $\dot{Q}_{\text{HEX}}$ from a heat exchanger with properties UA under a logarithmic mean temperature difference ΔT_{lm} between a hot and cold stream. Equation (4) illustrates the heat recovered $\dot{Q}_{\text{HP}}$ from a heat pump driven by the compressor work $\dot{W}$ with an efficiency, or coefficient of performance, COP. Notably, heat pumps require a heat source, for example industrial waste heat or district heating water. The COP depends on the temperatures of the heat source and sink and improves if the temperature difference decreases.

$$\dot{Q}_{\text{HEX}} = UA \cdot dT_{lm} \tag{3}$$

$$\dot{Q}_{\text{HP}} = \dot{W} \cdot COP \tag{4}$$

After the CO_2 is captured, it is conditioned, transported, and stored. This poses a thermodynamic challenge, exemplified by the pink line in the CO_2 phase diagram of Figure 4. The captured CO_2 is gaseous at 1 bar and 40 °C and contains impurities. To be transported by ship, as commonly proposed, the CO_2 must be purified and liquefied. Liquefaction occurs by compressing and cooling the gas in stages, for example to 15 bar and -30 °C. Purification of species like nitrogen and argon occurs post-liquefaction to reach a CO_2 purity above 99 %, using flash tanks and separators (Deng et al., 2019).

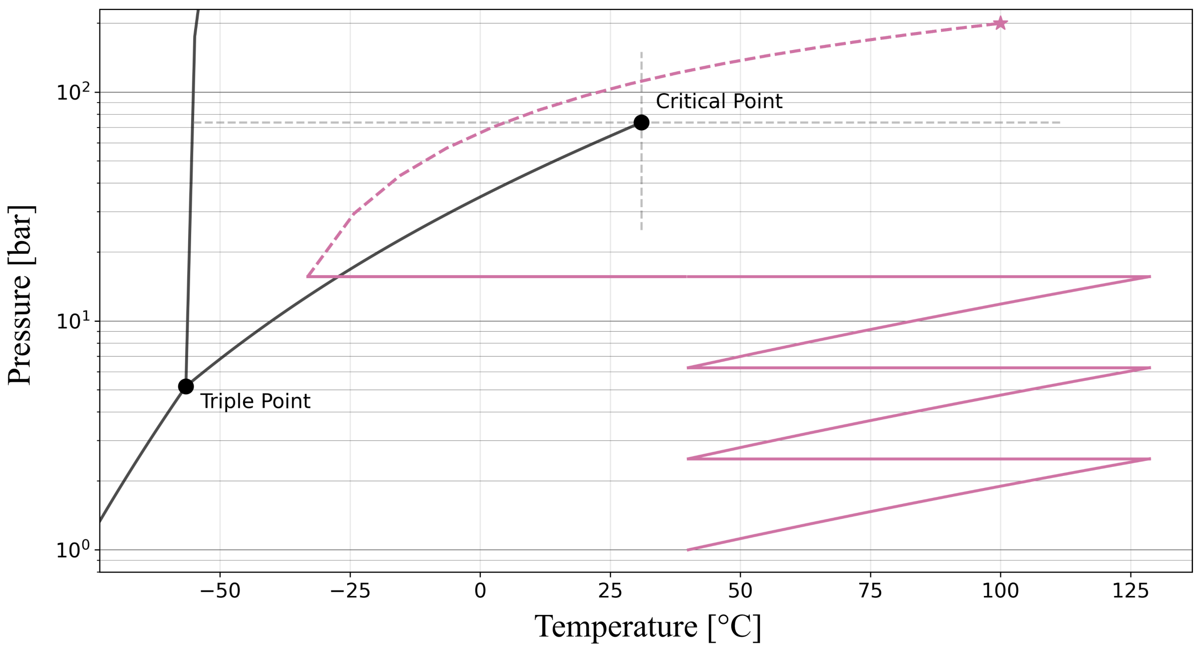

Figure 4: *Phase diagram of CO_2. The purple lines indicate how CO_2 is compressed and cooled to reach a liquid state suitable for transport. The liquid CO_2 is further compressed during storage into a supercritical fluid*: *The state above* 31 *°C and* 74 *bar.*

This example concerns ship transport of liquified CO_2, although transport via truck, train, barge, or pipeline is possible (Oeuvray et al., 2024). A common proposal for Swedish BECCS is to partner with the Norwegian transport and storage initiative Northern Lights (2025), who require CO_2 purities above 99.81 %. They receive the CO_2 at their storage terminal outside Bergen, which is followed by CO_2 compression and injection into underground reservoirs. Various CO_2 compression processes could be implemented. However, the process can be expected to be similar to the dashed pink line in Figure 4, where the final pressure and temperature in the storage reservoir would be around 200 bar and 100 °C at 2000 m depth (Oeuvray et al., 2024) and the CO_2 is injected as supercritical fluid (Torsen et al., 2018). Prominent examples of reservoir types include deep saline aquifers, depleted oil and gas field, or basalt rocks. The global storage potential is uncertain but in the order of thousands of gigatonnes (Zhang et al., 2024).

Naturally, CO_2 transport and storage pose logistical challenges beyond thermodynamic ones (Kjärstad and Johnsson, 2021; Karlsson et al., 2022). However, in the present work, transport and storage has been represented simply as a service available to decision makers at some costs. This assumption is contestable for large-scale BECCS (Lefstad et al., 2024) but is well-aligned with my case studies of Stockholm Exergi and E.ON.

2.2.3 Policy and Governance

Climate policies and governance structures are being implemented and adapted in Sweden and the EU to address the BECCS deployment gap (Fuss and Johnsson, 2021). These provide an institutional context for BECCS decision makers, including regulatory frameworks and incentives. The EU governance structure consists of three main pillars. Each pilar represents a set of sectors, their climate targets, and (sometimes overlapping) supporting regulations and policies. The overarching, legally binding target for EU Member States is net zero GHGs by 2050. Furthermore, a milestone target named "Fit for 55" establishes the aim for -55 % net emissions relative to 1990 levels by 2030, and a 2040 target is being negotiated (Fridahl et al., 2023). The pillars are described below.

Firstly, the Emissions Trading System (ETS) covers energy utilities, large industries, aviation, and maritime sectors. The ETS sets a cap on emissions which reduces every year. Compliant actors thus need to either decarbonize or pay for increasingly costly emission allowances. Durable CDR, like BECCS and DACCS, could be integrated into the system to offset residual emissions as the cap approaches zero, or to allow for a net-negative cap (Rickels et al., 2022).

Secondly, the Effort Sharing Regulation (ESR) covers domestic transport, buildings, small industries, waste, and non-CO_2 emissions from agriculture. EU Member States have differentiated targets to reduce these emissions based on their gross domestic product per capita. Starting from 2027, a second ETS system (ETS 2) will cover and reduce emissions from buildings and road transport, under which suppliers of fossil fuels are obliged to surrender allowances (European Commission, 2025a). However, some ESR emissions, such as agriculture or waste, could be especially hard-to-abate and may require offsetting (Fridahl et al., 2023).

Thirdly, the Land-Use, Land-Use Change and Forestry (LULUCF) Regulation covers sectors like forests, crop-, and wetlands. Member States must comply with the "no debit" rule, implying that land-use emissions are balanced by equivalent removals (European Commission, 2025b). Furthermore, the LULUCF sectors act as CO_2 sinks, of which a maximum of 262 $MtCO_2e$ can offset ESR emissions between 2021-2030. Similar (but restricted) offsetting flexibilities exist for ETS and ESR emissions. Notably, Member States are obliged to establish an aggregate LULUCF sink of 310 $MtCO_2e$ p.a. by 2030, of which only 225 $MtCO_2e$ can contribute to the Fit for 55 milestone target (Fridahl et al., 2023).

Emissions from ETS, ESR, and LULUCF sectors are illustrated in Figure 5. Two net-zero lines are shown, representing how ETS sectors may be either net-positive or net-negative, while ESR and LULUCF sectors are respectively expected to have net-positive and net-negative emissions. Faded colors represent illustrative future scenarios (not quantified projections). Similarly, the below-zero emissions of the ETS and the emissions coverage of ETS 2 are illustrative and not quantified. Black bars represent established or indicative targets: The net zero (-100 %) target and the Fit for 55 target have been enshrined in EU law, while the 2040 target of -90 % represents an indicative scenario. Note that the illustrated scenarios achieve about 57 % reductions by 2030, since the 310 Mt LULUCF sink is greater than the maximum 225 Mt sink that can be used towards the 55 % reduction target.

The net zero target is achieved if 100 % of remaining GHG emissions are balanced by removals into sinks by 2050 (Allen et al., 2022). Below zero is achieved if removals are further increased. Such a scenario could be realized if, e.g., sufficient capacities of BECCS and DACCS were integrated into the ETS, as illustrated by the net-negative ETS line. The ETS 2 lines illustrate how a second ETS system might contribute to reducing emissions in the ESR sector.

