MSc Thesis |Sustainable Development | Energy & Materials Track

Assessing the potential for Negative Emission Technologies in Austria

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ABSTRACT

Negative Emission Technologies (NET) are considered critical for achieving the goal of the Paris Agreement to limit global warming to 1.5°C or well below 2°C. NETs include both nature-based solutions and technological solutions, all coming with different technical, economic and environmental trade-offs to consider. Despite their importance and the urgent need for drastic climate action, little research has been conducted on a national level to determine the potential of these technologies. This is also the case for Austria. Consequently, this thesis aimed to fill this research gap by assessing the techno-economic and implementation potential for Afforestation & Reforestation/Forest Management, Biochar, Bioenergy Carbon Capture & Storage, Building with Biomass, Direct Air Carbon Capture & Storage and Soil Carbon Sequestration. In addition, feedstock competition and trade-offs were assessed. The results show the technical potential for negative emissions in Austria amounts to 39 Mt CO_2 for 2050 of which 30 Mt CO_2 can be realised cost-effectively at a carbon price of 100€ per tonne CO_2. The implementation potential amounts to 22 Mt CO_2 and 29 Mt CO_2 for 2030 and 2050, respectively. These results can be used as a basis for further research aimed at quantifying the indirect effects resulting from the implementation each NET. Furthermore, the potentials can assist policymakers in their decision on which NET portfolio to implement in Austria.

ACKNOWLEDGEMENTS

Firstly, I want to express my gratitude to the supervisor of my thesis, Martin Junginger. He was extremely helpful in assisting with the development of a research project that is both of high societal relevance and of personal interest to me. From the start of this project, he guided me with relevant advice and helped me solve every issue I encountered in the process. He provided critical comments through which I was able to considerable improve my research. I am further grateful to my second reader, Ernst Worrell, who assisted with the development of the research concept both by providing practical suggestions and asking the necessary questions. Finally, I would like to thank all the interviewees who have taken part in this process. Their expertise and knowledge have made a great contribution to this thesis.

EXECUTIVE SUMMARY

The continuous increase in greenhouse gas emissions poses a significant threat to the climate, necessitating urgent action to limit global warming to 1.5°C or well below 2°C by 2100, as specified in the Paris Agreement. However, the current nationally determined commitments of countries to reduce emissions fall short of the steep and deep reductions required to achieve Paris goals. As a result, negative emissions technologies (NET) are now considered imperative to compensate for emissions from hard-to-abate sectors and to reverse a potential temperature overshoot in the case of an exceeded global carbon budget. Austria has committed to achieving climate neutrality by 2040, however, little research has been conducted to assess the potential for NETs within the country.

Hence, this research aimed to determine the potential for negative emissions in Austria under technical, economic and implementation constraints and to assess potential trade-offs between these technologies. The research was based on a mix of methods, including literature research, expert interviews, a quantitative potential assessment, and scenario analysis to determine constraints arising from feedstock competition. Trade-offs were qualitatively assessed with the help of a Multi-Criteria Analysis. The following NETs were considered: Afforestation & Reforestation (AR) /Forest Management, Bioenergy Carbon Capture and Storage (BECCS), Biochar amendment (BC), Building with Biomass (BWB), Direct Air Carbon Capture and Storage (DACCS) and Soil Carbon Sequestration (SCS). The geographic scope of this research was confined to Austria. The temporal scope is based on 2030 and 2050, in line with the National Energy and Climate Plan (2030) and the Long Term Strategy (2050).

The results from this research have shown that the total implementation potential for negative emissions (29 Mt $CO_{2\text{-eq}}$ for 2050) is sufficient to compensate for emissions from hard-to-abate sectors (residual emissions for 2050 amount to between 13 and 23 Mt of $CO2_{\text{-eq}}$ for 2050). This potential can be considered cost-effective at a carbon price scenario of 100€ per tonne $CO_{2\text{-eq}}$. The analysis clearly shows the importance of nature-based solutions for providing negative emissions (23 Mt $CO_{2\text{-eq}}$). This comprises AR/Forest Management and SCS. This is followed by BECCS with an implementation potential of 4 Mt CO_2, and BWB with 2 Mt $CO_{2\text{-eq}}$. The results further show that BC amendment has a high technical potential (13 Mt $CO_{2\text{-eq}}$) but cannot be realised cost-effectively from a current cost perspective. The potential for deploying DACCS in Austria was considered to be 0 due to the limited geological storage capacity, the high energy requirements and economic considerations. Notably, there is sufficient inland storage capacity (between 400 and 510 Mt CO_2) for the cumulative carbon removal potential determined via BECCS (implementation potential of 43 Mt CO_2 from 2023 to 2050).

Even though the assessment clearly points towards nature-based carbon removals as the most important source for negative emissions by 2050, it must be noted that these removals are highly susceptible to reversal and have a relatively short permanence as compared to BECCS, BC or DACCS. Moreover, the potential shows a downward trend towards the end of the century due to global warming. Forests are even expected to become a carbon source rather than a sink. Thus, pursuing a diverse NET portfolio is highly recommended.

A relevant constraint to this thesis was the omittance of indirect effects, such as the impact on the energy system and on the total country GHG balance if the focus is put on maximising carbon storage in forests rather than fully utilising the annual forest stock increment. This could lead to considerably different outcomes and preferences for the technologies. Hence, to allow for a well-informed decision on which NET portfolio to implement in Austria, it is critical to first assess these impacts. A more detailed synthesis of the results can be found in the table below.

Table. Overview of the potentials determined for each NET, related costs, feedstock competition and trade-offs. The **+** refers to positive impacts, the **–** refers to negative impacts and the **?** refers to unknown impacts. The **/** means that there are no expected impacts.

Negative Emission Technologies	**AR/Forest Manage-ment**	**BECCS**	**BC**	**BWB**	**DACCS**	**SCS**	**Total**
Potentials (in Mt $CO_{2\text{-eq}}$)							
Technical potential (for 2050)	19	5	13	2	0	3	**44**
Avg. abatement costs (in € per tonne $CO_{2\text{-eq}}$)	76	75	221	0	735	45	
Techno-economic potential (for 2050)	19	5	0	2	0	3	**30**
Implementation potential (for 2030)	18	0	0	2	0	3	**22**
Implementation potential (for 2050)	19	4	0	2	0	3	**29**
Cumulative implementation potential (2023-2050)	117	43	0	38	0	85	**284**
TRL	8-9	8-9	6-7	8-9	5-7	8-9	
Feedstock competition							
The main feedstock competition arises between BECCS and BC. In case the forestry sector pursues a carbon stock accumulation scenario, this competition is further intensified, as less timber and forest residues are available for both material and energetic utilisation. In respect to BWB, there is sufficient timber available in both a carbon stock accumulation and a shortened rotation crop period scenario to supply the resources needed for the technical potential.							
Trade-offs							
Unambiguous mitigation benefit	Yes	Yes	No	Yes	Yes (but dependent on background energy system)	Yes	
Additionality	Easy to establish	Easy to establish	Easy to establish	Difficult to establish	Easy to establish	Difficult to establish	
Permanence	Short-medium	Long	Long	Short-medium	Long	Short	
Risk of reversibility	High	Low	Low	Medium	Low	High	
Sustainability							
Air pollution	+	-	/	/	-	/	
Biodiversity	+	/	/	/	/	/	
Circular economy	/	/	+	+	-	/	
Energy use	/	/	/	/	-	/	
Soil quality	+	/	+	/	/	+	
Water demand/ pollution	/	/	/	/	-	/	

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ABBREVIATIONS

AR	Afforestation and Reforestation
BECCS	Bioenergy Carbon Capture and Storage
BSL	Baseline
BWB	Building with Biomass
CCCA	Climate Change Centre Austria
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon Dioxide
CRCF	Carbon Removal Certification Framework
DACCS	Direct Air Carbon Capture and Storage
EC	European Commission
EU	European Union
EW	Enhanced Weathering
FOAK	First-of-a-kind
GHG	Greenhouse gas emission
HWP	Harvested wood products
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and other Products Use
LTS	Long term strategy
LULUCF	Land Use, Land-Use Change and Forestry
MCA	Multi-Criteria Analysis
MSW	Municipal solid waste
MRV	Monitoring, Reporting and Verification
Mt	Megatonne
MW	Megawatts
NDC	Nationally Determined Contributions
NECP	National Energy and Climate Plan
NET	Negative Emission Technology
NOAK	nth-of-a-kind
PCW	Post-consumer wood
R&D	Research and Development
RQ	Research question
SCS	Soil Carbon Sequestration
SOC	Soil organic carbon
SQ	Sub-question
TRL	Technology Readiness Level
WAM	With additional measures
WEM	With existing measures
WCS	Wood construction share
WtE	Waste to energy

1. INTRODUCTION

This section provides an introduction into the background and societal relevance for this research project. An overview is provided on existing research, from which the research gap is derived. Resulting from the research gap, the research objective of this thesis is defined. Lastly, the boundaries and scope defined for this research will be discussed.

1.1 Background

Scientists have been sounding the alarm for years regarding the dangers associated with the continuous increase in greenhouse gas (GHG) emissions. Widespread public urgency to avert the looming climate crisis had been lacking however, likely due to the absence of tangible global warming impacts. In recent years, there has been a noticeable increase in public awareness and, more importantly, political recognition of the urgency to combat climate change. As a response, many countries have set more ambitious mitigation targets, and some have even committed to achieving climate neutrality by 2050. Despite these commitments, progress in terms of reducing emissions has been slow while global emissions continue to rise.

The Intergovernmental Panel on Climate Change (IPCC) has developed various scenarios to guide efforts to meet the goals of the Paris Agreement (Rogelj, Shindell, et al., 2018). The Paris Agreement, which has been ratified by 194 parties, aims to limit global warming to 1.5°C or well below 2°C by 2100 as compared to pre-industrial levels. In order to align with a 1.5°C pathway, it will be necessary to achieve a reduction of approximately 50% of global emissions every decade until reaching net zero emissions around the middle of the century (Roe et al., 2019; Rogelj, Shindell, et al., 2018). However, the current commitments of countries, known as the Nationally Determined Contributions (NDCs), fall short of the steep and deep emissions reductions required according to the scenarios outlined by the IPCC (Rueda et al., 2021). Indeed, the national GHG reduction targets would have to be halved to achieve the 1.5°C reduction trajectories for 2030 from the IPCC (Rogelj, Shindell, et al., 2018), highlighting the substantial disparity between current commitments and the level of action required to meet the goals of the Paris Agreement.

Given the delay in mitigation efforts and the rapidly dwindling carbon budget, Negative Emissions Technologies (NET) or Carbon Dioxide Removals (CDR) constitute a critical component in all of the four 1.5°C-consistent pathway archetypes of the IPCC to avert a climate crisis, as shown by Figure 1 (Rogelj, Shindell, et al., 2018). NETs are imperative to compensate for emissions from hard-to-abate industries and to make up for a potential temperature overshoot in the case of an exceed global carbon budget (Obersteiner et al., 2018).

NETs can, thus, act as complementary solution for climate change mitigation by enabling the achievement of net negative emissions. NETs can be distinguished into nature-based solutions (e.g., Afforestation and Reforestation) and engineered or technological solutions (e.g., Bioenergy Carbon Capture and Storage) (Tanzer & Ramírez, 2019). The concern regarding technological NETs, however, is that large-scale deployment is slow and concerns have been made regarding their sustainability, potential, economic and technical feasibility (Rogelj, Shindell, et al., 2018). Nevertheless, three out of four IPCC pathway archetypes involve both technological and nature-based carbon removal options, highlighting the vital importance to gear up research efforts towards enabling the realisation of technological NETs in the near future.

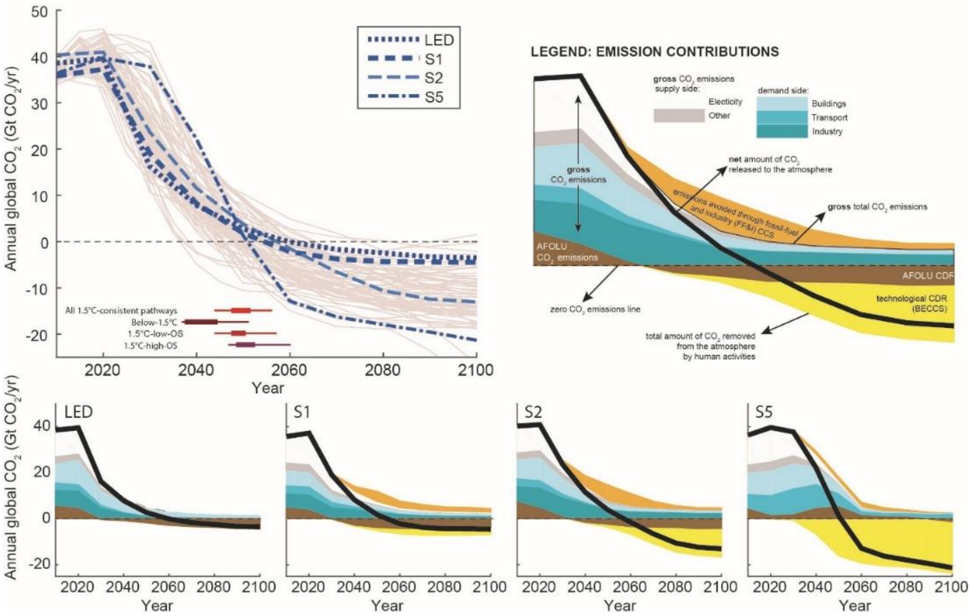


Figure 1. The four 1.5°C-consistent IPCC pathway archetypes. This figure represents four global 1.5°C-consistent pathway archetypes from the IPCC. The top-left panel presents the emission reductions required for each of these 4 emission pathways. The top-right panel provides a legend depicting the respective CO$_2$ mitigation measures associated with each colour. The bottom row presents the portfolio of mitigation measures assumed for each of the four illustrative pathway archetypes. The pathways S2 and S5 assume a low and high temperature overshoot, respectively.

Note. "From Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development", by Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Keshgi, S., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., & Vilarino, M. V, 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, p.113. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

In the European Union (EU), discussion around NETs has picked up with the recent proposal from the European Commission (EC) on the EU's Carbon Removal Certification Framework (CRCF) (Proposal for a Regulation on an EU Certification for Carbon Removals, 2022). The proposal aims to establish a certification system to ensure the credibility and transparency of carbon removal activities. Additionally, a few studies have been undertaken to assess the potential for the deployment of various NETs on a national and EU level (Alcalde et al., 2018; Rosa et al., 2021; Strengers et al., 2018). The EC has further published an analysis which shows that around 10% of 2018 GHG emissions will have to be removed via CDR in order to achieve the 2050 climate neutrality goals and to compensate for hard-to-abate emissions (2050 Long-Term Strategy. In-Depth Analysis in Support of the Commission Communication., 2018).

According to the Climate Change Centre Austria (CCCA) the national carbon budget for Austria amounts to 280 MtCO$_{2\text{-eq}}$ as of 2022, which has been derived from the global carbon budget under equity considerations (Steininger et al., 2022). Austrian GHG emissions (excl. land, land use change and forestry (LULUCF)) have been relatively constant in recent years, except for a dip in 2020 due to the Covid-19 pandemic, with total emissions amounting to 77.5 Mt CO$_{2\text{-eq}}$ in 2021. When accounting for net removals through LULUCF (10.4 Mt CO$_{2\text{-eq}}$) we arrive at annual net GHG emissions of approximately 67.1 Mt CO$_{2\text{-eq}}$. These numbers illustrate that without drastic emission cuts, the Austrian carbon budget would be exceeded before 2030, which further emphasises the need for considering an early-on deployment of NETs.

The Austrian Long Term Strategy 2050 (LTS) has specified the goal of becoming climate neutral by the year 2050 (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). The most recent government programme for the period 2020-2024 has even taken a step further and committed to achieving climate neutrality by 2040 (Republik Österreich, 2020). Deriving from the LTS, the residual, hard-to-abate emissions for Austria are projected to amount to between 13 and 23 Mt of $CO_{2\text{-}eq}$ by 2050 depending on the scenario considered (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). These emissions primarily stem from agriculture, industry and fuel consumption, and will have to be compensated through the deployment of NETs or Carbon Capture and Storage (CCS).

In the context of the LTS, three scenarios were developed showing different decarbonisation trajectories (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). These include a scenario “with existing measures” (WEM), one “with additional measures” (WAM), and a so-called “transition scenario” which foresees far-reaching emission reductions until 2050 by maximising the utilisation of nationally available energy resources and considerable lifestyle changes of the population. Notably, only the transition scenario achieves the goal of reaching climate neutrality by 2050. Deriving from this scenario, 4 exemplary pathways have been developed, shown in Figure 2. These indicate that, negative emissions will be required for all pathways to achieve climate neutrality in Austria.

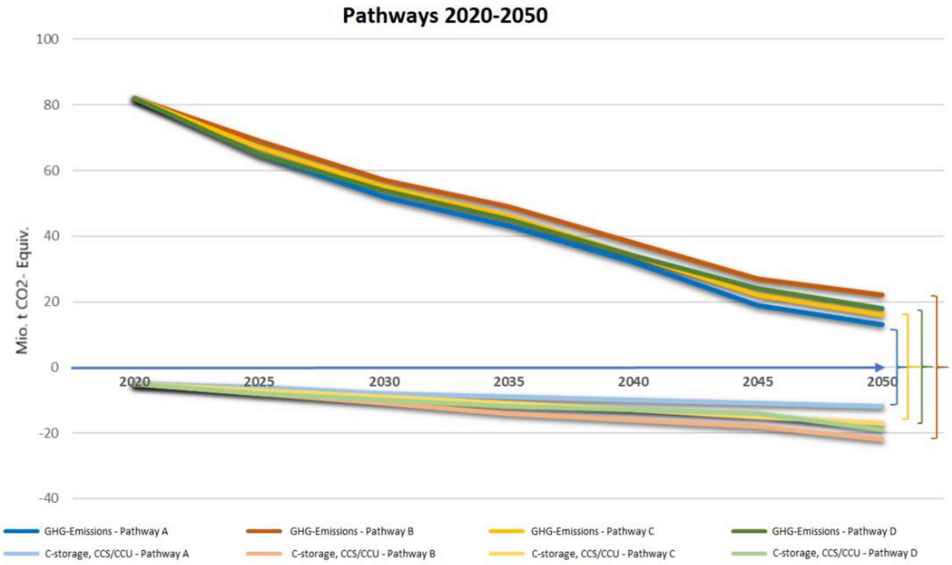


Figure 2. Four exemplary climate target pathways for Austria on the basis of the "Transition scenario".

