



UNIVERSITY OF HELSINKI

Social Marginal Abatement Cost of Negative Emissions

Incorporating Externalities into the Private Costs of Carbon Dioxide Removal

Master's thesis
Environmental and Resource Economics
Department of Economics and Management

Anna Havukainen

March 2024
University of Helsinki

Faculty Faculty of Agriculture and Forestry	Department Department of Economics and Management	
Author Anna Havukainen		
Title Social Marginal Abatement Cost of Negative Emissions - Incorporating Externalities into the Private Costs of Carbon Dioxide Removal		
Subject Environmental and Resource Economics		
Level/Instructor Master's thesis/Lassi Ahlvik, Kati Koponen	Month and year March 2024	Number of pages 47 p + 3 appendices.
<p>Abstract</p> <p>The essential role of Carbon Dioxide Removal (CDR) in mitigating further climate warming, alongside substantial emission reductions, is undeniable. However, the actions to remove carbon dioxide are not without consequences, necessitating the integration of external costs into decision-making processes based on cost-efficiency. Previous literature has dominantly focused on the private costs associated with carbon dioxide removal, excluding external costs and their impact on society. The objective of this thesis was to identify the Negative Emission Technologies and Practices (NETPs) that yield the lowest social costs, thereby providing insights into which NETPs should be prioritized for investments in CDR. This evaluation was conducted by developing a Social Marginal Abatement Cost Curve (SMACC) framework, to examine the potentials and social costs of various NETPs. The year under analysis was 2050, the target year for the European Union to achieve net-zero emissions.</p> <p>Results of a comprehensive life-cycle analysis, including impacts on human health and ecosystems, were monetized to establish external costs for each NETP. These external costs were subsequently incorporated with private costs, gathered from existing literature. The final step involved combining these social costs with NETPs' removal potentials to construct the SMACC curve. The SMACC identified the most feasible NETPs as Bioenergy with Carbon Capture and Storage (BECCS) with combustion technology, Direct Air Capture and Storage (DACCS) with High-Temperature Solid-Sorbent technology, and Enhanced Weathering.</p> <p>The study found that each impact category had a considerably different impact on the SMACC results, with human health impacts and ecosystem impacts providing distinct insights. The socially optimal prioritization was proved to be significantly different from cost-effective prioritization, indicating the importance of incorporating external costs into the analysis. As key conclusions, the policies applied to NETPs necessitate careful application to avoid supporting the implementation of NETPs associated with high negative externalities. Furthermore, to achieve optimal outcomes across the globe, the SMACC necessitates careful consideration of the characteristics of each region where the NETPs are to be implemented. The thesis recommends further research on the economic valuation of LCA results.</p>		
Keywords Carbon Dioxide Removal, Negative Emissions, Social Marginal Abatement Cost, SMACC		
Where deposited The Library of the University of Helsinki		
Additional information Developed from a research contribution to the European Commission's NEGEM project, commissioned by VTT Technical Research Centre of Finland.		

Tiedekunta Maatalous-metsätieteellinen tiedekunta		Laitos Taloustieteen osasto	
Tekijä Anna Havukainen			
Työn nimi Sosiaalinen rajapuhdistuskustannuskäyrä negatiivisille päästöille – Hiilidioksidin poiston ulkoisvaikutusten sisällyttäminen yksityisiin rajakustannuksiin			
Oppiaine Ympäristö- ja luonnonvarataloustieteet			
Työn laji / Ohjaajat Pro gradu / Lassi Ahlvik, Kati Koponen		Aika Maaliskuu 2024	Sivumäärä 47 s + 3 liitettä.
<p>Tiivistelmä</p> <p>Hiilidioksidin poistoa ilmakehästä tullaan tarvitsemaan ilmaston lämpenemisen hillitsemisessä, mittavien päästövähennysten rinnalla. Hiilidioksidin poistoon käytettäviin teknologioihin ja menetelmiin liittyy kuitenkin ulkoisvaikutuksia, minkä vuoksi ulkoiskustannukset on otettava huomioon kustannustehokkuuteen perustuvassa päätöksenteossa. Aiempi aihetta koskeva kirjallisuus keskittyy yksityisiin rajakustannuksiin, sulkien pois ulkoiskustannukset ja niiden seuraukset yhteiskunnalle. Tämän maisteritutkielman tavoitteena oli yksilöidä negatiivisten päästöjen teknologiat ja menetelmät, joiden sosiaaliset rajakustannukset ovat alhaisimmat, ja tuoda näin näkökulmaa siihen, mitkä teknologiat ja menetelmät tulisi priorisoida hiilidioksidin poistoon tehtävissä investoinneissa. Analyysi toteutettiin kehittämällä Sosiaalinen rajapuhdistuskustannuskäyrä (SMACC) -viitekehys negatiivisten päästöjen teknologioiden ja menetelmien potentiaalien, sekä sosiaalisten kustannusten tarkastelemiseksi. Analyysin viitevuosi oli 2050, Euroopan unionin nettonollapäästöjen tavoitevuosi.</p> <p>Negatiivisten päästöjen teknologioille ja menetelmille toteutetun elinkaariarvion tulokset, joka sisälsivät terveyteen ja ekosysteemeihin kohdistuvat ulkoisvaikutukset, arvoitettiin rahalliseen arvoon, tuottaen ulkoiskustannukset analysoiduille teknologioille ja menetelmille. Nämä ulkoiskustannukset lisättiin kirjallisuudesta analysoiduihin yksityisiin rajakustannuksiin. Lopuksi sosiaaliset rajakustannukset liitettiin teknologioiden ja menetelmien hiilidioksidin poistopotentiaaleihin, visualisoiden tulokset rajakustannuskäyrällä. SMACC:n tuloksena todettiin, että soveltuvimmat negatiivisten päästöjen teknologiat ja menetelmät vuonna 2050 ovat bioenergian tuotantoon yhdistetty hiilidioksidin talteenotto ja varastointi (BECCS) toteutettuna polttoteknologiolla, hiilidioksidin talteenotto suoraan ilmasta (DACCS) toteutettuna korkean lämpötilan talteenottoteknologiolla, sekä tehostettu rapautuminen.</p> <p>Tutkimus osoitti, että kukin vaikutusluokka vaikutti merkittävästi eri tavalla SMACC:n tuloksiin, sillä terveyteen liittyvät ulkoisvaikutukset ja ekosysteemiin liittyvät ulkoisvaikutukset muuttivat tulosten järjestystä eri suuntiin. Tärkeimmät johtopäätökset olivat, että politiikan ohjauskeinojen täytäntöönpanossa on kiinnitettävä erityistä huomiota siihen, että vältetään kannustimet sellaisille teknologioille, jotka tuottavat huomattavasti negatiivisia ulkoisvaikutuksia. Jotta hiilidioksidin poistossa päästäisiin haluttuun lopputulokseen kaikkialla maailmassa, on lisäksi tärkeää, että SMACC toteutetaan tapauskohtaisesti teknologioiden ja menetelmien käyttöönottosijainnin ominaisuudet huomioon ottaen. Tämän tutkielman myötä suositellaan lisätutkimusta elinkaarianalyysien tulosten taloudelliselle arvottamiselle.</p>			
Avainsanat - Nyckelord Hiilidioksidin poisto, Negatiiviset päästöt, Sosiaalinen rajakustannus, SMACC			
Säilytyspaikka Helsingin yliopiston kirjasto			
Lisätiedot Toteutettu tutkimuspanoksena Euroopan komission NEGEM-projektiin Teknologian Tutkimuskeskus VTT:n toimeksiantona.			

PREFACE

This thesis is written for the European Commission's NEGEM project. The thesis is fully funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869192 and is commissioned by the NEGEM project coordinator VTT Technical Research Centre of Finland.

I would like to thank my supervisors, Kati Koponen from VTT, and Lassi Ahlvik from the University of Helsinki for your expertise and effort in guiding me through five months of research work. I feel grateful for the opportunity to conduct my thesis on such a remarkable project.

The NEGEM project is a four-year research project, which will end at the end of May 2024, to quantify and deploy responsible negative emissions by assessing the realistic potential of Carbon Dioxide Removal and its contribution to climate neutrality. The project applies a multidisciplinary approach that goes beyond climate physics and climate economics and focuses on real-world perspectives. (European Commission, 2024a)

Table of Contents

1	Introduction	7
1.1	Background and Importance of the Study.....	7
1.2	Objectives of the Study.....	8
1.3	Scope of the Thesis.....	8
1.4	Structure of the Thesis	9
2	Literature Review	9
2.1	Carbon Dioxide Removal	9
2.2	Negative Emission Technologies and Practices.....	10
2.2.1	Terrestrial NETPs	11
2.2.2	BECCS.....	12
2.2.3	Chemical NETPs	14
2.3	Economic Valuation of the Social and Environmental Impacts.....	15
2.3.1	LCA in the context of CDR.....	15
2.3.2	Monetizing LCA Results	16
2.4	Marginal Abatement Cost Curve in the Context of CDR	17
3	Theoretical Framework	18
3.1	Social Marginal Abatement Cost Curve	18
3.1.1	Social Costs and Benefits	18
3.1.2	The Theory of SMACC.....	19
3.1.3	SMACC's Connection to Traditional Cost-Benefit Analysis.....	21
4	Methodology and data	22
4.1	Private Costs of NETPs	22
4.1.1	Data on the Costs of NETPs	22
4.1.2	Assumptions and Modifications for Costs.....	23
4.1.3	Mean Values for Costs.....	23
4.2	Carbon Capture Potentials for NETPs.....	24
4.2.1	Data on NETP Potentials.....	24
4.2.2	Assumptions and Modifications for Potentials	25
4.2.3	Mean Values for Potentials	26
4.3	NETP's Externalities and LCA Data.....	26
4.3.1	Data on NETPs' LCA Results	27
4.3.2	Assumptions and Modifications for LCA Data	29
4.4	Economic Valuation of Externalities.....	29
4.4.1	Understanding Monetizing Externalities	30
4.4.2	Economic Valuation.....	30

5	Results	31
5.1	Social MACC for NETPs	31
5.1.1	Terrestrial NETPs on SMACC.....	33
5.1.2	BECCS on SMACC	33
5.1.3	Chemical NETPs on SMACC.....	34
5.2	Applications of SMACC	34
5.2.1	SMACC without Land Use	34
5.2.2	SMACC Including Only Externalities for Human Health	35
5.3	Comparison of MACC and SMACC.....	36
5.4	Sensitivity Analysis.....	37
6	Discussion	39
6.1	Interpretation of Results	39
6.1.1	Identifying the NETPs with the Lowest Social Costs.....	39
6.1.2	Advantages of SMACC	40
6.1.3	Land Use in the Results.....	41
6.2	Limitations of the Study.....	41
6.2.1	Economic Valuation of Impacts.....	41
6.2.2	Geographical Considerations and Resource Utilization	42
6.3	Implications for Policy and Practice	43
6.3.1	Subsidies and Incentives.....	43
6.3.2	CDR in Emissions Trading Systems	44
6.3.3	Recommendation for Future Research	45
7	Conclusions.....	46
	References	48
	Appendices	55
	Appendix 1 Cost of CDR in 2050	55
	Appendix 2 CDR Potentials in 2050.....	56
	Appendix 3 BECCS Potentials from NEGEM modeling.....	57

1 Introduction

1.1 Background and Importance of the Study

The European Union (EU) finds itself at a pressing turning point as it faces the urgent challenge of reducing its greenhouse gas emissions to keep global warming well below 2 Celsius degrees. So far, government actions aimed at emission reductions have turned inadequate. (EEA, 2022; European Parliament, 2023) In response, the EU has shifted its focus towards the 2040 climate targets, underscoring the pivotal role of Carbon Dioxide Removal (CDR). The EU's 2040 climate target primarily emphasizes reducing net greenhouse gas emissions by 90% compared to 1990 levels. The development of effective methodologies and practices for carbon dioxide (CO₂) removal has become necessary as a supplementary measure in order to reach the 2050 targets of net zero emissions across the EU. (European Commission, 2024b; IPCC, 2023) CDR is firmly integrated into the EU climate policy for the coming decades. The Intergovernmental Panel on Climate Change (IPCC) emphasizes that CDR should be primarily used for hard-to-abate emissions (IPCC, 2022).

The annual CDR requirement for 2050 has been estimated to be around 10 Gt/year (National Academies of Sciences, 2019). Future CDR implementation will encompass both natural carbon sequestration mechanisms such as reforestation and sequestering carbon into soils, as well as negative emission technologies like Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS) (Cobo et al., 2023). These mechanisms are so-called Negative Emission Technologies and Practices (NETPs). In an ideal realm, the way forward would be to only adopt CDR approaches that impose no negative or harmful impacts. However, the reality in which we operate necessitates the consideration of cost-effectiveness alongside the strive for environmental and social impacts. As such a comprehensive analysis of the costs, benefits, and impacts of CO₂ removal with NETPs is essential to find sustainable pathways to meet the collective carbon removal commitments.

In addition, the IPCC acknowledges that missing pricing of externalities is a barrier to fulfilling the financing gap to meet long-term climate goals (IPCC, 2023). Decisions based on private costs solely are missing consideration of long-term impacts and their costs to society. This highlights the need for incorporating external costs into climate policymaking.

1.2 Objectives of the Study

This thesis is targeted at supporting policymaking in the realm of climate policy, particularly focusing on the transition to carbon-neutral and carbon-negative economies, as well as carbon removal in forthcoming decades. The analysis will take a deeper look into NETPs and aims to find the least harmful and most cost-efficient methods to remove CO₂ from the atmosphere to prevent the impacts of climate change and target global warming to stay well below 2 degrees, with an aim of 1.5 degrees.

While there are several tools and methods available for decision-makers to find and analyze the most cost-efficient solution for policymaking, both the public sector and business lack tools for socially optimal decision-making. Therefore, a key component of this analysis is the construction of a Social Marginal Abatement Cost Curve (SMACC) framework, which is achieved by calculating the social costs of NETPs. This process involves monetizing the results of a Life Cycle Analysis (LCA) and aggregating them to the private costs. The analysis brings the externalities alongside the cost-efficiency of the technologies and practices. Benefits occurring from NETPs will decrease the social cost, whereas negative externalities increase the social costs. The thesis aims to investigate the following research question:

Which Negative Emission Technologies and Practices provide the lowest social costs for deployment by 2050 to limit global warming to 1.5 degrees?

The response to the research question will be provided using the Social Marginal Abatement Curve for NETPs.

1.3 Scope of the Thesis

Carbon dioxide removal is a relatively longstanding practice, so far primarily addressed through so to speak natural solutions, such as afforestation and soil carbon sequestration. However, alternative practices have been explored to find the extent of their potential implementation and to supplement the traditional CO₂ removal methods with technology options. Novel technology methodologies have been developed for CDR, like BECCS and DACCS as truly promising ones of these. (European Commission, 2023; IEA, 2022)

Given the variety of options for removing carbon dioxide from the atmosphere, further research into their efficiency and potential externalities, both positive and negative, is essential. This thesis will focus on both, the environmental and social impacts of CDR methods. The research seeks to find the answer to the challenge of questioning whether

should we invest more in the latest carbon removal technologies, or should we focus on enhancing the use of existing, natural methods that function as carbon sinks. The carbon dioxide emission reduction actions are not part of this research.

The EU has set the year 2050 as the target for achieving net-zero CO₂ emissions. At the beginning of this research work the EU's targets for 2040 had not yet been published. Consequently, this research is aligned with the 2050 target.

1.4 Structure of the Thesis

Structurally the analysis in this thesis proceeds in five sections. Following this introduction chapter two provides a literature review on the Carbon Dioxide Removal and Negative Emission Technologies and Practices and valuation of externalities. The third chapter presents the theoretical framework of the Social Marginal Abatement Cost Curve. In chapter four, the process of data collection and data modifications including the methodology of incorporating external costs into the analysis is presented. This is followed by the presentation of the results in chapter five. Furthermore, chapter six discusses and analyzes the key findings of the thesis. The analysis is finalized with the conclusions of the thesis.

2 Literature Review

The following sections provide a comprehensive introduction to the concepts of Carbon Dioxide Removal (CDR) and Negative emission Technologies and Practices (NETPs). Furthermore, the literature on the economic valuation of external impacts and research on the utilization of the Marginal Abatement Cost Curve within the carbon dioxide removal context are reviewed.

2.1 Carbon Dioxide Removal

Global warming is primarily caused by greenhouse gas emissions in the atmosphere, with CO₂ accounting for a large proportion of these emissions (de Jonge et al., 2019; IPCC, 2023). To mitigate the adverse effects of climate change, societies seek the most effective solutions, one of which is CDR. CDR refers to a process that extracts CO₂ from the atmosphere and stores it in a manner intended to be permanent (Tanzer & Ramírez, 2019). CDR processes are the opposite of CO₂ emissions; thus, they can also be described as “negative emissions”.

Occasionally the term negative emissions is extended to include the removal of other greenhouse gases than CO₂, such as methane and nitrous oxide (Goglio et al., 2020).

NETPs and CDR have played a significant role in international climate policy discussions since the IPCC's Fifth Assessment Report (AR5) (IPCC, 2014). The IPCC mitigation scenarios indicate that to keep global warming well below 2 degrees, CDR will be needed to supplement drastic emission reductions. More detailed roles for the different time periods are defined in Working Group III contribution to the IPCC's AR6 (IPCC, 2023): In the near term CDR is needed for reducing net emission levels further, in the midterm for balancing residual emissions to help reach net-zero emissions, and in the long term for achieving and sustaining net-negative emissions.