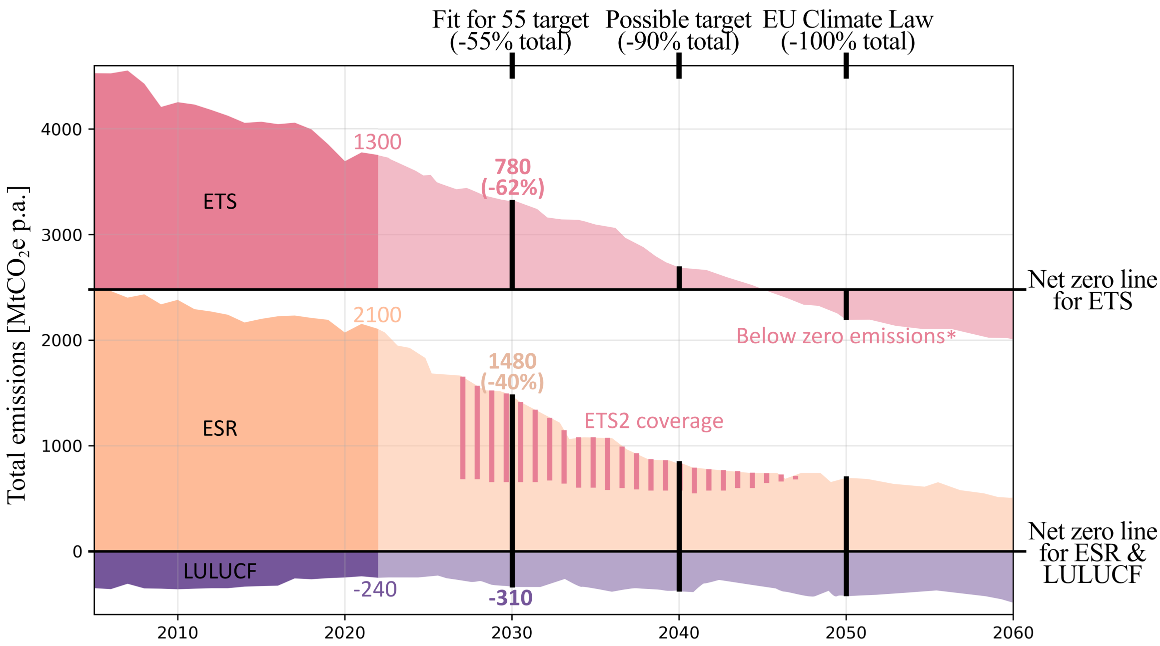

*Figure 5: Emissions and targets of the three main EU climate policy pillars: ETS, ESR, and LULUCF. Faded colors represent illustrative scenarios, not quantified projections. Black bars represent established and indicative targets. (*The ETS could achieve below zero emissions if BECCS, DACCS, or other durable CDR were integrated into the system).*

Sweden has domestic policies that contribute to these EU-wide targets. The country targets net zero GHGs by 2045, of which at least 85 % should be achieved by emissions reductions.

Remaining 15 % could be offset by forest sinks, international carbon credits, or BECCS. A BECCS capacity of 3-10 $MtCO_2$ by 2045 has been suggested in a Swedish Government Official Report (Rodriguez, 2024).

Financing policies are emerging to support these targets (Zetterberg et al., 2021). Sweden has implemented a state aid distributed via reverse auctions. Furthermore, BECCS projects can generate offset credits to be sold on voluntary carbon markets (VCMs) (Fridahl et al., 2024). As mentioned, BECCS credits could also be integrated into the ETS, either directly, or by being procured in advance and auctioned off later in time as credit demand increases (Rickels et al., 2022; Fridahl et al., 2023). Finally, fossil fuel producers could be obliged to store CO_2, thereby providing an incentive for both fossil CCS and durable CDR like BECCS (Jenkins et al., 2023).

Such financing policies are essential for decision makers interested in BECCS. Nevertheless, economic uncertainty is typically substantial, along with other uncertainties across technological, regulatory, and political dimensions (Stenström et al., 2024). To study robust investment conditions for BECCS, I have applied the decision-making framework RDM to three Swedish cases, as introduced in the following section.

2.2.4 Case Studies of Robust Decision Making

Applying RDM has helped me study case-specific conditions for Swedish decision makers. In paper (I), I studied robust investment conditions for Stockholm Exergi. They will retrofit an existing 400 MWth biomass-fired CHP plant with HPC capture, to then transport and store CO_2 using the Northern Lights infrastructure. They made their final investment decision in 2025 (Stockholm Exergi, 2025) after paper (I) was published. Important investment conditions concerned, for example, financing policy and sustainable biomass supply, as detailed later.

In paper (II), I studied robust investment conditions for E.ON in Malmö (Ramboll, 2023). They plan to invest in a new 175 MWth biomass-fired boiler in 2028 and potentially in CCS infrastructure later in time. Policy incentives and the choice of a robust capture technology, including amines, oxyfuel, or chemical looping, were in focus.

In paper (III), I studied robust investment conditions for 113 CHP plants and pulp mills across Sweden. The focus was not on financing, transport, or storage, but on how amine capture could be retrofitted and heat integrated efficiently to reduce costs and energy penalties.

These decision-making conditions were analyzed using RDM, which is a set of concepts and tools that support decision making under deep uncertainty (Lempert, 2019). Previous RDM research has studied, for example, long-term water planning in the Colorado river basin (Smith et al., 2022), BECCS investments in Helsinki (Lindroos et al., 2019), and climate policy in the United Kingdom (Workman et al., 2024). As detailed in the methodology section, RDM consists of three phases for framing, exploring, and choosing decisions of interests. These phases are participatory, by engaging stakeholders to the decision, and iterative.

Notably, since stakeholders and I shape the analysis jointly, we are not determining robust BECCS conditions objectively. Instead, the RDM process attempts to bridge the gap between the stakeholders' mental models and formal quantitative models (Lempert and Turner, 2021). This has epistemological implications, as discussed in the following section.

3. Methodology

Below, I first describe my stances on ontology, epistemology, and reflexivity. I then describe the framing, exploring, and choosing phases of RDM.

3.1 My Stances on Ontology, Epistemology, and Reflexivity

If the RDM methodology is shaped by me and decision makers, all holding diverse interests and worldviews, what can be said about the truth of the methodology's results? Answering this question requires an onto-epistemological stance. I base my ontology and epistemology on my understanding of how science works in practice.

My focus on the scientific practice is inspired by Demeritt's (2001) onto-epistemology of heterogenous constructionism. His and my departure point is that it is possible to represent truths and/or an objective reality through scientific knowledge, but that this knowledge is shaped by social processes. In practice, researchers model, measure, and debate an objective reality, implying that it cannot be separated from its representation. Put differently, a strict divide between "what is real" and "what is known" is perhaps not meaningful. It could be more meaningful to

1. consider scientific findings as representations of something ontologically real
2. not separate what is real from its representations
3. disclose the social contingency of scientific representations

These three practices are in line with Demeritt's suggestions and could, for example, contribute to making science more transparent in shaping (and being shaped by) climate policy (Demeritt, 2001). I believe the third practice could be especially useful. By disclosing the social contingency of scientific representations, the risks of fraud, bias, negligence, and hype could be reduced (cf. Ritchie, 2020). Disclosure and management of this contingency is also, according to Sterman (2002), necessary to effectively deal with complex systems and their simulation.

A similar practice has been labelled reflexivity (Knaggård et al., 2018) under which researchers reflect on their role and tacit research assumptions, while any implications are scrutinized and disclosed. Reflexivity has been leveraged to identify shortcomings of my own research project on BECCS (Christley et al., 2025) and could strengthen BECCS research more broadly (cf. Hansson et al., 2021).

RDM takes some steps towards more reflexive modelling. The methodology is transparent about being participatory and iterative. Furthermore, its ambition is to reveal how assumptions map to decision outcomes, and to explicitly frame models around what matters most (to the decision maker) while framing out what matters less. While the methodology is perhaps not "perfectly" reflexive, it could produce more transparent results than many other modelling methodologies. And while the methodology produces results that—-given my onto-epistemology—represent something ontologically real, this representation is socially contingent.

3.2 Robust Decision Making as Methodology

As mentioned, RDM consists of three iterative phases, illustrated in Figure 6. Firstly, the decision problem (e.g. whether to invest in BECCS) is framed together with stakeholders. Here, important uncertainties (X), levers (L), relationships (R), and measures of performance (M) are specified and formalized in a quantitative model. These are organized in a XLRM framework. Then, the decision is explored across a multitude of model scenarios. Finally, during the choosing phase, key scenarios are identified through data mining and sensitivity analysis. Key scenarios represent, in my analysis, key investment conditions. These three RDM phases are iterative and detailed in the following sections.