1.2 Research gap

Despite the pressing need for negative emissions, little analysis has been undertaken in Austria to comprehensively assess the potential for the deployment of NETs. The most prominent NETs have been determined by several relevant studies in the field (Fuss et al., 2014; Holz et al., 2018; Minx et al., 2018; Rueda et al., 2021). In addition, Building with Biomass is considered another viable option for Austria. With its large forest sector and abundant timber resources, Austria has the potential to achieve considerable negative emissions through biomass utilization in buildings (Kalt, 2018). Thus, the NETs to be discussed comprise:

- Afforestation and Reforestation (AR)/Forest management
- Bioenergy Carbon Capture and Storage (BECCS)
- Biochar (BC)
- Building with Biomass (BWB)
- Direct Air Carbon Capture and Storage (DACCS)
- Enhanced Weathering (EW)
- Ocean Fertilisation
- Soil carbon sequestration (SCS)

Some research has been carried out on NETs, but on an individual basis. A project, known as *"CareForParis",* has been carried out regarding **Afforestation and Reforestation/Forest Management** by the Austrian forest research institute and other national research organisations which led to the development of various scenarios for assessing the climate mitigation potential of the forest sector (Braun et al., 2020).

Rosa et al. (2021) have assessed the potential of **BECCS** across Europe, including Austria. However, this study only considers the technical potential and omits a detailed national analysis due to its broad geographical scope. Notably, this study does not discuss BECCS from biofuel production despite its considerable potential for BECCS deployment given the highly concentrated CO_2 stream in e.g., bioethanol production (Laude et al., 2011).

Estimates regarding both the implementation and technical potential as well as rough cost estimates for **biochar** application and **soil carbon sequestration** have been made on a global basis (P. Smith, 2016). Some estimates have been made for the carbon sequestration potential from biochar and compost amendment for Austria based on a scenario compatible with the 4 per mille objective, which aims to increase the soil organic carbon content by 4 ‰ (Soja et al., 2021). However, this estimate only shows the required increase in SOC to achieve the 4 pro mille goal rather than providing an accurate assessment of the techno-economic potential for biochar application under considerations of currently available and in the future deployable biochar production capacities. Another study projected a mitigation potential of 0.38 Mt $CO_{2\text{-eq}}$ per year for Austria under the assumption of utilising 10% of the annual forest biomass increment for biochar production (Bruckman & Klinglmüller, 2014).

Kalt (2018) has undertaken a scenario analysis of the climate benefits of **Building with Biomass**. This analysis provides a good basis for estimating the BWB negative emission potential under consideration of a baseline scenario (constant wood construction share (WCS)) and a moderate and rapid increase in WCS of residential buildings. The limitations of Kalt's (2018) study concern the exclusion of non-residential buildings and the potential changes in timber availability due to changing forest management practices. The carbon stock change for BWB for residential buildings has been estimated to amount to around 3 and 5 Mt carbon for the moderate and rapid increase scenario, respectively (Kalt, 2018).

Fasihi et al. (Fasihi et al., 2019) have undertaken a global techno-economic potential assessment of **DACCS** (in $MtCO_2$ captured per year). Potential estimates for Austria specifically are non-existent and there are no currently ongoing projects for the deployment of DAC.

In regard to **Soil Carbon Sequestration**, scenarios have been developed by the Austrian Agency for Health and Food Security on how the soil organic carbon stock could develop under a Business as Usual (BAU) scenario and 3 scenarios which differ in their management practices (i.e., additional carbon input of 5%, 10% and 20%) (Baumgarten et al., 2022). Economic and implementation aspects have not been considered.

The **sub-surface CO_2 storage potential** in Austria has been estimated at between 400 to 510 Mt CO_2 (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). Most of the currently planned CO_2 storage sites in Europe can be found in Northern Europe (Rosa et al., 2021). There is one prospective site in vicinity to Austria, though, which will be established in Northern Italy.

1.3 Research objective

The research gap reveals that at present, no comprehensive study exists that evaluates the techno-economic and implementation potential of the NETs relevant for Austria. The **research objective** for this thesis is, thus, to improve the understanding of the potential contribution of NETs to meet the Austrian goal of achieving climate neutrality. This master thesis aims to answer the following research question (RQ), which has been broken down into 5 sub-questions (SQ):

RQ: *What is the techno-economic and implementation potential for Negative Emission Technologies in Austria for 2030 and 2050?*

- **SQ1:** What is the future sustainable biomass potential that can be deployed for biomass-based NETs under consideration of domestically available biomass?
- **SQ2:** What is the technical potential for each NET and which part of this potential can be realised cost-effectively?
- **SQ3:** How does the availability of biomass influence the deployment of NETs?
- **SQ4:** What are potential trade-offs to consider for the deployment of the various NETs?
- **SQ5:** What is the implementation potential for each NET?

Given the low Technology Readiness Level (TRL) of **Enhanced Weathering** (TRL 1-5) connected with the restricted temporal scope of this study (2030, 2050), this technology will be excluded from the assessment (Bey et al., 2021). **Ocean fertilisation** has no national relevance as Austria is a landlocked country with no sea access.

This research constitutes a background study to help understand the opportunities for Austria to realise net negative emissions, thereby contributing to reaching the Austrian climate neutrality goal (Republik Österreich, 2020) and paving the way for an early-on deployment of NETs. This study can be used to guide policy decisions or research trajectories for NETs.

1.4 Boundaries and scope

The geographical scope of this study is confined to Austria. Hence, imports and exports of biomass are neglected, and domestic biomass is assumed to be available to contribute to Austrian mitigation targets. The techno-economic potential is assessed for 2050. The implementation potential is determined for both 2030 and 2050, which is in line with the temporal scope of the NECP and the LTS respectively. This study only considers the potential for gross negative emissions, which means that emissions arising due to transporting the required biomass for BECCS or emissions from the production of BC for example are not considered. Indirect effects, such as a decrease in energy conversion efficiencies due to the installation of CCS equipment or various environmental concerns will not be quantified but qualitatively discussed.

The potentials are based solely on C and CO_2 removal. However, it must be noted that various other technologies exist that remove non-CO_2 GHGs from the atmosphere (de Richter et al., 2017; Ming et al., 2021).

The deployment of BECCS and DACCS is ultimately constrained by the geological storage capacity. The Austrian storage potential for carbon dioxide is limited to between 400 and 510 Mt CO_2 (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). However, since estimates on the EU geological carbon storage capacity have shown that EU-wide storage capacity does not constitute a limiting factor for the deployment of these technologies in the next few decades, the availability of CO_2 storage will not be treated as a constraint for this study (Bey et al., 2021). Moreover, a large carbon storage site is planned to be established in Northern Italy which could potentially present a feasible storage option for Austrian CO_2 (Rosa et al., 2021).

2. THEORY

This research brings together various concepts from different fields of study. An introduction to the relevant concepts discussed in this thesis are provided in this chapter. Further information can be found by looking at the cited sources.

2.1 Negative Emission Technologies

The most relevant concept to be discussed in this paper are NETs, which are commonly also referred to as Carbon Dioxide Removals (Jackson et al., 2017). Negative emissions can be achieved by capturing and storing capturing biogenic emission sources, as these are characterised as carbon neutral during combustion. Another option is to remove carbon dioxide directly from the atmosphere or to enhance the natural carbon sink capacity. In line with the CRCF proposal by the EC (Proposal for a Regulation on an EU Certification for Carbon Removals, 2022), this thesis will follow the therein stated definition which reads as follows: "'carbon removal' means either the storage of atmospheric or biogenic carbon within geological carbon pools, biogenic carbon pools, long-lasting products and materials, and the marine environment, or the reduction of carbon release from a biogenic carbon pool to the atmosphere" (p.10).

NETs can be distinguished into nature-based solutions (NBS) and technology-based solutions (TBS) (Zelikova, 2020). Figure 3 provides a visual overview of the various NETs discussed and their respective storage mediums. As discussed above EW and OF will be excluded from this analysis.

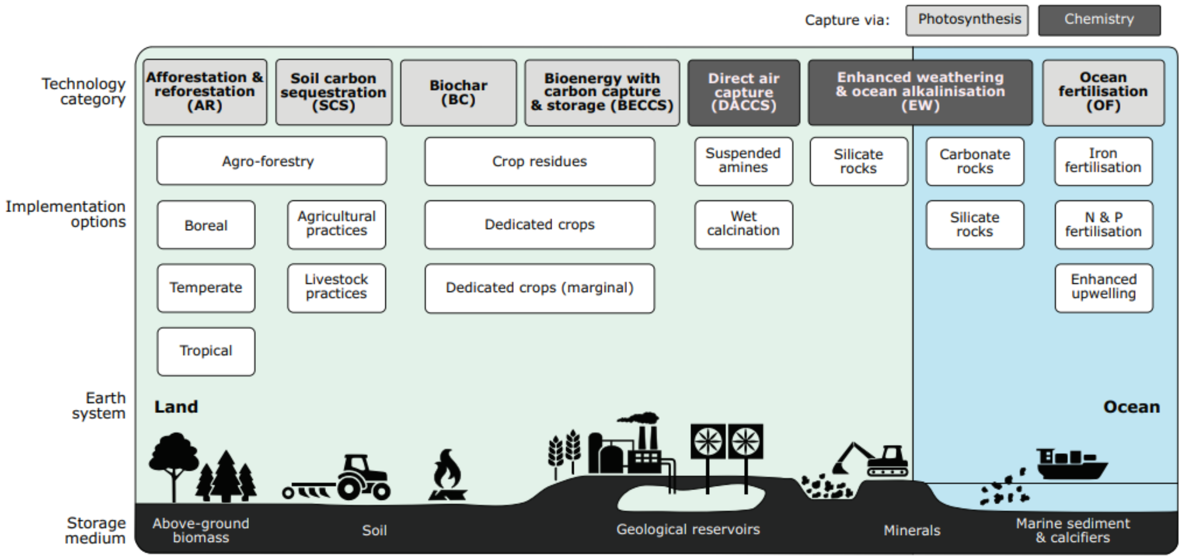


Figure 3. Overview of the various options for achieving negative emissions, their implementation options, respective earth system and storage medium.
Note. From "Negative emissions—Part 1: Research landscape and synthesis", by Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M, 2018, *Environmental Research Letters*, 13(6), p. 6 (https://doi.org/10.1088/1748-9326/aabf9b). CC-BY-NC.

Afforestation and Reforestation belong to the category of *nature-based solutions* and involve the practice of enhancing the natural carbon sink through the planting of trees/establishment of forests as well as through **forest management** (Minx et al., 2018). Through creating this additional carbon sequestration capacity negative emissions are achieved. According to the IPCC (2019) afforestation is defined as the "conversion to forest of land that historically has not contained forests" (p.804), whereas reforestation refers to the “conversion to forest of land that has previously contained forests but that has been converted to some other use” (p.822).

BECCS (*TBS*) refers to the installation of carbon capture and storage technology at bioenergy plants (IPCC, 2019). This means that a CO_2 stream from biogenic origin is separated, compressed, and subsequently transferred to a geological storage site. Notably, the BECCS potential for negative emissions is strongly dependent on the type of biomass used, location-specific characteristics of biomass cultivation, harvesting, emissions involved in transporting the biomass and the type of final energy produced, or simply put on the whole value chain of bioenergy production (Fajardy & Mac Dowell, 2017; Hanssen et al., 2020). Table 1 provides an overview of the various industries that could create negative emissions through BECCS.

Table 1. Overview of industries with potential for BECCS deployment.

Sector	**Description of BECCS system**
Biomethane upgrading (Gentile et al., 2022)	Biogas can be produced through anaerobic digestion of biogenic waste materials. This waste includes for example agricultural waste materials (mainly crop residues and livestock manure) or food waste. During the upgrading process from biogas to biomethane, CO_2 needs to be separated from methane. Through capturing and storing this CO_2-stream negative emissions can be achieved.
Bioethanol (Johnson et al., 2014; Laude et al., 2011)	Bioethanol is produced through the fermentation of either traditional (e.g., cereal grains, sugar cane, sugar beets), second-generation (lignocellulosic biomass) or third-generation (algal biomass) feedstocks. The fermentation process typically releases a highly concentrated CO_2 stream (>98% vol%) which provides a viable opportunity to achieve negative emissions through BECCS.
Cement production (Tanzer, Blok, & Ramírez, 2021; Yang et al., 2021)	Cement production is a highly carbon intensive process, with around 60% of process emission arising from limestone calcination. The residual share of emissions can be allocated to fuel combustion. According to Yang et al. (2021), only 6 to 10% of total emissions from cement production can become biogenic given the poorer heating values of bio-based fuels and the high emission share from calcination (a fossil-fuel based process). Currently combustion fuels are primarily based on fossil fuels (coal and lignite) or on industrial waste from fossil origin (e.g., tyres, non-recyclable plastics). Through increasingly replacing conventional fuels with biomass and biogenic waste coupled with the installation of CCS, negative emissions become possible.
Chemicals (Strengers et al., 2018)	The chemical industry presents another opportunity for BECCS deployment in the case that fossil-based feedstocks are substituted with biogenic ones. These novel biobased chemical production pathways can enable the carbon neutral production of products with a short lifespan (e.g., olefins or transport fuels).
Pulp & Paper (Onarheim et al., 2017; Tanzer, Blok, & Ramírez, 2021)	In the pulp and paper industry around 75% of on-site emissions stem from the combustion of process wastes. These process wastes are of biogenic origin. Thus, these process emissions can be classified as biogenic and can be captured and stored via CCS. However, the application of CCS is highly energy intensive, as flue gases are distributed between various point sources and the CO_2 concentration in the flue gas only amounts to around 20%.
Steelmaking (Tanzer, Blok, & Ramírez, 2021; Yang et al., 2021)	The utilisation of biogenic rather than fossil-based reducing gas for the direct reduction of iron steelmaking route gives rise to increasing biogenic emissions, which could be captured and stored to achieve negative emissions. Another process, called HIsarna, allows for increased fuel flexibility in

	steelmaking. This process is still under development but depicts a promising option for BECCS deployment in the future.
Thermal power plants (Gough & Upham, 2011)	In biomass co-firing plants, coal is partially substituted with biomass to produce electricity and heat through the combustion of both coal and biomass in highly efficient coal boilers. There are also thermal power plants primarily powered by biomass. By applying CCS at these facilities, biogenic emission sources can be effectively utilised to achieve negative emissions.
Waste to energy (Pour et al., 2018)	By capturing the biogenic CO_2 emitted through the treatment of the organic fraction from municipal solid waste, negative emissions can be achieved.

The respective conversion technologies for bioenergy and biochar production are depicted in Table 2. For this study, the main biomass conversion technologies analysed include both thermochemical processes (combustion, pyrolysis) and bio-chemical processes (fermentation, anaerobic digestion). These processes have been derived from the bioenergy products looked at for achieving negative emissions. Gasification is not considered given the considerable challenges involved in making the technology technically and economically feasible, especially in regard to syngas conditioning (Abdul Malek et al., 2020). Biomass gasification could become a highly efficient NET in the future due to the production of pure CO_2 for various syngas applications if the technical challenges can be overcome. Further elaborations can be found in Chapter 5.2.1 on the techno-economic potential for the chemical industry.

Table 2. Overview of biomass conversion technologies and resulting products relevant for this study.

Conversion process	**Conversion process**	**Main products**	**Useful by-products**	**Description**
Thermo-chemical	Combustion	Electricity Heat	/	Modern biomass combustion refers to the process of controlled burning of solid biomass to produce electricity and heat (Jenkins et al., 2019).
	(Slow) Pyrolysis	Biochar	Bio-oil, pyrolytic gas	Pyrolysis refers to the process of converting organic materials under anaerobic conditions at high temperatures into bio-oil, biochar and pyrolytic gas (Kirubakaran et al., 2009). The difference between pyrolysis and gasification lies in the inert environment needed for pyrolysis.
Bio-chemical	Fermentation	Bio-ethanol	Electricity	Fermentation is an anaerobic process where carbohydrates are broken down into ethanol through microorganisms, mostly yeast (Tse et al., 2021).
	Anaerobic digestion	Biogas, Bio-methane	Digestate	Anaerobic digestion refers to the process of breaking down biodegradable material under the absence of oxygen through microorganisms (Momayez et al., 2019). The resulting product is biogas which can further be upgraded into biomethane.

Biochar (*TBS*) can be produced by heating biomass in an oxygen-limited or oxygen-free environment at elevated temperatures (Cha et al., 2016). Biochar can then be applied to soils, where it remains as a carbon storage medium for a period of several decades to hundreds of years. Negative emissions are achieved by storing biomass carbon in soils for a long period of time, that would have decomposed more rapidly in forests (Bey et al., 2021). This only holds true under the condition that the converted biomass has been produced sustainably and is regrown.

BWB *(TBS)* involves the substitution of conventional construction materials with wood-based products. This leads to a decrease in GHG emissions due to material/product substitution effects since wood-based products show lower life-cycle emissions. In addition, it provides for long-term storage in buildings as the degradation of carbon from timber products is delayed by several decades, which is also referred to as carbon stock/storage effect (Kalt, 2018). The carbon stock/storage effect can be classified as negative emissions as renewable biogenic carbon in the form of wood is taken out of forests and effectively stored in buildings for a long period of time which creates a negative carbon balance.

DACCS is a nascent *technological solution* to remove carbon dioxide directly from the atmosphere. It can be distinguished between high temperature aqueous solutions (HT DAC) and low temperature solid sorbent (LT DAC) systems (Fasihi et al., 2019). According to a study by Fasihi et al. (2019) LT DAC systems are preferred over HT DAC systems given the option to utilise waste heat from other energy systems as well as the relatively lower heat supply costs. The first large-scale plant is expected to start operating in the United States around 2025 (IEA, 2022). As of now, 11 DAC plants have reached an advanced development stage. Under the assumption that all of these plants continue with construction, DAC capacity would amount to only 5.5 Mt CO_2 in 2030. Notably, the majority of current DAC projects utilise the captured CO_2 rather than storing it.

SCS *(NBS)* refers to the enhancement of the natural carbon sink of soils by adopting alternative management techniques (Bey et al., 2021). This can be achieved by, for example, implementing crop rotations with higher carbon fixation, applying cover cropping or changing the land use form from arable land to grassland.

2.2 Technology Readiness Levels

NETs vary starkly in their level of technological maturity. This variation can be assessed with the concept of TRL which provides a comparable measurement system to determine said maturity within 9 increments (Mankins, 1995). Table 3 depicts a short description of each level. Building on this classification, Table 4 shows the TRL level for each NET.