Based on Paris Agreement targets, EU countries should decrease their CO₂ emissions to net zero by 2050 (Fankhauser et al., 2022). However, referring to the emission reduction progress so far, this target is impossible to meet only with CO₂ emission reduction (European Commission, 2024b; Gambhir & Tavoni, 2019). In addition, emission reductions have a long payback time before the accumulation of CO₂ stops (Krieler et al. 2012); thereby to reach net zero targets by 2050 and net negative emissions by the end of the century, CO₂ removal in the atmosphere is needed on an extensive scale.

Nevertheless, relying too much on CDR poses risks; it is important to note that the aim of CDR is not to enable further increases in CO₂ emissions. Rather it serves as a tool to help decelerate the most urgent climate heating until effective actions to reduce CO₂ emissions internationally are implemented (Terlouw et al., 2021). In fact, the process of removing one ton of CO₂ from the atmosphere is not "symmetrical" to the release of one ton of CO₂. This implies that removing a ton of CO₂ does not fully compensate for the impact of a released ton (Zickfeld et al., 2021). Even with CDR, economies must achieve major emission reductions.

2.2 Negative Emission Technologies and Practices

Negative Emission Technologies and Practices (NETPs) are methods to implement CDR and can be both nature-based and technical solutions. Following the IPCC's (2023) definition, the CDR portfolio consists of the following NETPs: afforestation, reforestation, improved forest management, soil carbon sequestration, biochar, BECCS, DACCS, enhanced weathering, peatland and coastal wetland restoration, blue carbon, ocean alkalinity enhancement, and ocean fertilization, as illustrated in Figure 1.

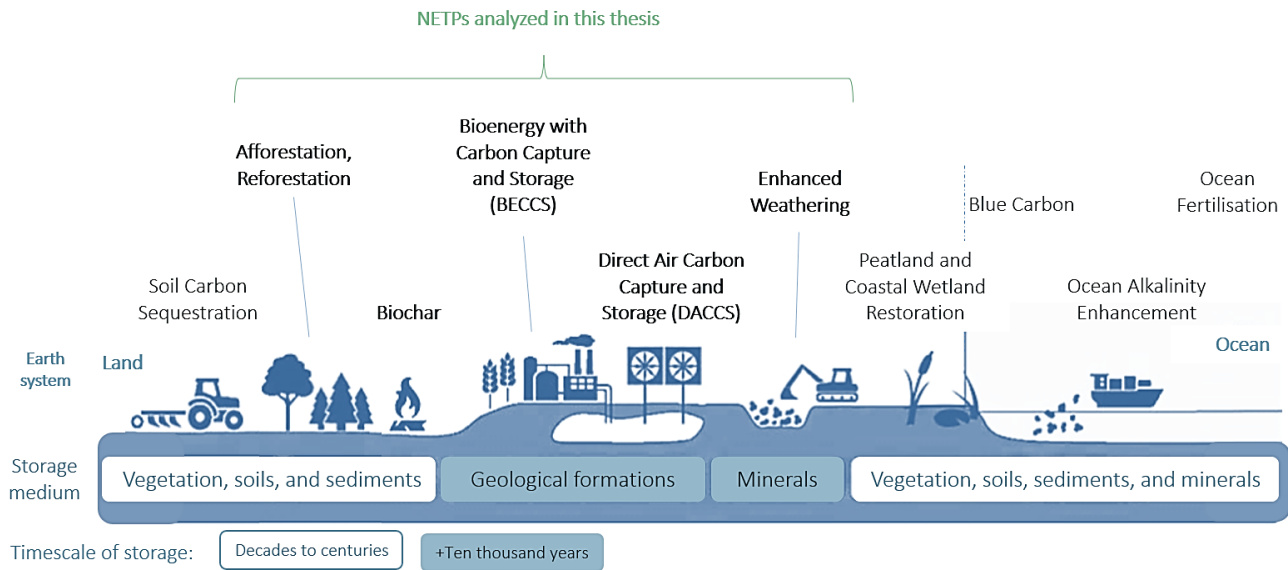


Figure 1 The Negative Emission Technologies and Practices. Adapted from (IPCC, 2023).

The scope of the NEGEM project has determined which NETPs will be further analyzed in this thesis. These NETPs were chosen at the beginning of the NEGEM project and are based on a preliminary assessment of their potential scalability, feasibility, and impact on achieving the CDR targets (Cobo et al., 2020). Consequently, soil carbon sequestration, peatland and coastal wetland restoration, and ocean-based NETPs are excluded from this thesis. The technologies and practices that will be analyzed will be introduced in more detail in the following subchapters. NETPs can be further classified into terrestrial NETPs, BECCS, and chemical NETPs (Cobo et al., 2023).

2.2.1 Terrestrial NETPs

In this analysis, the terrestrial NETPs cover the following CDR methods: afforestation, reforestation, and biochar. Afforestation and reforestation can sequester CO₂ through the natural process of photosynthesis. The captured CO₂ circulates back into the ecosystem through a series of processes such as organic matter decomposition, erosion, and wildfire (Cobo et al., 2023). All the terrestrial NETPs utilize a biotic storage of CO₂ (Shahbaz et al., 2021).

Afforestation refers to the practice of establishing forests in areas that were not originally (or at least in 50 years) forests, while reforestation involves replanting previously harvested areas (Fuss et al., 2018). A significant share of the potential for CO₂ capture in forests is located in tropical regions (Doelman et al., 2020). Afforestation and reforestation are often mixed and regarded as one single concept. However, it's important to notice significant

differences between them; due to the substantial land area occupation, afforestation has been found to be notably harmful to indigenous people and biodiversity as it requires the conversion of areas that have previously fulfilled functions other than being a forest. On the other hand, reforestation has been discovered to be more resilient to future climate shocks due to the local ecosystem's previous existence as forests. (Kaine et al., 2023; Ota et al., 2020) However, both afforestation and reforestation are relatively challenging in terms of land area requirements. (Doelman et al., 2020; Fuss et al., 2018).

Forest conservation and sustainable forest management are vital for mitigating climate change and conserving biodiversity. Nevertheless, activities aimed at preventing forest degradation such as those under the REDD+ program, are not classified as NETPs as they do not create new carbon sinks (Cobo et al., 2023). Despite the challenges, forestation is considered competitive in terms of cost and easy-to-implement practice, but the permanence of carbon storage is uncertain and dependent on external factors such as drought, pests, and wildfires in the long term (Chiquier, Fajardy, et al., 2022; Fuss et al., 2018).

The third type of terrestrial NETP is biochar, a carbon-rich product of a biomass process. The primary process to produce biochar is pyrolysis, which creates a solid biochar product at high temperatures. (Schmidt et al., 2019) Biochar is used for application to increase the nutrient level of soil (Fuss et al., 2018; Hepburn et al., 2019). The process of converting biomass into biochar is not highly efficient (around 30%-50%) (Schmidt et al., 2019). However, biochar is regarded as a promising NETP because, unlike other terrestrial NETPs, biochar has the ability to sequester CO₂ permanently (Shahbaz et al., 2021). This makes biochar a unique natural CO₂ storage alternative. Another promising terrestrial NETP is soil carbon sequestration. This NETP aims to store CO₂ in soil organic matter by increasing the carbon content of soil through changes in land management (Cobo et al., 2023; Fuss et al., 2018). It is outside the scope of this thesis and will not be analyzed in detail.

2.2.2 BECCS

Bioenergy with Carbon Capture and Storage (BECCS) provides two separate services: bioenergy and CO₂ removal (Hepburn et al., 2019). BECCS covers a variety of technologies for bioenergy conversion processes that are combined with CO₂ capture and storage (CCS). The biomass, or bioenergy crops used for these processes may originate from forests, agricultural lands, and residual biomass from the forest industry for instance. (Cobo et al.,

2023; Hanssen et al., 2020) The growth of biomass involves sequestration of CO₂ naturally. This CO₂ is subsequently captured during the processing phase and permanently stored in geological formations, resulting in negative emissions. It is crucial to underscore the importance of ensuring that the biomass utilized in BECCS is produced sustainably (Rosa & Mazzotti, 2022).

BECCS technologies are relatively novel and have only been implemented on a small scale currently (Smith et al., 2023). Value added through chemical and fuel production alongside CO₂ removal makes BECCS technologies attractive NETPs (Ganeshan et al., 2023). The BECCS technologies studied in this analysis are combustion-BECCS for power production, Fischer–Tropsch diesel produced with CCS, and gasification to hydrogen (H₂).

Combustion is a well-established thermochemical process to generate usable energy from biomass. The process itself is mature and has been primarily used for generating electricity and heat, but combining combustion with CCS has emerged lately. The process involves the transformation of carbon in the biomass into CO₂ and capturing and storing it. (Cobo et al., 2023; Shahbaz et al., 2021)

Gasification stands for another thermochemical energy process that can be utilized as a BECCS technology. This process involves reacting biomass into carbon monoxide, hydrogen, and CO₂ at high temperatures, without combustion. These products are further processed into synthetic gas or hydrogen, and finally, the CO₂ generated from the process is captured and stored. (Ganeshan et al., 2023; Shahbaz et al., 2021) According to Cobo et al (2023), gasification has greater energy efficiency than combustion.

When the gasification process is primarily implemented for hydrogen production, it is referred to as gasification to H₂ (Ahlström et al., 2022). The Fischer–Tropsch process can also be integrated with gasification. When combined with Fischer–Tropsch synthesis, gasification serves as an advanced technology for creating liquid end products, such as biodiesel, from synthetic gas (Shahbeik et al., 2022). Both of these processes employ biomass as a feedstock and incorporate gasification as a component of the process, but their end products differ. Gasification produces gaseous H₂ whereas Fischer–Tropsch generates liquid end products. A few biomass gasification plants exist already in operation, but these facilities have not yet integrated CCS into their processes (Cobo et al., 2023).

Other promising BECCS technologies include but are not limited to, ethanol fermentation, liquefaction, and pyrolysis processes (Cobo et al., 2023). For Nordic regions that are rich in

biomass resources and have a strong forest industry, the application of BECCS in pulp mills presents an intriguing option (Kuparinen et al., 2023; Onarheim et al., 2017). Furthermore, given the extensive district heating system in these regions, the application of BECCS combined with Combined Heat and Power (CHP) plants offers an interesting solution (Gustafsson et al., 2021).

2.2.3 Chemical NETPs

Chemical NETPs' CO₂ removal is based on the chemical reactions between greenhouse gases and other compounds (Cobo et al., 2023). Chemical NETPs considered in this analysis are enhanced weathering and Direct Air Carbon Capture and Storage (DACCS).

Enhanced weathering means accelerating the natural weathering process by spreading small grain-sized rocks to land areas. The rocks used are silicate and carbonate rocks and the carbon removal is based on the rock's chemical absorption which is due to the rock's dissolution. (Zhang et al., 2022) The sequestration is not instant but might take from months to decades (Beerling et al., 2020), resulting in permanent CO₂ storage in the rock minerals (Chiquier, Patrizio, et al., 2022). Enhanced weathering faces challenges in its supply chain; very large quantities of rock are needed for sequestration, and the process of carbon removal through enhanced weathering requires excavation, rock grinding, and transport, which in turn generate large emissions (Chiquier, Patrizio, et al., 2022).

DACCS represents a novel technical solution for CDR. DACCS facilities are designed to capture CO₂ directly from the air, and the absorption of CO₂ is facilitated through chemical solvents and sorbents, after which the CO₂ is processed onwards into permanent geological storages (Keith et al., 2018). DACCS has been predicted to present the highest potential capacities in the discussed NETPs.

Heavy reliance on DACCS carries significant risks, including potential CO₂ leakage, and rapid depletion of global CO₂ storage capacities, as the potential of CO₂ removal is significantly higher compared to other NETPs (Lux et al., 2023). In addition, DACCS facilities have a high energy demand. Therefore, the technology is dependent on CO₂-neutral energy sources to reach optimal outcomes (Fuhrman et al., 2020). The primary DACCS technologies are High-temperature Liquid-Sorbent (HTLS) and Low-Temperature Solid-Sorbent (LTSS), (Cobo et al., 2023).

Table 1 Summary of the NETPs.

NETPs	Abbr.	Description	Storage	Permanence
Afforestation	AFF	Planting forests in areas where there has not been forest before	Standing forests	Low
Reforestation	REF	Planting forests in areas previously covered by forest	Standing forests	Low
Biochar	BC	Solid biomaterial that stores CO ₂ in the agricultural process	Soil and sediment	High
Combustion (BECCS)	COMB	Production of bioenergy electricity by combustion process combined with CCS	Geological storage	Very high
Fischer–Tropsch (BECCS)	FT	Production of liquid biofuels by FT process combined with CCS	Geological storage	Very high
Gasification to H ₂ (BECCS)	H2-GAS	H ₂ gas production by gasification combined with CCS	Geological storage	Very high
HTLS-DACCS	HTLS	Capturing CO ₂ directly from the air using high-temperature technology with chemical liquid sorbent combined with CCS	Geological storage	Very high
LTSS-DACCS	LTSS	Capturing CO ₂ directly from the air using low-temperature technology with chemical solid sorbent combined with CCS	Geological storage	Very high
Enhanced weathering	EW	Sequestering CO ₂ to crushed rock minerals	Minerals	Very high

CCS = Carbon Capture and Storage.

2.3 Economic Valuation of the Social and Environmental Impacts

While NETPs are intended to make a positive impact by reducing global warming, it is crucial to consider both, social and environmental negative impacts from implementing these technologies and practices. On the other hand, some NETPs have positive impacts that occur from their usage, referred to as co-benefits. (Fuss et al., 2018; Terlouw et al., 2021) This analysis utilizes the Life Cycle Analysis (LCA) carried out in the NEGEM project to consider these impacts for each NETP individually. Later these impacts will be translated into social costs using economic valuation techniques.

2.3.1 LCA in the context of CDR

LCA is an ISO 14040/44 standardized method, and it is widely employed to analyze the environmental and social impacts of products or services, with the objective of considering all impacts throughout their lifecycle (ISO 2006). When utilized for analyzing CDR, LCA is implemented to identify and evaluate the external impacts of NETPs as well as compare the

trade-offs between different CDR implementation paths. Comprehensive LCA studies analyzing CDR are relatively scarce (Dong et al., 2019). However, Cobo et al. (2022) have successfully conducted an assessment of various NETPs with a focus on BECCS and DACCS technologies.

LCA is a valuable instrument to support decision-making processes for CDR deployment (Honegger et al., 2021; Sadhukhan, 2022). Nevertheless, it is essential to be careful when applying LCA to NETPs, especially in the accurate accounting of negative emissions. For example, there is a risk of misinterpreting avoided emissions created through the substitution of counterfactual products as negative emissions (Terlouw et al., 2021). Another risk relates to the definition system boundary for the LCA, as NETPs are extensive entities and the characteristics among technologies and practices vary largely (Goglio et al., 2020).

2.3.2 Monetizing LCA Results

Monetizing environmental and social impacts is one mechanism to transfer LCA results into a unified, monetary value (Pizzol et al., 2017). Assigning monetary value by economic valuation to LCA results simplifies understanding the magnitude of external impacts and enables including LCA results alongside monetary analyses, as well as even justifies a high price of implementation of a practice (Huysegoms et al., 2018). Economic valuation offers incentives for mitigating environmental and social damages (Martino & Kenter, 2023). In some instances, monetized externalities may gain even a higher price than the product or service itself, due to the criticality or remarkability of the externality, indicating a notable market failure (Sovacool et al., 2021). This highlights the importance of monetization as a tool integrated with impact assessment, while also emphasizing the need for careful consideration in its application.

The commercial sector has initiated integrating evaluation of climate-related damages into their decision-supporting instruments utilizing cost-benefit analysis, where impacts are assessed in monetary terms (Dong et al., 2019). Extensive studies on integrating valued externalities into governmental decision-making have been carried out in the EU over the past few decades (European Commission et al., 2005). However, the integration of these practices into policy implications has been slow at least for the challenge of quantifying intangible aspects of environmental and social issues (Sovacool et al., 2021).

2.4 Marginal Abatement Cost Curve in the Context of CDR

The Marginal Abatement Cost Curve (MACC) is a tool used by policymakers to make informed decisions about pollution reduction based on cost efficiency. It graphically represents the costs and potentials of various pollution reduction practices, demonstrating the marginal cost of reducing an additional unit of pollution, as introduced by McKittrick (1999).

When used in non-market policies, MACC aids in creating a portfolio for the implementation of NETPs (Jiang et al., 2020). In CDR context the MACC estimates the direct costs of CO₂ removal for each technology under consideration. The MACC has been successfully applied with CDR in some studies, for instance in a Swedish case study (Johnsson et al., 2020) where the NETPs were ranked based on their total CO₂ capture costs. As a result of this application, there is a stepwise curve, with each bar representing one CDR technology, the height indicating the marginal abatement cost (MAC), and the width showing the potential of CO₂ removal.

Several studies have explored the applications of MACC that incorporate the co-benefits of technologies alongside the private cost (Huang et al., 2016; Yang et al., 2018). These studies consider the additional benefits of CO₂ reduction as a part of their analysis. Yet, these studies do not integrate negative externalities into the analysis, nor regard the co-benefit as monetized values. Moreover, the focus of these studies is on CO₂ reduction rather than CO₂ removal.

In this thesis, no previous research was found that combines social costs with marginal abatement costs or includes monetized impacts alongside the costs and potentials of CDR. Therefore, this thesis fills a gap in the literature where both negative and positive externalities are considered as external costs and specifically seeks to provide an application to MACC in the field of carbon dioxide or greenhouse gas emission removal.

3 Theoretical Framework

This chapter presents the theory of the Social Marginal Abatement Cost Curve (SMACC) and the theoretical concepts related to it. The theory has evolved during this thesis process and is therefore a new application. The following chapters supplement the core theory by introducing key economic concepts that are linked to SMACC theory and are vital to understanding the theory's connection to environmental economics.