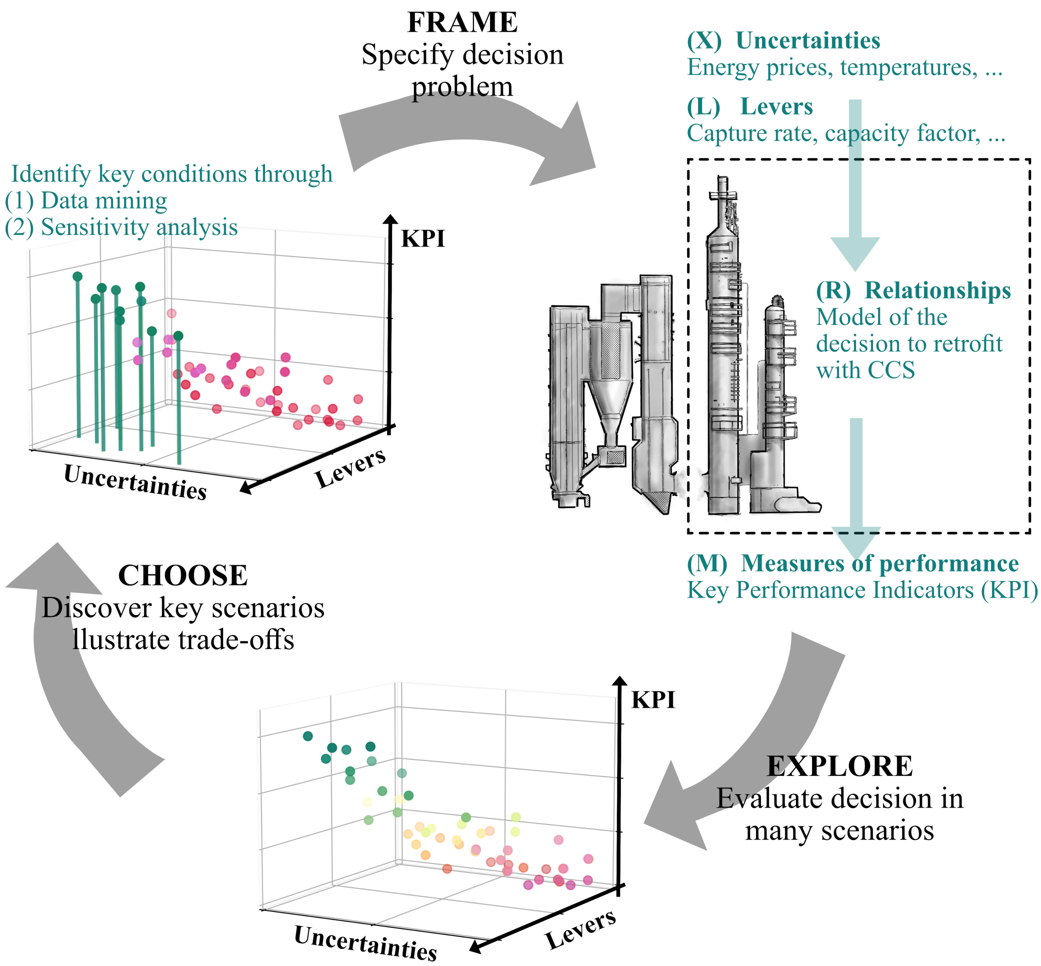

Figure 6: The BECCS decision problem is iteratively framed within a model, explored across many scenarios, and analyzed to identify key investment conditions. The model is represented by a XLRM framework.

3.2.1 Framing Investment Decisions

Across the appended papers, the framing phase was conducted through interviews and formal and informal meetings with stakeholders, and by reviewing relevant peer-reviewed and gray literature. Examples include interviews with Stockholm Exergi employees, who identified conditions under which their BECCS investment would fail or succeed, the PhD theses of Rodriguez (2024) and Lefvert (2024), who identified tensions in and conditions for Swedish BECCS deployment, and meetings with E.ON representatives, to discuss technical and economic conditions for a BECCS investment in Malmö. Generally speaking, a particular framing produces a distinct definition of the problem, what is at stake, and what solutions are needed by foregrounding and backgrounding certain elements (Williams and Sovacool, 2019).

During the framing phase I constructed an XLRM modelling framework, as shown in Figure 6. From my epistemological viewpoint, the framework can be considered a set of assumptions about the representation/reality of a BECCS investment. Notably, the framework includes foregrounded elements of a BECCS investment (such as CDR revenues) and excludes backgrounded elements (such as social acceptance). While such frameworks are tailored to each study, Table 2 exemplifies the framework from paper (II).

Table 2: The framing phase results in an XLRM modelling framework. Uncertainties and levers of the XLRM framework are exemplified below for the Malmö BECCS case. Refer to paper (II) for details.

(X) Uncertainties	Low	High	Unit	Reference *	Usage
Operational parameters					
Full load operating hours	4000	5000	h/yr	Ramboll (2023)	The number of hours the CHP plant operates per year.
Price electricity	10	100	EUR/MWh	Beiron & Thunman (2024)	
Price district heating	50	95	% of electricity price	Assumed	District heating prices are set locally and adapted to the regional electricity price.
Cost biomass	20	100	EUR/MWh	Beiron & Thunman (2024)	The input fuel cost.
Cost CO_2 transport	52	70	EUR/tCO_2	Est. from Kjärstad & Johnsson (2021)	Includes ship transport at 15 bar(g), harbor and terminal costs, CO_2 injection, monitoring, and closure.
Cost amine makeup	25	35	SEK/kg	Ramboll (2023)	Costs for replacing amine solvent and oxygen carriers.
Cost oxygen carriers	200	600	EUR/t	Lyngfelt & Leckner (2015)	Costs for replacing amine solvent and oxygen carriers.
Price CRC	50	400	EUR/tCO_2	Assumed	A price incentive from voluntary CRC markets.
Price increase ETS	0	10	EUR/(tCO_2*yr)	Assumed	ETS allowance prices increase at this rate and are capped in some scenarios.
Price cap ETS	200	350	EUR/tCO_2	Assumed	ETS allowance prices increase at this rate and are capped in some scenarios.
Capital cost parameters					
Economic lifetime	20	30	yr	Beiron & Johnsson (2024)	The economic lifetime of CO_2 capture technologies.
Discount rate	5	10	%	Beiron & Johnsson (2024)	Discount rate of costs/revenues.
CAPEX amine plant	153	230	MEUR	Ramboll (2023)	Capital costs of the amine capture plant incl. CO_2 compression and liquefaction.
CAPEX exponent fuel reactor	0.48	0.72	-	Farajollahi & Hossainpour (2022)	Represents β in CAPEX $= \alpha \cdot x^{\beta}$, used to estimate base CAPEX costs of fuel reactor and ASU.
CAPEX compression & liquefaction	20	30	MEUR/ (kgCO_2/s)	Deng et al. (2019)	Used to estimate capital costs of CO_2 compression (15 bar) and liquefaction.
OPEX fixed	3.6	5.4	MEUR/yr	Ramboll (2023)	Includes staff and maintenance.
EPC cost factor	5	15	%	Ramboll (2023)	Cost factors that escalate base CAPEX estimates, in line with established CCS cost methodologies (cf. Ali et al., 2019).
Contingencies cost factor	15	35	%	Ramboll (2023)	Cost factors that escalate base CAPEX estimates, in line with established CCS cost methodologies.

(X) Uncertainties	Low	High	Unit	Reference *	Usage
Owners' cost factor	3	7	%	Ramboll (2023)	Cost factors that escalate base CAPEX estimates, in line with established CCS cost methodologies.
Overrun cost factor	0	45	%	Beiron & Johnsson (2024)	An additional cost factor reflecting unexpected cost overruns.
Immaturity cost factor	0	400	%	Assumed	Reflects uncertainties of low-TRL chemical-looping CCS.
dT log mean temp. diff.	350	530	°C	Est. from Crafoord & Lewenhaupt (2025)	Used to determine areas and costs of convective heat exchangers after the chemical-looping fuel reactor.
Heat transfer coefficient U	40	50	W/(m2K)	Casarosa et al. (2004)	Used to determine areas and costs of convective heat exchangers after the chemical-looping fuel reactor.
CEPCI	750	950	-	University of Manchester (2024)	Chemical Engineering Plant Cost Index used to transform outdated cost estimates to 2024 values.
Fuel reactor efficiency	0.8	0.95	$molO_2/molO_2$, stoichiometric	Assumed	Determines what fraction of fuel is oxidized by oxygen carriers in the CLC fuel reactor.
Policies and shocks					
Reversed auction	True/False			cf. Fridahl et al. (2024)	Adds a revenue of 160 EUR/tCO_2 for 15 years.
ETS integration	True/False			cf. Rickels et al. (2022)	Enables the alternative to sell CRCs to the ETS price.
ETS procurement	True/False			cf. Rickels et al. (2022)	Enables the alternative to sell CRCs to the ETS cap level.
Bioshortage	True/False			Assumed	Increases biomass costs by 10% per year for 10 years.
Powersurge	True/False			Assumed	Increases electricity prices by 20% per year for 3 years.
Loadchange	-1500/0/1500		h/yr	Assumed	Increases or decreases full-load operating hours of the plant.
(L) Levers					
Investment delay	5/10/15/25		yr	Assumed	The number of years after the boiler investment in which any CCS investments occur.
Capture rate	86	94	%	Assumed	The fraction of CO_2 captured.

** If parameter ranges were available, these were taken directly from the references. If only point estimates were available, ranges were constructed based on the author's best judgment.*

Notably, the models assume that BECCS is built and operated over a technological lifetime. Cost and revenues are therefore quantified annually. However, most assumptions are constant over time, such as electricity prices, unless altered by scenario effects. For example, the "Powersurge" shock in Table 2 increases the assumed electricity price by 20 % per year for 3 consecutive years.

As shown in Figure 6, the model and its parameters are used to simulate a decision and how it performs. In papers (I) through (III), performance is measured in terms of CO_2 capture costs or NPV. These performance metrics were chosen to align with the decision makers framing of the BECCS problem, which mainly concerned its business case , and are illustrated stylistically by Equations (5) and (6). Here, $CAPEX$ represents upfront capital expenditures while $OPEX$ represents costs of energy, solvent or oxygen carrier makeup, transport, storage, and fixed operations and maintenance. Revenues include sales of energy and CDR credits. All costs and revenues are annualized using a discount rate DR and an economic lifetime t_{lifetime}

$$CO_2 \text{ capture cost} \left[\frac{€}{\text{tCO}_2}\right] = \frac{\text{CAPEX}_{\text{annualized}} + \text{OPEX}}{\text{captured CO}_2} \tag{5}$$

$$\text{NPV [€ million]} = \sum_{t=0}^{t_{lifetime}} \frac{\text{revenues}(t) - \text{costs}(t)}{(1 + \text{DR})^t} \tag{6}$$

Quantifying Equations (5) and (6) requires the simulation of energy balances, costs, and revenues of a BECCS investment. Details of these simulations and their assumptions can be found in papers (I) through (III). Throughout these papers, I also assess the performance metric regret. Regret is a useful metric since it assigns value to a decision relative to counterfactual decisions. RDM attempts to identify decisions that do not necessarily optimize, but that achieve low regret across a wide range of scenarios (Lempert, 2019). In this work, I quantify regret using Equation (7).

$$\text{regret}_{\text{decision}} \text{ [€ million]} = \text{NPV}_{\text{alternative decision}} - \text{NPV}_{\text{decision}} \tag{7}$$

Another aspect of great importance for BECCS is energy efficiency. Beyond paper (III), I have mainly assessed energy efficiency implicitly through its substantial impact on operational costs and revenues. I will not formulate a single energy efficiency metric in this thesis, but will discuss energy efficiency impacts of three major choices that decision makers face:

1. The choice of CO_2 capture technology and how energy is supplied to it.
2. Whether fuel input is increased after a BECCS retrofit, to compensate for potential energy penalties.
3. Whether and how heat exchangers and heat pumps are integrated to recover process heat.