Table 3. Description of Technology Readiness Levels as defined by the EC (2014).

Level	**Description**
TRL 1	Basic principles observed.
TRL 2	Technology concept formulated.
TRL 3	Experimental proof of concept.
TRL 4	Technology validated in lab.
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 7	System prototype demonstration in operational environment.
TRL 8	System complete and qualified.
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

Table 4. Overview of NETs, their respective TRL levels and the reasons for this classification according to Bey et al. (2021); Kampman et al. (2023); Smith et al. (2023).

NET	TRL	Reasoning
AR/Forest Management	8-9	Widespread implementation in Europe has been proven.
BECCS	8-9	Operation and commercialisation have been proven. TRL depends on the bioenergy sector.
BC amendment	6-7	BC production has been previously applied on a large scale whereas large-scale trials for application under field conditions are lacking.
BWB	8-9	BWB has been proven on a large scale and has been widely applied in several parts of Europe. Progress is still to be made in regard to utilising deciduous tree biomass.
DACCS	5-7	DACCS can be deployed with various technologies that involve different TRL levels. Depending on technology: prototype demonstration, pilot plant development and commercialisation have been proven so far.
EW	3-4	Low TRL level, as technology is still in Research & Development phase.
SCS	8-9	Deployable measures to enhance soil carbon sinks have been previously implemented.

2.3 QUALITY criteria

The EC has defined criteria in the EU CRCF, which are meant to guarantee the quality and comparability of CDRs. The CRCF presents a voluntary framework aiming to ensure the accurate and reliable reporting of carbon removals (Proposal for a Regulation on an EU Certification for Carbon Removals, 2022). The criteria are presented in Table 5.

Table 5. QUALITY criteria and their fulfilment conditions as determined by the CRCF (Proposal for a Regulation on an EU Certification for Carbon Removals, 2022).

Criteria	Condition for fulfilment
Quantification	CDR activities shall be accurately measured. The climate mitigation benefit must be unambiguous, i.e. any greenhouse gas emissions resulting from the implementation of the CDR must not outweigh the removed carbon.
Additionality	CDR activities have to provide additional benefits, i.e. they have to go beyond compliance with existing practices and regulations and are implemented due to the incentive provided by the regulation. They shall be measured against a baseline (BSL).
Long-term storage	Risks associated with carbon dioxide release from storage have to be monitored and mitigated. Liability mechanisms will be set in place to ensure that issues threatening the long-term storage of carbon are addressed by the operator during the monitoring period. In the case that carbon is stored either in products or through enhanced natural sinks (also referred to as carbon farming), the carbon shall be considered released after the monitoring period.
Sustainabil**ity**	There shall be no negative impacts resulting from the implementation of the CDR activity for other environmental objectives as for example climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, circular economy transition, air pollution or biodiversity protection.

2.4 Techno-economic and implementation potential

The **theoretical** potential represents the maximum amount of negative emissions that can be achieved when solely accounting for fundamental biophysical limits (Torén et al., 2011). The **technical** potential refers to the part of the theoretical potential that can be utilised under consideration of current technological limits or constraints. The **techno-economic** potential goes a step further and additionally accounts for economic feasibility. This study will also consider the **implementation potential**, i.e., the part of the techno-economic potential termed feasible to implement under consideration of technological readiness, limitations in respect to upscaling and deploying the technologies (i.e., technological upscaling) and the availability of the required infrastructure.

2.5 Biomass availability

To achieve negative emissions with biomass-based technologies, it is critical that the biomass has been sourced sustainably (Fuss et al., 2018). This is because emissions associated with the production of biomass resulting from the direct (also referred to as land use change, LUC) or indirect conversion of land (indirect land use change, ILUC) for biomass cultivation, could potentially negate the mitigation benefit of these NETs (e.g., BC, BECCS, BWB).

2.6 Scenario analysis

Scenarios entail the exploration of various future pathways by considering different circumstances through alternative assumptions and factors (Duinker & Greig, 2007). Scenario analysis aims to play out 'what if' questions to assess potential consequences of uncertainty. Thus, scenarios can be a useful tool to guide policy-makers in their decision-making processes (Fauré et al., 2017).

According to Börjeson et al. (2006) scenarios can be divided into the following three types:

1. Predictive: this type comprises forecasts and what-if scenarios. It deals with the question '*What will happen*?'.
2. Explorative: this category includes external and strategic scenarios. It answers the question '*What can happen*?'.
3. Normative: this entails preserving or transformative scenarios. It deals with the question '*How can a specific target be reached?*'.

For this thesis, explorative scenarios will be used. Explorative scenarios aim at assessing potential future developments and their consequences under consideration of alternative strategies (Börjeson et al., 2006).

2.7 Marginal Abatement Cost Curve

The purpose of a Marginal Abatement Cost Curve (MACC) is to present a visual overview of different GHG mitigation options. This is done by ranking various options according to their GHG abatement potential (in Mt $CO_{2\text{-eq}}$) and associated marginal abatement costs (in €/t $CO_{2\text{-eq}}$) for a specific target year (Eory et al., 2018). Thus, each point along the MAC curve shows the marginal cost of achieving an additional amount of GHG emission reduction in year X (Huang et al., 2016). Policymakers or other interested stakeholders can then derive the most cost-effective mitigation portfolio to achieve the desired GHG emission reduction.

According to the approach used, MACCs can be classified into bottom-up, top-down or hybrid, where bottom-up focusses more on technological details (i.e., by performing a measure-explicit ranking) and top-down more on economy-wide impacts (i.e., by determining the potential opportunity costs for arriving at a certain mitigation target) (Huang et al., 2016). Some of the shortcomings of MACCs comprise the exclusion of effects resulting from the interaction between measures and the uncertainty of future costs (Vogt-Schilb & Hallegatte, 2014).

2.8 Multi-criteria analysis

Multi-criteria analysis can be used as a structured tool to analyse and assess potential alternatives under consideration of competing evaluation criteria (Ness et al., 2007; Ren, 2021). It constitutes a widely recognised method for facilitating decision-making processes that deal with complex situations involving various alternatives, objectives or types of data (Ahmed et al., 2020). Thereby it can help with the identification of trade-offs between different policy options by providing the possibility to incorporate both qualitative and quantitative data (Ness et al., 2007). The MCA process involves the following steps (Department for Communities and Local Government, 2009):

1. Definition of the decision-context, incl. the aim of the MCA.
2. Identification of the alternative options to be assessed.
3. Identification of the aim of the MCA and the criteria to evaluate the consequences of each option.
4. Scoring each option against the determined criteria.
5. Weighting of the criteria to determine the relative importance of each factor (optional).
6. Calculate scores for each alternative.
7. Ranking of the analysed options (optional).
8. Conduct sensitivity analysis on scores and weighting (optional).

3. METHODS

This research aims to determine the potential for NETs that are of relevance for achieving carbon neutrality in Austria under consideration of technical, economic, and implementation constraints. This section will elaborate on the methods used and the sub-steps needed to answer each SQ and arrive at the desired outcome of this thesis. Firstly, the approach for answering each research question is explained. Secondly, an overview of the available data and respective sources is provided.

3.1 Technical framework

The technical framework presents an overview of the research approach for each SQ and shows how these are connected. The framework is presented in Figure 4.

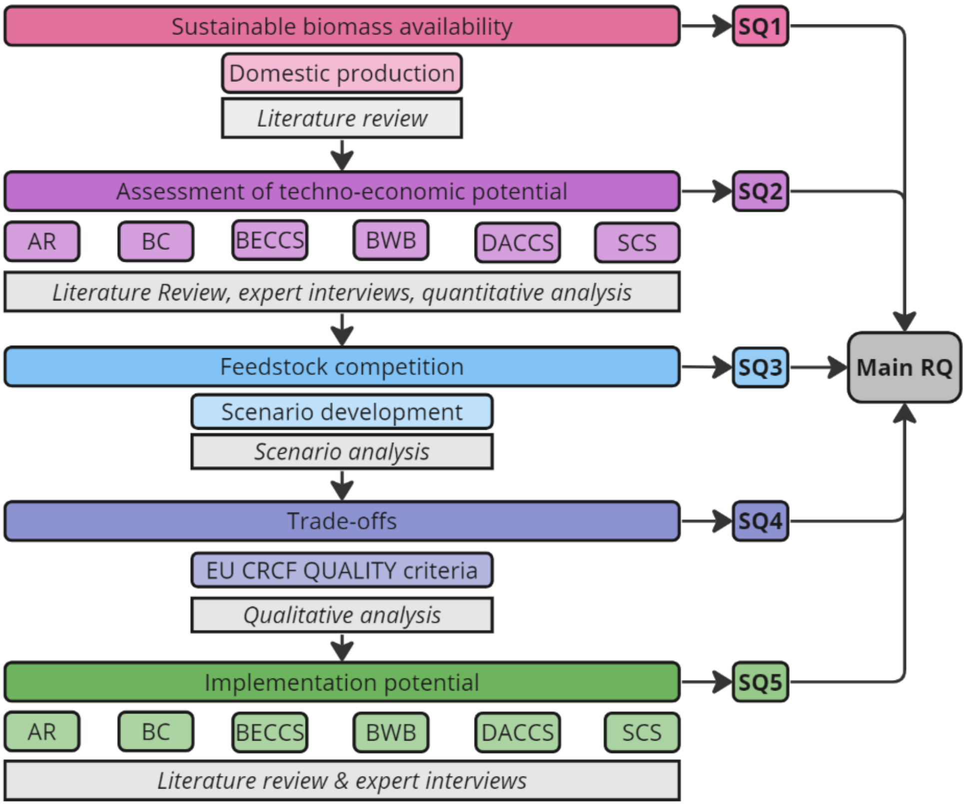


Figure 4. Overview of the research strategy. Grey boxes indicate the method used for answering the respective SQ.

3.2 SQ1: Sustainable Biomass potential

Approach

In order to determine the availability of various biomass feedstocks required for certain NETs (BC, BECCS and BWB), literature research was conducted. This data will also be used for the scenario analysis to answer SQ3. To ensure that the carbon removed through CDR activities is not offset by emissions stemming from land-use change, unsustainable residue removals or logging volumes, only the sustainable biomass potential was considered.

This thesis only considers the domestic production of biogenic feedstocks and, hence, disregards any biomass imports or exports. As this research is aimed at depicting opportunities for realising negative emissions in Austria, accounting for an increase/decrease of biomass imports/exports would go beyond the defined geographical scope and time constraints.

Data availability

The study on sustainable biomass availability in the EU from Panoutsou and Maniatis (2021) was found to be the most suitable for the purpose of this research, as it provides country-specific data for three scenarios on various degrees of feedstock mobilisation for both 2030 and 2050. Additionally, it considers different types of feedstocks from agriculture, forestry and biowaste. This allows for a more detailed assessment when determining the biomass available for each NET. The sustainability of biomass has been assessed according to the criteria determined by the Renewable Energy Directive II (RED II). Notably, the Low Mobilisation scenario can be considered as the Baseline scenario. These potentials only account for technical constraints and do not consider cost-effectiveness. The main scenario assumptions are depicted in Table 6.

Table 6. Description and main assumptions for the three scenarios on sustainable biomass availability from Panoutsou and Maniatis (2021). The scenarios differ in their degree of biomass mobilisation.

Scenario	**Key assumptions**
Scenario **1** - Low Mobilisation **(LOW)**	• Agricultural and forestry practices remain at 2020 levels • 25% of degraded, abandoned, unused land is cultivated for biomass crops • Utilising residues and wastes is the main focus for bioeconomy
Scenario **2** - Improved Mobilisation **(MEDIUM)**	• Agricultural and forestry management practices improve through e.g., agroforestry, cover crops, improved harvesting etc. • 50% of degraded, abandoned, unused land is cultivated for biomass crops • Utilising residues and wastes is the main focus for bioeconomy
Scenario **3** - Enhanced availability through R&I and improved mobilisation **(HIGH)**	• Agricultural and forestry management practices improve through e.g., agroforestry, cover crops, improved harvesting etc. • 75% of degraded, abandoned, unused land is cultivated for biomass crops • R&I helps achieve higher yields, enhanced equipment efficiency for harvesting and crops become more resilient to climate change impacts • Utilising residues and wastes is the main focus for bioeconomy

To account for the complex interactions between the forest carbon stock and timber removals, data was extracted from the CareforParis project (Ledermann et al., 2020) for determining the availability of sawn wood and industrial roundwood for two opposing scenarios. One scenario emphasises the accumulation of the forest carbon stock ('carbons stock accumulation scenario') and the other focusses on increased timber production ('shortened rotation period scenario'). In this respect, the carbon stock accumulation scenario can be considered as a low biomass mobilisation scenario, whereas the shortened rotation period scenario refers to a high biomass mobilisation scenario. Hence, due to data availability, only the low and high mobilisation scenario will be considered.

3.3 SQ2: Techno-economic potential

SQ2 was answered by conducting literature review to retrieve the required quantitative data points and by carrying out expert interviews to discuss the assumptions taken for assessing the techno-economic potentials. The approach for determining the technical potential for each NET differs due to the heterogeneous nature of the various sectors assessed. The technical potential will be assessed for 2050.

3.3.1 Afforestation and Reforestation, Forest Management

Approach

The assessment of the maximum carbon removal potential for AR/Forest Management is quite challenging to due to the complex interactions between the carbon stored in above- and below-ground (i.e., forest soils) biomass and logging volumes, changing climate conditions and several other factors. Given that learning how to model these complex interactions would have gone beyond the time constraints of this research, existing scenario data was analysed.

Data availability

Scenario data from the CareforParis project (Ledermann et al., 2020), which has been carried out by the Austrian Federal Research Centre for Forests, was used to assess the technical potential for this NET. The aim of the CareforParis project was to explore the effects of climate change and alternative forest management practices (e.g., increased logging volumes, modified tree species composition) on the carbon balance of forests up to the year 2150.

The scenario chosen to determine the technical negative emissions potential was the carbon stock accumulation scenario, as it represents the potential increase in the carbon sequestration potential of forests to contribute to climate mitigation (Ledermann et al., 2020). This was achieved by modelling an expansion of protected forest area and a consequent decrease in logging volumes. The main assumptions are shown in Table 7.

Table 7. Relevant assumptions taken in the CareforParis project for the carbon stock accumulation scenario (Ledermann et al., 2020).

Forest area	**Assumption**
National parks/biosphere parks (core zones), wilderness area Dürrenstein, Natural forest reserves	Utilisation restrictions increase from currently 1.2% to 5% of the productive forest area (by 2100).
National parks/biosphere parks (outer zones), Natura 2000	Utilisation restrictions increase from 20% (2020) to 30% (2020-2050)
Other protected areas (e.g., landscape conservation) and migration corridors	Utilisation restrictions increase from 10% (2020) to 15% (2020-2050)
All other productive forest area	Utilisation restrictions increase from 5% (2020) to 10% (2020-2050)

3.3.2 Bioenergy Carbon Capture and Storage

Approach

For the assessment of the technical BECCS potential, existing large-scale point sources for biogenic emissions were considered to allow for a technically feasible operation of CCS equipment. In this context, installations are considered large-scale when their capacities exceed 50 megawatts (MW). This threshold has been chosen due to data availability on input fuels and related emissions. In addition, the potential of collecting distributed sources (agricultural residues, food waste and livestock manure) for bioenergy production was considered. In line with the study conducted by Rosa et al. (2021), it was assumed that these feedstocks are converted to biomethane via anaerobic digestion with subsequent biogas upgrading coupled with CCS.

As elaborated in the theory section, negative emission can be achieved through bioethanol production, the cement and chemical industry, pulp and paper industry, biomass-powered thermal power plants, the steel industry and WtE plants.

Firstly, literature research was conducted to determine whether each of these industries provides a relevant source of biogenic emissions in Austria. From this review it was concluded, that the chemical and the steel industry do not constitute a viable source for negative emissions in Austria. Thus, these industries were not further considered. Negative emissions from biomethane production were determined according to Equation 1. To determine the negative emission potential the biomethane yield of the respective feedstocks needs to be considered. The CO_2 stream from the biogas upgrading process is then derived from the biomethane potential. By accounting for the CO_2 capture rate the potential for negative emissions can be determined. The potential for existing point sources was calculated according to Equation 2. The potential can be derived from the availability of biogenic emissions for each industry and the respective capture rate.

Equation 1. Negative emissions from biomethane production from distributed sources.

$$Negative\ emissions\ \left(in\ \frac{Mt\ CO_2}{year}\right) = \frac{mass\ FS * biomethane\ yield\ FS}{density\ CH_4\ * CH_4\ share\ biogas} * CO_2\ share\ biogas * density\ CO_2\ * capture\ rate * 10^{-6}$$

Equation 2. Negative emissions from existing point sources.

$$Negative\ emissions\ \left(in\ \frac{Mt\ CO_2}{year}\right) = CO_2\ emissions * biogenic\ emissions\ share * capture\ rate$$

Data availability

To assess the potential of biomethane production from distributed feedstock sources, data on biomass availability was extracted from the high mobilisation scenario (feedstock available for bioenergy) as assessed by Panoutsou and Maniatis (2021). Data on biogenic emissions from existing point sources was extracted from the European Pollutant Release and Transfer Register (E-PRTR) for the pulp & paper industry, biomass-powered thermal power plants and WtE plants (EC, 2023). For bioethanol production and the cement industry, industry reports were used. The data used for calculating the technical potential for negative emissions from distributed sources and large-scale existing point sources can be found in Table 8.

Table 8. Parameters used for determining negative emissions for existing point sources.