To comprehend the motivation and economic background of the topic, it is crucial to understand the existence of the risk of a market failure if the implementation of NETPs is merely based on their cost-efficiency. Until investments in CDR reach a large scale globally, understanding the impacts of technologies and practices is needed, as market prices fail to cover the environmental and social impacts associated with the life cycle of the NETPs. It is also notable that clean air, biodiversity, and health are considered non-market goods. (Pigou, 1920; Stern, 2022)

3.1 Social Marginal Abatement Cost Curve

One aim of the Social Marginal Abatement Cost Curve (SMACC) is to find a balance between the quantity of CO₂ emissions and the efforts to avoid or sequester these emissions to minimize societal costs. The amount of CDR is optimal when the social marginal cost is zero and thus a point where the costs and benefits of NETPs meet. Without incorporating the externalities into the analysis, the marginal costs and benefits are not on a socially optimal level, and the future costs from unwanted environmental impacts are not considered.

3.1.1 Social Costs and Benefits

An externality can be positive if a market transaction generates an external benefit, or negative if the externality is a cost for affected agencies. The external benefits and costs are borne by agents that are not directly part of the market transaction, as originally presented by Meade (1973). Benefits increase an individual's wellbeing, whereas costs are perceived to decrease the wellbeing. These changes in wellbeing are quantified in monetary values as external costs. Traditionally, benefits are viewed as avoided costs, meaning that by preventing a negative externality, it is possible to avoid incurring costs. (Karlsson et al., 2020)

For CDR, the externalities can be positive or negative and thus they are presented as external costs and benefits. Benefits (positive externalities) gain a negative monetary value when economically valued while costs (negative externalities) gain a positive monetary value. Adding harmful and advantageous effects to the investment cost adds up to the real cost of carbon removal (Sovacool et al., 2021). Therefore, it is crucial to reflect the externalities in the cost of a good or service, in the NETP investments as well.

3.1.2 The Theory of SMACC

SMACC is an extension of the Marginal Abatement Cost Curve (MACC) integrating social costs and benefits with the private costs. SMACC evaluates abatement strategies not only based on their economic efficiency but also on their societal impact and environmental consequences. It could be said that SMACC integrates aspects of cost-benefit analysis into cost-efficiency analysis, establishing a simple and graphical tool for communicating results to the decision-making process. SMACC can be applied to CO₂ removal strategies, CO₂ emission reduction, and other strategies such as those analyzed by MACC.

Unlike MACC, which only considers private abatement costs, the SMACC combines external marginal costs (EMC) and private marginal costs (PMC) of abatement to obtain Social Marginal Abatement Costs (SMAC). The formula for SMAC is given by:

$$SMAC = PMC + EMC \quad (1)$$

Where PMC stands for private marginal cost, and EMC stands for external marginal cost.

The external costs incorporated in SMACC are costs related to human health and ecosystems. These costs can be both positive and negative. If the net impacts of an abatement action are positive, the SMAC falls below the private abatement cost.

SMACC can significantly alter the ranking order of the technologies compared to MACC, indicating that some NETPs that are not attractive in terms of cost-efficiency alone may prove to be socially more optimal choices than the cheaper NETPs when externalities are included, or vice versa. In essence, the net costs of private and external costs determine the SMACC curve, leading to a marginal cost curve divergent from traditional MACC.

SMACC plots the abatement actions, or in CDR context the CO₂ removal technologies and practices along the x-axis, with the y-axis representing the social marginal abatement cost of achieving an additional unit of CDR (\$/tCO₂). The x-axis is the abatement potential of

CO₂ (GtCO₂/year), where the width of each step represents the CDR potential of the NETP during the analysis period. All the NETPs are ordered from least costly to most costly in terms of social costs (from left to right), as shown in Figure 2.

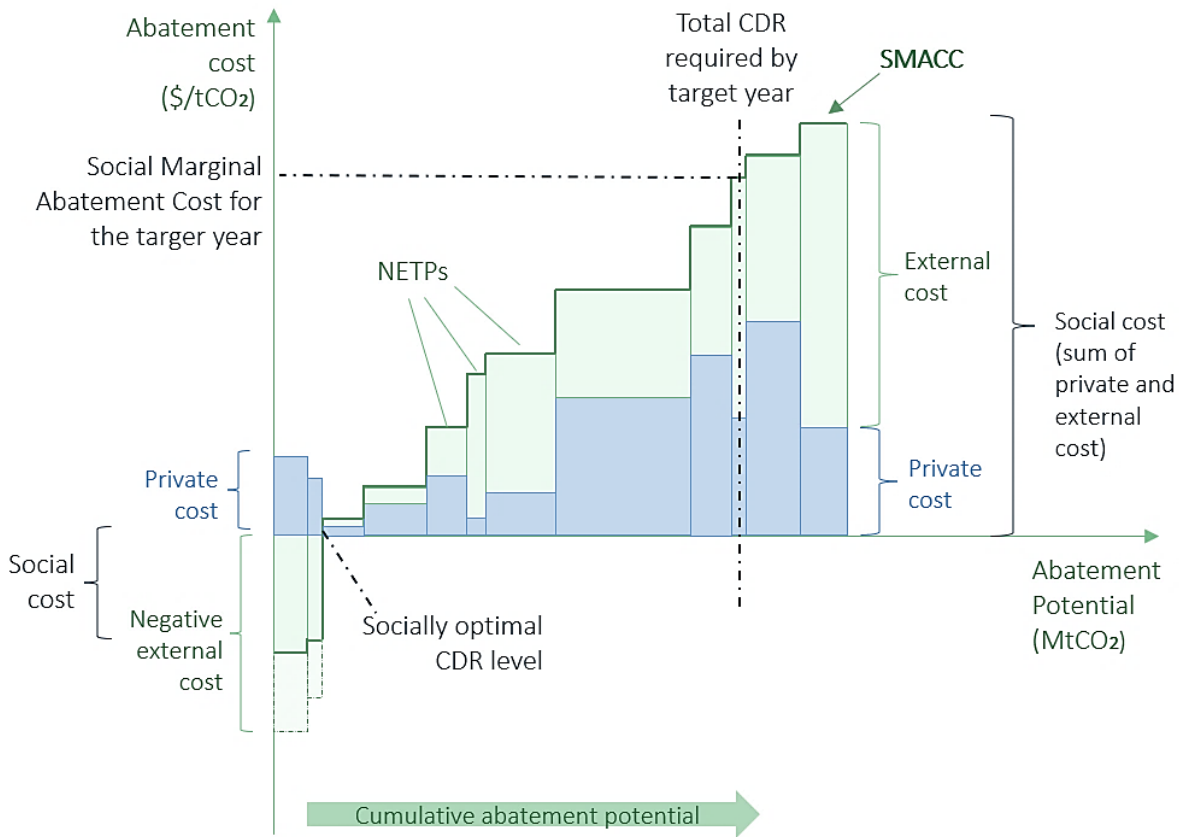


Figure 2 The Social Marginal Abatement Cost Curve (SMACC).

The economically efficient abatement actions with minimal negative externalities are on the left side of the curve. As we move to the right, the social costs of the actions increase. This is not necessarily due to an increase in abatement cost, but rather the amount of negative externalities that lift the NETP higher on the curve, illustrated with positive external costs. NETPs with a mix of high abatement cost and high negative externalities appear on the far right, whereas NETPs with relatively high abatement costs may move to the left if they have positive or low negative externalities. Even if there are no NETPs with negative abatement costs, the high quantity of positive externalities may lead to a negative social cost. The point where the SMACC intersects the x-axis denotes the socially optimal quantity of CDR. At this intersection, the social cost of CDR is zero. Any further CDR incurs a social cost.

SMACC allows for identifying the optimal combination of actions considering both cost-effectiveness and societal impact. Consequently, governments may replace MACC with

SMACC to design climate policies that account for external impacts. Simultaneously, companies may assess cost-effective emission reduction strategies while anticipating social and environmental consequences. SMACC highlights actions that benefit society as a whole and ensures equity considerations regarding the fair distribution of costs and benefits. This approach does not incorporate all social costs, such as the recreational value of NETPs, but only the social costs that can be generated from the externalities analyzed in this context, enabling focusing on human health and ecosystem impacts solely. However, compared to MACC, SMACC faces the challenge of accurate estimation of external costs. Economic valuation of externalities is difficult due to their far-reaching effects that are not straightforward to measure and therefore require careful analysis (Naime et al., 2020).

To conclude, the SMACC guides toward more resilient decision-making that not only mitigates climate change at the time of implementation but also anticipates the impacts that occur from utilizing the NETPs. Furthermore, it promotes social well-being alongside minimal environmental effects while leading to a more optimal order of NETP implementation to meet the CDR target. SMACC creates a bridge, linking the fields of economics, environmental science, and policy.

3.1.3 SMACC's Connection to Traditional Cost-Benefit Analysis

Cost-benefit analysis is used to include environmental impacts in the cost-efficiency analysis of projects or policies. Cost-benefit analysis measures all consequences of a project, such as effects on users and non-users, and externalities. (Manso et al., 2021) Furthermore, Cost-benefit analysis is used to justify the importance of considering externalities resulting from a decision or a policy and it is widely incorporated into environmental policy. In the context of CDR, this analysis delves into the cost of abating CO₂ emissions from the atmosphere, as it requires funding from businesses or governments for implementation. SMACC brings the benefits of the actions alongside cost-efficiency analysis but does not follow the traditional framework of cost-benefit analysis. SMACC offers a visually intuitive method for comparing various actions, while cost-benefit analysis does not inherently visualize the results.

4 Methodology and data

This thesis examines applying external costs to the Marginal Abatement Cost Curve in the context of various NETPs. Thereby the data for the SMAACC are the private costs for NETPs, specifically the costs incurred in capturing one ton of CO₂ (\$/tCO₂), the abatement potentials or CO₂ capture potentials for each NETP (GtCO₂/year), and the external costs generated by conducting an economic valuation of the Life Cycle Assessment results for NETPs. The values used are projected for the year 2050. The methodology of incorporating externalities into the SMAACC will be presented in the following sections.

4.1 Private Costs of NETPs

4.1.1 Data on the Costs of NETPs

The estimations of the private costs of removing one ton of CO₂ for each NETP have been carefully gathered from relevant research papers and reports. These sources, authored by NETP experts, provide cost estimates that consider the dynamic nature of cost landscapes with a particular emphasis on projections for this thesis' target year 2050. It is noteworthy that the costs associated with new technologies tend to decline along with research and development, creating uncertainty for relatively long-term estimates. In addition, the novelty of a technology has a significant effect on the estimates; the maturity of the technology aids in narrowing the range of cost estimates whereas cost estimation for more novel technologies is more challenging. (Roussanaly et al., 2021) Table 2 provides an overview of the cost data for NETPs, see Appendix 1 for a comprehensive list of estimations by reference. The minimum and maximum values in Table 2 represent the range of values across the entire body of literature cited.

Table 2 The range of costs in the literature for NETPs in 2050.

NETPs	Minimum and maximum values of the cost estimations \$/tCO ₂	References
REF	-40 to 50	(Baker et al., 2020; Fuss et al., 2018; Hepburn et al., 2019)
AFF	-40 to 50	(Baker et al., 2020; Fuss et al., 2018; Hepburn et al., 2019)
BC	-70 to 133	(Baker et al., 2020; Fuss et al., 2018; Hepburn et al., 2019)
FT	20 to 76	(Fuss et al., 2018; Shahbaz et al., 2021)
H2	29 to 64	(Baker et al., 2020; Fuss et al., 2018)
COMB	47 to 288	(Baker et al., 2020; Fuss et al., 2018)
EW	50 to 200	(Beerling et al., 2020; Fuss et al., 2018; Hepburn et al., 2019)
HTLS	100 to 440	(Baker et al., 2020; Lux et al., 2023; Young et al., 2023)
LTSS	101 to 730	(Baker et al., 2020; Lux et al., 2023; Young et al., 2023)

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H2), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS)

4.1.2 Assumptions and Modifications for Costs

The distinction between afforestation and reforestation is often indefinite, and all the references cited handle afforestation and reforestation as a singular concept. However, in this analysis, afforestation and reforestation will be considered as distinct NETPs. Consequently, both NETPs are assigned with same cost estimate value for private cost. Additionally, in some instances for DACCS technologies, a reference only provides a cost estimate for carbon sequestration, excluding the cost of CO₂ storage. In such cases, a storage cost of 10 \$/tCO₂, as per estimates provided by Smith et al. (2021) and Lux et al. (2023) has been added to the private cost. Another modification considers costs presented in a currency other than USD. These values have been converted to USD using the average currency exchange rate for 2023. The exchange rate from € to \$ utilized was 1,0788 (OECD, 2023).

4.1.3 Mean Values for Costs

Most of the provided estimates in the literature are presented as ranges. To construct visually interpretable marginal cost curves, a single cost value for each technology is required. In this study, to formulate a robust abatement cost, mean of minimum and maximum values have been employed from each NETP's costs for 2050, derived from inspected sources presented in Appendix 1. This statistical approach, assuming uniform distribution and utilizing midpoints of the sources' ranges, generates mean values from the entire data. Figure 3 presents the minimum and maximum values across the literature and indicates where the mean values fall within all the values examined in the literature.

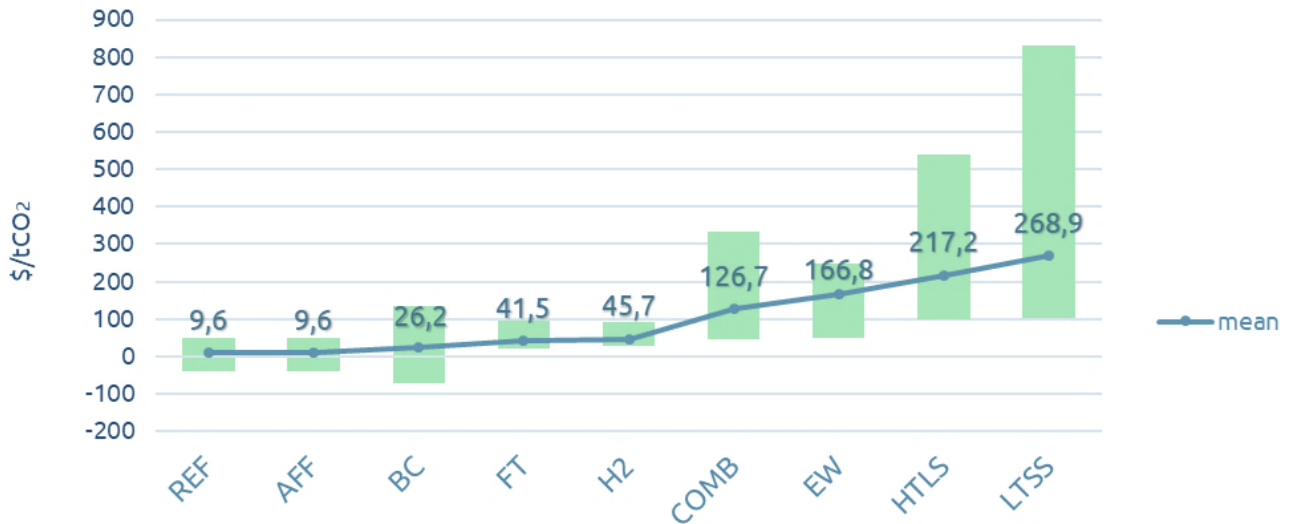


Figure 3 The range and mean of private costs for NETPs in 2050.

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer-Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

4.2 Carbon Capture Potentials for NETPs

4.2.1 Data on NETP Potentials

The methodology employed for the estimation of CDR potentials for NETPs has been conducted in a manner similar to that of cost estimates. The data sources have been literature and comprehensive reports. From these sources, mean values have been derived using the midpoints of the provided ranges. These estimates are grounded in expert predictions and are projected for the year 2050. Table 3 provides an overview of the data of potentials for NETPs, see Appendix 2 for a comprehensive list of estimations by reference. The minimum and maximum values in Table 3 represent the range of values across the entire body of literature cited.

Table 3 The range of the global potentials in the literature for NETPs in 2050.

NETPs	Minimum and maximum values of the estimations of potentials GtCO₂/year	References
REF	0,5 to 10,1	(Austin et al., 2020; Cobo et al., 2023; Fuss et al., 2018; Roe et al., 2019)
AFF	0,5 to 10,1	(Austin et al., 2020; Cobo et al., 2023; Fuss et al., 2018; Roe et al., 2019)
BC	0,3 to 6,6	(Fuss et al., 2018; Hepburn et al., 2019; Roe et al., 2019; Shahbaz et al., 2021)
FT	0,1 to 5,8	(Cobo et al., 2023; Hanssen et al., 2020)
H ₂	0 to 0,02	(Hepburn et al., 2019)
COMB	2,5 to 10	(Cobo et al., 2023)
EW	0,5 to 4	(Beerling et al., 2020; Fuss et al., 2018; Hepburn et al., 2019)
HTLS	0,5 to 40	(Fuss et al., 2018; Hepburn et al., 2019)
LTSS	0,5 to 40	(Fuss et al., 2018; Hepburn et al., 2019)

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS)

4.2.2 Assumptions and Modifications for Potentials

The potentials presented are technical potentials representing the maximum amount of CDR that can be achieved under ideal conditions. However, the potentials that will be utilized in 2050 can vary significantly depending on a variety of factors such as economic, social, and environmental constraints for the NETP implementation. Furthermore, the potentials vary widely depending on the geographical location where the NETP has been implemented. Therefore, it is crucial during the actual implementation phase to consider the specific characteristics of the region. The sources used in this analysis primarily focus on Europe and the United States.