3.2.2 Exploring Scenarios

The second phase of RDM involves the exploration of a decision across a range of scenarios to identify, for example, high- and low-regret decisions. Scenarios are sampled from input parameters of an XLRM framework. I use Latin hypercube sampling, as is common within RDM (Lempert, 2019). Using this technique, each parameter range is divided into bins, and samples are then taken evenly from each combination of bins (Preece and Milanovic, 2016). Such sampling assigns the same weight to “likely” and “unlikely” scenarios. This implies that I do not assume probability distributions of input parameters, nor that I can draw conclusions on the statistical likelihood of scenario outcomes. However, it is possible to assess the robustness of a decision across a range of deeply uncertain scenarios, which is the idea of RDM (Lempert, 2019). A decision is considered robust if it

- has low costs relative to other decisions across the scenarios
- is energy efficient relative to other decisions across the scenarios
- has zero or negative regret across the scenarios

From deliberation with decision makers, I interpreted policy scenarios to have substantial impact on regret. To simulate this impact, I modelled policies as scenario-dependent price incentives per ton of stored CO_2. The explored policies and price levels are visualized in Figure 7.

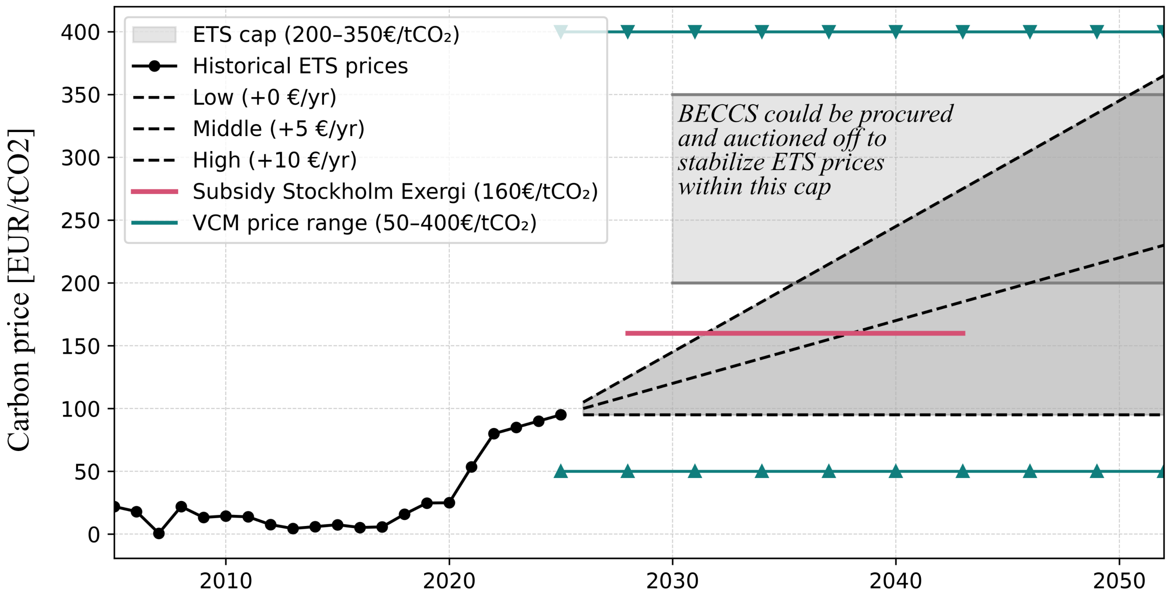

Figure 7: BECCS credits could be subsidized through reverse auctioning, as for Stockholm Exergi (pink line), or sold on a VCM (teal lines), or integrated and sold on the EU ETS market (gray fields). To enable early incentives and stabilize future ETS prices, BECCS credits could be procured in advance and auctioned off later in time. The illustrated ranges were taken from paper (II) and should be considered uncertain

Note that the timeline for and interactions between these potential policy incentives differ. In papers (I) and (II), I explored scenarios which combined a reverse auction subsidy and voluntary carbon market revenues. To avoid double counting of CDR, it is unlikely that these incentives could be stacked with revenues from a BECCS-integrated ETS market (cf. Dufour et al., 2024).

I therefore mainly explored scenarios in which BECCS decision makers pick between one of a few available policy incentives, prioritizing the highest incentive available in any given scenario.

3.2.3 Identifying Key Investment Conditions

The choosing phase of RDM is about identifying key scenarios and choosing a robust decision. It can also lead to the exploration of new scenarios or the reframing of the decision problem. Here, scenarios refer to a combination of model parameters (investment conditions) and their outcomes. Extreme scenarios, for example of very low regret and capture costs, are of interest. Inverse scenarios, such as those of very high regret, are also of interest. Essentially, during this phase, key investment conditions that lead to extreme outcomes are distilled from the large set of modelled conditions.

Methods for identifying key conditions vary. A simple approach is to visualize the modelled scenarios, for example by plotting regret against the CDR price and identifying a relevant price threshold. I have also employed algorithms, including data mining through Classification and Regression Trees (CART) and a Patient Rule Induction Method (PRIM) and Sobol and Random Forest sensitivity analysis. I describe these algorithms briefly below, while the reader may refer to the appended papers for details. Below, a data point refers to a single scenario, i.e., a single combination of parameters and the model outcomes given those parameters.

The CART algorithm works by splitting the scenario data into branches. One branch might have CDR prices below 50 EUR/tCO_2, while the other branch has prices above 50 EUR/tCO_2. Another split could be made to create a child branch, where scenarios have CDR prices below 50 EUR/tCO_2 but also biomass costs above 60 EUR/MWh. Using such splits, the whole scenario data set can be characterized. The finesse of doing this is that splits are chosen that maximize the density of high (or low) regret scenarios in one branch. For example, the branch with CDR prices below 50 EUR/tCO_2 and biomass costs above 60 EUR/MWh could represent scenarios of high regret relative to all other scenarios. Put differently, high- and low-regret scenarios can be identified from these branches. See Lempert (2008) for details.

While not reliant on a tree structure, the PRIM algorithm also maximizes the density of high (or low) regret scenarios (Lempert, 2008). It starts with the original data set of scenarios. It then removes data points by filtering parameter ranges. For example, the originally explored biomass prices could be 30-80 EUR/MWh to then be filtered to 40-80 EUR/MWh. Filtering, or "peeling", of the data set continues as long as it increases the density of high (or low) regret scenarios in the remaining data set. In this example, peeling could continue until biomass prices are between 60-80 EUR/MWh, which could represent high-regret scenarios.

Moreover, Sobol's sensitivity analysis can be used to quantify the influence of parameters on model outcomes (Rosolem et al., 2012). The algorithm quantifies parameter influence as a set of indices. The 1st order index quantifies the direct effects attributable to each parameter. For example, an increase in CDR prices may directly lead to lower regret. The 2nd order index quantifies interaction effects between two parameters. For example, an increase in ETS prices could have high 2nd order effects if we explore scenarios in which CDR is/is not integrated into the ETS system. Finally, the total order sensitivity index quantifies all 1st, 2nd, 3rd, . . . , Nth effects. It is the index I have mainly relied on when comparing the relative importance of model parameters.

Finally, Random Forest sensitivity analysis can be an alternative to the Sobol method if parameter importance needs to be quantified across models. A Random Forest is essentially a set of tree structures, each characterizing a subset of the scenario data. These are constructed analogously to CART tree structures, meaning that the data is split to maximize the density of high (or low) regret scenarios. This implies that, across all trees, important parameters will frequently split the data while unimportant parameters will not. For example, if most trees split the data based on the CDR price, then the CDR price can be considered relatively important. Overall, the Random Forest algorithm quantifies to what extent each parameter contributes to splitting the data across all trees. See paper (III) or Antoniadis et al. (2021) for more details.

Importantly, all key conditions cannot be satisfactorily characterized by algorithms. Another approach is to interview decision makers and ask them to identify conditions that would cause a BECCS investment to fail or succeed, as was done in paper (I). I asked:

- "What are potential vulnerabilities that could cause the BECCS strategy to fail?"
- "What are potential actions that could be taken to manage these vulnerabilities?"
- "What are potential opportunities that could increase the BECCS strategy's chance of success?"
- "What are potential actions that could be taken to capitalize on these opportunities?"

Identifying key conditions through such questions and algorithms combines both qualitative and quantitative methods. In the following section, I will therefore integrate and analyze both qualitative and quantitative results. I have interpreted four overarching conditions as especially relevant for BECCS investment decisions, given how they were discussed by decision makers and their quantified importance.

4. Analysis of Key Decision-Making Conditions

In this section, I present and analyze key conditions for BECCS investment decisions. Key conditions include power and agency; policy coalitions; robust technology choices; and responsible bioenergy.

4.1 Power and Agency

I have previously framed the climate problem around carbon emissions and political power. Along this line, power can be considered an enabler of (and barrier to) BECCS investments. The capacity of actors to shape and benefit from policy, regulation, and discourse seems to be a critical condition for BECCS investments to happen.