Parameters	**Value**	**Source**
Biomethane production		
Feedstock (FS) availability (in t)	See SQ1	Panoutsou and Maniatis (2021)
Biomethane yield manure (in t Biomethane/t FS)	0.011	(Scarlat et al., 2018)
Biomethane yield agricultural residues (in t Biomethane/t FS)	0.15	(Rosa et al., 2021)
Biomethane yield biowaste (in t Biomethane/t FS)	0.255	(Rosa et al., 2021)
Avg. share CO2 in biogas (in vol%)	40	(Rosa et al., 2021)
Capture efficiency during biogas upgrading	90%	(Baciocchi et al., 2012)
Density CO_2 (in t/m^3) [1]	0.001842	
Density CH_4 (in t/m^3) [1]	0.000668	
Bioethanol production		
Production capacity bioethanol plant (in m^3)	240,000	(AGRANA, 2010)
Density ethanol (in kg/m^3)	789	(Muhaji & Sutjahjo, 2018)
Biogenic emission factor (in t CO_2/t ethanol)	0.95	(Tanzer, Blok, & Ramírez, 2021)
Capture rate	98%	(Bains et al., 2017)
Cement industry		
Total CO_2 emissions (in Mt CO_2)	2.95	(TU Wien Science Center, 2021)
Biogenic emission share	8%	(TU Wien Science Center, 2021)
Capture rate	90%	(Onarheim et al., 2017)
Pulp and paper industry		
Total CO_2 emissions (in Mt CO_2)	3.87	E-PRTR (EC, 2023)
Capture rate	90%	(Onarheim et al., 2017)

---

[1] At Normal Temperature and Pressure (NTP)

Biogenic emission share (= emissions from process waste)	75%	(Tanzer, Blok, & Ramírez, 2021)
Thermal power plants (biomass-powered)		
Total CO_2 emissions (in Mt CO_2)	0.18	E-PRTR (EC, 2023)
Biogenic emission share	99%	E-PRTR (EC, 2023)
Capture rate	90%	(IEAGHG, 2019)
Waste-to-energy (non-hazardous)		
Total CO_2 emissions (in Mt CO_2)	1.96	E-PRTR (EC, 2023)
Biogenic emission share (= avg. biogenic waste fraction in Austrian WtE plants)	56%	(Schwarzböck, 2015)
Capture rate	90%	(Onarheim et al., 2017)

3.3.3 Biochar

Approach

Considering that this report aims to determine the maximum biochar potential, we assume that biochar is produced via slow pyrolysis due to the relatively high biochar output as compared to fast pyrolysis (Libra et al., 2011). The total cumulative potential for negative emissions from the direct application of biochar to agricultural soils was calculated as depicted in Equation 3. This potential is based on the maximum application rate of BC to the total agricultural area in Austria. To determine carbon removals, the average carbon content of biochar is used and. Furthermore, the partial decay or mineralisation of BC in soils is accounted for. The potential for the year 2050 is constrained by biomass availability. Thus, Equation 4 was used to assess the maximum BC production potential per year from all biomass, that is domestically available for bioenergy production (under consideration of sustainability constraints) and technically suitable for BC production.

Equation 3. Cumulative potential from biochar amendment to agricultural soils.

$$
\begin{aligned}
Negative\ emissions\ \left(in\ \frac{Mt\ CO_{2-eq}}{year}\right) \\
&= Agricultural\ area * BC\ application\ rate * carbon\ content\ BC \\
&\quad * (1 - BC\ decomposition\ factor) * CO_2\ conversion\ factor
\end{aligned}
$$

Equation 4. Negative emissions from biochar production under consideration of the availability of suitable, sustainable biomass for bioenergy production in Austria.

$$
\begin{aligned}
Negative\ emissions\ \left(in\ \frac{Mt\ CO_{2-eq}}{year}\right) \\
&= Mass\ FS * carbon\ content\ FS\ * recovered\ biomass\ carbon\ in\ BC\ * (1 - BC\ decomposition\ factor) \\
&\quad * CO_2\ conversion\ factor
\end{aligned}
$$

Data availability

The BC decomposition rate depends on several factors such as the feedstock used, type of soil applied to or pyrolysis process (Wang et al., 2016). It has been shown that the decomposition rate is highest in the period shortly after BC application. Around 97% of the amended BC is assumed to persist in soils for more than a century. Hence, for this study a decay of 3% of the biochar carbon will be considered in the potential. Table 9 depicts the data used for calculating the potential.

Table 9. Parameters used for determining negative emissions for BC deployment.

Parameters	**Value**	**Source**
Feedstock availability (=biomass from all FS categories, excl. sawnwood, from high mobilisation scenario available for bioenergy)	See SQ1	(Panoutsou & Maniatis, 2021)
Carbon content FS	See Table 23	To be found in Table 23

Average biochar yield per dry weight initial biomass (Slow pyrolysis)	35%	(Libra et al., 2011)
Carbon recovered in biochar from initial biomass carbon	50%	(Bruckman & Klinglmüller, 2014; Lehmann et al., 2021)
Avg. carbon content BC	75%	(Schmidt et al., 2020)
Max. BC application rate (in t BC/ha)	50 t/ha	(Jeffery et al., 2011; Tisserant & Cherubini, 2019)
Total agricultural area in Austria (in Mha)	2.66 Mha	(Soja et al., 2021)
BC decomposition factor over 100 years	3%	(Wang et al., 2016)
C to CO_2 conversion factor	3.67	

3.3.4 Building with Biomass

Approach

To determine the technical potential for BWB, literature research and expert interviews were conducted. The expert interview (A. Teischinger, personal communication, April 26th 2023) helped with assessing the maximum wood construction share that can be deemed technically feasible. Depending on the wood construction share, a certain amount of sawn wood is needed. In this context, a building is considered as a wood construction if more than 50% of the building's load bearing structure is made of wood or wood-based materials (Stingl et al., 2011). With this information the technical potential can be calculated as depicted in Equation 5.

Equation 5. Negative emissions from BWB.

$$Negative\ emissions\ \left(in\ \frac{Mt\ CO_{2-eq}}{year}\right) = Sawn\ wood\ required\ for\ WCS\ of\ 44\% * CO_{2-eq}\ stored\ in\ HWP * 10^{-3}$$

Data availability

The data used for determining the technical potential for BWB is shown in Table 10.

Table 10. Parameters used for determining negative emissions from BWB.

Parameters	**Value**	**Source**
Current wood construction share	22%	(Stingl et al., 2011)
Max. wood construction share considering technical constraints	44%	(A. Teischinger, personal communication, April 26th 2023)
$CO_{2\text{-eq}}$ stored in $1m^3$ Harvested wood products (HWP)	752 kg	(Robertson et al., 2012)
Sawn wood required for WCS of 44%	3.1 Mm^3	(Stingl et al., 2011)

3.3.5 Direct Air Carbon Capture and Storage

Approach

To determine the negative emission potential for DACCS in Austria, literature research was conducted. The primary factors considered were the availability of sufficient energy to supply the relatively high energy requirements of DACCS facilities and the availability of geological storage sites.

Data availability

To assess the required energy needed for capturing 1 Mt CO_2 via DACCS, a study by McQueen et al. (2021) was used. The required energy was compared against the current low carbon energy production in Austria, as reported in Austria's National Inventory report, to evaluate the availability of sufficient renewable energy (Anderl et al., 2022).

3.3.6 Soil Carbon Sequestration

Approach

To determine the negative emission potential from SCS, it was evaluated how enhanced soil management practices can increase SOC. Given the complexity of modelling SOC changes, data was extracted from existing research.

Data availability

Roe et al. (2021) have estimated the potential for SCS by applying enhanced management practices for both grassland and arable land (i.e., croplands), which both falls under the category of agricultural land. To determine the potential for SCS in croplands, it was assumed that a shift from conventional management practices to no-till management occurs. Additionally, an increase in carbon inputs is modelled by applying cover cropping. In respect to SOC changes for grasslands, it was assumed that the grazing pressure was reduced in conventionally managed pastures. The management of degraded rangelands was improved from current management practices to nominally managed.

3.3.7 Economic assessment

Approach

Given the time constraints of this thesis, costs will be assessed via literature review rather than by conducting a cost assessment particularly for the Austrian context. To allow for the consideration of a large number of cost estimates, a comprehensive academic review was used as the first point of reference. To narrow down large global cost ranges, the most applicable source for the methodological context and geographical scope of this thesis will be used. In addition, cost estimates will be discussed with experts where feasible. Estimates indicated in USD have been converted to EUR at the current (3.7.2023) exchange rate of 0.92 USD/EUR. Hence, the cost estimates are based on current price estimates and do not account for potential cost reductions to be made in the future, except when indicated otherwise.

This thesis only considers the additional costs arising for achieving negative emissions which will be referred to as abatement costs. Both explicit (i.e., direct costs for e.g., the installation of CCS equipment) and implicit costs (i.e., opportunity costs in respect to e.g., a loss of profits due to a decrease in logging volumes) are considered. Thus, this definition does not comprise costs incurred during the normal operation of a bioenergy plant or expenses related to biomass cultivation. Minimum and maximum costs will be provided where available; however, the techno-economic potential will be based on the average of the cost range.

To assess the cost-effectiveness of the technical potentials, a carbon price scenario of 100€ per tonne $CO_{2\text{-eq}}$ was chosen, as it reflects the middle of the range for carbon prices in 2030 and the lower bound of the range for 2050 when looking at IPCC 1.5°C pathways (Rogelj, Popp, et al., 2018; Rogelj, Shindell, et al., 2018). This is in line with the temporal scope of this thesis.

Data availability

The review used was conducted by Fuss et al. (2018). The study provides a comprehensive overview of the costs identified for each NET from numerous studies. A more applicable estimated was used for AR/Forest Management from (Pfemeter et al., 2023). For BECCS a detailed cost assessment for each industrial process discussed in this thesis was conducted by the Global CCS Institute (Kearns et al., 2021). To determine the costs for capturing CO_2 they assumed solvent-based capture process using Monoethanolamine (MEA), as the process has been proven to be commercially available and suitable for a variety of industrial applications. It was assumed that CO_2 will be transported via pipeline as it represents the most established transport mode for large volumes. Costs for establishing a CO_2 pipeline network have been disregarded. CO_2 was assumed to be stored in geological formations given its high TRL level (9) and the permanence of storage.

For BC a more detailed cost assessment was found in a study conducted by the Bruckmann and Klinglmüller (2014). For BWB the cost estimate was taken from Bey et al. (2021) and was discussed with an expert (G. Rappold, personal communication, May 16th 2023). For DACCS cost estimates were assumed from Fuss et al. (2018). Estimates for SCS were derived from Born and Schijndel (2018).

3.4 SQ3: Feedstock competition

Approach

Given that the techno-economic potential did not account for feedstock competition, it was important to identify whether there were any bottlenecks arising due to limited sustainable feedstock availability. To determine potential constraints, three scenarios were developed, each focusing on a different NET or combination of NETs. An overview of these scenarios and the main assumptions taken are depicted in Table 11. Notably, these results will be used to qualitatively discuss the feasibility of implementation for each NET. However, due to limited data availability on current feedstock utilisation, it is not possible to quantitatively determine how feedstock competition will influence the implementation of the respective NETs.

Table 11. Overview of the 3 chosen scenarios, their respective strategies and main assumptions taken.

Scenario	**Strategy**	**Description**
1	Carbon removals through carbon farming and BC amendment	• Emphasis is put on maximising the carbon sink in soils (through both BC and SCS) and in forests through forest management. • This goes in hand with an expansion of the protected forest area and a consequent decrease in logging volumes. All technically suitable feedstock is allocated to BC production leading to a considerable decrease in BECCS deployment.
2	Carbon removals through timber construction	• The focus is set on maximising carbon dioxide removals through material utilisation, i.e., BWB. • Increased timber utilisation goes in hand with an increase in logging volumes.
3	Carbon removals through BECCS	• This scenario emphasises the generation of bioenergy coupled with a widespread installation of CCS. • Logging volumes are increased as compared to scenario 1 to increase the availability of industrial roundwood for energetic utilisation.

To assess the total negative emission potential with varying emphasis on NETs under the constraint of limited biomass availability, it was first necessary to determine the carbon content and fixed carbon content of the various feedstocks analysed. This data was collected through literature research. For some feedstock categories, a representative feedstock was chosen, if there was no data available for the feedstock category as a whole. In the case that the source indicated a range, the average was used.

With this data negative emissions can be calculated for each feedstock category. Equation 1 (Anaerobic digestion, BECCS), Equation 4 (Pyrolysis, Biochar), Equation 5 (BWB), Equation 6 (Fermentation, BECCS) and Equation 7 (Combustion, BECCS) show the conversion route for arriving at the potentials. Equation 6 is based on the occurrence of a near-pure CO_2 stream from the fermentation process which allows for the capture of a certain share of biomass carbon (Fajardy et al., 2019). Biogenic emissions from biomass combustion are derived from the carbon content of the biomass under the assumption of a complete combustion process (Motghare et al., 2016).

The respective values for the parameters can be found in Table 13. Notably, these conversion processes are more complex in practice, but the equations shown below provide sufficient accuracy for the purpose of this thesis. The equation for calculating negative emissions from existing points sources differs from Equation 2. This is because here the potential is based on feedstocks for the purpose of the scenario analysis, whereas for the technical potential assessment the estimate is derived from the biogenic emissions from each industry.

Equation 6. Conversion route for fermentation (BECCS).

$$\begin{aligned} Negative\ emissions\ \left(in\ \frac{Mt\ CO_2}{year}\right) &= Mass\ FS * carbon\ content\ FS\ * share\ of\ biomass\ carbon\ released\ during\ fermentation \\ &* CO_2\ conversion\ factor * capture\ rate \end{aligned}$$

Equation 7. Conversion route for combustion (BECCS).

$$Negative\ emissions\ \left(in\ \frac{Mt\ CO_2}{year}\right) = Mass\ FS\ * carbon\ content\ FS * CO_2\ conversion\ factor *\ capture\ rate$$

As compared to the technical potentials determined for BECCS in SQ2, the scenarios do not distinguish between various bioenergy sectors (e.g., WtE, pulp and paper, thermal power plants fired by biomass, etc.). Hence, only a total estimate for the BECCS potential based on relevant conversion routes is provided. The main constraint influencing these potentials is sustainable feedstock availability. The scenarios neither consider economic factors nor constraints arising due to implementation bottlenecks.

Lastly, deriving from the NET focus defined for each scenario, specific assumptions were taken on feedstock allocation. For BECCS, three conversion pathways were considered, i.e., combustion, anaerobic digestion and fermentation. Feedstocks were allocated to the most technically suitable conversion pathway based on feedstock characteristics such as moisture or lignin content. In the case that a feedstock category comprises feedstocks with varying characteristics which makes them suitable for different conversion pathways, the available biomass per feedstock category was distributed equally among all suitable conversion pathways. The assumptions for each scenario are shown in Table 12. Based on all these assumptions, the negative emission potentials for each scenario were determined.

The scenario analysis will be conducted in three runs. The first run will be carried out considering biomass availability as the only constraint. The second run will account for both biomass availability and technical limitations. That means that the technical potentials calculated in SQ2 are set as constraints in the scenarios. This results in a reduced utilisation of the available feedstock. Thus, in the third scenario any unused feedstock, which is available for bioenergy, will be reallocated from BECCS to BC and vice versa. For example, in run 2 and 3 the BECCS potential is constrained by the technical potential determined in SQ2. Thus, feedstocks originally allocated to BECCS could be left unused in run 2, if the potential from run 1, which is solely limited by biomass availability, exceeds the technical potential.

Notably, agricultural residue removals influence SOC and, hence, the negative emission potential for SCS. However, there has been little research so far on the extent of this impact. Given the complexity of modelling this interaction and the time constraints of this thesis, it will be assumed that the impact from sustainable residue removals on SCS is negligible.

Table 12. Assumptions taken on feedstock allocation for each scenario and conversion technology based on technical suitability and scenario assumptions.

Feedstock allocation	**% of total biomass available for each conversion process**														
Scenario	**Scenario 1**					**Scenario 2**					**Scenario 3**				
Conversion process	Combustion	Pyrolysis	AD	Fermentation	Timber construction	Combustion	Pyrolysis	AD	Fermentation	Timber construction	Combustion	Pyrolysis	AD	Fermentation	Timber construction
Agriculture															
Cereal straw	0%	100%	0%	0%	0%	0%	50%	50%	0%	0%	0%	0%	100%	0%	0%
Maize stover	0%	100%	0%	0%	0%	0%	50%	50%	0%	0%	0%	0%	100%	0%	0%
Oil crop field residues	0%	100%	0%	0%	0%	0%	50%	50%	0%	0%	0%	0%	100%	0%	0%
Agricultural prunnings	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Manure	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%
2nd agricultural residues	0%	100%	0%	0%	0%	0%	50%	25%	25%	0%	0%	0%	50%	50%	0%
Lignocellulosic crops	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Forestry															
Sawn wood	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%
Industrial roundwood (for bioenergy)	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Primary forest residues	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Sec. Forest residues & PCW	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Biowaste															
Paper cardboard	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Wood waste	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Animal & mixed food waste	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%
Vegetal waste	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%
MSW	0%	100%	0%	0%	0%	50%	50%	0%	0%	0%	100%	0%	0%	0%	0%
Other assumptions	• Stock accumulation scenario from CareforParis project used for sawn wood + industrial roundwood availability (this scenario was chosen as it allows for the highest negative emissions in forests)					• Shortened rotation period scenario from CareforParis project used for sawn wood + industrial wood availability (this scenario was chosen as it provides the highest sawn wood supply)					• Shortened rotation period scenario from CareforParis project used for sawn wood + industrial wood availability (this scenario was chosen as it provides the highest wood supply for bioenergy)				

Data availability

Data on the biomass carbon content can be found in Table 23 with the respective sources. Data on feedstock availability was taken from the results from SQ1 (HIGH Mobilisation scenario, feedstock potential for bioenergy for 2050). The technical suitability for each conversion process was based on the results from the S2BIOM project (Vijs et al., 2015). The parameters used for determining negative emissions from bioethanol production and combustion related BECCS processes can be found in Table 13.

Table 13. Parameters used for Equation 6 and 7.

Parameters	**Value**	**Source**
Biomass availability	See SQ1	(Panoutsou and Maniatis, 2021; Ledermann et al., 2020)
Carbon content of each FS	See Table 23	See Table 23
Capture rate combustion	90%	(IEAGHG, 2019)
Carbon released during fermentation	15%	(Fajardy et al., 2019)
Capture rate fermentation	98%	(Bains et al., 2017)

3.5 SQ4: Trade-offs: QUALITY criteria

Approach

To allow for a comprehensive assessment of the various NETs analysed, it is important to discuss potential trade-offs resulting from the implementation of the NETs. CDR activities in the EU will have to comply with the EU CRCF to be officially certified as negative emissions, once the legislation is adopted. Thus, a Multi-Criteria Analysis (MCA) was conducted with the goal of determining the compatibility of the analysed NETs with the criteria defined in the CRCF as well as to assess potential trade-offs in regard to for example permanence or sustainability (Proposal for a Regulation on an EU Certification for Carbon Removals, 2022). The alternative options to be assessed include the NETs discussed in this thesis. Each NET will be evaluated according to the scoring criteria indicated in Table 14. This will be done through literature research. The various options will not be weighted, as this would require the consultation of an expert panel, which would go beyond the scope and time constraints of this thesis.

These findings do not directly impact the implementation potential. However, these results provide a comprehensive picture of the side-effects associated with the implementation of each NET. In addition, they reveal possible difficulties that could arise in respect to the certification for each NET. In this regard, this results can help guide the discussion on which NETs are most feasible to implement in the Austrian context.