Potentials for combustion-BECCS, gasification to H₂, and Fischer–Tropsch have been integrated into the total BECCS potential, given that they all fall under BECCS technologies and the quantity of biomass and capacity of BECCS facilities is a limiting factor for their simultaneous implementation. The literature gives estimates for each of these three technologies, but because they do not consider the fact that all these technologies are deployed concurrently, and thus, the potentials cannot reach such high potentials for all of them simultaneously. Consequently, the mean value for BECCS has been allocated using the proportions modeled in the NEGEM project, which reflect the realistic extent of the potentials when in simultaneous use, see Appendix 3 for accurate values (Lehtilä et al.,

2022). After all, these proportions align with the intermediate potential estimates presented in the literature.

Again, the potential for afforestation and reforestation has been estimated as a singular entity. Therefore, the entire potential for afforestation and reforestation has been equally divided, under the assumption that both of these NETPs will be employed in future CDR scenarios. A similar constraint occurs for DACCS potentials. No references were found that were able to provide separate estimates for main DACCS technologies. As a result, the entire DACCS potential has been evenly divided between HTLS and LTSS technologies.

4.2.3 Mean Values for Potentials

Figure 4 illustrates the ranges presented in cited sources of CO₂ capture potentials. The darker circle shows the minimum estimates for the capture potential whereas the lighter circle presents the maximum potential estimated in 2050. Here, as well the novelty of technology widens the gap between the minimum and maximum potentials. However, the sources indicate that the technologies can be ranked in order of magnitude in terms of the potential.

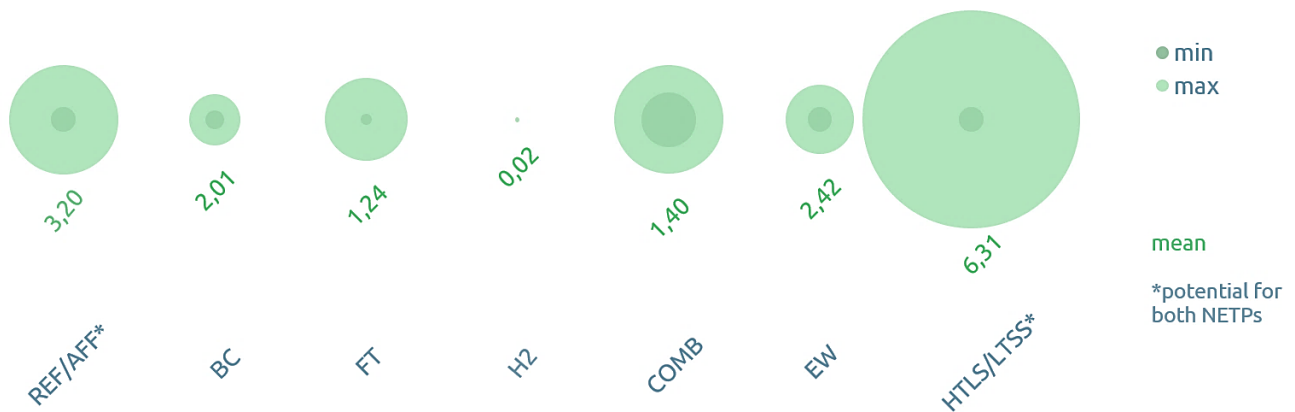


Figure 4 Minimum and maximum potentials for NETPs in 2050 presented in the literature, and averages calculated for NETPs.

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

4.3 NETP's Externalities and LCA Data

Life Cycle Assessment for the NETPs analyzed in this thesis has been conducted within the NEGEM project and the results will be examined further and economically valued into monetary values. The next chapters describe the process and data in more detail.

4.3.1 Data on NETPs' LCA Results

There are several different LCA frameworks, of which ReCiPe will be examined further in this analysis. Some of the LCA frameworks concentrate on environmental impacts solely, whereas ReCiPe's focus is on human health damage, loss of species, and damage to resource availability. In addition, ReCiPe considers both, terrestrial and water ecosystems. (Van der Giesen et al., 2020) (ISO 14040/44 (ISO 2006))

The NEGEM LCA is created using the ReCiPe 2016 framework, including 23 impact categories (midpoints), as illustrated in Figure 5. All these midpoints are included in the overall social cost. These midpoints are further divided into three endpoint categories: Damage to human health, Damage to ecosystems, and Damage to resource availability. Each impact within the midpoint category is first assigned a separate unit, which are then converted into one of three units at Endpoint level: Damage to human health is measured in Disability-Adjusted Life Years (DALYs/tCO₂), Damage to ecosystems is measured in local species loss integrated over time (Species.year/tCO₂), and Damage to resource availability is measured in resource scarcity surplus cost (\$/tCO₂). (Huijbregts et al., 2017) A more severe negative impact on human health, ecosystem, or resource availability, results in a higher endpoint value. The NEGEM LCA was implemented using a hierarchic perspective, which inspects a time horizon of 100 years. The results in this LCA are exclusively expressed in terms of endpoint units, no midpoint units are available (Cobo, 2024).

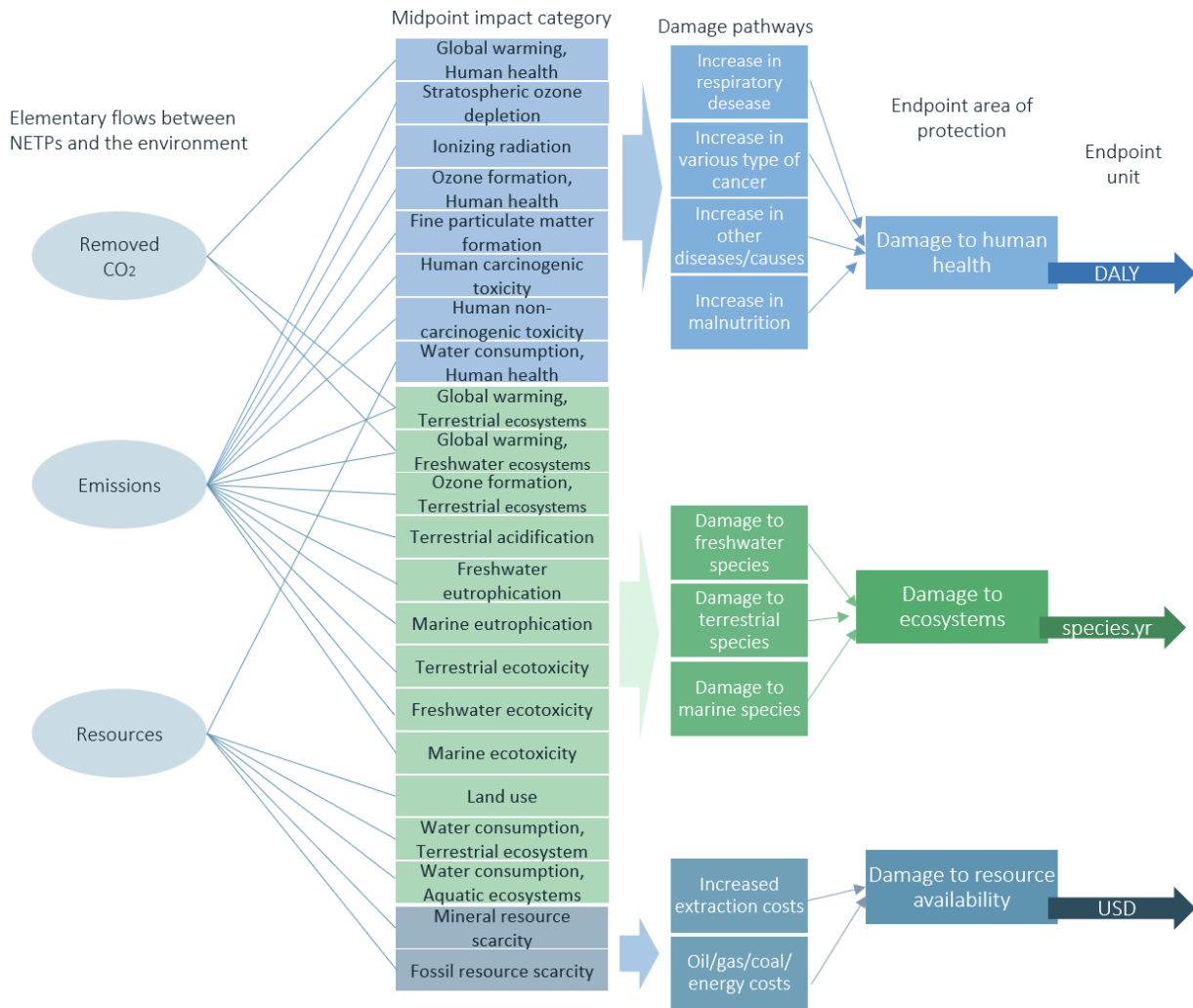


Figure 5 Links between NETPs and the damage caused to ReCiPe assessed areas. Adapted from (Cobo, Serrano, et al., 2022; Huijbregts et al., 2017).

Several critical limitations for the NEGEM LCA results are as follows: Firstly, forests under analysis are presumed to be tropical forests. Secondly, the biomass utilized for BECCS technologies is miscanthus and land for the crops planted has initially been grassland. Thirdly, the energy source for DACCS plants is derived from renewable wind energy. And lastly, the mineral employed for the enhanced weathering process is dunite (Cobo, 2024).

The summarized results of LCA, which are available to the public, are displayed in Table 4. The analysis within the thesis contains more comprehensive LCA results that enabled the calculation of external costs for each midpoint separately. However, due to confidentiality constraints, these detailed findings cannot be disclosed.

Table 4 Summarized LCA results (Cobo, 2024).

NETPs	Human health	Endpoint Ecosystems	Resources
	DALYs/ MtCO ₂	species.year/ MtCO ₂	USD ₂₀₁₃ / MtCO ₂
AFF	11,8	26,7	30600000
REF	-541	10,2	3000000
BC	381	7,61	-35000000
COMB-MISC	-1250	-0,647	-2100000
H2-GAS-MISC	-1030	1,84	16700000
FT-MISC	-885	1,95	-70000000
HTLS-DACCS-WIND	-763	-2,43	47800000
LTSS-DACCS-WIND	-576	-2,35	8200000
EW-DUN	-151	-2,6	3800000

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H2), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS). Biomass: Miscanthus (MISC), Energy source: Wind energy (WIND), Rock mineral: Dunite (DUN)

4.3.2 Assumptions and Modifications for LCA Data

The only alteration to the LCA data is the exclusion of the Damage to resource availability impact category from this analysis. This decision is predicated on the assumption that the market price of resources utilized in the implementation of NETPs accounts for the damage to resource availability. The reasoning behind this assumption is that market prices typically reflect resource scarcity, and the private cost of a resource can be seen as a proxy for its scarcity or damage to its availability. To avoid double-counting in the monetizing phase of LCA results, Damage to resource availability cannot be included in the external costs. Consequently, the analysis focuses only on the endpoints Damage to human health, and Damage to ecosystems, derived from the LCA results to ensure a more accurate assessment.

4.4 Economic Valuation of Externalities

The next section explains the process of deriving the external costs to calculate the social costs for all the NETPs analyzed. It introduces the sources of monetary values for the external impact units and finally combines the LCA data with those values to achieve the external costs to be utilized further in the analysis.

4.4.1 Understanding Monetizing Externalities

When the impacts assessed in LCAs are translated into endpoint units, they can be weighted to generate the impacts on a common matrix for decision support. This is an optional step in LCA and may be implemented in non-monetary weighting principles as well. Commonly economic valuation for impacts has been conducted in traditional cost-benefit analyses. (Dong et al., 2019) For instance, following the EU Commission's updated Economic Appraisal Vademecum (2021), the impacts are often monetized. In this thesis, the purpose is to generate social costs, so the externalities are needed in monetary units.

Economic valuation for ReCiPe LCA results has been assigned earlier in a few contexts (Dong et al., 2019; Sadhukhan, 2022) to express impacts in the monetary unit. The monetization for ReCiPe endpoint results has been applied by weighting LCA results with monetization factors adapted from the ReCiPe model.

4.4.2 Economic Valuation

Within the scope of this research, there were no primary valuation studies conducted. Instead, values derived from other studies have been adapted for use in this research, utilizing weighting in non-monetary units. This approach enables assigning monetary values to the endpoint units generated in the LCA.

Weidema (2009) originally conducted an economic valuation for ReCiPe endpoint results. These values have been estimated by the budget constraint method. Dong et al. (2019) have further analyzed the economic valuation for DALYs and species.year units based on Weidema's research, yielding values of 109,000 US\$₂₀₁₇/DALY and 39,000,000 US\$₂₀₁₇/species.year. Due to the time divergence between the primary valuation and this analysis, a future value adjustment is necessary to transfer these values in a novel analysis. No other adjustments were made, as the primary study's context was compatible with this research context; Weidema's study has been applied in a global context as well.

The values for DALY and species.year have been discounted to future value for the year 2050. For this analysis, a discount rate of 2% has been utilized, as it has been recommended for cost-benefit analyses of long-term problems (Emmerling et al., 2019), a category into which this analysis falls. Additionally, discount rates of 1% and 3% were examined, resulting in no significant differences in the values. Therefore, the monetized values used to value the LCA results in this analysis are 210,000 US\$₂₀₅₀/DALY and 75,000,000

US\$₂₀₅₀/species.year. These values were applied as coefficients to the DALY and species.year results to derive external costs. The monetized values as external costs are presented in the results section. The external costs of human health encompass all the monetized midpoint impacts that fall under the Damage to Human Health category from the ReCiPe framework, as depicted in Figure 5. Similarly, the external costs for ecosystems include all monetized midpoint impacts that are categorized under Damage to Ecosystems.

5 Results

The next chapter introduces the findings of the thesis focusing on the resulting Social Marginal Abatement Cost Curve (SMACC). First, the SMACC and a cost breakdown for social costs are presented, supplementing the results with some applications to enhance the understanding of the effect of each impact and finally presenting a sensitivity analysis of the results.

5.1 Social MACC for NETPs

The SMACC employed in this thesis is depicted in Figure 6.

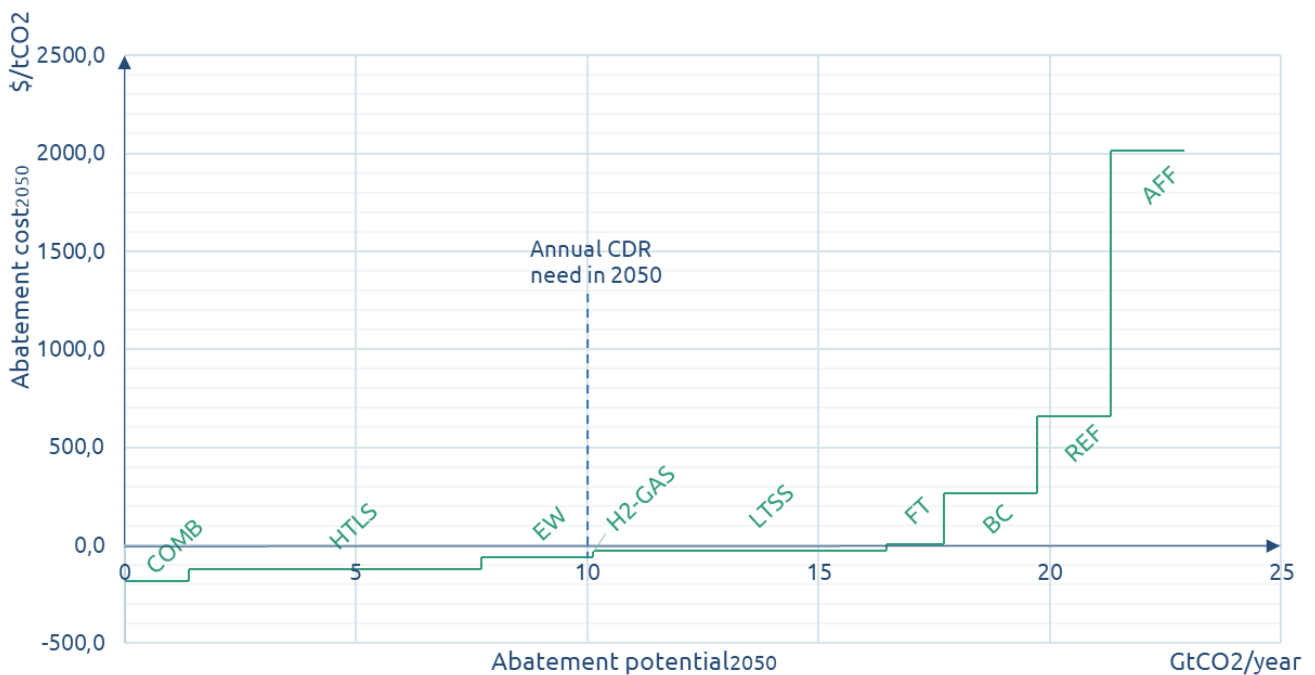


Figure 6 The Social Marginal Abatement Cost Curve for NETPs in 2050.

Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

Figure 6 illustrates the SMACC for CO₂ capture for the nine NETPs under examination, paralleled with the CDR requirements projected for 2050. The NETPs are arranged along the x-axis, from the lowest to the highest social cost, taking into account both health and ecosystem impacts. In total, all the nine NETPs account for up to 22,9 Gt/year CDR potential.

As the annual CDR requirement for 2050 has been estimated at around 10 Gt/year, therefore, utilizing the first three NETPs: combustion-BECCS (COMB), HTLS-DACCS (HTLS), and Enhanced Weathering (EW), the global CDR requirement will be achieved at the cost of EW, i.e., -59,565 \$/tCO₂. The middle segment of the curve consists of the remaining BECCS technologies (H₂-GAS and FT) and LTSS-DACCS. Finally, all the terrestrial NETPs are located at the end of the curve, resulting highest social costs among the compared NETPs. The social costs remain negative until 16,46 GtCO₂/year, and therefore implementing CDR up to this point is beneficial to society.