This finding is supported by interview results from paper (I), with selected examples in Table 3. The Table lists vulnerabilities and opportunities of deploying BECCS and actions that could be taken to address these. These results concern Stockholm Exergi and could therefore be considered case specific. However, I believe the Stockholm Exergi case is of particular relevance since they are the only Swedish actor who has taken a final investment decision on BECCS (as of 2025). Note that I frequently use the word “lobby” in the results below, while Stockholm Exergi may prefer softer terms like “advocacy”. My aim is not at all to criticize their efforts, but to describe the political power required to realize BECCS.

Table 3: A selection of vulnerabilities and opportunities—along with possible adaptive actions—of investing in BECCS. Color legend: pink=political conditions, purple=market conditions, yellow=social conditions, green=regulatory conditions.

	Vulnerability (V) or Opportunity (O)	Possible adaptive actions
pink	(V) Article 6 [of the Paris Agreement] could be interpreted in a way that forbids the energy utility to claim negative emissions, e.g. due to double claiming or lacking additionality.	Perform general lobby work in national, European and global forums.
		Gain support for co-financing and co-claiming of negative emissions from decision makers: national politics, energy authorities, Nordic Council of Ministers, EU politics etc.
		Investigate the value of applying BECCS without selling the negative emissions as a service.
		Reassess the BECCS strategy, potentially focusing on waste-CCS.
pink	(O) The new national government (Sweden) shows strong support for CDR and BECCS	Seize additional grants for BECCS operation support.
		Seize political momentum to push for regulation supporting BECCS.
pink	(V) BECCS frontrunners are relying too much on ”research arguments” which are insufficient to overcome political barriers.*	Allocate more resources on lobbying and the positive narrative of BECCS.
pink	(V) How the combination of EU support, state support and VCM revenues will function is uncertain.	Showcase that a solely state-driven BECCS chain will not utilize society's resources efficiently.
pink	(V) Countries in the BECCS value chain could be involved in major disruptive geopolitical events, such as war.	Reassess the BECCS strategy, focusing on energy security.
pink	(O) Negative emission quota obligations could be enforced on companies with considerable residual emissions.	Increase prices of negative emissions to capitalize on increased demand.
purple	(V) The VCM demand for negative emissions could be lower than expected.	Perform political lobby work in local, regional, national, European and global forums.
		Establish long-term negative emissions contracts before BECCS deployment.
		Lobby for national quota obligations.
		Investigate other state or EU support options.
purple	(V) The energy utility is dependent on investment decisions of external transportation and storage actors, and vice versa.	Continuously negotiate with downstream actors for a synchronized value chain establishment.
		Make preparations for different transportation options (ship, railway or transportation hub configurations).
		Work to establish CO_2 hubs for shared transportation infrastructure.
		Lobby for state support to establish shared infrastructure.
purple	(V) The competition for biomass may increase e.g. from transport sectors' intensified biofuel usage.	Adapt energy conversion process to lower-quality biomass.
	(O) In a future with constrained bioenergy supply BECCS frontrunners could be prioritized bioenergy buyers.	Not assessed.
yellow	(V) Bio-practices are regarded unsustainable by members of the European parliament.	Showcase cascading principles and how differences in forestry practices affect sustainability criteria.

Vulnerability (V) or Opportunity (O)	Possible adaptive actions
	Collaborate with rest of bio industry, e.g. national actors, Euroheat & Power, Bioenergy Europe. Ensure any negative emissions contracts are treating the case of biomass being labelled as unsustainable.
(V) Indifferent of the outcomes of biomass disagreements, these are damaging the image of bio-based combined heat and power plants.	Analyze and showcase the current and future role of bio-based combined heat and power plants for district heating.
(V) Indifferent of the analysis of BECCS benefits, the investment depends on "gut feelings" of decisionmakers.	Ensure the decision is participatory by educating on/illustrating BECCS for decisionmakers.
(V) Negative emissions are integrated into EU ETS, raising concerns that CDRs are deferring other mitigation efforts.	Ensure negative emissions integration is delayed until other mitigation options reach critically high price levels.
(V) Biomass practices of upstream biomass are classified as non-renewable by the EU.	Follow Renewable Energy Directive III and use Forest Stewardship Council certified biomass. Include strengthened biodiversity criteria when sourcing biomass. Plan for reduced biomass usage.
(V) BECCS relies on multiple new laws which are not prioritized in multiple political departments.	Perform political lobby work in local, regional and national forums. Identify appropriate modifications of London Protocol; CCS Directive; laws on handling CO_2 and industrial electricity taxes. Coordinate lobbying efforts with other companies with shared interests.

** Interviewee(s) argued that there may exist research-based evidence for the BECCS case, but that this is insufficient when social and political momentum is dependent on emotional or "positive image" arguments.*

Table 3 illustrates that Stockholm Exergi acts beyond the "normal" system boundaries of an energy utility, whose business-as-usual activities involve the investments in and dispatch of heat and electric power. Through political (rather than electric) power, Stockholm Exergi could shape policies for negative emissions trading, secure government state aid via reverse auctions, defend bioenergy from restrictive regulation, and enter CO_2 transport and storage contracts. Seemingly, actions beyond normal system boundaries enabled their BECCS investment.

That actions beyond normal system boundaries were needed also highlights the role of agency. Rodriguez (2024) noted that political (and other) uncertainties cause actors to not actively pursue BECCS. Instead, actors are satisfied with monitoring BECCS policy developments while prioritizing other technologies over which they have greater agency. Furthermore, many bioenergy actors remain reluctant to take on responsibility for CDR since they perceive themselves as having contributed to emissions reductions already, and since it could be unfair to expect them to offset fossil emitters who have not made similar reduction efforts (Rodriguez, 2024).

Another reflection, stemming from my engagement with stakeholders, concerns the agency of individual leaders (a suitable Swedish translation could be “eldsjälar”). My impression is that a few driven individuals push for broad system changes conducive to BECCS, and that these individuals are successful if they mobilize coalitions of (sufficiently influential) supporting actors. However, while interesting, this finding is not fully reflected in my empirics. Additional research would be needed to draw strong conclusions, such as research on collaborative leadership (Ansell, 2016), discourse coalitions (Hajer, 2006) or actor-networks (Latour, 1999). But I suspect that individual leadership is an important condition for BECCS investments to occur.

Finally, I note that power can be exercised by framing BECCS in particular ways (cf. Almqvist Ingersoll, 2025; Williams and Sovacool, 2019). Stockholm Exergi, E.ON, and the actors interviewed by Rodriguez (2024) and Lefvert (2024) framed the BECCS problem as a business case problem. This framing foregrounds issues of costs and revenues while backgrounding other issues (like equity or biodiversity). The business case framing is also apparent in my application of RDM, where economic scenarios and performance indicators were in focus. Furthermore, in Table 3, many actions frame BECCS in a particular way to gain policy support. For example, that co-financing of negative emissions by the public and private sectors would be economical, that BECCS has an overall positive narrative, or that cascading use of biomass is a sustainable practice. BECCS deployment may therefore be conditioned on substantial framing efforts.

4.2 Policy Coalitions

While the need for policy incentives for BECCS is well-established (cf. Rodriguez, 2024; Lefvert, 2024) the impact of specific policy instruments on BECCS investment decisions has typically not been quantified. Based on Equation (7), I have assessed how policy instruments influence regret, i.e., the NPV difference between investing in BECCS and not doing so. For Stockholm Exergi’s HPC investment, I found that the regulation of negative emissions trading was the most important condition to achieve low regret. This condition has the highest total sensitivity index (0.44), as shown in the leftmost Sobol sensitivity plot of Figure 8. Here, total sensitivity indices are visualized by outer circle diameters and 2^{nd} order sensitivity indices are visualized by grey edges.

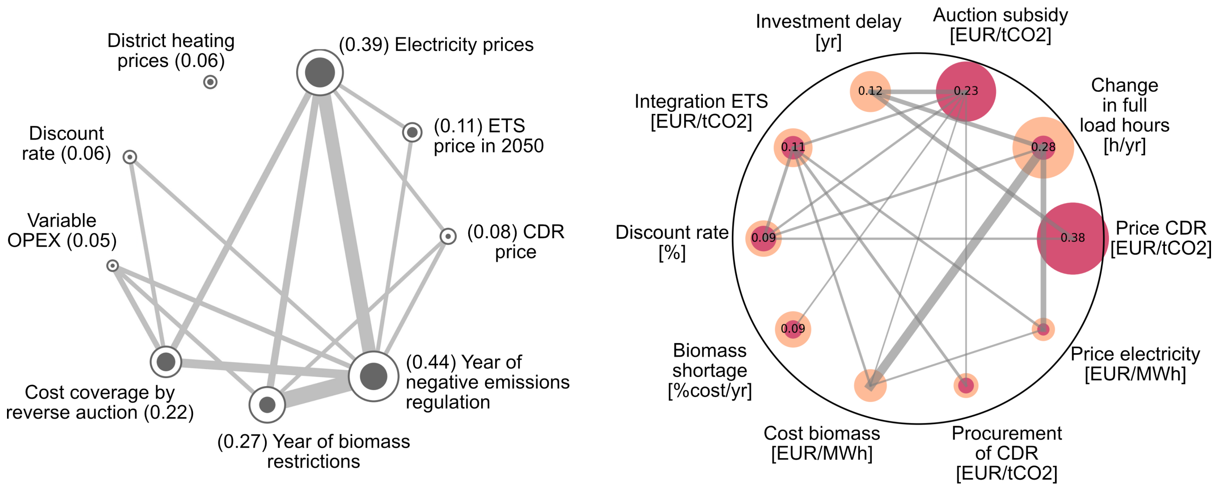

Figure 8: Important conditions for Stockholm Exergi's HPC investment (left) and E.ON's amine investment (right). Importance was quantified using Sobol sensitivity analysis. Outer circle diameters represent total order sensitivity indices, and their numerical values are annotated. Inner circle diameters and grey edges represent 1^{st} *and* 2^{nd} *order sensitivity indices, respectively*

That negative emissions trading is regulated implies that policymakers provide regulatory certainty of how BECCS credits are used, especially if sold for corporate offsetting and simultaneously subsidized by governments (cf. Dufour et al., 2024). In the case of E.ON, corporate offset buyers on a VCM were modelled as a CDR price and government support was modelled as a flat reverse auction subsidy. Both were among the most influential parameters on regret, as represented by their high total order sensitivity indices of 0.38 and 0.23 in the rightmost Sobol plot of Figure 8. For these parameters, the pink and yellow circles overlap since the 1^{st} and total sensitivity indices are almost the same.