Table 14. MCA Scoring criteria for each criterion defined by the EU CRCF.

CRCF Criteria	**MCA Score**	**Scoring Criteria**
Quantification	1	The mitigation benefit of the NET is easy to measure and unambiguous.
	2	The measurement of the mitigation benefit can be challenging due to e.g. technical, logistical or financial reasons. The mitigation benefit can be unambiguously stated.
	3	The measurement of the mitigation benefit is highly complex and requires substantial financial and technical capabilities and/or the mitigation benefit cannot be unambiguously determined.

Additionality	1	The implementation of the CDR activity cannot be carried out without an additional incentive provided by the regulation. The activity goes beyond compliance with existing practices and regulation.
	2	It can not be unambigously determined whether the CDR activity is carried out due to an additional incentive provided. The activity goes beyond compliance with existing practices and regulation.
	3	The CDR activity could have been implemented without an additional incentive provided. It does not go beyond compliance with existing practices and regulations.
Long-term storage	1	The nature of the NET ensures a permanent storage of carbon dioxide. Risks associated with the release of carbon dioxide are minimal and easy to monitor.
	2	The NET allows for a long term carbon storage. There are certain risks for carbon leakage associated with its implementation but these are easy to monitor.
	3	The implementation of the NET does not guarantee long term carbon storage. There are considerable risk associated with the release of carbon dioxide from the storage and/or these risks are difficult to monitor.
Sustainabil**ity**	1	The implementation of the CDR produces co-benefits for other environmental objectives. There are no environmental risks associated with its implementation.
	2	There are neither imminent nor long-term negative environmental impacts resulting from the implementation of the CDR activity.
	3	The CDR activity leads to imminent and/or could cause long-term adverse environmental impacts.

Data availability

Relevant data to determine the score for all NETs for each CRCF criteria was found in various academic papers as well as through the discussion with experts. As the main point of reference a literature review by Fuss et al. (2018) was used.

3.6 SQ5: Implementation potential

Approach

The implementation potential is part of the techno-economic potential. In addition, it considers the following factors: technological maturity, scalability (i.e., market growth restrictions), the availability of required infrastructure and feedstock competition between NETs. The potential will be determined for both 2030 and 2050. The potential will be based on literature research as well as data from previous SQs.

To provide an estimate on the cumulative implementation potential for each NET, a rough assessment was conducted. The cumulative potential is calculated for the period between 2023 and 2050. For BECCS industries where the implementation potential for 2030 was evaluated at 0, but the full techno-economic potential is to be realised by 2050, it was assumed that the installation of CCS was done gradually in equally distributed time steps across the time period between 2031 and 2050. Thus, if there are 10 bioenergy plants in an industry to install CCS at, every second year between 2023 and 2050 another plant would be equipped with CCS. For BC deployment, the implementation potential was not considered as the cost-effective potential is 0. The potential for BWB is based on the same assumption, as the yearly implementation potential for 2030 was calculated (i.e., an annual increase of the WCS of 1%). The cumulative potential for AR/Forest Management and SCS can be retrieved from the scenario literature.

Data availability

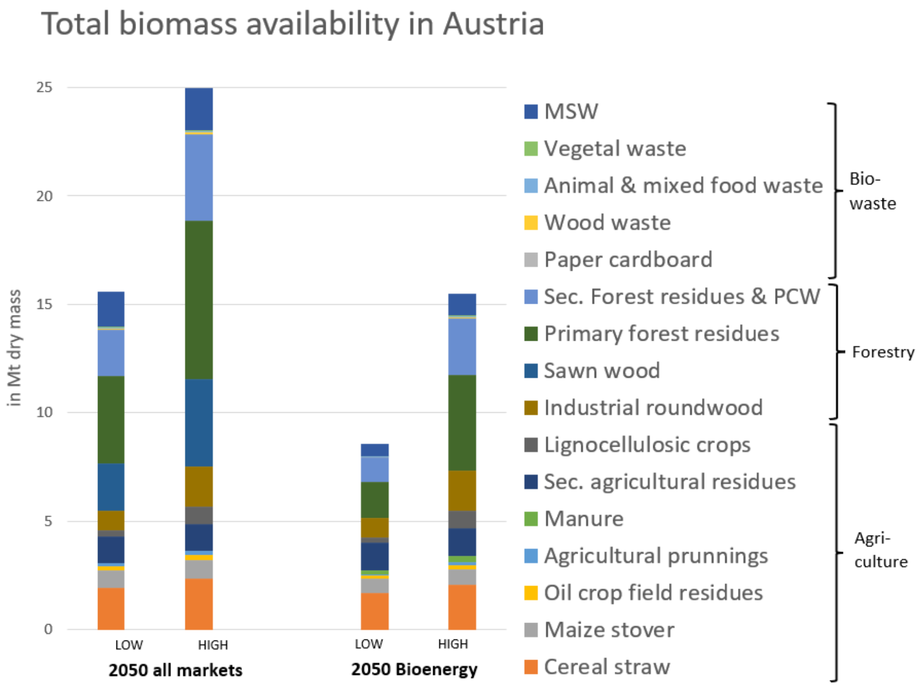
Data on the TRL for each NET is based on Bey et al. (2021); Kampman et al. (2023); Smith et al. (2023). To determine the scalability of NET deployment, industry data was used as well as the literature review from (Jackson et al., 2017).

4. BIOMASS AVAILABILITY

This section provides an overview of the sustainable biomass potential available in Austria. It presents the results for SQ1. Notably, the estimated potential is characterised as a technical potential and, hence, economic constraints are not accounted for. The potential is categorised by its source, i.e., agriculture, forestry and biowaste. Potentials are indicated for 2050, as well as for 'all markets' and specifically for 'bioenergy'. The difference between the 'all markets' and 'bioenergy' potential stems from deducting the demand for material use of each feedstock category from the total estimate under BSL projections of material demand. A detailed description of the various feedstocks adhering to each feedstock category can be found in Appendix I (Chapter 11).

Figure 5 provides an overview of the total availability of domestic, sustainable biomass for a low and high mobilisation scenario as calculated by Panoutsou and Maniatis (2021). The potential for timber (i.e., sawn wood and industrial roundwood) is based on Ledermann et al. (2020).

Figure 5. Total sustainable biomass potential for a low and high mobilisation scenario.

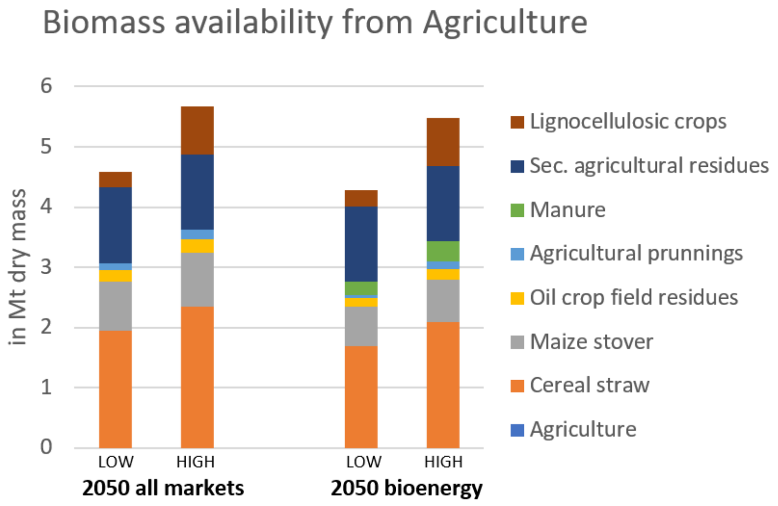


4.1 Agriculture

The potential for sustainable biomass from agriculture is presented in Figure 6 and includes (Panoutsou & Maniatis, 2021):

- Field crop residues
- Agricultural prunings
- Manure
- Secondary residues from agro-industries
- Lignocellulosic crops (only grown on unused, abandoned and degraded land).

Figure 6. Sustainable biomass potential from Agriculture for a low and high mobilisation scenario.[2]

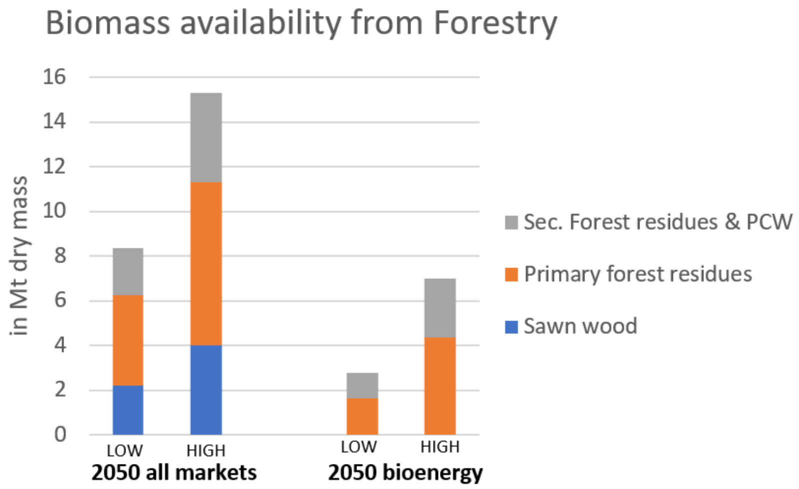


4.2 Forestry

The potential for biomass from forestry is shown in Figure 7. It has been categorised into (Ledermann et al., 2020; Panoutsou & Maniatis, 2021):

- Sawnwood (only available for material use)
- Industrial roundwood
- Primary forest residues
- Secondary forest residues & Post Consumer Wood (PCW).

Figure 7. Sustainable biomass potential from Forestry for a high and low mobilisation scenario.



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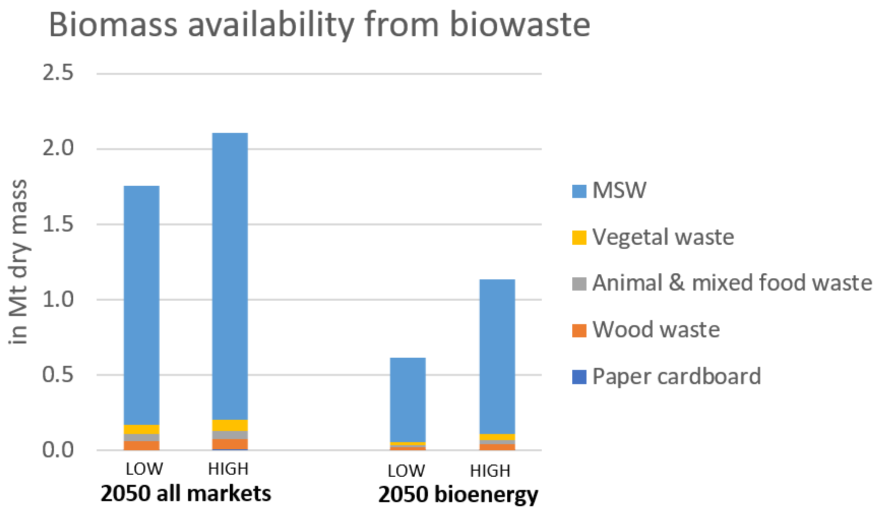
[2] The estimate for secondary agricultural residues has been adjusted according to a study undertaken by the Austrian Environmental Agency (Reisinger et al., 2012). This was done, because the estimate provided by Panoutsou and Maniatis (2021) was unreasonably high as compared to the estimate provided by Reisinger et al. (2012) (higher by a factor of 10) and as compared to estimates for other EU countries from the same study. For example, for the low mobilisation scenario for 2030 (all markets) Austria was estimated to produce 4.79 t of secondary agricultural residues per ha agricultural land, as compared to Italy and Germany with only 0.27 and 0.22t/ha. No response was received when contacting the authors of the study. Thus, the estimate provided for this feedstock category should be treated with care, as it is based on different assumptions than were taken for the other feedstock categories. Most importantly, it is based on data from 2012 and was not adjusted for different mobilisation scenarios for 2030 and 2050.

4.3 Biowaste

The potential for biowaste is depicted in Figure 8 and includes (Panoutsou & Maniatis, 2021):

- MSW
- Vegetal waste
- Animal & mixed food waste (incl. animal fats)
- Wood waste
- Paper and cardboard.

Figure 8. Sustainable biomass potential from biowaste for each scenario.



5. TECHNO-ECONOMIC POTENTIAL

This section presents the assessment of both the technical and techno-economic potential for NETs in Austria. It provides the results for SQ2. Firstly, the main assumptions for assessing each potential will be repeated. Secondly, the respective abatement cost estimates from various sources will be discussed and evaluated.

5.1 Afforestation & Reforestation, Forest management

5.1.1 Technical potential

Forests make up approximately 48% of the total land area in Austria amounting to 4,015,000 hectares in 2023 (Lackner et al., 2023). The forest area has experienced a steady gradual increase over the past decade and is expected to continue growing in the future, albeit at a slower pace. The main increments can be found in the mountainous regions of western Austria. Only a small portion has been actively afforested, as most of the growth takes place on formerly cultivated agricultural land, including alpine pastures, through natural seed dispersal (Rappold et al., 2006).

Forests are an important contributor for climate change mitigation (Lackner et al., 2023). The annual forest increment is larger than the removal, resulting in a steady timber stock increase amounting to a new maximum of 1.18 billion m^3 in 2023. Currently 89% of the annual timber increment is being harvested. Around a third of the forest area (42%) is characterised as protection forest with use restrictions.

The harvested timber follows three main utilization pathways (Lackner et al., 2023). The first pathway involves processing the timber at sawmills and further transforming it into high-value wood products. The second pathway focuses on utilising the timber as a material in the paper and board industry. The third pathway involves directly using the timber for energy purposes.

The Austrian Forest Research Institute (Bundesforstwirtschaftsinstitut) has created various scenarios to depict the potential future development of the forest carbon sink in their *CareForParis* project (Ledermann et al., 2020). One scenario aims to illustrate the potential increase of the forest carbon sink by expanding the protected forest area. This expansion would result in a decrease in timber removals and an increase in the forest carbon stock. This scenario, however, does not account for a further expansion of forest area. As discussed with the *CareForParis* project lead, this constraint primarily arises from limitations inherent to the modelling software used (T. Ledermann, personal communication, May 3rd 2023). More importantly, it can be justified with the fact that the potential for forest expansion is severely limited, as forests already cover approximately half of Austria’s land area and due to the prevailing competition between agriculture and forestry (T. Ledermann, personal communication, May 3rd 2023).

Considering the restricted potential for forest expansion in Austria, the main opportunity for achieving negative emissions from AR/Forest Management lies in expanding the protected forest area and imposing further utilisation restrictions. This would result in a decrease in logging volumes and, consequently, an increase in the forest carbon sink. Thus, the stock increase scenario modelled in the CareforParis project represents the maximum potential for realising negative emissions in Austria’s forests (Ledermann et al., 2020). This leads to a technical potential of **19.44 Mt $CO_{2\text{-eq}}$** for **2050** through forest management.

5.1.2 Abatement costs

The cost estimates provided by Fuss et al. (2018) refer to forest expansion through either afforestation or reforestation and are, thus, not applicable to the potential estimated in this thesis, which is based on a change in management practises. The expansion of the protected forest area with utilization restrictions does not incur any explicit (i.e., direct) costs. The opportunity costs for not utilising a certain timber stock from forests were estimated by assessing the average obtainable price for the whole tree biomass from a spruce tree. Spruce represents the most dominant tree species (Lackner et al., 2023). Considering both material and energetic utilisation, Pfemeter et al. (2023) calculated a price of 0.28€ per kg C from tree biomass, which corresponds to **76.3€ per tonne $CO_{2\text{-eq}}$**. Thus, the full technical potential can be considered cost-effective at a carbon price of 100€ per tonne CO_2.

5.2 Bioenergy Carbon Capture and Storage

5.2.1 Technical potential

Biomethane production

By upgrading biogas to biomethane negative emissions can be achieved. Deriving from the assumptions discussed in the methods section, the total potential for negative emissions from biomethane production from distributed sources amounts to **1.08 Mt CO_2 for 2050**. The distributed sources analysed include agricultural residues (both primary and secondary), food waste and manure with potentials amounting to 1.05 Mt CO_2, 0.006 Mt CO_2 0.03 Mt CO_2, respectively. Food waste refers to both vegetal waste and animal & mixed food waste as categorised by Panoutsou and Maniatis (2021). This negative emission potential corresponds to a biomethane production volume of 941 million Nm^3.

Bioethanol Production

Biomass used for bioethanol production conventionally stems from food crop cultivation, including maize, sugarcane or other starchy food crops (Tanzer, Blok, & Ramírez, 2021). A more sustainable option would be to utilise cellulosic biomass (e.g., coppice wood or grasses) or biogenic wastes from agriculture. Austria has one large-scale bioethanol plant in operation (Österreichischer Biomasseverband, 2021). There are also 9 biodiesel plants and several vegetable oil installations, but these are all small-scale and thus do not constitute a feasible BECCS option. In Austria, bioethanol is currently produced through the fermentation of corn (49%), wheat (28%), starch sludge (16%) and triticale (4%). However, there is sufficient sustainable biomass available to substitute the currently used food crops. At the plant's maximum production capacity, biogenic emissions amount to 0.18 Mt CO_2. With a capture efficiency of 98% the technical potential amounts to **0.18 Mt CO_2 for 2050.**

Cement Production

In Austria, biogenic CO_2 emissions already account for 8% of total emissions from cement production which is close to the maximum (10%) as estimated by Yang et al. (2021). It is not expected that the uptake of biogenic fuels will considerably increase in the future as stated by the CEO of the Austrian cement industry association (S. Spaun, personal communication, April 13th 2023). Hence, this leads to a technical potential of **0.21 Mt CO_2 for 2050** after accounting for a capture rate of 90%.

Chemical Industry

As explained in the theory section, negative emissions can be achieved in the chemical industry when substituting conventional fuels with bio-based alternatives (i.e., through biomass gasification) to generate the high-temperature heat needed for e.g., steam reforming or cracking processes to produce bulk chemicals (Tanzer, Blok, & Ramirez, 2021). However, the production of bulk chemicals constitutes a minor branch in the Austrian industry. The only key source for CO_2 emissions in chemicals production, as classified by the National Inventory Report, results from Ammonia production (Anderl et al., 2022). All other branches either primarily emit non-CO_2 GHGs (mainly CH_4) or do not constitute key emission sources and are, thus, not further considered. Notably, CH_4 could also be captured, but the focus of this thesis was confined to CO_2. All CO_2 emissions from ammonia production stem from natural gas use. The currently most promising route to sustainable ammonia production lies in the synthesis of nitrogen and hydrogen (Ornes, 2021). Hydrogen could be produced via biomass gasification and subsequent syngas conditioning. However, despite some recent innovations and breakthroughs there are still considerable challenges involved in making these processes feasible on a large-scale from a technical and economic perspective. The major challenges revolve around the biomass gasification technology and the required syngas conditioning to produce ammonia (Sansaniwal et al., 2017). Considering these technical barriers and the lack of an existing biogenic point source, the technical potential for the chemical industry is considered to amount to **0 Mt CO_2** from a current perspective.