The variety between the social costs for CDR is significant, ranging from -183,88 \$/tCO₂ to 2015,17 \$/tCO₂, and will be further analyzed with a cost breakdown.

Table 5 presents all the External Costs (EC) incorporated into the above SMACC, the private costs (PC), and the Marginal Social Cost (MSC) as the sum of these costs.

Table 5 Cost breakdown for NETPs, arranged from lowest MSC to highest.

NETPs	PC \$/tCO ₂	EC for human health \$/tCO ₂	EC for ecosystems excluding LU \$/tCO ₂	EC for Land Use \$/tCO ₂	MSC \$/tCO₂
COMB	126,65	-262,03	-227,96	179,45	-183,88
HTLS	217,17	-159,91	-182,50	0,35	-124,90
EW	166,83	-31,55	-199,45	4,60	-59,57
H ₂ -GAS	45,65	-215,11	-166,42	304,22	-31,66
LTSS	268,89	-120,65	-178,20	2,34	-27,61
FT	41,50	-185,34	-163,26	309,38	2,28
BC	26,23	-0,31	19,41	217,23	262,56
REF	9,63	-113,42	-137,22	901,04	660,03
AFF	9,63	2,48	-69,23	2072,28	2015,17

NETPs: Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer-Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS), Biomass: Miscanthus (MISC), Energy source: Wind energy (WIND), Rock mineral: Dunite (DUN)

Land use (LU) presents a significant portion of ecosystem impacts occurring from land use, and hence, it has been examined separately from the social costs for ecosystems. The subsequent figure (Figure 7) provides a visual breakdown of the costs presented in Table 5. This visualization offers a more comprehensive understanding of the factors contributing to the high social cost for some NETPs and highlights which external costs occur as negative.

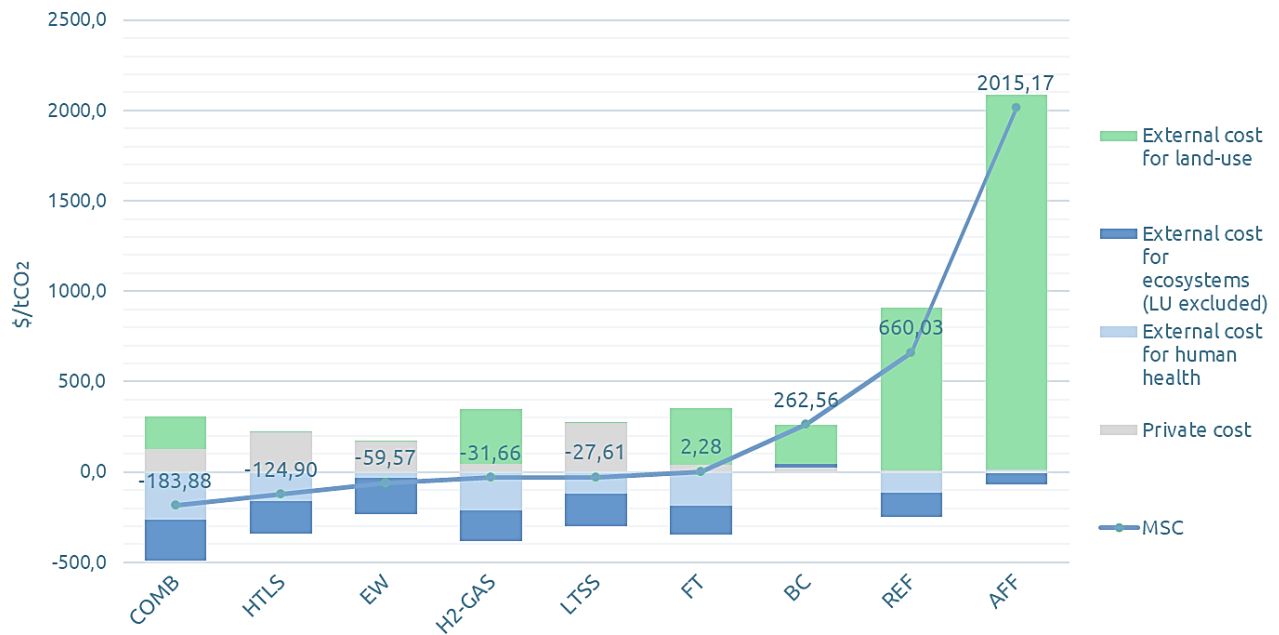


Figure 7 Visual breakdown of Social Costs for the NETPs.

Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer-Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

5.1.1 Terrestrial NETPs on SMACC

The terrestrial NETPs, which have the smallest private costs, are positioned at the end of the SMACC. The positioning is primarily attributed to the high land use requirement in the case of reforestation and afforestation. Biochar, despite having a lower land use cost, incurs a high net social cost due to not reaching any negative costs. It is noteworthy that afforestation is the only NETP that incurs a positive external cost for human health, although minor (2,48 \$/tCO₂).

5.1.2 BECCS on SMACC

Combustion-BECCS locates the initial position on the SMACC. This placement is due to its lowest external cost in both for human health and for ecosystems excluding land use, both less than -200 \$/tCO₂. Other BECCS technologies (gasification to H₂ and Fischer-Tropsch) are in fourth and sixth position respectively. Although these NETPs do have lower private

costs than combustion, they have higher external costs for land use and do not achieve as low external costs for other categories, as combustion does. For all BECCS technologies, although their private costs are higher than terrestrial NETPs', the negative costs and lower land requirements contribute to their feasible positioning.

5.1.3 Chemical NETPs on SMACC

Chemical NETPs are notably the least demanding in terms of land use. DACCS technologies also indicate competitive negative costs from ecosystem and human health externalities. However, as their private costs are the highest, they fall in the middle of the SMACC. Enhanced weathering is the least competitive with the external costs of the chemical NETPs, particularly related to human health.

5.2 Applications of SMACC

Given the significant proportion of land use costs, this section presents an analysis of the SMACC excluding external costs occurring from land use. Additionally, to gain a more comprehensive understanding of health impacts' significance in the total external costs, a version of SMACC that includes only health costs of all the external costs, is presented as well. A common observation for both these applications is that negative social costs are reached to a greater extent compared to the initial SMACC. In both cases, at least the first four NETPs along the curve reach negative social costs.

5.2.1 SMACC without Land Use

Figure 8 depicts the SMACC excluding land use costs. The order of the NETPs on the curve is notably different in this scenario compared to the SMACC presented in the previous chapter. The terrestrial NETPs have moved down the curve, with reforestation now appearing first and afforestation being the fifth NETP. The BECCS NETPs position between afforestation and reforestation, while the chemical NETPs have moved further to the right.

With this order of the NETPs, more technologies and practices are needed to reach the annual CDR need; now six NETPs, reforestation, Fischer–Tropsch, gasification to H₂, combustion, afforestation, and enhanced weathering, fulfill the target. In the earlier version, the NETPs with high potentials were at the beginning of the curve, resulting in the CDR target with fewer NETPs.

This application allows for a more accurate examination of the ecosystem impacts. It is evident, that the BECCS technologies, afforestation, and reforestation are the most feasible in terms of cost efficiency and low ecosystem impacts.

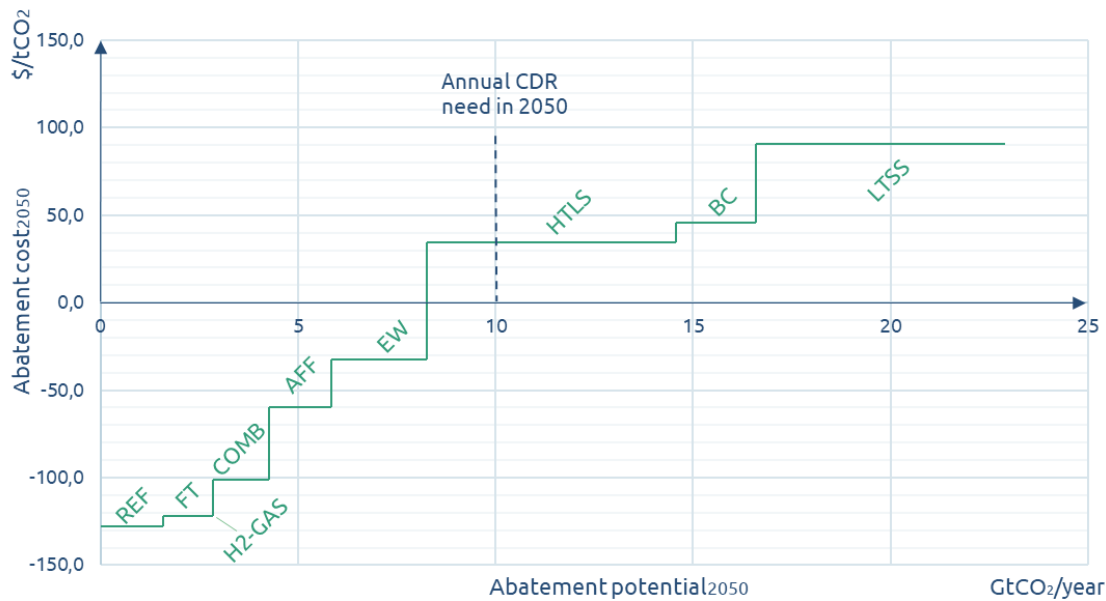


Figure 8 The SMACC including externalities on human health and ecosystems without land use. Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer-Tropsch (FT), Gasification to H₂ (H2), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

5.2.2 SMACC Including Only Externalities for Human Health

In the application of SMACC that includes health externalities only, the order of NETPs along the curve varies slightly again, as presented in Figure 9. The chemical NETPs position the last. The order of BECCS and terrestrial NETPs varies slightly, but none surpass chemical NETPs. In terms of health externalities, enhanced weathering moves even higher up the curve. After all, this application draws the same conclusion about the feasibility of BECCS and terrestrial NETPs, as seen in 5.2.1.

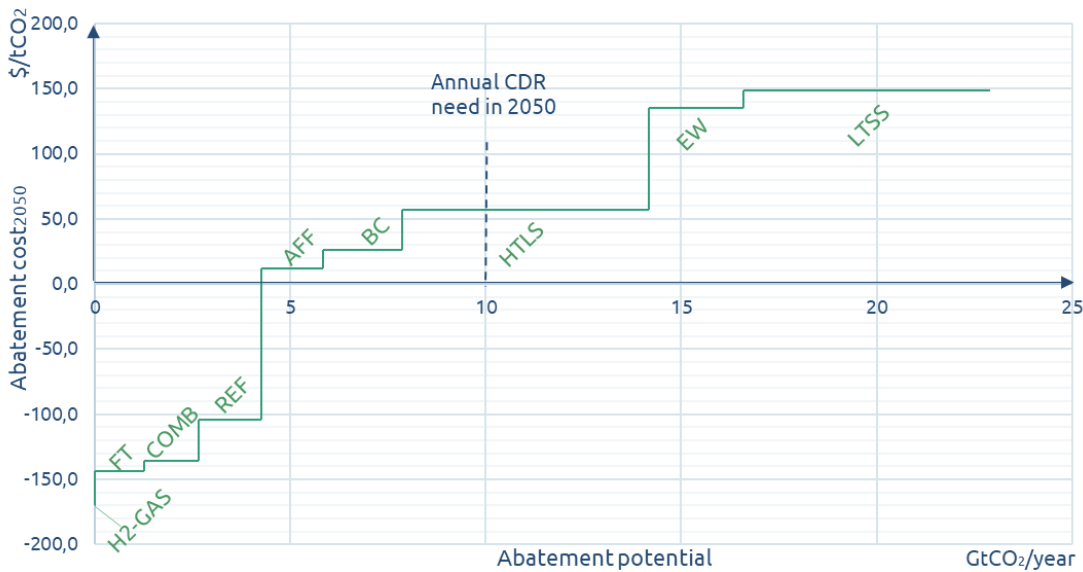


Figure 9 SMACC including only externalities on human health. Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

5.3 Comparison of MACC and SMACC

In an analysis of the NETPs using traditional MACC, we can contrast the cost of CDR without the inclusion of externalities. The traditional MACC, which is illustrated in Figure 10 solely considers private costs. The arrangement of NETPs in the traditional MACC deviates from the SMACC, as anticipated. This deviation prioritizes terrestrial NETPs and positions chemical NETPs at the end of the curve. From an economic standpoint, the implementation of DACCS would not be financially judicious according to this MACC.

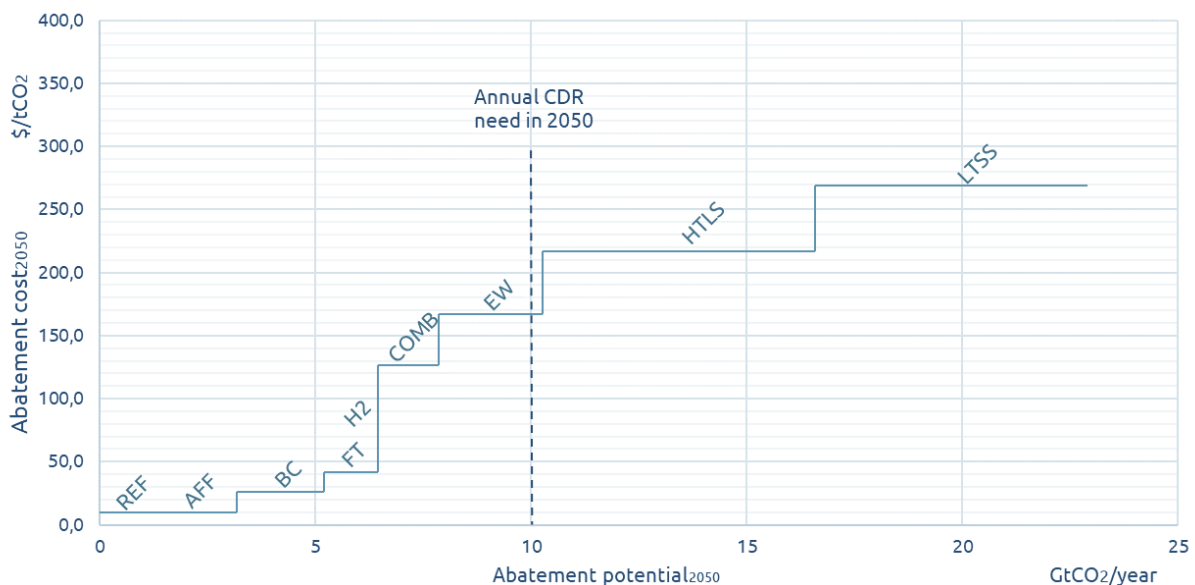


Figure 10 Traditional MACC, presenting only the private costs. Reforestation (REF), Afforestation (AFF), Biochar (BC), Fischer–Tropsch (FT), Gasification to H₂ (H₂), Combustion-BECCS (COMB), Enhanced Weathering (EW), HTLS-DACCS (HTLS), LTSS-DACCS (LTSS).

The next figure (Figure 11) draws the SMACC and MACC in parallel to enable another perspective for observation. A significant difference between SMACC and MACC suggests that extending MACC with social costs as SMACC can greatly affect the perceived cost-effectiveness of NETPs. When examining the level that needs to be removed in 2050, the cost of CDR is still negative for 10 GtCO₂/year as read from the SMACC, whereas cost the of MACC is more than 200 \$/tCO₂ higher. Interpreting this, CDR could therefore be seen as gaining benefits to society, whereas MACC demonstrates CDR to be a cost.

The SMACC graph remains below MACC for a long time, up to CDR of 19,7 GtCO₂/year. Above that point SMACC finally exceeds MACC. In this transition point, the social cost of NETPs starts to surpass their benefits, when analyzed with the method used in this thesis.

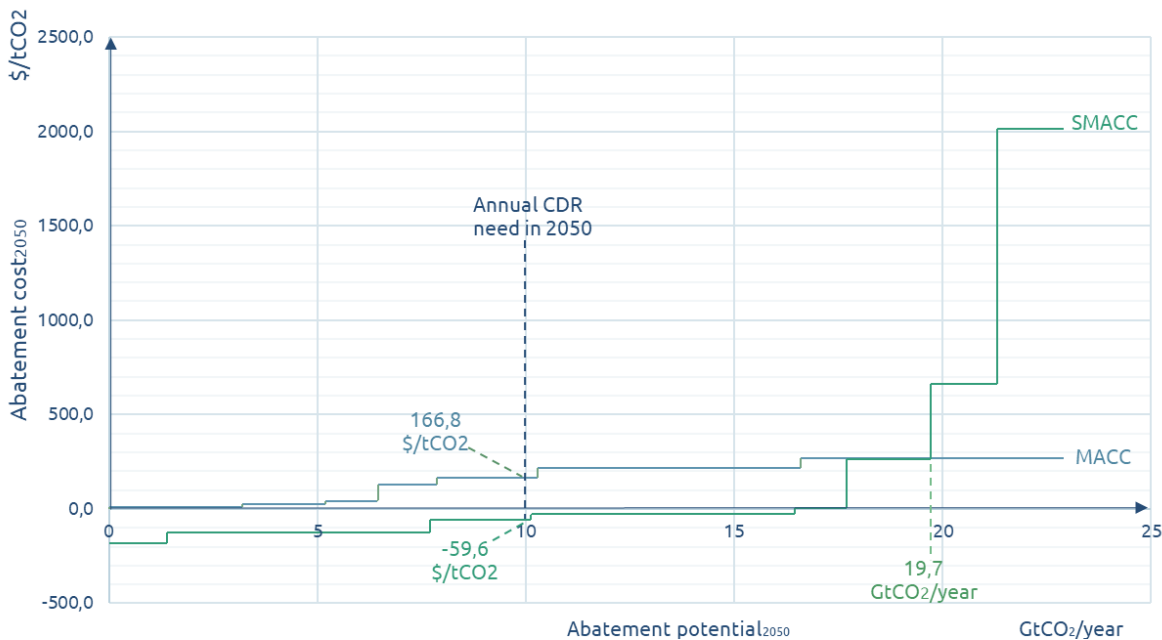


Figure 11 Comparison of the MACC and the SMACC.