An alternative policy to create BECCS demand is to integrate CDR into the EU ETS. I found this policy to be most effective if combined with a public procurement scheme (see Section 2.3.3). BECCS credits could be procured by a governmental agency ahead of demand, when fossil ETS allowance prices are still low, and auctioned off later in time to keep a rising allowance price within a price ceiling (Rickels et al., 2022). The impact of these two ETS-integration cases—either without or with procurement of BECCS credits—are contrasted by Figures 9 and 10 for the case of E.ON.

In terms of NPV, E.ON may regret investing in amine BECCS depending on how quickly ETS prices increase. This is illustrated in Figure 9, where BECCS credits are not procured by a governmental agency. The box plots span the 1^{st} to 3^{rd} quartile (the box heights) while their whiskers extend to 1.5 times the quartile range. Circles represent outliers. Box colors represent the fraction of scenarios with positive regret. The Figure shows that ETS prices would need to increase quickly (8.66-10 EUR/tCO_2 p.a.) in the coming years for the investment to be robust. If prices increase slower than 8.66 EUR/tCO_2 p.a., the investment leads to regret in more than 67% of scenarios, as indicated by the purple and black box colors.

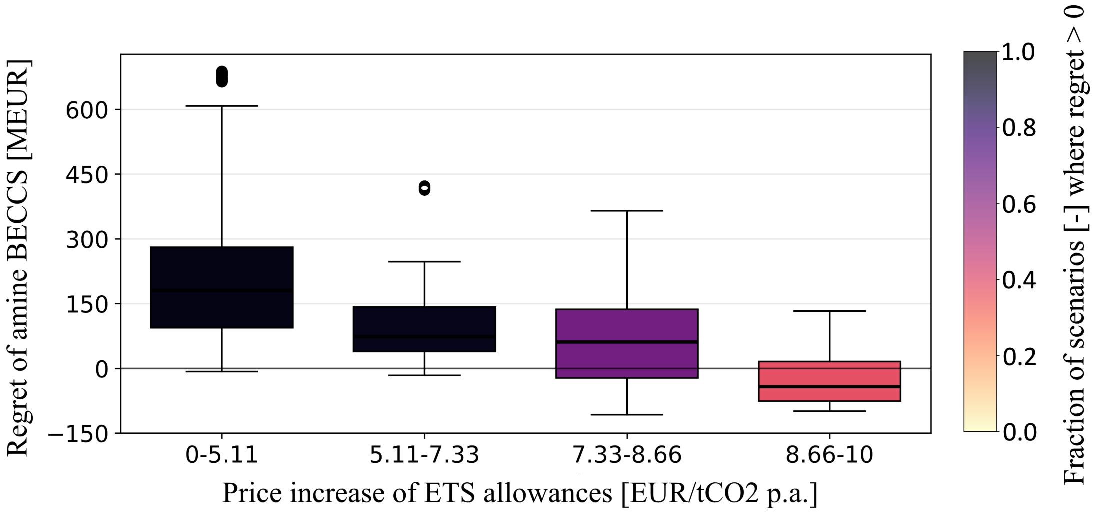

Figure 9: Scenarios of regret if E.ON invests in amine BECCS and the ETS is the main revenue stream (without a procurement scheme). Boxes show ranges of regret and how these depend on the assumed rate of ETS price increases. Positive regret is undesirable for E.ON, while negative regret is desirable.

Contrastingly, the investment could be more robust if BECCS credits are integrated into the ETS through public procurement, as illustrated in Figure 10. E.ON could then sell credits to the current ETS price or to a procurement price (determined by a scenario-dependent price ceiling of ETS allowances). This implies that ETS prices can increase at a slower rate without causing a high-regret investment, as shown in the Figure. If prices increase at 5.11 EUR/tCO_2 p.a., or faster, investing in BECCS has low or negative regret across most scenarios (illustrated by the pink and orange boxes). Below 5.11 EUR/tCO_2 p.a., the investment still leads to regret in 73% of scenarios.

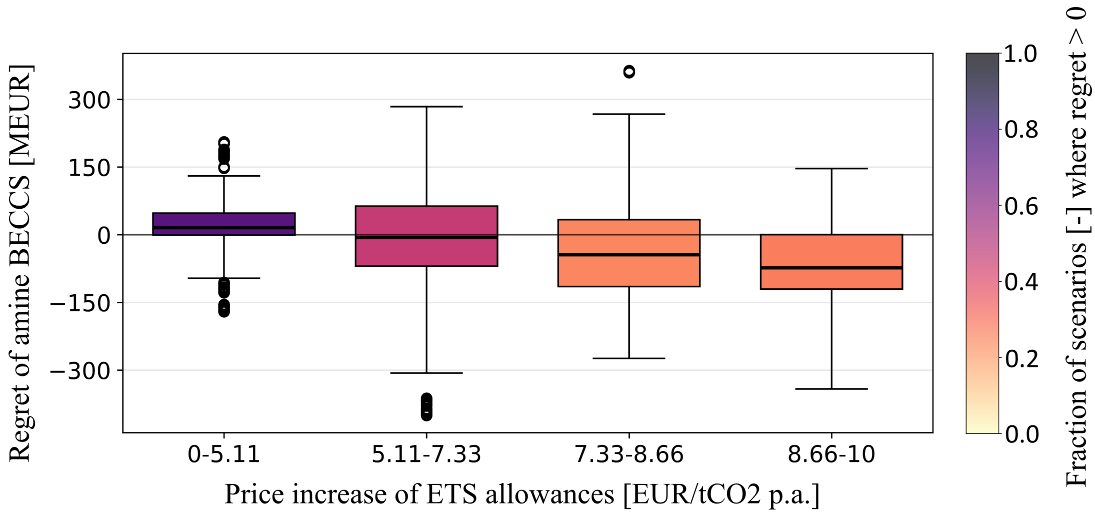

Figure 10: Scenarios of regret if E.ON invests in amine BECCS and the ETS is the main revenue stream (including a public procurement scheme). Boxes show ranges of regret and how these depend on the assumed rate of ETS price increases. Positive regret is undesirable for E.ON, while negative regret is desirable.

As implied, the most important conditions modelled are CDR revenues, either from a VCM or ETS market or from reverse auction subsidies. The required CDR price and subsidy support were further analyzed using CART in papers (I) and (II). In Table 4, I exemplify CART results, and compare with indicative costs and revenues for Stockholm Exergi. These are indicative since they are based on news announcements, so strong conclusions cannot be drawn. However, the reverse auction subsidy of 160 EUR/tCO_2 could be considered a lower bound estimate of the required revenues for Stockholm Exergi. Another relevant level could be 480 EUR/tCO_2, if assuming that 1/3 of revenues are covered by the auction and 2/3 by VCM buyers, as implied by the Stockholm Exergi CEO in a news statement (Dagens Industri, 2025). While the CEO statement is not a rigorous revenue estimate, it may imply that my analysis of the required incentives in paper (I) could be significantly underestimated, as indicated in Table 4.

Table 4: Key reverse auction and VCM scenarios for the Stockholm Exergi and E.ON cases.

	Stockholm Exergi – Paper (I)	**Stockholm Exergi – Actual****	**E.ON – Paper (II)**
Key reverse auction scenario	• Reverse auction covers 0–100% of an operating cost of 54–143 EUR/tCO_2*	• Reverse auction covers ~160 EUR/tCO_2	• Reverse auction covers 160 EUR/tCO_2
Key VCM scenario	• VCM trading is regulated before 2030. • CDR prices exceed 151 EUR/tCO_2.	• VCM contracts were entered between 2024–2025 (e.g., 5 Mt over 10 years by Microsoft). • CDR revenues could cover 2/3 of total costs (implied by CEO).	• CDR prices exceed 185 EUR/tCO_2.
Modelled outcome	The BECCS investment has zero regret in more than 96% of scenarios, even if electricity prices exceed 82 EUR/MWh.	N/A	The BECCS investment has zero or negative regret in more than 75% of scenarios.

** The cost coverage of the reverse auction subsidy varied across scenarios, but was assumed additional to VCM revenues.*

*** Since the tabulated numbers are based on news announcements by Stockholm Exergi* (2025) *and Dagens Industri* (2025)*, they cannot be used to draw strong conclusions on the actual incentives and costs.*

An interesting detail is that Stockholm Exergi may have committed to an investment decision without having secured revenues for the full plant lifetime (of 25+ years) since the Microsoft contract applies for 10 years and the reverse auction subsidy applies for 15 years. Relatedly, in NPV calculations such as Equation (6), costs and revenues are typically discounted over time and therefore have greater impact if imposed early on. This could imply that early incentives matter more than the security of future incentives. This conclusion is in agreement with my conclusion that the ETS may provide more effective incentives if BECCS credits are integrated into the system through public procurement: otherwise, since ETS prices may rise slowly, the ETS incentive could be too low early in time when it matters the most for investments.