Pulp and Paper

To realise negative emissions in the pulp and paper industry, the biogenic emissions from the combustion of process wastes can be captured. These account for roughly 75% of total emissions (Tanzer, Blok, & Ramírez, 2021). With a capture rate of 90% this leads to a negative emission potential of **2.61 Mt CO_2 for 2050**.

Steelmaking

Applying BECCS at blast furnaces for steel production is only considered by a few studies (Tanzer, Blok, & Ramírez, 2021). The achievement of negative emissions is deemed unlikely, though, due to considerable emissions from charcoal production. Another option could be to utilise biogenic reducing gas for the direct reduction of iron (DRI) steelmaking process. Considering that steel is produced through the Blast Furnace – Basic Oxygen Furnace process (BF/BOF) in Austria, this does not prove to be a viable option. The so-called HIsarna process presents a green steelmaking route (Griffin & Hammond, 2021). This process is still under development but could technically allow for negative emissions due to its fuel flexibility. However, Austria’s steelmaking industry aims to decarbonise its production through pursuing the hydrogen-direct reduction (H-DR) route, which does not allow for BECCS (Held, 2019). Hence, steelmaking is not considered as a viable option for BECCS in this study and the potential amounts to **0 Mt CO_2 by 2050**.

Thermal Power Plants

In Austria, as of 2020 all coal-fired power plants have been shut down (Umweltbundesamt, 2023). Consequently, there is no potential by switching from coal-fired power plants to biomass-powered ones. However, there is one large-scale thermal power plant in Vienna primarily powered by biomass (EC, 2023). By capturing these biogenic emissions a technical potential of **0.16 Mt CO_2** for 2050 can be achieved at a capture rate of 90% (IEAGHG, 2019).

Waste to energy

A few WtE plants represent large-scale point sources for biogenic emissions in Austria (EC, 2023). By capturing these biogenic emissions resulting from the combustion of biogenic waste, negative emissions can be achieved. At a capture rate of 90%, the technical potential can be estimated at roughly **0.98 CO_2 for 2050**.

Total technical potential across all industries

Adding up the potential from all relevant industries, the total BECCS potential amounts to **5.22 Mt CO_2 for 2050**. Table 15 provides an overview.

Table 15. Overview of BECCS potential across all industries.

Industry	**Technical potential (in Mt CO_2)**
Anaerobic digestion	1.08
Bioethanol production	0.18
Chemicals	0
Cement production	0.21
Pulp and paper	2.61
Steelmaking	0
Thermal power plants	0.16
Waste to energy	0.98
Total	**5.22**

5.2.2 Abatement costs

Fuss et al. (2018) report a cost range for BECCS between 14 and 368€ per tonne CO_2. The costs vary significantly depending on the source for CO_2 capture. For ethanol fermentation costs have been reported at 18 to 161€ per tonne CO_2, whereas for CO_2 sources from combustion BECCS costs have been estimated at between 81 and 265€ per tonne CO_2. Given that these large cost ranges are all dependent on various assumptions such as transport distance or capture technology, a study that provides a comprehensive assessment across relevant BECCS industries was used to improve comparability (Kearns et al., 2021).

The costs for BECCS can be categorised into (Kearns et al., 2021):

1. Costs for capturing CO_2, which requires the purification of CO_2 from a gas stream to around 95 vol% purity;
2. Costs for dehydration and compression or liquefaction of CO_2, which also depends on the transport method;
3. Costs for transporting CO_2, which can be done via pipeline, ship or truck;
4. Costs for CO_2 injection, storage (and potentially for monitoring and verification).

The costs for each industry are depicted in Table 16. The ranges reported here stem from differences in capture capacity and transport distance (Kearns et al., 2021). Notably, these cost estimates account for the opportunity costs arising from a decrease in the plant's bioenergy production. This is done by assigning a price to the energy required for capturing the CO_2.

Table 16. Abatement costs for each BECCS sector split into the various cost categories. Minimum and maximum values are reported.

Costs (in €/ton CO_2)	**Capture costs**		**Dehydration & compression**		**Transport costs**		**Injection & storage**		**Total**		
Industry	Min	Max	Min	Max	Min	Max	Min	Max	Min	Avg.	Max
Anaerobic digestion	0	9	11	21	2	22	2	9	**15**	**38**	**61**
Bioethanol	0	9							**15**	**38**	**61**
Cement	46	59							**61**	**86**	**111**
Pulp and paper	48	68							**63**	**92**	**120**
Thermal power plants	55	75							**70**	**99**	**127**
Waste to energy	55	75							**70**	**99**	**127**

Hence, based on the average cost estimates the full technical potential for all industries can be realised cost-effectively at a carbon price of 100€ per tonne CO_2.

5.3 Biochar

5.3.1 Technical potential

Common assumptions for BC application rates range between within 20 and 50 t BC per hectare (Tisserant & Cherubini, 2019). Even higher application rates up to 170t BC per hectare have been used in some studies that estimate negative emission potentials (Jeffery et al., 2011; Lenton, 2010). However, in temperate climate regions application rates above 50t BC per hectare were reported to reduce yields (Jeffery et al., 2011). Thus, 50t BC per hectare should be considered the maximum.

By incorporating a maximum of 50 tonnes of BC per hectare of agriculturally managed soil in Austria (2.66 Mha), the total cumulative potential reaches 355 Mt CO_2. The maximum technical potential to be achieved on a yearly basis must account for biomass availability constraints. Thus, the technical potential amounts to **13.33 Mt $CO_{2\text{-eq}}$ for 2050**. Feedstock competition was not accounted for.

5.3.2 Abatement Costs

Fuss et al. (2018) report that CO_2 prices of between 82 and 110€ per tonne CO_2 should render biochar application economically feasible. However, a study undertaken by Bruckman and Klinglmüller (2014) calculated costs of between **193€ and 248€ per tonne $CO_{2\text{-eq}}$**. This study is based on the context of Austria. Due to the study's geographic scope and its cost definition, the estimate by Bruckman and Klingmüller (2014) is deemed more relevant. The estimate also accounts for revenues from electricity generation from syngas (i.e., a by-product of pyrolysis). Potential economic benefits stemming from increased yields are not accounted for. This can, however, be justified with the fact that the extent of the positive impact on soil productivity has not yet been determined with certainty (Jeffery et al., 2011). Consequently, the technical potential for BC does not present a cost-effective solution at a carbon price of 100€ per tonne CO_2.

5.4 Building with biomass

5.4.1 Technical potential

According to Stingl et al. (2011) the yearly current wood construction share amounts to 22% of the total built volume. This figure from 2011 represents the most recent estimate available on the WCS. As discussed with A. Teischinger (personal communication, April 26th 2023), a senior researcher from the Austrian University of Natural Resources and Life Sciences, a WCS share of 22% can still be considered a valid baseline assumption. Based on this WCS, approximately 1.5 million m^3 of wood construction products are needed (Stingl et al., 2011). To produce these construction products about two to three times the amount of tree biomass is required. Based on the expert opinion of A. Teischinger a doubling of the WCS to 44% can be deemed feasible (A. Teischinger, personal communication, April 26th 2023). This upper limit accounts both for constraints due to biomass availability and technical limitations related to wood construction. For example, wooden buildings cannot entirely be constructed from timber but also require conventional construction materials.

A wood construction share of 44% requires roughly 3.1 million m^3 of timber construction products (Stingl et al., 2011). This corresponds to 1.32 Mt of timber on a dry basis and leads to a yearly technical potential for negative emissions of **2.33 Mt $CO_{2\text{-eq}}$ for 2050**.

5.4.2 Abatement Costs

No cost estimates on BWB have been reported by Fuss et al. (2018). However, as discussed with an expert on BWB, wood construction does not incur any significant additional costs as compared to conventional construction, which can be considered as the BSL (G. Rappold, personal communication, May 16th 2023). This assessment was further confirmed by Bey et al. (2021). There are no known opportunity costs for BWB. Thus, costs for negative emissions through BWB are assumed at **0€ per tonne $CO_{2\text{-eq}}$**. The full technical potential can, hence, be realised cost-effectively at a carbon price of 100€ per tonne CO_2.

5.5 Direct Air Carbon Capture and Storage

5.5.1 Technical Potential

In theory, the potential for DACCS deployment can be considered unlimited (Fuss et al., 2018; Strengers et al., 2018). However, certain constraints arise due to land availability, but the main limitation is the high energy requirement of DACCS plants (Bey et al., 2021). Capturing only 1 Mt CO_2 via DACCS would require on average 8.1 PJ_{elec} for a liquid-solvent based plant (McQueen et al., 2021), which corresponds to over 4% of current Austrian low-carbon energy production (Anderl et al., 2022). Furthermore, the decarbonisation of the Austrian industry will require large-scale electrification, likely leading to a doubling of electricity demand by 2050 (S. Spaun, personal communication, April 13th 2023), which further limits the availability of additional low-carbon energy to power a DACCS plant. Consequently, it can be concluded that from a current perspective there is **no technical potential** for DACCS deployment in Austria in 2050 given its considerable energy demand.

5.5.2 Abatement costs

DACCS is still a relatively costly NET. There are a few factors that determine the economic viability of DACCS and, hence, the optimal siting of DACCS plants (Fasihi et al., 2019). The most decisive factor concerns the availability or access to abundant low-cost and low-carbon electricity sources (Qiu et al., 2022). According to projections, solar PV will be the lowest-cost energy source in the long run, likely to be produced equatorial regions due to the high solar energy potential (McQueen et al., 2021).

Another major factor is the availability of sufficient geological storage capacity located near the capturing plant (IEAGHG, 2021). Considering that the geological capture capacity in Austria is limited and competition would arise with other carbon removal methods (i.e., BECCS and CCS), this presents another major constraint to achieve a cost-effective future deployment of DACCS in Austria.

First-of-a-kind DACCS plants incur costs between **550 and 920€ per tonne CO_2**, whereas costs are expected to considerably decrease to between 92 and 275€ per tonne CO_2 as global capacity increases (Fuss et al., 2018). These numbers are, however, inherently uncertain as no large-scale DACCS plant exist yet. In addition, these costs strongly depend on the availability of low-cost energy sources and the proximity to geological storage facilities (Fasihi et al., 2019; IEAGHG, 2021). Given the discussed technical and economic constraints for DACCS deployment, DACCS does not present a feasible solution for realising negative emissions in Austria.

5.6 Soil carbon sequestration

5.6.1 Technical potential

Through enhanced soil management the soil organic carbon (SOC) content of agricultural soils can be increased (Roe et al., 2021). Various management practices can be applied. The technical potential discussed here can be realised with no-till management and cover cropping for croplands, reduced grazing pressure for managed pastures and improvements in the management of degraded rangelands for grasslands. According to Roe et al. (2021), the technical potential for SCS amounts to 1.19 Mt CO_2 in croplands and 2.00 Mt CO_2 in grasslands for 2050. This leads to a total technical SCS potential of **3.19 Mt $CO_{2\text{-eq}}$ for 2050**.

5.6.2 Abatement costs

Global costs for negative emissions through SCS have been reported to range between -41€ and 92€ per tonne CO_2 depending on the measure taken (Fuss et al., 2018). Born and Schijndel (2018) have conducted a cost assessment for the Netherlands for similar measures and arrived at a cost range between 40€ and 50€ per tonne CO_2 (Strengers et al., 2018). Considering that the Dutch estimate is geographically more applicable to Austria than the global estimate, we will assume costs to be within the range of **40€ and 50€ per tonne $CO_{2\text{-eq}}$.** Moreover, the estimate by Born and Schijndel (2018) aligns with the cost definition of this thesis. Hence, the full techno-economic potential can be realised cost-effectively.

6. FEEDSTOCK COMPETITION

This section provides results for SQ3. It aims to assess potential constraints to the feedstock potentials due to feedstock competition. This will be determined by conducting a scenario analysis. Notably, these scenarios do not account for indirect effects.

A detailed description of the three scenarios analysed and the respective assumptions taken can be found in Chapter 3.4. Each scenario emphasises a different carbon removal strategy, as follows:

- Scenario 1: Carbon removals through carbon farming (i.e., AR/Forest Management and SCS) and BC amendment
- Scenario 2: Carbon removals through timber construction
- Scenario 3: Carbon removals through BECCS.

The scenario analysis involved three runs which can be distinguished by the constraints applied and the feedstock utilisation rate:

- Run 1: No technical constraints applied, the only constraint to the potentials is biomass availability, 100% feedstock utilisation rate.
- Run 2: Technical constraints applied according to technical potentials determined in Chapter 5, limited feedstock utilisation, non-used biomass was not reallocated to other uses.
- Run 3: Technical constraints applied according to technical potentials, unused feedstocks from run 2 were reallocated to other suitable conversion pathways.

6.1 Scenario run 1

The results from run 1 show that without accounting for technical constraints Scenario 1 clearly leads to the highest amount of negative emissions with 35.28 Mt $CO_{2\text{-eq}}$ in 2050. This is followed by Scenario 3 with negative emissions of 20.36 Mt $CO_{2\text{-eq}}$ and Scenario 2 with 17.94 Mt $CO_{2\text{-eq}}$. Hence, it can be concluded that following a negative emissions strategy based on carbon removals through carbon farming and BC amendment represents the most desirable pathway from a theoretical perspective. The findings further show that in a scenario, which aims to maximise negative emissions via BWB or BECCS, the forest carbon sink transitions to a carbon source leading to additional emissions of 9.03 Mt $CO_{2\text{-eq}}$ per year. Without technical constraints, the full sustainable biomass potential can be utilised for negative emissions in all scenarios.

Table 17. Scenario run 1. This run only accounts for constraints due to biomass availability.

	Scenario 1	**Scenario 2**	**Scenario 3**
Negative emissions (in Mt $CO_{2\text{-eq}}$, 2050)	**Carbon farming and BC**	**Timber construction**	**Bioenergy Carbon Capture & Storage**
Afforestation & Reforestation/ Forest Management	19.40	-9.03	-9.03
Bioenergy Carbon Capture & Storage	0.11	10.60	19.14
Biochar	8.75	6.15	0.00
Building with Biomass	3.84	7.07	7.07
Soil Carbon Sequestration	3.19	3.19	3.19
Total	**35.28**	**17.94**	**20.36**
Utilisation rate of feedstock available for bioenergy	**100%**	**100%**	**100%**

6.2 Scenario run 2

To account for technical constraints, run 2 puts a cap on the respective potentials according to the technical potentials determined in Chapter 5. Scenario 1 still achieves the highest negative emissions, whereas negative emissions from Scenario 2 and 3 are considerably smaller than in the first scenario run. This shows that a strategy focussed on BECCS is significantly limited by the availability of existing point sources that provide the opportunity for installing CCS equipment. It can be seen that in each scenario the maximum technical potential for BWB can be realised, which means that there is sufficient domestic sawn wood available even when pursuing a carbon stock accumulation strategy in forests. In Scenario 1, 61% of the domestically available sawn wood is utilised, whereas only 33% are utilised in Scenario 2 and 3. This can be explained by the fact that the sawn wood potential in the high biomass mobilisation scenario assumed for Scenario 2 and 3 is significantly larger than in Scenario 1. This is applicable to both run 2 and 3. Considering that a reallocation of biomass was not conducted in scenario run, a considerable amount of biomass available for bioenergy is left unutilised in both Scenario 2 and 3.

Table 18. Scenario run 2. This run accounts for technical limitations without performing feedstock reallocation.

	Scenario 1	**Scenario 2**	**Scenario 3**
Negative emissions (in Mt $CO_{2\text{-}eq}$, 2050)	**Carbon farming and BC**	**Timber construction**	**Bioenergy Carbon Capture & Storage**
Afforestation & Reforestation/ Forest Management	19.40	-9.03	-9.03
Bioenergy Carbon Capture & Storage	0.11	4.68	5.22
Biochar	8.75	6.12	0.00
Building with Biomass	2.33	2.33	2.33
Soil Carbon Sequestration	3.19	3.19	3.19
Total	**33.78**	**7.29**	**1.71**
Utilisation rate of feedstock available for bioenergy	**100%**	**77%**	**45%**

6.3 Scenario run 3

When performing a reallocation of non-used biomass to other NETs (i.e., from BC to BECCS and vice versa), the negative emission potential can be significantly enhanced for Scenario 2 and 3 as depicted in Table 19. The findings show that a strategy based on carbon farming and BC amendment achieves the highest amount of negative emissions when accounting for feedstock competition and technical constraints. Both in run 1 and 3 a 100% of the feedstock available for bioenergy is utilised. The difference in negative emissions between scenario run 1 and 3 can be largely explained by the higher potential for BWB in run 1, as sawn wood was not reallocated to energetic utilisation. Another important finding is that even though a smaller % of total biomass is allocated to BC in Scenario 2 and 3 as compared to Scenario 1, the potential remained almost equal. This can be explained by the increased availability of forest residues in Scenario 2 and 3 which become available for bioenergy production due the shortened rotation period scenario assumed for the forestry sector.

Table 19. Scenario Run 3. Scenario results when accounting for technical limitations and performing feedstock reallocation.

	Scenario 1	Scenario 2	Scenario 3
Negative emissions (in Mt $CO_{2\text{-eq}}$, 2050)	**Carbon farming and BC**	**Timber construction**	**Bioenergy Carbon Capture & Storage**
Afforestation & Reforestation/ Forest Management	19.40	-9.03	-9.03
Bioenergy Carbon Capture & Storage	0.11	5.22	5.22
Biochar	8.75	8.73	8.73
Building with Biomass	2.33	2.33	2.33
Soil Carbon Sequestration	3.19	3.19	3.19
Total	**33.78**	**10.46**	**9.20**
Utilisation rate of feedstock available for bioenergy	**100%**	**100%**	**100%**

Thus, taking feedstock competition and technical constraints into consideration, a technical potential of **34 Mt $CO_{2\text{-eq}}$ for 2050** can be realised by pursuing a carbon removal strategy based on carbon farming and BC amendment. The main conclusion to be taken from these results is that the main feedstock competition lies between BECCS and BC production, but the three NETs AR/Forest Management, BECCS and BC compete for land used for biomass cultivation. Given the technical constraints to timber construction, there should be no issue due to feedstock competition.