5.4 Sensitivity Analysis

Finally, the results present a sensitivity analysis for the costs and potentials of NETPs in 2050. The estimates span a wide range, pointing out the importance of considering the possibility of the lowest and highest potentials and private costs across various scenarios.

The cost sensitivity is analyzed regarding the lowest and highest private costs given in the literature, including all external costs as in Table 5. The cost difference for removing 10 GtCO₂/year is as high as 293 \$/tCO₂, as depicted in Figure 12. In a low-cost scenario, the optimal CO₂ removal would exceed 17 Gt/year, whereas in a high-cost scenario, it would only be beneficial up to 3,8Gt/year.

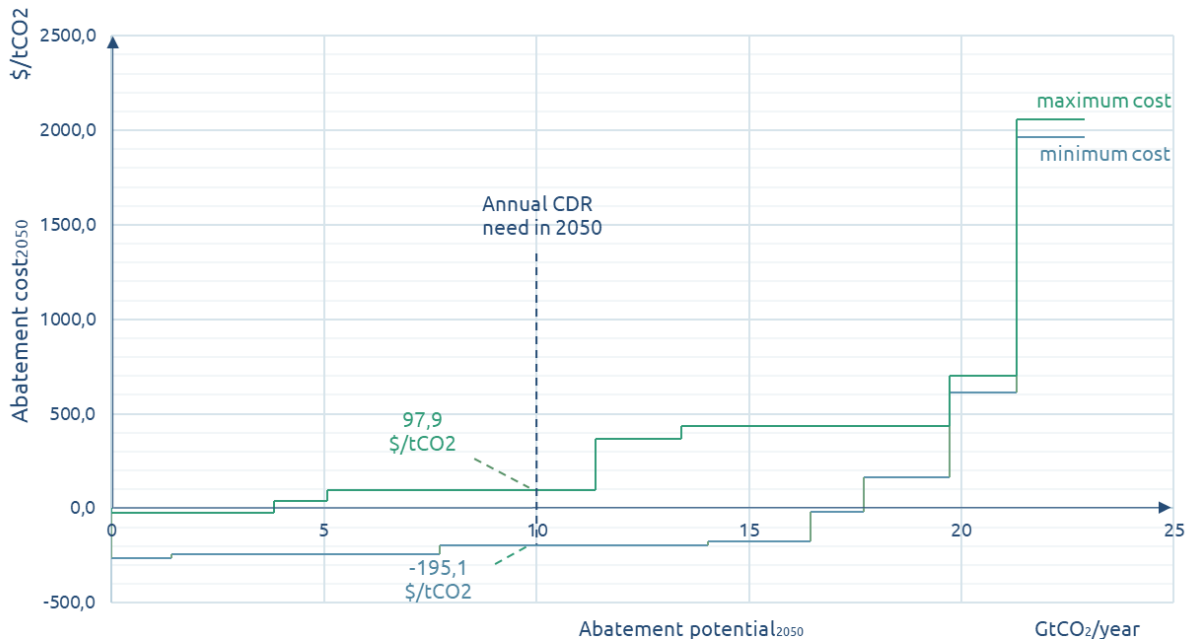


Figure 12 Sensitivity analysis of the social marginal abatement costs.

The sensitivity for potentials is illustrated in Figure 13, utilizing the lowest and highest estimates found in the literature. The difference between these two scenarios is substantial; the low-potential scenario achieves only 4,3 GtCO₂/year removal, falling short of the CDR needed in 2050. Conversely, the high-potential scenario extends up to 72,3 GtCO₂/year presenting an unrealistic scale. In this scenario, the optimal quantity of CDR is 54,2 GtCO₂/year, and the annual target is met using only one NETP at a social cost of -183 \$/tCO₂.

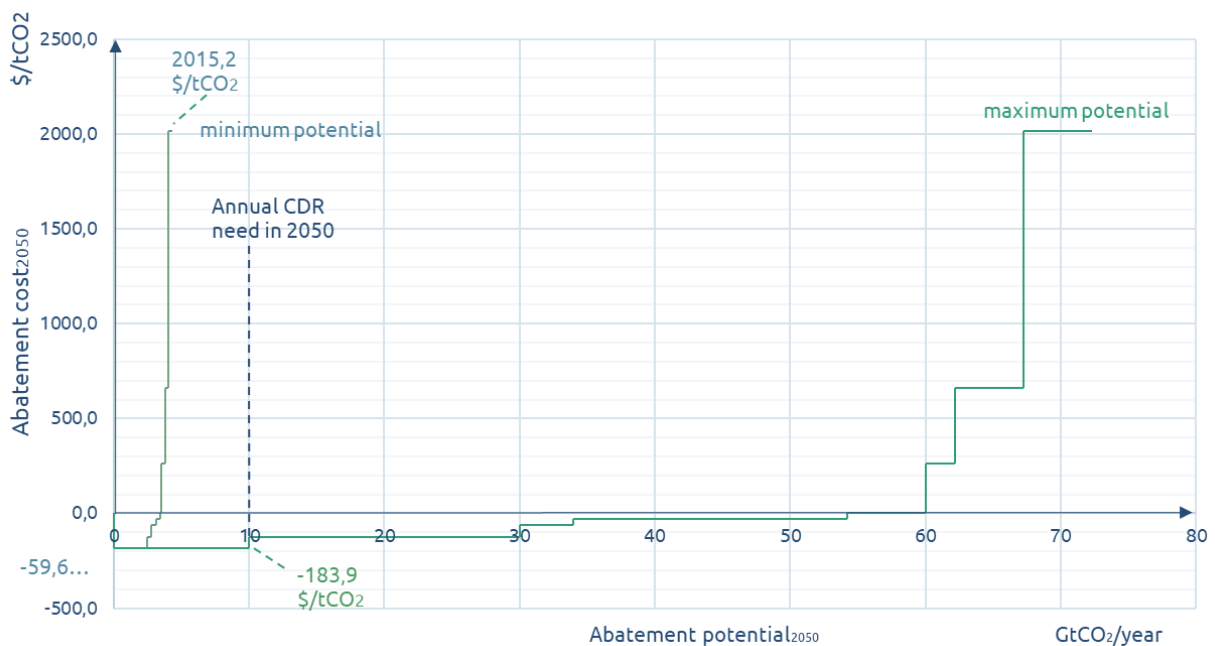


Figure 13 Sensitivity analysis of the CDR potentials.

6 Discussion

Finally, this chapter discusses the findings derived from this thesis along with the research limitations. The insights gained from the findings form a set of recommendations on policy implications for the deployment of NETPs and provide suggestions for future research.

6.1 Interpretation of Results

6.1.1 Identifying the NETPs with the Lowest Social Costs

The SMACC enables the prioritization of abatement options or in this context the NETPs from least harmful and economically viable to most harmful and inefficient in terms of cost. The NETPs that present the lowest social costs are Combustion-BECCS, DACCS-HTLS, and enhanced weathering. Consequently, these technologies emerge as the most viable NETPs in this analysis, considering their externalities on human health and ecosystems, based on the evaluation with the ReCiPe framework.

To enable a more comprehensive analysis of the various applications, Table 6 provides a ranking of the NETPs with each application of SMACC analyzed in this study. The NETPs are given a ranking from 1 to 10, with 1 being the lowest social cost and 10 being the highest. The NETPs are arranged in descending order based on the average ranking of all three applications, indicated in brackets beside the NETP name. Placement on MACC is not counted in this, the corresponding MACC position is indicated in the last column.

Table 6 Ranking of the NETPs for all the SMACC applications.

NETP (average ranking)	SMACC	SMACC excluding LU	SMACC with only health impacts	MACC
Gasification to H ₂ (2,67)	4	3	1	4
Combustion-BECCS (2,67)	1	4	3	5
Fischer Tropsch (3,33)	6	2	2	3
Reforestation (4,33)	8	1	4	1
DACCS-HTLS (5,33)	2	7	7	7
Enhanced weathering (5,67)	3	6	8	6
Afforestation (6,33)	9	5	5	1
Biochar (7)	7	8	6	2
DACCS-LTSS (7,67)	5	9	9	8

If we look at the placements of NETPs throughout the whole analysis, gasification to H₂ and combustion-BECCS achieve the same overall ranking and place first, followed closely by Fischer Tropsch. These technologies confer positive impacts on human health and ecosystems, and if expert forecasts hold, their abatement cost will also be feasible. Reforestation ranks highly in the applications of SMACC and is therefore placed after the BECCS options. Reforestation is followed by DACCS-HTLS and enhanced weathering which benefit from their smaller land requirements. Afforestation, biochar, and DACCS-LTSS places last and do not yield favorable results in any of the SMACCs. These NETPs do not offer sufficient benefits to offset their private costs. This is crucial to observe, as afforestation and biochar represent positions 1 and 2 based on the MACC curve, and therefore they might be prioritized in NETP implementation if the decision was to be based on cost-efficiency solely.

6.1.2 Advantages of SMACC

Utilizing SMACC instead of MACC offers several advantages as an instrument for decision-making in CDR implementation. One key insight derived from the results of this analysis is that following cost-efficiency in the implementation of CDR may not always lead to socially optimal outcomes. The differences between SMACC and MACC become apparent when considering the incentives provided by SMACC for CDR investments. This becomes particularly evident at the beginning of the curve where negative costs are visible. The early investment in CDR not only is important to initiate large-scale CO₂ removal and thereby mitigate global warming, but it also brings benefits in terms of affluent ecosystems and human health, and thus cost benefits to society.

Moreover, SMACC fosters a more resilient approach to CDR implementation. The implementation utilizing SMACC can lead to a more stable transition, avoiding pitfalls in investments in NETPs. This is due to its ability to take a more comprehensive view of the costs and benefits associated with each NETP. Under the MACC approach, investments might be directed towards NETPs that appear to have low cost or high CO₂ removal potential but could turn out to be detrimental after the investments have been made.

However, it is important to note that the benefits derived from positive externalities are not immediate, and occur as benefits to society rather than profits from CDR. The benefits materialize for example as avoided costs from damages but may take years to become

apparent. Consequently, the SMACC requires a more careful interpretation compared to the MACC, which has more direct monetary effects.

6.1.3 Land Use in the Results

In this research, land use was observed to constitute a significant share of the external costs associated with ecosystem impacts. While high land area requirements are a critical factor in ecosystem damage, an analysis excluding this factor provides insights into the ecosystem impacts beyond that. When land use is excluded from the results, the order of MACC and SMACC exhibit similar patterns; terrestrial and BECCS NETPs emerge as the most feasible to implement.

Regardless of how land use is valued, it will be imperative to consider land use as an ecosystem impact, as the availability of land will present challenges in the future. Land requirements for food production, for instance, will significantly influence the amount of land available for CDR. If land availability worsens, which is likely with increasing population growth, the valuation of land will escalate, and other positive impacts may not offset this deficiency. In such a scenario, DACCS technologies will likely gain more favorable positions in SMACCs, making their implementation more probable compared to, for instance, reforestation.

6.2 Limitations of the Study

6.2.1 Economic Valuation of Impacts

A primary limitation of this study arises from the uncertainties related to the economic valuation of LCA results. The data was solely available in endpoint units, restricting the valuation to DALYs and species.year. The availability of midpoint units could have facilitated a more precise valuation, as it would have enabled the determination of equivalent prices for each impact, thereby yielding more realistic external costs. For instance, if land use would have been evaluated in square meters instead of species.year, it might have played a less significant role in the external costs, leading to a more straightforward comparison of the results.

Moreover, the SMACC presented in this analysis only accounts for ecosystem and human health impacts. It does not consider other factors such as the recreational value of the NETPs, which could have significantly reduced the social cost of afforestation and

reforestation. However, this analysis focuses solely on ecosystem and health impacts, enabling a concentrated perspective on these aspects.

While the concept of pricing environmental and social impacts has been controversial, this thesis from an economist's perspective, acknowledges that economic valuation is not beyond dispute. Instead, it seeks to provide insights into decision-making heavily reliant on the monetary value of CDR.

6.2.2 Geographical Considerations and Resource Utilization

Another critical observation is that the geographical location significantly influences the SMACC results. For instance, afforestation and reforestation as NETPs are highly location dependent, and their impacts are remarkably different in for instance habituated areas than in an undisturbed wilderness (Kaine et al., 2023). A similar observation can be made for the biomass cultivated for the use of BECCS. The impact of NETP is influenced by the location of the crop site and the type of soil. (Jones & Albanito, 2020) On the other hand, DACCS offers more flexibility in terms of location.

Given the influence of regional differences on the SMACC results, it is imperative to adopt a region or country-specific approach when implementing SMACC. This country-tailored approach would enable the identification and prioritization of the most feasible NETPs for each region at the beginning of the curve. The uniqueness of each NETP's externalities, such as the type of local biomass utilized and the land area available for the purpose of CDR, further highlights the necessity for a country-specific SMACC. Moreover, the geographical characteristics of each country, particularly the distance of CO₂ storage location, should be taken into account, especially when NETPs are applied at point sources of CO₂ emissions (Kujanpää et al., 2023).

This analysis considers the phasing out of fossil fuels, so only renewable energy sources are handled. Therefore, the prospect that DACCS would be operated by fossil fuels is not considered, but it is important to acknowledge the possibility of it and ensure that fossil fuels will not be enabled in DACCS utilization. Careful considerations need to be made when interpreting the results for the NETP implementation, and the LCAs need to be conducted again considering the NETP implementation location and resources utilized.

6.3 Implications for Policy and Practice

6.3.1 Subsidies and Incentives

As the main research question of this thesis was to identify the most feasible NETPs, the identified NETPs must be implemented at a scale that can significantly impact carbon dioxide removal. For instance, the example of the successful promotion of wind power to become the dominant energy source underscores the importance of incentives to facilitate the adoption of technologies, such as NETPs, even if they were not initially the most cost-efficient options in terms of their private costs (Nicolini & Tavoni, 2017).

Externalities, currently excluded from market considerations, need serious attention. Without market intervention, NETPs at the beginning of SMACC should receive incentives to ensure their implementation does not falter due to high private costs. The positive impacts of these NETPs will justify the investments. Furthermore, incentivizing these NETPs will trigger scale effects, eventually driving down their costs. Similar policy instruments as wind turbines have gained in the beginning of their deployment could be presented for BECCS technologies; a tax benefit for generating bioenergy with certain BECCS technologies and utilizing the most sustainable, and feasible biomass sources. These investment tax credits could help the energy industry to incorporate BECCS more into their operations as well. Other incentives could be government funding of the most feasible NETPs or subsidy schemes following Denmark or the United Kingdom's targeted subsidy programs (Fajardy & Greenfield, 2023), or a reversed auctioning system adopted in Sweden (Kujanpää et al., 2023).

If a NETP is positioned in the middle of the curve mainly due to its high private cost, policies should encourage their research, development, and innovation (R&D&I) aimed at cost reduction. As soon as the private cost decreases as much as the social cost reaches zero, the implementation of these NETPs should be highly promoted. Therefore, R&D&I resources should be allocated to DACCS technologies to ensure large-scale capture potentials, particularly in case the future CDR demand significantly exceeds projections.

On the other hand, the NETPs at the end of the curve necessitate further research to minimize their negative externalities. It is essential to explore potential improvements in their implementation to mitigate damage to ecosystems and human health. If the negative externalities are not deductible, utilization of these NETPs should be prohibited.

Regional differences require careful consideration in the incentive policy. For instance, BECCS should not be subsidized in areas where it is not sustainable to grow biomass for the purpose. In addition, while reforestation in former forests is likely safe, afforestation requires thorough analysis to prevent damaging an area's cultural or ecological significance.

Finally, this analysis underscores the need to secure sufficient land for CDR. This could be achieved by reducing land use for food production, a current major occupier that could be minimized (EAT-Lancet Commission, 2019). Policies promoting so-called planetary diets should be emphasized, as this could free up land for CDR (Werner et al., 2022). Figure 14 summarizes the policy instruments for sustainable CDR.