A final reflection is that none of the incentives studied seem to operate under “free market” logic, i.e., that supply and demand of CDR is organized without government interventions. Even the VCM requires the stewardship of policymakers to set integrity standards for offsetting and to clarify (non-)possibilities for mixed revenue streams (Dufour et al., 2024). And while an integrated ETS market could enable trading of CDR credits, I found this policy to provide more robust incentives if BECCS were integrated into the system through public procurement. The latter finding was specific to the E.ON case, but holds some general truth since other Nordic BECCS projects could be expected to have similar price levels. Therefore, for BECCS investments to occur, the policy challenge may not be to establish "free" CDR markets without policymaker involvement, but to establish coalitions of policymakers and industries that govern both supply and demand of BECCS.

4.3 Robust Technology Choices

A key condition for robust BECCS is robust capture technology. Since my definition of robustness considers both energy efficiency and economic performance, I will discuss both metrics. Regarding energy efficiency, most capture technologies can perform well when integrated into Swedish CHP systems, as illustrated by Table 5. While electricity generation is generally reduced, especially for post-combustion technologies, substantial waste heat can be recovered for district heating purposes. Naturally, the capture technologies could be less energy efficient than what is here estimated, if actually deployed.

Table 5: Energy efficiency of capture technologies applied to the Stockholm Exergi and E.ON cases.

Case	Fuel input, LHV [MW]	Heat output [MW]*	Power output [MW]	CHP output /Fuel input [–]*	Reference
Stockholm Exergi					
Baseline	400	330	118	1.12	Levihn (2023)
HPC	400	424	40	1.16	Levihn (2023)
E.ON					
Baseline	174	140	48	1.08	Ramboll (2023)
Amines	174	140	32	0.98	Ramboll (2023)
Oxyfuel	174	140	31	0.98	Ramboll (2023)
Chemical looping	174	140	41	1.04	Paper (II)

** The heat output includes condensation of flue gas water vapor, which is not included in the LHV of the fuel. This is why the CHP output can exceed the fuel input on a LHV basis.*

Beyond these two cases, in paper (III), I identified key conditions for energy-efficient and low-cost BECCS if 113 biomass- and waste-fired CHP plants and pulp mills implement amine capture. These conditions are visualized by the Random Forest sensitivity analysis results of Figure 11. Here, the x axis represents the normalized importance of each parameter, where parameters that frequently predict regret are considered more important (see Section 3.2.3). The most important condition for biomass-fired CHP is plant utilization, i.e., the full-load operating hours per year. Essentially, increasing full load hours leads to lower CO_2 capture costs, since the CCS equipment costs are allocated to greater volumes of CO_2.

For waste-fired CHP, the utilization of heat pumps for waste heat recovery is the most important condition, since heat (below 47 °C) can be recovered given electric work at a ratio equal to the COP (between 2.3 and 3.8). Finally, the most important condition for pulp mills is electricity prices, since redirecting steam for an amine plant incurs a penalty on power generation. This penalty can be circumvented if the mills are equipped with additional bark boiler capacity. Additional biomass can then be combusted to generate steam for the capture process while retaining power generation, thereby reducing capture costs (cf. Lacaze-Masmonteil, 2024).

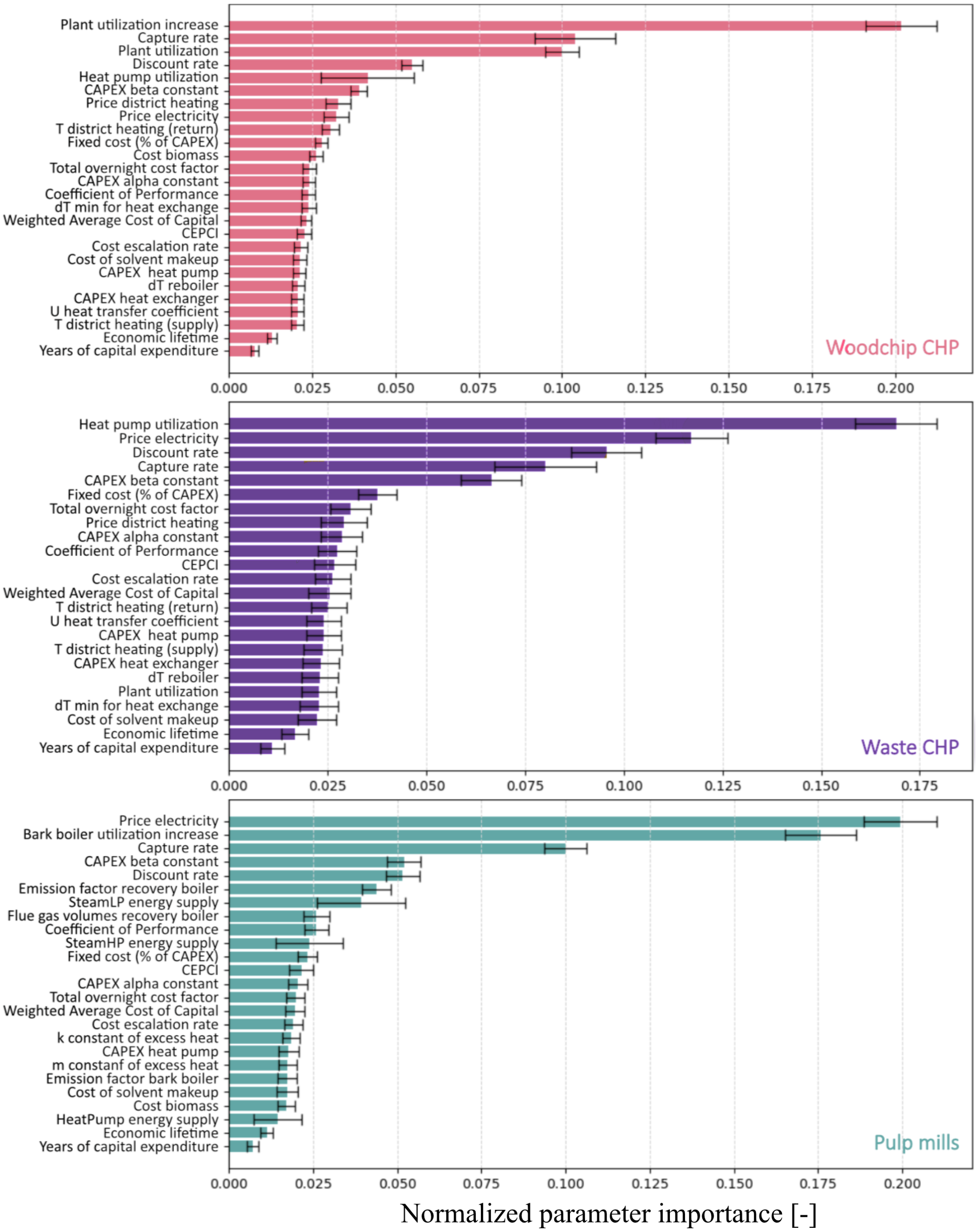

Figure 11: Conditions influencing energy- and cost-efficient BECCS were identified using Random Forest sensitivity analysis. The analysis concerns 113 Swedish plants, including biomass- and waste-fired CHP plants and standalone pulp mills.

Other technologies than amines could be more robust, under certain conditions. I applied CART to the E.ON case in paper (II) and found that CAPEX is the main condition determining whether oxyfuel or chemical looping could be more robust. If the oxyfuel air separation unit is cheaper than 211 MEUR, amines lead to regret in more than 60 % of scenarios. If the chemical looping

CAPEX is only 270 % more expensive than anticipated, or less, amines lead to regret in more than 90 % of scenarios. The implication is that decision makers may regret amines if promising novel capture technologies are not explored. For example, by estimating oxyfuel and chemical looping CAPEX rigorously.

Instead of amines, I note that Stockholm Exergi opted for HPC, which has been less researched in the context of CCS coupled with power generation and CHP. One reason is their previous experience with HPC for gas upgrading (Levihn et al., 2019). However, it is possible that costs of their first-of-a-kind plant have escalated (cf. Beiron and Johnsson, 2024). What constitutes a "robust" technology choice may therefore not only relate to costs (and energy efficiency) but to actor-specific experience with a technology and with the associated networks of suppliers.

4.4 Responsible Bioenergy

Finally, the responsible use of bioenergy is a key condition for the implementation of BECCS. While the term "responsible use" is contestable and fluid, I present my analysis below.

In Table 3, Stockholm Exergi emphasized that upstream biomass must adhere to existing standards, such as the Renewable Energy Directive and the Forest Stewardship Council, and that they may strengthen their biodiversity criteria when sourcing biomass for BECCS. Furthermore, they framed a cascading use of biomass as responsible, i.e., where biomass is prioritized for high-value products while residues are used for bioenergy services.

Similarly, many Swedish and Finnish bioenergy actors perceive themselves as enablers of others to achieve climate goals by providing biomass-based products, fuels, and CHP. They also consider themselves enablers of circular economy and industrial symbiosis, and emphasized the importance of a net-negative forest sink and of substitution effects from replacing fossil products and fuels (Rodriguez et al., 2021). Furthermore, forestry residues that are not used for biomass products cause CO_2 emissions if left to decompose, as illustrated by Figure 4 in Hammar and Levihn (2020) (in their example, although at a logarithmically reducing rate, about 50 % of the CO_2 originating from residues is emitted after 10-15 years). From a climate perspective, all else equal, these decomposition emissions could therefore be mitigated by BECCS.

Given the above, I interpret responsible bioenergy as biomass value chains where:

- Biomass is prioritized for products while production residues are converted into fuels or CHP
- Bioenergy conversion is coupled with carbon capture
- Biomass is sourced from biodiverse and net-negative forests

While results of this research, the above criteria could be considered simplified. For more holistic assessments of responsible bioenergy the reader may refer to e.g. Berndes et al. (2016), Cowie et al. (2021), Vera et al. (2022), or Calvin et al. (2021).