7. TRADE-OFFS

This section provides results for SQ4. It assesses the ease of compliance with the QUALITY criteria as defined by the EU CRCF using an MCA. A description of these criteria can be found in the Theory section (Ch. 2.3). In this respect, trade-offs regarding for example permanence or sustainability will be evaluated. The scoring criteria for the MCA can be found in the Methods section (Ch. 0). Firstly, each technology will be assessed individually. Secondly, a comprehensive overview of the MCA results for all NETs will be provided.

7.1 Assessment of each technology

7.1.1 Afforestation and Reforestation, Forest Management

The verification of carbon removals via AR/Forest Management is covered by the LULUCF Regulation and IPCC Guidelines (Bey et al., 2021). However, there are certain challenges associated with the **quantification** of the mitigation benefit for this NET. These include for example the limited accuracy of field measurements, issues associated with the validity of allometric modelling choice and the sampling uncertainty in regard to the plot size (Temesgen et al., 2015). These factors might lead to an overestimation of carbon stocks. Moreover, measuring soil organic carbon stocks in forest ecosystems provides substantial logistical and financial challenges which explains the lack of consideration in current certification schemes (Haya et al., 2023). Nonetheless, the mitigation benefit of the CDR activity can be unambiguously determined as there are no considerable GHG emissions associated with the implementation of the NET.

As has been determined in the previous chapters, the main potential for this NET arises from the expansion of the protected forest area and a consequent decline in timber harvest volumes. Given that the sawn wood industry is an important contributor to the Austrian economy (Lackner et al., 2023), it is highly unlikely that this potential would be realized without additional incentives. Moreover, there are no regulatory measures that foresee a considerable expansion of the protected forest area. Hence, **additionality** is given.

Regarding the guarantee of **long-term carbon storage**, forest ecosystems are vulnerable to human-induced as well as natural-induced disturbances (Lecina-Diaz et al., 2021). Hard to avoid natural disturbances such as pests, wildfires or climate change threaten the additional carbon removals achieved. Human disturbances include for example land use change or timber harvesting (Haya et al., 2023). As can be seen by the scenarios developed by the Austrian Forest Research Institute, forest carbon stocks are at high risk of reversibility (Weiss et al., 2020). Even for scenarios where considerable carbon dioxide removals take place, in the long-term (after 2100) Austrian forests will turn into a net carbon sink. In this regard, forest carbon removals have a medium permanence as compared to geological sinks (P. Smith, Haszeldine, et al., 2016). Given the high risk of reversal and the foreseeable end to the forest carbon sink, this NET ranks low on long-term carbon storage.

Forest management has positive side-effects on the environment including biodiversity protection and the provision of clean air (Haya et al., 2023, 2023). Thus, the CDR activity provides co-benefits for other environmental objectives and thereby fulfils the **sustainability** criterion.

7.1.2 Bioenergy Carbon Capture and Storage

Given that emission data for large-scale bioenergy plants is already accurately reported in Austria, the **quantification** of gross carbon removals through the installation of CCS units should not prove challenging (Anderl et al., 2022). Emissions related to biomass growing are accounted for through IPCC guidelines (Bey et al., 2021). In addition, the RED II directive sets certain sustainability criteria for feedstocks to be rated as zero-emissions. Notably, the large-scale deployment of BECCS might not always lead to net negative emissions due to the potential threat of deforestation to produce the necessary biomass (Fuss et al., 2018). A review of various LCAs conducted on BECCS has found a net negative GWP for all studies assessed (Jeswani et al., 2022), but disregards emissions from land use change. However, the BECCS potential defined in this thesis only considers the availability of sustainable biomass resources. Hence, these risks can be considered negligible in the context of this thesis and the unambiguity of the mitigation benefit can be assumed for this thesis.

Currently there is no existing legislation or practices in Austria that require the installation of CCS units at bioenergy plants. Hence, **additionality** of the NET can be substantiated. Given that BECCS permanently stores carbon underground, there is little risk of reversal (Fuss et al., 2018). Leakage cannot be fully precluded, but it is not regarded as a major obstacle as considerable research goes into how to effectively monitor and verify these negative emissions and how to detect and remedy potential leaks (Bui et al., 2018; Fuss et al., 2018). Hence, it can be concluded that BECCS scores high on **long-term storage**.

Concerning the sustainability impacts of BECCS, it has been found that large-scale BECCS deployment could have negative impacts on land degradation, biodiversity and freshwater availability (Jeswani et al., 2022). On a global level BECCS could also lead to food security issues due to increased land competition even if a food-first principle is applied (Reilly et al., 2012). These risks, however, should be negligible when only accounting for domestically available sustainable biomass resources (i.e., excluding food crops), as has been assumed for in this thesis. Nevertheless, due to widespread biomass trade these risks cannot entirely be precluded with certainty. The installation of CCS equipment at existing bioenergy plants leads to an efficiency or energy penalty (Bey et al., 2021). Research has suggested, however, that this penalty could be largely offset by recovering the resulting waste heat from the capture process (Babin et al., 2021). Moreover, the installation of BECCS poses certain risks. In the case of overpressure, CCS could cause the pollution of potable water, lead to increased seismic activity or leaks, and result in adverse environmental impacts at the site of leakage (Fuss et al., 2018; P. Smith, Davis, et al., 2016). Hence, given all these risk factors BECCS receives a low score on **sustainability**.

7.1.3 Biochar

The IPCC has issued guidelines on how to estimate carbon removals from BC amendment (Bey et al., 2021). However, there are considerable challenges associated with determining the climate benefit from biochar application. Environmental conditions and biochar characteristics considerably influence soil GHG balance which has been shown by the large differences in results achieved through varying experimental conditions (Kamali et al., 2022; Zhang et al., 2020). A review by Zhang et al. (2020) has shown that the direct application of biochar has resulted in an increase of CH_4 and CO_2 emissions with a simultaneous decrease in N_2O emissions. Nevertheless, most studies considered in the review have shown that application of biochar has led to a significant climate mitigation benefit. Another review by Tisserant and Cherubini (2019) have found that the application of biochar can either lead to slight positive emissions (0.04 $tCO_{2\text{-eq}}$) or negative emissions (1.67 $tCO_{2\text{-eq}}$) per tonne feedstock. Given the complexities in understanding the climate feedback mechanisms resulting from biochar application and the lack of an unambiguous climate benefit, biochar scores low on **quantification**.

A widespread direct application to soils does not pose economically feasible as no sufficient incentive is provided (G. Soja, personal communication, April 19th 2023). Thus, the current primary application of biochar is indirect by mixing it with animal feed to improve animal health or manure to enhance soil quality. Consequently, for the direct application of BC to agricultural soils **additionality** can be substantiated, as the activity goes beyond compliance with existing regulation and there would be no direct biochar application to agricultural soils without an incentive provided.

Through the pyrolysis process biomass carbon is stored in the biochar in recalcitrant form. A certain percentage of the removed carbon is expected to decay over time. Currently, 3% of the biochar carbon are assumed to decompose over a period of 100 years (Wang et al., 2016). When accounting for the decomposition in the certification process, the **long-term storage** of the carbon removals can be assured. The risk of reversal is low (Bey et al., 2021).

The risk of imminent environmental impacts from direct soil application of biochar is low (Tisserant & Cherubini, 2019). On the contrary, biochar provides the co-benefit of enhancing soil fertility and water retention capacity. Studies have also found that BC amendment can lead to enhanced crop productivity whereas the effect on yield can be either positive or negative depending on various factors such as soil type or location-specific management conditions (Jeffery et al., 2011). Moreover, pyrolysis can present an effective waste management strategy for potentially contaminated feedstocks, such as animal manure or sewage sludge (Khan et al., 2021). However, there has been too little research on long-term in-field experiments to rule out long-term adverse impacts (Kamali et al., 2022). These could include a change in surface albedo or black carbon emissions from soils, eutrophication or acidification (Tisserant & Cherubini, 2019). Thus, the **sustainability** score of biochar application to soils is low.

7.1.4 Building with Biomass

Timber construction from sustainable forest management presents a clear and unambiguous climate mitigation benefit as compared to conventional building structures from concrete and steel (Duan et al., 2022; Woodard & Milner, 2016). Life cycle assessment has been widely applied by numerous studies to quantify the GHG balance of timber construction (Duan et al., 2022). The IPCC has defined clear guidelines for assessing carbon removals and the EC has developed Monitoring, Reporting and Verification (MRV) rules for measuring biogenic storage in harvested wood products (HWP) (Bey et al., 2021). Thus, BWB meets the **quantification** criteria given its relatively easy measurement and unambiguous climate benefits.

Given that a considerable number of buildings are currently constructed with timber (Stingl et al., 2011), it may be difficult to determine whether BWB would have been carried out without additional incentives provided by a new regulation. Moreover, BWB does not go beyond compliance with existing practices. Hence, the **additionality** score has been evaluated as low.

Even though the permanence of BWB is relatively short as compared to BECCS and DACCS, BWB allows for **long-term carbon storage** throughout the duration of the lifespan of the building with average lifetimes of between 80 and 100 years (Hepburn et al., 2019). There are reversibility risks associated with the release of carbon in the case of the decommissioning of the building but these can be easily mitigated via monitoring (Bey et al., 2021). Moreover, reversal can be avoided by reusing or repurposing construction materials.

The replacement of carbon-intensive conventional construction materials yields significant positive GHG substitution effects (Braun et al., 2020). Moreover, timber from decommissioned buildings can be reused and thereby aligns with the principles for cascading use (Bey et al., 2021). This further supports the transition towards a circular economy. In the case of sustainable forest management, there are no considerable negative environmental impacts resulting from timber construction (Puettmann et al., 2021). Thus, **sustainability** for BWB is ranked as high.

7.1.5 Direct Air Carbon Capture and Storage

Currently there are no harmonised guidelines on how to account for DACCS neither by the IPCC nor the EU ETS. However, the mitigation benefit of DACCS can be easily quantified as the CO_2 captured and energy used can be directly measured (Bey et al., 2021). The net climate benefit of DACCS is strongly dependent on the background energy system. The energy system needs to be decarbonised in order to ensure a high net sequestration efficiency and enhance the climate change mitigation potential. In the case of a low-carbon energy supply, DACCS can provide for an unambiguous mitigation benefit (Madhu et al., 2021). Hence, the score for DACCS on **quantification** is high.

Given that there are no existing practices or regulations promoting the use of DACCS, the **additionality** of the CDR activity should be easy to determine. Furthermore, there is no other benefit to the NET other than removing carbon from the atmosphere (Madhu et al., 2021). DACCS presents a **long-term carbon** removal option by permanently storing captured carbon underground. The risk of reversibility is low.

Regarding **sustainability** considerations, DACCS is a highly material and energy-intensive NET and does not provide any co-benefits for the environment (Bey et al., 2021; Qiu et al., 2022). Similar to BECCS, the installation of CCS equipment poses environmental risks in the case of leakage. Other potential environmental issues include land use, particulate matter emissions and water depletion for large-scale deployment (Madhu et al., 2021). Hence, DACCS scores low on sustainability.

7.1.6 Soil Carbon Sequestration

The quantification of carbon removals through SCS is regulated via IPCC guidelines and the EU LULUCF regulation (Bey et al., 2021). Nevertheless, the **quantification** of carbon removals through soil carbon sequestration proves challenging due to the lack of soil carbon data on a granular level and associated uncertainties in quantifying carbon sequestration due to the complexity of climate and biophysical interactions (Lugato et al., 2014). Moreover, it has been reported that the high costs for MRV could impose a financial burden to farmers, especially for small-scale farms (Bey et al., 2021). There are clear and unambiguous climate mitigation benefits resulting from enhancing soil carbon through management practices (Paustian et al., 2019). Hence, the score for quantification has been determined as medium.

To allow for a widespread improvement in soil organic carbon contents of agricultural soils, policies are needed that adequately compensate farmers for accruing additional costs from enhanced management practices (Paustian et al., 2019). Given that improvements in soil carbon sequestration through enhanced agricultural management for croplands have been practiced for more than a quarter century in Austria (Baumgarten et al., 2021), it might be difficult though to determine whether the CDR activity has been implemented due to an additional incentive and whether it complies with the **additionality** criterion. Furthermore, certain Common Agricultural Policy (CAP) measures already promote the enhancement of SOC stocks (Bey et al., 2021).

SCS can in theory represent a **long-term carbon storage** option, but as compared to BECCS or DACCS it has a relatively short permanence. In addition, the risk of reversibility is high and carbon release can happen quickly (Bey et al., 2021). Risk factors include a change in management practices as well as climate change (Paustian et al., 2019).

In terms of **sustainability** aspects, soil carbon sequestration enhances soil health and fertility, improves soil water retention capacity, enhances climate resilience and prevents soil erosion (Paustian et al., 2019; Rumpel et al., 2020). Thus, SCS provides considerable co-benefits for other environmental objectives. Studies have reported that enhancing SOC might involve long-term environmental trade-offs such as the offsetting of N_2O emissions or changes in the water balance of agro-ecosystems (Lugato et al., 2014; Rumpel et al., 2020). These risks, however, are derived from SCS measures that were not applied for the potential estimate of this thesis. Hence, SCS scores high on sustainability.

7.2 Comparison of NETs

A comparison of the various NET assessed in this thesis according to the QUALITY criteria as determined by the EU CRCF is shown in Table 20. The MCA shows that only the NETs AR/Forest Management, BWB and SCS provide co-benefits for other environmental objectives whereas all other NETs either lead to other imminent negative environmental impacts or pose long-term environmental risks. According to these criteria, SCS is the worst performer due to challenges associated with measuring its mitigation benefit, the difficulty in determining additionality and the risk of reversibility for carbon removals. Both BECCS and DACCS present high scores for quantification, additionality and long-term storage but score low regarding sustainability. AR/Forest Managements scores well on sustainability and additionality, but there are certain challenges associated with determining additionality and risks associated with carbon release. BWB meets all CRCF criteria except for additionality. BC involves challenges associated with determining the unambiguity of its climate benefit and long-term environmental risks in respect to its direct application to soils.

Table 20. Comparison of NETs according to QUALITY criteria defined by EU CRCF and respective MCA scores.

	Criteria Score				**Average Score**
NET	**Quantification**	**Additionality**	**Long-term storage**	**Sustainability**	
AR, Forest Management	2	1	3	1	1.75
BECCS	1	1	1	3	1.5
Biochar	3	1	1	3	2
BWB	1	3	2	1	1.75
DACCS	1	1	1	3	1.5
SCS	2	3	3	1	2.25

8. IMPLEMENTATION POTENTIAL

This section assesses the implementation potential for each NET, taking into account the TRL, upscaling constraints and the availability of required infrastructure. In addition, potential constraints due to feedstock competition from SQ3 will be discussed. The results can be used to answer SQ5.

8.1 AR/Forest Management

The techno-economic potential for AR/Forest Management amounts to 19.4 Mt $CO_{2\text{-eq}}$ for 2050. AR/Forest Management has a high TRL (8-9) (Bey et al., 2021). In addition, given that the potential is based on an expansion of use restrictions in the forest, there are no constraints in respect to technological upscaling to the implementation potential. Moreover, in contrast to, for example, BECCS this NET does not require large infrastructure (Fuss et al., 2018). Hence, it can be assumed that the full techno-economic potential of **19.4 Mt $CO_{2\text{-eq}}$** can be implemented **for 2050**. The implementation potential for 2030 is slightly smaller with **18.2 Mt $CO_{2\text{-eq}}$** per year. The cumulative potential for negative emissions from AR/Forest Management amounts to **117 Mt $CO_{2\text{-eq}}$ by 2050**.

The full realisation of this potential will lead to a decreased availability of timber and forest residues. Nevertheless, this does not cause any constraints to the potentials determined for BECCS and BWB, as these potentials are mainly limited by the occurrence of large-scale point sources and technical limitations to wood construction, respectively. Moreover, it has been shown that a strategy focused on carbon removals and BC amendment leads to the highest technical potential for negative emissions when accounting for feedstock competition, as informed by the scenario analysis.

8.2 BECCS

The TRL for BECCS differs depending on the bioenergy sector (Bey et al., 2021; Kampman et al., 2023; S. Smith et al., 2023). For combustion based BECCS the TRL was evaluated at 8, whereas for the biofuel industry (i.e., bioethanol and biomethane production) the TRL was estimated at 9 (Bey et al., 2021; Kampman et al., 2023; S. Smith et al., 2023). Solely, deriving from the technological readiness of the technologies, it would be reasonable to assume that the potentials could be upscaled by 2030. However, to transport the captured CO_2 to geological storage locations a widespread CO_2 transportation network is required. Given that this necessitates considerable infrastructure deployment coupled with the lack of existing plans in this regard, it was assumed that BECCS will be implemented after 2030.

As has been shown by the scenario analysis, BECCS and BC compete for feedstocks. Thus, depending on the carbon removal strategy pursued the potential for BECCS could be constrained. However, given that from a current perspective there is no implementation potential for BC due its high costs, it can be expected that sufficient biomass is available for BECCS deployment. In addition, the BECCS potential are all derived from established industries, except for biomethane production, which implies that feedstock availability does not pose a constraint from a current perspective.

8.2.1 Biomethane production

The techno-economic potential amounts to 1.08 Mt CO_2. Biogas upgrading can either be done directly at the site of biogas production which would result in only smaller volumes of biogas to be upgraded (Havrysh et al., 2019). The alternate option would be to collect biogas from a number of production sites and upgrade the biogas at a central location creating a scale advantage and efficiency increase. Thus, the latter option would allow for a more cost-effective installation of CCS but would require a well-managed gas collection network. Given that the feedstock sources for biogas production are highly distributed, the full techno-economic potential will be difficult to implement. However, due to limited data available on the spatial distribution of the analysed feedstocks and of potential new biogas production sites, no estimate can be taken for the implementation potential for negative emission from biogas upgrading.

8.2.2 Bioethanol production

The techno-economic potential for bioethanol production amounts to 0.18 Mt CO_2. Given that there is only one Austrian bioethanol plant, which has already installed CCU, it is reasonable to assume that the full techno-economic potential will be realised by 2050. Thus, the implementation potential for bioethanol amounts to **0 Mt CO_2 for 2030** and **0.18 Mt CO_2 for 2050**. The **cumulative** potential amounts to **1.8 Mt CO_2** by 2050, when assuming the implementation of BECCS at the bioethanol plant in 2040.