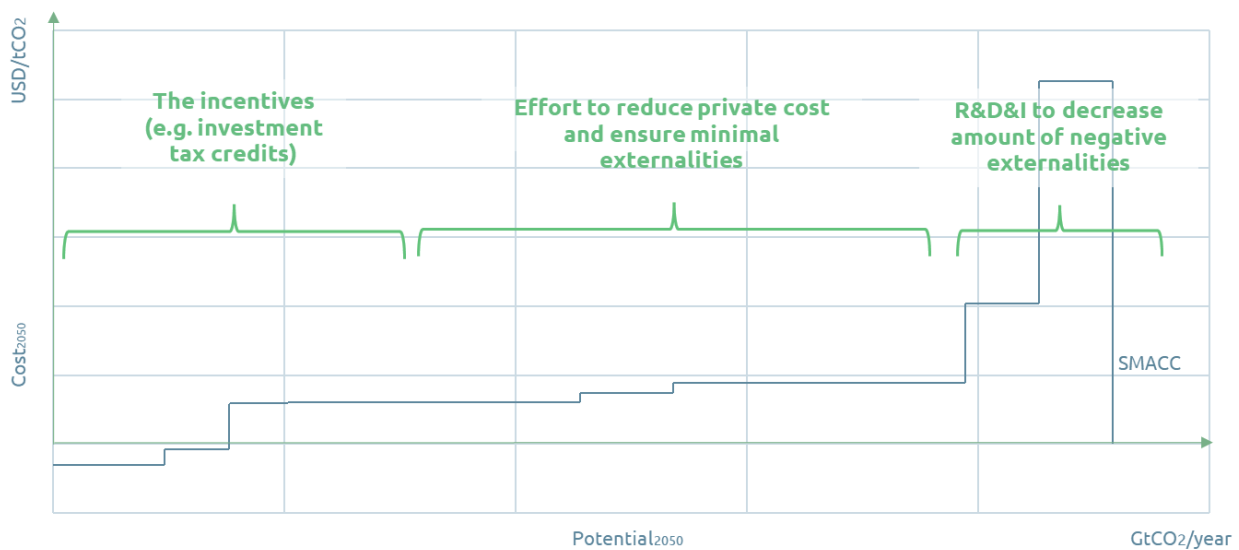


Figure 14 Policy instruments for NETP implementation.

6.3.2 CDR in Emissions Trading Systems

Integrating CDR into the EU Emissions Trading System (EU ETS) as well as other regional emissions trading systems, has recently emerged as a point of discussion of negative emissions (Bednar et al., 2023; Rickels et al., 2021). The concept of CO₂ removal could be incorporated into these emissions trading systems either as an integral part of their scope resulting in negative emissions in the system, or in the form of carbon credits or certificates (Hickey et al., 2023). Such an integration could serve as an additional incentive for CDR to achieve carbon removal targets.

However, from this analysis' perspective, noting CDR in emissions trading is a rather controversial issue. It could potentially encourage the use of NETPs that have high negative externalities, with the sole aim of maximizing the CO₂ removal potential to benefit from the

trading. It could also lower the threshold for releasing emissions and then recapturing them, as they could be easily compensated with CO₂ removal within the scope of the emissions trading system.

Therefore, if the CDR were to be linked to emission trading systems, it is crucial to establish a framework that specifies which NETPs are permitted to perform CDR to be accepted as negative emissions to minimize the change of utilizing harmful NETPs. In this context, a regional SMACC could serve as a useful tool, as it could assist in identifying feasible NETPs for a given region. This would help to exclude NETPs with high negative externalities from the trading system and thereby assist in defining the NETPs that would be accepted to result in negative emissions. This approach would subsequently aid in the equitable distribution of CDR responsibilities among regions, a topic that has been recognized by Fyson et al. (2020)

Furthermore, since CDR should be specifically employed for the effort-sharing sector, CO₂ removal should be targeted only in sectors that cannot further reduce their emissions but require removals to achieve net zero emissions. This would ensure that the benefits of CDR and emissions trading systems are maximized while minimizing potential misuse of CDR.

6.3.3 Recommendation for Future Research

For future research, this thesis could serve as a foundation for the SMACC utilizing a more precise valuation of impacts. The utilization of midpoint LCA units could yield more precise results, and the probability of reaching more realistic external costs would be higher. Primary valuation studies of the impacts could be implemented further to reach the desired outcomes with externalities valuation. In addition, the SMACC could be extended to consider social impacts beyond human health and to environmental impacts beyond ecosystems, to create even more comprehensive social costs. Furthermore, the implementation of methods, such as Monte Carlo simulations or robust decision-making (Koponen & Le Net, 2021; Wealer et al., 2021) would instill a degree of certainty for long-term forecasting of costs and potentials for CDR, thereby providing a robust framework for future investments by generating multiple possible outcomes, encompassing future scenarios of CDR scale-up and various socio-economic trajectories.

7 Conclusions

Carbon Dioxide Removal will feature prominently in climate policy in the coming decades and is increasingly becoming a focal point across various industries, such as bioenergy, forestry, and industries with emissions hardest to abate. Given that NETPs constitute significant and longstanding investments, their implementation necessitates particularly careful planning and execution.

The objective of this research was to determine the NETPs that exhibit the lowest social costs, thereby identifying the most feasible technologies and practices for implementation to fulfill CDR requirements. This approach considered a comprehensive range of factors, including the external impacts of the NETPs, their costs, and their potentials for CO₂ removal. The analysis was conducted through the SMACC framework, a novel methodology developed within the scope of this thesis.

The analysis identified the most and least feasible NETPs within the SMACC framework applied in this study. According to the SMACC framework and, the top three NETPs in terms of their social costs in 2050 are combustion-BECCS, HTLS-DACCS, and Enhanced Weathering. These results are based on the technology assumptions and LCA results from the NEGEM project. The three NETPs referred to are projected to be capable of achieving the target of 10 Gt CO₂ removal in 2050. In SMACC, reforestation and afforestation emerged as the least feasible NETPs, primarily due to their extensive land use requirement. This underscores land use as one of the factors contributing to significant regional variation in the SMACC results. Therefore, it is emphasized that the SMACC should be applied on a regional basis, with careful consideration of local characteristics and conditions.

The ranking of the NETPs along the curve exhibited slight variations depending on the perspective, with chemical NETPs resulting in the highest social costs related to human health, whereas DACCS technologies and biochar resulting the highest social costs when land use was not included in ecosystem impacts. In both of these applications reforestation, afforestation, and BECCS technologies were positioned at the beginning of the curve.

As CDR is an action to offset hard-to-abate emissions, it is crucial to ensure its effective and responsible implementation. However, the most efficient and sustainable mitigation measure is to limit further CO₂ emissions to the greatest extent possible, thereby minimizing the need for CDR. This is also substantiated by the fact that the removal of one ton of CO₂ does not fully offset the impact of an emitted ton of CO₂. Furthermore, the sensitivity

analysis of the CDR potential of NETPs potentials revealed that, under a scenario of low potentials, the implementation of all NETPs analyzed would be insufficient to meet the requirement of 10 Gt of CDR.

The NETPs identified as most feasible are not efficient in terms of their private costs yet. Consequently, there is a pressing need for subsidies and incentives in the application of CDR. It is also crucial to ensure that these policies do not unintentionally support NETPs that could have detrimental effects in a certain region.

In conclusion, the application of SMAcc can lead to more informed and conscious decision-making in the deployment of NETPs. It offers a more comprehensive framework than MACC in terms of regarding the externalities, providing a holistic view of the issue analyzed. SMAcc is an invaluable tool for decision-makers in domains of climate change mitigation, especially in the realm of CDR. It provides readily interpretable results, highlighting important aspects of external impacts to consider when prioritizing investments in NETPs and initiates the discourse on responsible implementation of NETPs.

References

- Ahlström, J. M., Walter, V., Göransson, L., & Papadokonstantakis, S. (2022). The role of biomass gasification in the future flexible power system – BECCS or CCU? *Renewable Energy*, *190*, 596–605. <https://doi.org/10.1016/j.renene.2022.03.100>
- Austin, K. G., Baker, J. S., Sohngen, B. L., Wade, C. M., Daigneault, A., Ohrel, S. B., Ragnauth, S., & Bean, A. (2020). The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications*, *11*(1), 5946. <https://doi.org/10.1038/s41467-020-19578-z>
- Baker, Sarah E., Stolaroff, Joshuah K., Peridas, George, Pang, Simon H., Goldstein, Hannah M., Lucci, Felicia R., Li, Wenqin, Slessarev, Eric W., Pett-Ridge, Jennifer, Ryerson, Frederick J., Wagoner, Jeff L., Kirkendall, Whitney, Aines, Roger D., Sanchez, Daniel L., Cabiyo, Bodie, Baker, Joffre, McCoy, Sean, Uden, Sam, Runnebaum, Ron, Wilcox, Jennifer, Psarras, Peter C., Pilorge, Helene, McQueen, Noah, Maynard, Daniel, & McCormick, Colin. *Getting to Neutral: Options for Negative Carbon Emissions in California*. United States. <https://doi.org/10.2172/1597217>
- Bednar, J., Macinante, J., Baklanov, A., Hall, J. W., Wagner, F., Ghaleigh, N. S., & Obersteiner, M. (2023). Beyond emissions trading to a negative carbon economy: A proposed carbon removal obligation and its implementation. *Climate Policy*, 1–14. <https://doi.org/10.1080/14693062.2023.2276858>
- Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrazio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., ... Banwart, S. A. (2020). Potential for large-scale CO₂ removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. <https://doi.org/10.1038/s41586-020-2448-9>
- Chiquier, S., Fajardy, M., & Mac Dowell, N. (2022). CO₂ removal and 1.5 °C: what, when, where, and how? *Energy Advances*, *1*(8), 524–561. <https://doi.org/10.1039/D2YA00108J>
- Chiquier, S., Patrizio, P., Bui, M., Sunny, N., & Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing, and permanence of CO removal pathways. *Energy & Environmental Science*, *15*(10), 4389–4403. <https://doi.org/10.1039/D2EE01021F>
- Cobo, S. (2024). *NEGEM-WP1 LCA results* [Dataset]. Zenodo. <https://doi.org/10.5281/zenodo.10497443>
- Cobo, S., Galán-Martín, Á., Tulus, V., Huijbregts, M. A. J., & Guillén-Gosálbez, G. (2022). Human and planetary health implications of negative emissions technologies. *Nature Communications*, *13*(1), 2535. <https://doi.org/10.1038/s41467-022-30136-7>
- Cobo, S., Negri, V., Valente, A., Reiner, D. M., Hamelin, L., Dowell, N. M., & Guillén-Gosálbez, G. (2023). Sustainable scale-up of negative emissions technologies and practices: Where to focus. *Environmental Research Letters*, *18*(2), 023001. <https://doi.org/10.1088/1748-9326/acacb3>
- Cobo, S., Serrano, R. C., & Guillén-Gosálbez, G. (2022). *Report on comparative life-cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources* (D3.8) NEGEM. <https://www.negemproject.eu/wp-content/uploads/2023/04/D3.8-Comparative-sustainability-assessment-of-NETPs.pdf>

- Cobo, S., Valente, A., Galán-Martín, Á., & Guillén-Gosálbez, G. (2020). *Justification of NETPs chosen for the NEGEM project*. [Unpublished confidential document].
- de Jonge, M. M. J., Daemen, J., Loriaux, J. M., Steinmann, Z. J. N., & Huijbregts, M. A. J. (2019). Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents. *International Journal of Greenhouse Gas Control*, 80, 25–31. <https://doi.org/10.1016/j.ijggc.2018.11.011>
- Doelman, J. C., Stehfest, E., van Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., Gernaat, D. E. H. J., van den Berg, M., van Zeist, W.-J., Daioglou, V., van Meijl, H., & Lucas, P. L. (2020). Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Global Change Biology*, 26(3), 1576–1591. <https://doi.org/10.1111/gcb.14887>
- Dong, Y., Hauschild, M., Sørup, H., Rousselet, R., & Fantke, P. (2019). Evaluating the monetary values of greenhouse gases emissions in life cycle impact assessment. *Journal of Cleaner Production*, 209, 538–549. <https://doi.org/10.1016/j.jclepro.2018.10.205>
- EAT-Lancet Commission. (2019). *Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems*. *The Lancet Commissions*, 393(10170), 447–492 [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- EEA. (2022) *Trends and projections in Europe 2022 (10/2022)*. Publications Office of the European Union. <https://data.europa.eu/doi/10.2800/16646>
- Emmerling, J., Drouet, L., Wijst, K.-I. van der, Vuuren, D. van, Bosetti, V., & Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. *Environmental Research Letters*, 14(10), 104008. <https://doi.org/10.1088/1748-9326/ab3ccc>
- European Commission. (2021). *Economic Appraisal Vademecum 2021-2027—General Principles and Sector Applications*. https://ec.europa.eu/regional_policy/en/information/publications/guides/2021/economic-appraisal-vademecum-2021-2027-general-principles-and-sector-applications
- European Commission. (2023). *Carbon Capture, Use and Storage*. https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage/overview_en#why-do-we-need-carbon-capture-use-and-storage
- European Commission. (2024a). *NEGEM Project*. https://cinea.ec.europa.eu/featured-projects/negem_en
- European Commission. (2024b). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (COM/2024/63)*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN>
- European Commission, Directorate-General for Research and Innovation, Bickel, P., Friedrich, R. (2005). *ExternE – Externalities of Energy. Methodology 2005 update*. Publications Office.
- European Parliament. (2023, March 28). *EU progress towards 2020 climate change goals (infographic)*. Climate change. <https://www.europarl.europa.eu/news/en/headlines/society/20180706STO07407/eu-progress-towards-2020-climate-change-goals-infographic>
- Fajardy, M., & Greenfield, C. (2023, July 11). *Bioenergy with Carbon Capture and Storage—Energy System*. IEA. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage>

- Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., & Wetzler, T. (2022). The meaning of net zero and how to get it right. *Nature Climate Change*, *12*(1), 15–21. <https://doi.org/10.1038/s41558-021-01245-w>
- Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., & Clarens, A. F. (2020). Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nature Climate Change*, *10*(10), Article 10. <https://doi.org/10.1038/s41558-020-0876-z>
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. <https://doi.org/10.1088/1748-9326/aabf9f>
- Fyson, C. L., Baur, S., Gidden, M., & Schleussner, C.-F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nature Climate Change*, *10*(9), 836–841. <https://doi.org/10.1038/s41558-020-0857-2>
- Gambhir, A., & Tavoni, M. (2019). Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation. *One Earth*, *1*(4), 405–409. <https://doi.org/10.1016/j.oneear.2019.11.006>
- Ganeshan, P., V S, V., Gowd, S. C., Mishra, R., Singh, E., Kumar, A., Kumar, S., Pugazhendhi, A., & Rajendran, K. (2023). Bioenergy with carbon capture, storage and utilization: Potential technologies to mitigate climate change. *Biomass and Bioenergy*, *177*, 106941. <https://doi.org/10.1016/j.biombioe.2023.106941>
- Goglio, P., Williams, A. G., Balta-Ozkan, N., Harris, N. R. P., Williamson, P., Huisingh, D., Zhang, Z., & Tavoni, M. (2020). Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. *Journal of Cleaner Production*, *244*, 118896. <https://doi.org/10.1016/j.jclepro.2019.118896>
- Gustafsson, K., Sadegh-Vaziri, R., Grönkvist, S., Levihn, F., & Sundberg, C. (2021). BECCS with combined heat and power: Assessing the energy penalty. *International Journal of Greenhouse Gas Control*, *110*, 103434. <https://doi.org/10.1016/j.ijggc.2021.103434>
- Hanssen, S. V., Daioglou, V., Steinmann, Z. J. N., Doelman, J. C., Van Vuuren, D. P., & Huijbregts, M. A. J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. *Nature Climate Change*, *10*(11), 1023–1029. <https://doi.org/10.1038/s41558-020-0885-y>
- Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019). The technological and economic prospects for CO₂ utilization and removal. *Nature*, *575*(7781), 87–97. <https://doi.org/10.1038/s41586-019-1681-6>
- Hickey, C., Fankhauser, S., Smith, S. M., & Allen, M. (2023). A review of commercialisation mechanisms for carbon dioxide removal. *Frontiers in Climate*, *4*. <https://www.frontiersin.org/articles/10.3389/fclim.2022.1101525>
- Honegger, M., Michaelowa, A., & Roy, J. (2021). Potential implications of carbon dioxide removal for the sustainable development goals. *Climate Policy*, *21*(5), 678–698. <https://doi.org/10.1080/14693062.2020.1843388>

- Huang, S. K., Kuo, L., & Chou, K.-L. (2016). The applicability of marginal abatement cost approach: A comprehensive review. *Journal of Cleaner Production*, 127, 59–71. <https://doi.org/10.1016/j.jclepro.2016.04.013>
- Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, 22(2), 138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- Huysegoms, L., Rousseau, S., & Cappuyens, V. (2018). Friends or foes? Monetized Life Cycle Assessment and Cost-Benefit Analysis of the site remediation of a former gas plant. *Science of The Total Environment*, 619–620, 258–271. <https://doi.org/10.1016/j.scitotenv.2017.10.330>
- IEA. (2022). *Direct Air Capture 2022*. <https://www.iea.org/reports/direct-air-capture-2022>
- IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. <https://www.ipcc.ch/assessment-report/ar5/>
- IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. <https://doi.org/10.1017/9781009157940>.
- IPCC. (2023). *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg3/>
- Jiang, H.-D., Dong, K.-Y., Zhang, K., & Liang, Q.-M. (2020). The hotspots, reference routes, and research trends of marginal abatement costs: A systematic review. *Journal of Cleaner Production*, 252, 119809. <https://doi.org/10.1016/j.jclepro.2019.119809>
- Johnsson, F., Normann, F., & Svensson, E. (2020). Marginal Abatement Cost Curve of Industrial CO₂ Capture and Storage – A Swedish Case Study. *Frontiers in Energy Research*, 8. <https://www.frontiersin.org/articles/10.3389/fenrg.2020.00175>
- Jones, M. B., & Albanito, F. (2020). Can biomass supply meet the demands of bioenergy with carbon capture and storage (BECCS)? *Global Change Biology*, 26(10), 5358–5364. <https://doi.org/10.1111/gcb.15296>
- Kaine, G., Edwards, P., Polyakov, M., & Stahlmann-Brown, P. (2023). Who knew afforestation was such a challenge? Motivations and impediments to afforestation policy in New Zealand. *Forest Policy and Economics*, 154, 103031. <https://doi.org/10.1016/j.forpol.2023.103031>
- Karlsson, M., Alfredsson, E., & Westling, N. (2020). Climate policy co-benefits: A review. *Climate Policy*, 20(3), 292–316. <https://doi.org/10.1080/14693062.2020.1724070>
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO₂ from the Atmosphere. *Joule*, 2(8), 1573–1594. <https://doi.org/10.1016/j.joule.2018.05.006>