It is possible to quantify the value of biomass usage pathway, as was done in Millinger et al. 2025). Similar to previous arguments, they found that biogenic carbon contributes with higher system value (lower system costs) if prioritized for products rather than bioenergy. Furthermore, biomass residues that are used for bioenergy also contribute with high system value if integrated with carbon capture. Notably, for these carbon capture applications, it makes little difference whether BECCS or e-fuel production is prioritized (Millinger et al., 2025).

Aligned with the above, it could be possible to deploy carbon capture at a range of Swedish CHP and industrial sites without increasing biomass usage, as showed in paper (III). This case could contribute to responsible bioenergy usage since it demands no additional biomass sourcing, while still realizing the system benefits of bioenergy carbon capture described in Millinger et al. The possibility of integrating BECCS at Swedish sites without increasing biomass usage has also been highlighted by Lefvert (2024).

The results from paper (III) are visualized in Figure 12. I simulated a range of scenarios to identify conditions under which 113 biomass- and waste-fired CHP plants and pulp mills could capture their CO_2 (19 Mt in total) at low costs, without combusting additional biomass. Scenarios of interest included those where CO_2 capture costs of CHP plants and pulp mills were below 120 and 80 EUR/tCO_2, respectively, and where the CHP penalty of carbon capture was kept below 450 kWh/tCO_2. The color of each plant indicates the fraction of scenarios that meet these criteria, while circle diameters represent gross CO_2 emissions.

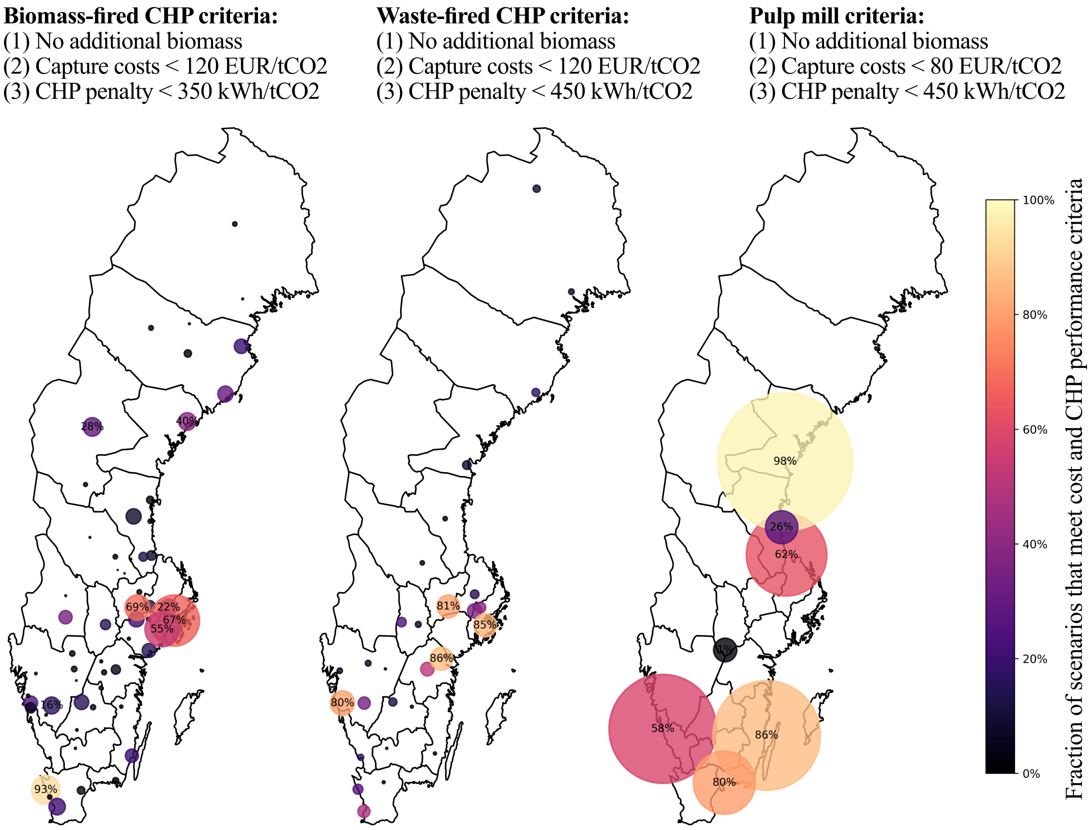

Figure 12: *Carbon capture could be integrated into* 113 *biomass- and waste-fired CHP plants and pulp mills without combusting additional biomass. Under certain conditions, capture costs could then be kept below* 120 *or* 80 *EUR/tCO_2 and CHP penalties below* 450 *and* 350 *kWh/tCO_2* (*indicated by the Figure*) *across many scenarios. These conditions include the efficient utilization of waste heat and low electricity prices.*

The main conditions that enable low-cost and energy-efficient BECCS in Figure 12 include the utilization of heat pumps and low electricity prices. Such criteria were applied for all plants, as detailed in paper (III). For example, COP values between 3.14-3.8 and electricity prices below 67 and 45 EUR/MWh (depending on the plant) were applied for biomass-fired CHP. Whether these conditions are realizable is contestable but possible. For example, the Swedish Energy Agency's latest scenarios portray electricity prices between 50-70 EUR/MWh by 2050 (Energimyndigheten, 2025b). Therefore, the argument that BECCS can be realized without combusting additional biomass stands, but the cost of such BECCS applications could be higher depending on both site-specific and system-wide technoeconomic conditions.

5. Reflections and Conclusions

In this section, I reflect on the blind spots of system models and on the transparency of this work. I then conclude.

5.1 The Blind Spots of System Models

This research identified important conditions for decision making on BECCS. While not a novel insight, I note that BECCS investments seem to be misrepresented in IAMs and other top-down, cost-optimizing system models: Bioenergy actors are not deploying BECCS in an orchestrated fashion driven by a global carbon price (currently). It could therefore be unhelpful to research cost-optimal BECCS scenarios if these remain blind to the main drivers of deployment, including power, agency, and specific policy instruments and their coalitions.

Naturally, such system models primarily serve other purposes, like producing scenarios of the full energy system transition. But their portrayal of BECCS seems to oversimplify its deployment and therefore oversimplify the climate transition (cf. Hansson et al., 2021). This risk could be applicable to other CDR (Carton et al., 2020). That said, such scenarios can function to legitimize BECCS, since actors refer to the scenarios to legitimize their projects (Lefstad et al., 2024). Therefore, I conclude that the representation of BECCS in system models remains important to BECCS developers, but risks oversimplifying the transition. While these risks have been acknowledged in the latest IPCC assessment report, IAM scenarios have remained reliant on substantial CDR capacities (IPCC, 2023).

5.2 Transparent Science

A final reflection concerns the transparency of this research. The reader should note that the research was shaped by inherently social processes, including the deliberation with stakeholders during RDM, debates with my research group, manuscript revisions during peer review, and the translation of BECCS into quantitative models. While I believe the research represents the reality of decision making on Swedish BECCS, the representation is contingent on such processes. This implies that certain viewpoints have been foregrounded (like the needs of bioenergy actors) and others backgrounded (like the risks of mitigation deterrence). A holistic understanding of BECCS therefore requires additional, diverse, and—hopefully—transparent research perspectives.

Practically speaking, all models and data of this work have been made available in online repositories or supplementary materials of papers (I) through (III). Running the models requires basic knowledge on Python and how to install the required packages. Further guidance can be found in Hadjimichael et al. (2020) and Kwakkel (2017). All interview results can be found in the supplementary material of paper (I).

Naturally, a limitation of the research is that I am not myself in a decision-making position. I may therefore not have captured every key aspect of BECCS decision making.

5.3 Conclusions

In this work, I explored conditions under which Swedish decision makers could commit to robust, energy-efficient, and economic investments in BECCS. Four key conditions were discussed.

Firstly, current BECCS actors need to exercise political power to shape policy, regulation, and discourse to their benefit. Accordingly, actions beyond normal system boundaries of bioenergy actors are needed to establish agency over BECCS projects.

Secondly, the two cases studied would require incentives from subsidies and markets actively governed by policymakers. I found that Stockholm Exergi could invest under various scenarios of reverse auction subsidies and electricity prices if CDR prices exceed 151 EUR/tCO_2. In practice, while the full costs and revenues are unknown, the company has secured a subsidy of 160 EUR/tCO_2 and it is possible that up to 480 EUR/tCO_2 would be needed to cover costs for the first 10-15 years of operation. Considering E.ON, CDR market incentives above 185 EUR/tCO_2 and a reverse auction subsidy of 160 EUR/tCO_2 could be required to reach a robust investment decision. Incentives from a CDR-integrated ETS market could be insufficient, although integrating CDR into the system through public procurement would improve its reliability.

Thirdly, investments require robust CO_2 capture technologies. Amine and HPC capture can generally be integrated with high energy efficiency in Sweden owing to opportunities for heat recovery within district heating networks and standalone pulp mills. Furthermore, oxyfuel and chemical looping could enable low-cost and low-regret BECCS relative to amines, but this potential is contingent on rigorous CAPEX estimates by decision makers.

Finally, robust BECCS investments rely on and can contribute towards responsible bioenergy, here interpreted as the energy conversion of residues from product value chains that source biomass from biodiverse and net-negative forests. Across 113 CHP plants and pulp mills, around 19 $MtCO_2$ could be captured annually without combusting additional biomass, with cost and energy efficiencies mainly driven by electricity price and heat integration variations. Accordingly, efficient integration could realize system-wide benefits of carbon capture from bioenergy while avoiding excessive biomass extraction.

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