- Koponen, K., & Le Net, E. (2021). Towards robust renewable energy investment decisions at the territorial level. *Applied Energy*, 287, 116552. <https://doi.org/10.1016/j.apenergy.2021.116552>
- Kujanpää, L., Koponen, K., Linjala, O., Mäkikouri, S., & Arasto, A. (2023). *Teknologisten hiilinielujen mahdollisuudet ja niiden edistäminen Suomessa (5/2023)*. Suomen ilmastopaneeli. <https://www.ilmastopaneeli.fi/wp-content/uploads/2023/12/ilmastopaneelin-raportti-5-2023-teknologisten-hiilinielujen-mahdollisuudet-ja-niiden-edistaminen-suomessa.pdf>
- Kuparinen, K., Lipiäinen, S., Vakkilainen, E., & Laukkanen, T. (2023). Effect of biomass-based carbon capture on the sustainability and economics of pulp and paper production in the Nordic mills. *Environment, Development and Sustainability*, 25(1), 648–668. <https://doi.org/10.1007/s10668-021-02074-9>
- Lehtilä, A., Koljonen, T., Manninen, H., & Similä, L. (2022). *Quantitative assessments of NEGEM scenarios with TIMES-VTT, preliminary results (D8.2)*. NEGEM. https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D8.2_NEGEM-scenarios.pdf
- Lux, B., Schneck, N., Pfluger, B., Männer, W., & Sensfuß, F. (2023). Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system. *Energy Strategy Reviews*, 45, 101012. <https://doi.org/10.1016/j.esr.2022.101012>
- Martino, S., & Kenter, J. O. (2023). Economic valuation of wildlife conservation. *European Journal of Wildlife Research*, 69(2), 32. <https://doi.org/10.1007/s10344-023-01658-2>
- McKittrick, R. (1999). A Derivation of the Marginal Abatement Cost Curve. *Journal of Environmental Economics and Management*, 37(3), 306–314. <https://doi.org/10.1006/jeeem.1999.1065>
- Meade, J. E. (1973). *The theory of economic externalities: The control of environmental pollution and similar social costs*. Sijthoff.
- Naime, J., Mora, F., Sánchez-Martínez, M., Arreola, F., & Balvanera, P. (2020). Economic valuation of ecosystem services from secondary tropical forests: Trade-offs and implications for policy making. *Forest Ecology and Management*, 473, 118294. <https://doi.org/10.1016/j.foreco.2020.118294>
- National Academies of Sciences, E., and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press. <https://doi.org/10.17226/25259>
- Nicolini, M., & Tavoni, M. (2017). Are renewable energy subsidies effective? Evidence from Europe. *Renewable and Sustainable Energy Reviews*, 74, 412–423. <https://doi.org/10.1016/j.rser.2016.12.032>
- OECD. (2023). *Exchange rates (indicator)* [Dataset]. <https://doi.org/10.1787/037ed317-en>
- Onarheim, K., Santos, S., Kangas, P., & Hankalin, V. (2017). Performance and costs of CCS in the pulp and paper industry part 1: Performance of amine-based post-combustion CO₂ capture. *International Journal of Greenhouse Gas Control*, 59, 58–73. <https://doi.org/10.1016/j.ijggc.2017.02.008>
- Ota, L., Herbohn, J., Gregorio, N., & Harrison, S. (2020). Reforestation and smallholder livelihoods in the humid tropics. *Land Use Policy*, 92, 104455. <https://doi.org/10.1016/j.landusepol.2019.104455>

- Pigou, A. C. (1920). *The Economics of Welfare*. Macmillan.
- Pizzol, M., Laurent, A., Sala, S., Weidema, B., Veronesi, F., & Koffler, C. (2017). Normalisation and weighting in life cycle assessment: Quo vadis? *The International Journal of Life Cycle Assessment*, 22(6), 853–866. <https://doi.org/10.1007/s11367-016-1199-1>
- Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2021). Integrating Carbon Dioxide Removal Into European Emissions Trading. *Frontiers in Climate*, 3(690023), 1-10. <https://www.frontiersin.org/articles/10.3389/fclim.2021.690023>
- Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M. J. S., Sanderman, J., Smith, P., Stehfest, E., & Lawrence, D. (2019). Contribution of the land sector to a 1.5 °C world. *Nature Climate Change*, 9(11), 817–828. <https://doi.org/10.1038/s41558-019-0591-9>
- Rosa, L., & Mazzotti, M. (2022). Potential for hydrogen production from sustainable biomass with carbon capture and storage. *Renewable and Sustainable Energy Reviews*, 157(112123). <https://doi.org/10.1016/j.rser.2022.112123>
- Roussanaly, S., Berghout, N., Fout, T., Garcia, M., Gardarsdottir, S., Nazir, S. M., Ramirez, A., & Rubin, E. S. (2021). Towards improved cost evaluation of Carbon Capture and Storage from industry. *International Journal of Greenhouse Gas Control*, 106(103263). <https://doi.org/10.1016/j.ijggc.2021.103263>
- Sadhukhan, J. (2022). Net zero electricity systems in global economies by life cycle assessment (LCA) considering ecosystem, health, monetization, and soil CO₂ sequestration impacts. *Renewable Energy*, 184, 960–974. <https://doi.org/10.1016/j.renene.2021.12.024>
- Schmidt, H.-P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W., & Kammann, C. (2019). Pyrogenic carbon capture and storage. *GCB Bioenergy*, 11(4), 573–591. <https://doi.org/10.1111/gcbb.12553>
- Shahbaz, M., AlNouss, A., Ghiat, I., McKay, G., Mackey, H., Elkhailifa, S., & Al-Ansari, T. (2021). A comprehensive review of biomass based thermochemical conversion technologies integrated with CO₂ capture and utilisation within BECCS networks. *Resources, Conservation and Recycling*, 173, 105734. <https://doi.org/10.1016/j.resconrec.2021.105734>
- Shahbeik, H., Peng, W., Kazemi Shariat Panahi, H., Dehghani, M., Guillemin, G. J., Fallahi, A., Amiri, H., Rehan, M., Raikwar, D., Latine, H., Pandalone, B., Khoshnevisan, B., Sonne, C., Vaccaro, L., Nizami, A.-S., Gupta, V. K., Lam, S. S., Pan, J., Luque, R., ... Aghbashlo, M. (2022). Synthesis of liquid biofuels from biomass by hydrothermal gasification: A critical review. *Renewable and Sustainable Energy Reviews*, 167, 112833. <https://doi.org/10.1016/j.rser.2022.112833>
- Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., & Paltsev, S. (2021). The cost of CO₂ transport and storage in global integrated assessment modeling. *International Journal of Greenhouse Gas Control*, 109, 103367. <https://doi.org/10.1016/j.ijggc.2021.103367>
- Smith, S. M., Geden, O., Nemet, G. F., Gidden, M. J., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M. W., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G. P., Pratama, Y., ... Minx, J. C. (2023). *The State of Carbon Dioxide Removal—1st Edition*. University of Oxford's Smith School of Enterprise and the Environment. <https://doi.org/10.17605/OSF.IO/W3B4Z>

- Sovacool, B. K., Kim, J., & Yang, M. (2021). The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities. *Energy Research & Social Science*, 72, 101885. <https://doi.org/10.1016/j.erss.2020.101885>
- Stern, N. (2022). Towards a carbon neutral economy: How government should respond to market failures and market absence. *Journal of Government and Economics*, 6, 100036. <https://doi.org/10.1016/j.jge.2022.100036>
- Tanzer, S. E., & Ramírez, A. (2019). When are negative emissions negative emissions? *Energy & Environmental Science*, 12(4), 1210–1218. <https://doi.org/10.1039/C8EE03338B>
- Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: A critical review. *Energy & Environmental Science*, 14(4), 1701–1721. <https://doi.org/10.1039/DOEE03757E>
- Van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, 259, 120904. <https://doi.org/10.1016/j.jclepro.2020.120904>
- Wealer, B., Bauer, S., Hirschhausen, C. v., Kemfert, C., & Göke, L. (2021). Investing into third generation nuclear power plants—Review of recent trends and analysis of future investments using Monte Carlo Simulation. *Renewable and Sustainable Energy Reviews*, 143, 110836. <https://doi.org/10.1016/j.rser.2021.110836>
- Weidema, B. P. (2009). Using the budget constraint to monetarise impact assessment results. *Eco-Efficiency: From Technical Optimisation to Reflective Sustainability Analysis*, 68(6), 1591–1598. <https://doi.org/10.1016/j.ecolecon.2008.01.019>
- Werner, C., Lucht, W., Gerten, D., & Kammann, C. (2022). Potential of Land-Neutral Negative Emissions Through Biochar Sequestration. *Earth's Future*, 10(7), e2021EF002583. <https://doi.org/10.1029/2021EF002583>
- Yang, X., Teng, F., Xi, X., Khayrullin, E., & Zhang, Q. (2018). Cost–benefit analysis of China's Intended Nationally Determined Contributions based on carbon marginal cost curves. *Transformative Innovations for a Sustainable Future – Part III*, 227, 415–425. <https://doi.org/10.1016/j.apenergy.2017.08.016>
- Young, J., McQueen, N., Charalambous, C., Foteinis, S., Hawrot, O., Ojeda, M., Pilorgé, H., Andresen, J., Psarras, P., Renforth, P., Garcia, S., & van der Spek, M. (2023). The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets. *One Earth*, 6(7), 899–917. <https://doi.org/10.1016/j.oneear.2023.06.004>
- Zhang, S., Planavsky, N. J., Katchinoff, J., Raymond, P. A., Kanzaki, Y., Reershemius, T., & Reinhard, C. T. (2022). River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering. *Limnology and Oceanography*, 67(S2), S148–S157. <https://doi.org/10.1002/lno.12244>
- Zickfeld, K., Azevedo, D., Mathesius, S., & Matthews, H. D. (2021). Asymmetry in the climate–carbon cycle response to positive and negative CO₂ emissions. *Nature Climate Change*, 11(7), Article 7. <https://doi.org/10.1038/s41558-021-01061-2>

Appendices

Appendix 1 Costs of CDR in 2050

Technology	Smith et al. (2023) ^a (\$/tCO ₂)	Other literature (\$/tCO ₂)	Mean of all cost estimates (\$/tCO ₂)
DACCS	100-300		
LTSS-DACCS		101,4-225,5 ^{1(b,c)} 170-730 ² 193,2 ³	268,89
HTLS-DACCS		111,1-250,3 ^{1(b,c)} 100-440 ² 200,8 ³	217,17
Enhanced weathering	50-200		
		50-200 ⁴ 157-194 ⁵ max. 200 ⁶	166,83
BECCS	15-400		
Gasification to H ₂		28,7-63,9 ³ 30-60 ⁴	45,65
FT Gasification		20-40 ⁴ 30-76 ⁷	41,5
Combustion		88-288 ⁴ 46,6-84 ³	126,65
Afforestation/Reforestation	0-240		
		5,0-50 ⁴ -40-10 ⁶ 16,4 ³	9,63
Biochar	10-345		
		30-120 ⁴ (-70)-(-60) ⁶ 4,4-133 ³	26,23

1) (Lux et al., 2023) 2) (Young et al., 2023) 3) (Baker et al., 2020) 4) (Fuss et al., 2018) 5) (Beerling et al., 2020) 6) (Hepburn et al., 2019) 7) (Shahbaz et al., 2021) 8) (Roe et al., 2019) 9) (Cobo et al., 2023) 10) (Hanssen et al., 2020) 11) (Austin et al., 2020)

a) Smith et al. (2023) are presented separately as a benchmark, as the report presents wide ranges for estimates in 2050 and is one of the most recent comprehensive reports on CDR. b) Converted from € to \$ c) 10\$/tCO₂ storage cost added

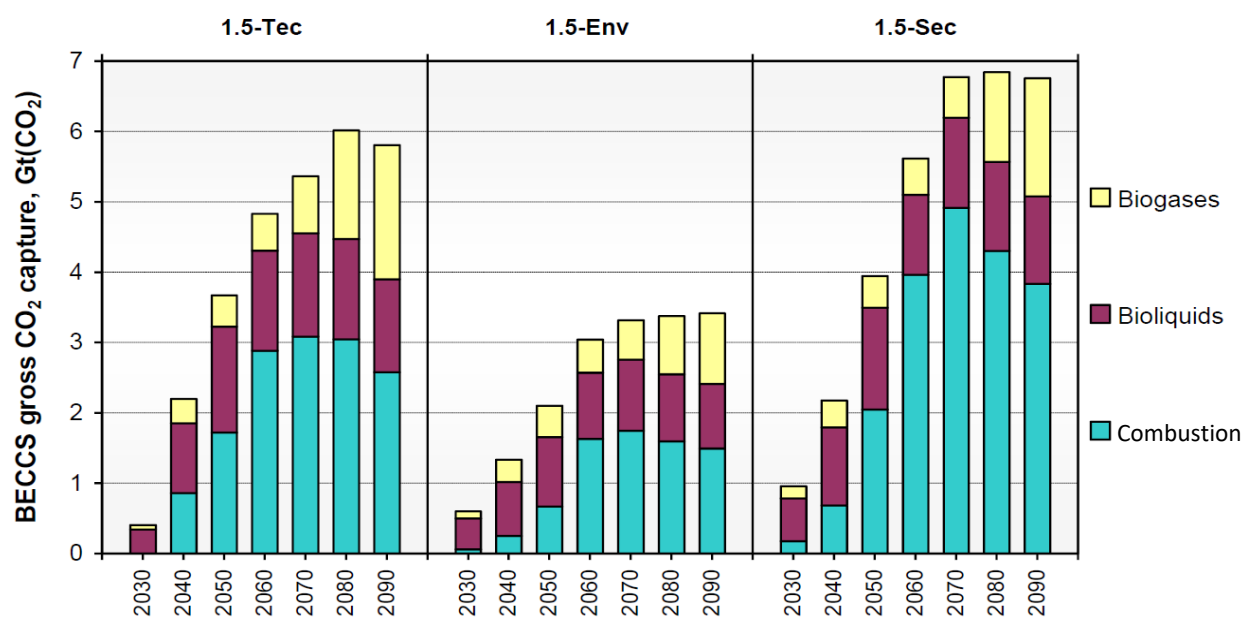
Appendix 2 CDR Potentials in 2050

Technology	Smith et al. (2023) ^(a) (GtCO ₂ /year)	Other literature (GtCO ₂ /year)	Mean of all potential estimates (GtCO ₂ /year)
DACCS	5-40	0,5-5 ⁽⁴⁾ 5-40 ⁽⁶⁾	12,63
HTLS-DACCS & LTSS-DACCS			12,63/2 =6,31
Enhanced weathering	2-4	2-4 ⁽⁴⁾ 0,5-2,0 ⁽⁵⁾ 2-4 ⁽⁶⁾	2,42
BECCS	0,5-11	0,5-5 ⁽⁴⁾ 0,7 ⁽⁸⁾ 0,5-11 ⁽⁶⁾	3,07
Gasification to H ₂		0,00 ⁽⁶⁾ percentage of BECCS = 1% ^(b)	0,01*3,07 =0,02
FT Gasification		0,1-5,8 ⁽⁹⁾ 0,1-0,2 ⁽¹⁰⁾ percentage of BECCS = 41% ^(b)	0,41*3,07 =1,24
Combustion		2,5-10 ⁽⁹⁾ percentage of BECCS = 46% ^(b)	0,46*3,07 =1,40
Afforestation/Reforestation	0,5-10	0,5-3,6 ⁽⁴⁾ 2,6-5,6 ⁽⁹⁾ 1,2-2,6 ⁽¹¹⁾ 0,5-10,1 ⁽⁸⁾	3,20
Afforestation & Reforestation			3,20/2 =1,6
Biochar	0,3-6,6	0,5-2 ⁽⁴⁾ 0,3-2 ⁽⁶⁾ 3,45 ⁽⁸⁾ 2,2 ⁽⁷⁾	2,01

1) (Lux et al., 2023) 2) (Young et al., 2023) 3) (Baker et al., 2020) 4) (Fuss et al., 2018) 5) (Beerling et al., 2020) 6) (Hepburn et al., 2019) 7) (Shahbaz et al., 2021) 8) (Roe et al., 2019) 9) (Cobo et al., 2023) 10) (Hanssen et al., 2020) 11) (Austin et al., 2020)

a) Smith et al. (2023) are presented separately as a benchmark, as the report presents wide ranges of estimates in 2050 and is one of the most recent comprehensive reports on CDR. b) The percentages of different BECCS technologies are derived from NEGEM modeling results for BECCS applications in 2050 (Lehtilä et al., 2022). This model comprises three distinct scenarios on NETP applications. To find the realistic potential for each BECCS technology, an average has been computed from these three scenarios. Subsequently, the proportion of each technology was calculated about the total BECCS application. These proportions were then applied to the central tendency estimate, which was derived from the literature reviewed. For more information, see Appendix 3

Appendix 3 BECCS Potentials from NEGEM modeling



Contribution of BECCS by application (Lehtilä et al., 2022).

Scenario	Tec	Env	Sec	Average of three scenarios	%
BECCS technology	Mt	Mt	Mt	Gt	
Biogases	448	445	452	0,45	14 %
H2-GAS	0	19	36	0,02	1 %
Bioliquids	1504	988	1447	1,31	41 %
FT	752	494	724	0,66	41 %
COMB	1721	669	2046	1,48	46 %
Total	3673	2102	3945	3,24	100 %

Values for the contribution of BECCS by application in 2050 (Lehtilä et al., 2022).