8.2.3 Cement production

The techno-economic potential amounts to 0.21 Mt CO_2. For 2050, it can be deemed feasible to install CCS at all the cement production plants in Austria due to their small number (9) and the long time period between 2031 and 2050. Hence, the implementation potential amounts to **0.21 Mt CO_2 for 2050** and **0 Mt CO_2 for 2030**. When breaking down the biogenic emissions into each plant, the capture capacity is relatively low. However, given that the installation of CCS at cement plants not only captures biogenic but also fossil CO_2 emissions (total industry emissions amount to 2.95 Mt CO_2), it is reasonable to assume that the total capture capacity is sufficient to ensure technical feasibility. The **cumulative** potential for cement production accumulates to **1 Mt CO_2 by 2050** when implementing CCS at a new plant every two to three years starting from 2031.

8.2.4 Pulp and paper

The techno-economic potential amounts to 2.61 Mt CO_2. Until 2050 the full potential can be deemed realistic to implement due to the sufficiently long time period and the limited number (10) of large-scale pulp and paper plants to install CCS at. Hence, the implementation potential for the pulp and paper industry amounts to **0 Mt CO_2 for 2030** and **2.61 Mt CO_2 for 2050.** The **cumulative** potential amounts to **29 Mt CO_2 by 2050** when implementing CCS every 2 years at another pulp and paper plant starting from 2031.

8.2.5 Thermal power plants

The techno-economic potential amounts to 0.16 Mt CO_2. There is only one large-scale biomass powered thermal power plant registered in the E-PRTR. Thus, it is reasonable to assume that by 2050 this plant can be equipped with CCS. The implementation potential equals the techno-economic potential with **0.16 Mt CO_2 for 2050.** For **2030** the potential is **0 Mt CO_2**. The **cumulative** potential amounts to **2 Mt** CO_2 by 2050 when implementing CCS at the thermal power plant starting from 2040.

8.2.6 Waste to Energy

The techno-economic potential amounts to 0.98 Mt CO_2. The negative emissions to be achieved for the techno-economic potential stem from a small number of plants (7) and, thus, there should be no upscaling constraints to the implementation potential until 2050. The implementation potential for WtE plants amounts to **0 Mt CO_2 for 2030** and **0.98 Mt CO_2 for 2050**. The **cumulative** potential for WtE amounts to **10** Mt CO_2 by 2050 when implementing CCS at a new plant every 3 years commencing in 2031.

8.3 Biochar

Even though it is expected that BC amendment will be ready for large-scale implementation within a decade (Royal Academy of Engineering, 2018), the implementation potential is assessed at **0 Mt CO_{2eq} for both 2030 and 2050** given its high costs. As determined in chapter 5.3.2, there is no cost-effective potential and, hence, no implementation potential to consider.

8.4 BWB

The techno-economic potential for BWB amounts to 2.33 Mt CO_2 by 2050. Regarding technological readiness, no constraints arise for the potential due to its high TRL of 8-9 (Bey et al., 2021; Kampman et al., 2023; S. Smith et al., 2023). As discussed in an expert interview a 1% increase of the wood construction share can be deemed realistic (G. Rappold, personal communication, May 16th 2023). This leads to a yearly implementation potential of **0.74 Mt $CO_{2\text{-eq}}$ by 2030** and **2.3 Mt $CO_{2\text{-eq}}$ by 2050**. Hence, the full techno-economic potential can be implemented by 2050. The **cumulative** potential amounts to **38 Mt $CO_{2\text{-eq}}$ by 2050**.

There is no constraint to the potential due to feedstock competition, considering that there is sufficient domestic sawn wood available both under a forest stock accumulation and a shortened rotation period scenario in forests. Trade flows are, however, not considered due to the scope of the research.

8.5 DACCS

Given that the techno-economic potential has been assessed at **0 Mt CO_2**, there is no implementation potential to consider.

8.6 SCS

The techno-economic potenital of 3.19 Mt CO_2 requires enhanced management practices for both croplands and grasslands. The measures assumed in the potentials have all been commercially applied (TRL 8-9) (Bey et al., 2021). Thus, there are no technical constraints to the implementation of the potential. In addition, the measures identified (i.e., no-till management and cover cropping in croplands, and reduced grazing pressure for managed pastures and improvements in the management of degraded rangelands for grasslands) can be either implemented immediately or within the term of a growing season. Thus, there are no limitations due to the upscaling of the technology. Moreover, these measures do not require the deployment of large-scale infrastructure. Given that there is no data on the potential for 2030 and as the time period until the full technical potential will be realised is not known, no estimate on the implementation potential for 2030 can be taken. However, considering that there are no implementation constraints, it is reasonable to assume that the full techno-economic potential of **3.19 Mt $CO_{2\text{-eq}}$** can be implemented **for 2050.** The cumulative potential amounts to a total of **85 Mt $CO_{2\text{-eq}}$ by 2050**.

For this thesis we assumed that there would be no competition between SCS and agricultural residue-based NETs (i.e., BECCS and BC). However, in practice there might be an impact on carbon removals via SCS depending on the rate of residue removal for BECCS or BC production.

9. SYNTHESIS OF RESULTS

The purpose of this section is to provide a comprehensive overview of the results from each SQ. To avoid unnecessary repetition, the results were summarised in Table 21.

Table 21. Synthesis of results.

Negative Emission Technologies	**AR/Forest Manage-ment**	**BECCS**	**BC**	**BWB**	**DACCS**	**SCS**	**Total**
Potentials (in Mt $CO_{2\text{-}eq}$)							
Technical potential (for 2050)	19	5	13	2	0	3	**44**
Avg. abatement costs (in € per tonne $CO_{2\text{-}eq}$)	76	75	221	0	735	45	
Techno-economic potential (for 2050)	19	5	0	2	0	3	**30**
Implementation potential (for 2030)	18	0	0	2	0	3	**22**
Implementation potential (for 2050)	19	4	0	2	0	3	**29**
Cumulative implementation potential (2023-2050)	117	43	0	38	0	85	**284**
TRL	8-9	8-9	6-7	8-9	5-7	8-9	
Feedstock competition							
The main feedstock competition arises between BECCS and BC. In case the forestry sector pursues a carbon stock accumulation scenario, this competition is further intensified, as less timber and forest residues are available for both material and energetic utilisation. In respect to BWB, there is sufficient timber available in both a carbon stock accumulation and a shortened rotation crop period scenario to supply the resources needed for the technical potential.							
Trade-offs							
Unambiguous mitigation benefit	Yes	Yes	No	Yes	Yes (but dependent on background energy system)	Yes	
Additionality	Easy to establish	Easy to establish	Easy to establish	Difficult to establish	Easy to establish	Difficult to establish	
Permanence	Short-medium	Long	Long	Short-medium	Long	Short	
Risk of reversibility	High	Low	Low	Medium	Low	High	
Sustainability							
Air pollution	+	-	/	/	-	/	
Biodiversity	+	/	/	/	/	/	
Circular economy	/	/	+	+	-	/	
Energy use	/	/	/	/	-	/	
Soil quality	+	/	+	/	/	+	
Water demand/ pollution	/	/	/	/	-	/	

10. DISCUSSION

This section provides a comprehensive discussion of the results of this thesis. Firstly, limitations of the research in respect to the scope of the thesis will be introduced. In addition, limitations regarding the assumptions taken and related uncertainty factors will be discussed. Secondly, implications to be derived from the research findings will be provided and the research findings will be compared against existing research. Thirdly, recommendations for further research and for policymakers will be given.

10.1 Limitations of research

10.1.1 Scope of research

Given that this research aimed to assess the potential for all NETs relevant for the Austrian context, a rather wide scope has been set for this analysis. Deriving from this wide scope certain limitations arise, as it was not possible to dedicate an extensive amount of detail to each of the CDR technologies assessed due to time constraints. Hence, it must be noted that the purpose of this research was to, firstly, present an overview of the alternative options for realising negative emissions in Austria and, secondly, to provide a rough estimate on how large the potential for each of the NETs could be under certain assumptions. In this regard, this research depicts a technology-focused analysis and, thus, any socio-political aspects regarding the deployment of NETs were not considered. These aspects could considerably lower the estimated potential. Notably, other country-specific assessments such as the NET potential assessment for the Netherlands (Strengers et al., 2018) applied a similar scope.

Moreover, due to time constraints this thesis only assessed the gross amount of negative emissions to be achieved when implementing certain NETs. Hence, emissions arising due to the implementation or operation of the technologies were not considered. Nevertheless, the analysis on trade-offs showed that each of the NETs would lead to unambiguous climate, except for biochar amendment which showed no potential for implementation. Additionally, indirect effects, such as a decrease in bioenergy production due to the installation of CCS equipment (because of a decrease in conversion efficiency) or adverse environmental impacts, were solely assessed and discussed on a qualitative basis. Both indirect effects and emissions arising due to the installation of NETs could have a considerable impact on the GHG balance of Austria and should be considered in a further analysis.

This analysis only considered biomass availability based on the production of domestic feedstocks. Thereby, biomass trade flows were disregarded. This specifically affects the potential for BWB, as Austria both imports and exports large timber flows. However, as has been shown in the scenario analysis, the domestic sawn wood production both under a forest accumulation and shortened rotation period scenario considerably exceeds the sawn wood required to supply the technical potential for BWB.

In this thesis, the availability of CO_2 storage capacity was not regarded as a constraint, assuming that sufficient capacity is available abroad. Given the lack of definite plans on where these storage sites will be located in the future and how much residual capacity there will be for Austrian CO_2 in other countries, there are large uncertainties associated with the CO_2 storage potential. A lack of suitable and available CO_2 storage capacity within sufficient proximity to biogenic point sources could, thus, significantly limit the potential for BECCS deployment in the long term after exceeding the inland capacity for geological carbon storage (between 400 and 510 Mt CO_2). However, deriving from the cumulative implementation potential identified for BECCS (43 Mt CO_2), there is sufficient inland geological storage capacity for BECCS at least until 2050. Notably, there may be competition between fossil-CCS and BECCS for storage capacity, further restricting its availability for negative emissions.

The temporal scope of this thesis has been set to 2030 and 2050 in line with the main climate and energy targets. In respect to developments until 2050 from both a technical and economic perspective, considerable uncertainty exists. For example, large-scale soil amendment of biochar has not been researched sufficiently in large-scale and long-term field experiments. Thus, it is not yet possible to rule out long-term environmental risks with certainty. As a result, adverse developments in these matters could severely compromise the deployment of BC.

10.1.2 Assumptions and uncertainty

To determine the availability of biomass, data was extracted from a study by Panoutsou and Maniatis (2021). This study aimed to assess the sustainable biomass potential for Europe for both 2030 and 2050. Considering the wide geographical scope of their research, it can be assumed that a study with a more granular focus would produce more exact estimates on the actual feedstock potential for Austria. In addition, considerable uncertainties exist regarding the type of crops cultivated or the availability of land for growing energy crops.

Moreover, for the scenario analysis it was assumed that all biomass available for bioenergy purposes can be utilised for the deployment of NETs. This does, however, not account for the fact that a considerable amount of feedstock is currently used for small- or medium-scale bioenergy production (Pfemeter et al., 2023). Thus, the available biomass for negative emissions could be considerably smaller. However, this should have an impact on the implementation potential determined for BECCS for 2050, as the potential is primarily based on existing point sources.

To assess the potential for AR/Forest Management, data from the scenario analysis conducted by Ledermann et al. (2020) was used. This data is based on a more pessimistic climate scenario (RCP 8.5) which assumes that global temperatures will increase by 4.8°C by 2100 as compared to 2000 (Rogelj, Shindell, et al., 2018). This assumption impacts the potential for AR/Forest Management, as a more optimistic climate scenario would allow for a larger and more permanent carbon sink of Austrian forests. These scenarios are largely based on the speed of progress on climate action and the realisation of deep emission reductions on a global scale, which is inherently uncertain.

The potential for BECCS is mainly based on the existence of large point sources for biogenic emissions (except for anaerobic digestion). Depending on future developments regarding the extent and structure of bioenergy production, this potential could become larger as the Austrian long term strategy foresees a considerable increase in bioenergy production (Bundesministerium für Nachhaltigkeit und Tourismus, 2019). Moreover, the scale of biogenic emissions from cement production and the pulp and paper industry strongly depends on demand volumes. The potential for biogenic emission from WtE plants also depends on factors such as circular economy measures or population developments.

The main constraint for biochar deployment was shown to be the availability of suitable biomass which is, thus, also the main uncertainty for this potential as discussed in the previous sub-chapter on the scope of research. Regarding the potential for BWB, it was assumed that a WCS of 44% presents the technical limit as discussed with an expert in the sector (A. Teischinger, personal communication, April 26th 2023). Given that this presents a relatively rough assumption, the potential for BWB could be somewhat smaller or larger depending on the WCS assumed. Moreover, technical progress on, for example, material use efficiency (i.e., using less material per m^3 built volume) could also affect the potential in the future.

The potential for DACCS was assumed to be 0. However, with considerable improvements in respect to the energy requirements for the operation of DAC, there could be some technical potential for deployment in Austria. The implementation of DACCS in Austria is, however, not realistic given the limited geological storage capacity and the lack of abundant low-cost renewable energy sources.

To determine the technical potential for SCS, data was extracted from a study conducted by Roe et al. (2021). This potential was derived from modelling the carbon sequestration potential of a number of measures aimed at enhancing the SOC. Hence, somewhat different results could be achieved by modelling different carbon sequestration measures. Moreover, there is still considerable uncertainty regarding the realisation of the potential carbon sequestration rates in practice (Lugato et al., 2014). Adding to that, the carbon sequestration potential of soils is ultimately constrained by an upper sink saturation limit leading to decrease in sequestration rates with time (Wiesmeier et al., 2020). This limit is strongly dependent on the soil type. Further research should be directed towards identifying this limit for Austria.

The cost estimates for the various NETs were based on different studies which all applied slightly different assumptions regarding their calculations. By choosing studies with similar assumptions on the type of costs comprised (i.e. only the additional costs for carbon removals were considered), the comparability of the various estimates was enhanced. However, the cost estimates should still be treated with caution, also due to the uncertainty of cost developments in the future.

10.2 Theoretical implications

10.2.1 Comparison to existing research

This thesis fits within a large body of research addressing potentials, costs and limitations for NETs. Most studies focus on a global analysis of a specific NET or a combination of a few NETs (e.g., land-based NETs) rather than providing a comprehensive assessment for a certain region, as has been done in this study. Other known analyses within the European Union have been conducted for Ireland (McMullin et al., 2016) and the Netherlands (Strengers et al., 2018). In contrast to this thesis, the analyses by McMullin et al. (2016) and Strengers et al. (2018) also assess the potential for Enhanced Weathering. However, Enhanced Weathering has been intently disregarded due to its low TRL and the restricted temporal scope of this study (2030, 2050).

Regarding the individual assessment of each technology, the scenario data from the CareforParis project was used to determine the technical potential for AR/Forest Management. This is the only known data source indicating a potential for AR/Forest Management for Austria. In respect to BECCS, Rosa et al. (2021) arrive at a technical potential of approximately 5 Mt CO_2 for BECCS for Austria. This estimate is quite similar to the estimate for this thesis (5.22 Mt CO_2). Minor differences in the distribution of negative emissions across industries can be explained by different data used for biomass availability to determine the potential for biomethane production and by the country-specific data (e.g., share of biogenic emissions in Austria in WtE plants vs. avg. share of biogenic emissions in Europe) used in this thesis. In addition, negative emissions from thermal power plants powered by biomass and from bioethanol production were not considered by Rosa et al. (2021).

In respect to the potential for biochar deployment, Bruckman and Klinglmüller (2014) estimated a potential of 0.38 Mt $CO_{2\text{-eq}}$ per year. However, it is based on an abstract assumption of utilising 10% of the annual forest biomass increment for biochar production. The technical BC potential for Austria (22 Mt $CO_{2\text{-eq}}$) evaluated in this thesis is considerably smaller than the one for the Netherlands (110 Mt $CO_{2\text{-eq}}$), even though the land area suitable for BC application in Austria is significantly larger (2.66 Mha in AT vs. 0.82 Mha in the NL). This large difference can be explained by the fact that Strengers et al. (2021) did not take biomass availability into consideration for assessing the technical potential.

Kalt (2018) has developed scenarios on the resulting carbon storage potential from increasing the WCS in Austria. In his rapid increase scenario, Kalt (2018) found a yearly negative emission potential through BWB of roughly 0.9 Mt $CO_{2\text{-eq}}$. In this thesis, the potential has been assessed at 2.33 Mt $CO_{2\text{-eq}}$. The difference can partly be explained by the fact that Kalt (2018) only looked at residential buildings, whereas this thesis considered all building types.

There is no existing study estimating the potential for DACCS deployment in Austria. Estimates have been taken on a country level by both the Netherlands and Ireland. Similar to this thesis, both reports have come to the conclusion that there is no potential until 2050 from a current perspective due to high uncertainties associated with cost developments, the low TRL and the high energy requirements (McMullin et al., 2016; Strengers et al., 2018).

Regarding the potential for SCS, Baumgarten et al. (2022) have conducted a scenario analysis on SOC developments under varying carbon input assumptions. Deriving from the data from the most ambitious scenario by Baumgarten et al. (2022), the SCS potential amounts to roughly 2.6 Mt $CO_{2\text{-eq}}$. This estimate, however, is based on abstract carbon input assumptions and not connected to any specific management practices that actually enhance SOC. Consequently, the modelling of specific measures that enhance SOC in both grasslands and croplands, which has been assumed in this thesis, was considered to represent a more adequate assessment.

The implementation potentials are partially based on the technology's TRL. There is widespread consensus in literature on the high TRL (8-9) of conventional NETs (i.e., AR/Forest Management, BWB, SCS). However, in respect to BC amendment, there is some discrepancy on the TRL reported by various studies. In this thesis, a TRL of 6-7 was assumed (Bey et al., 2021; S. Smith et al., 2023) in contrast to a TRL of 3-6 as reported in the assessment of NETs for the Netherlands by Strengers et al. (2018). However, the estimate for the TRL of 3-6 is based on an outdated article from 2016 and since then there has been significant progress regarding research on BC amendment through a number of pilot trials (Kampman et al., 2023).

10.2.2 Implications of research findings

The research findings clearly show that the enhancement of the forest carbon sink provides the largest opportunity for negative emissions in Austria. However, this result should be treated with caution as the decision to extend utilisation restrictions in forests has widespread implications. Firstly, it will lead to a decrease in logging volumes, effectively reducing feedstock availability for bioenergy production. The decrease in bioenergy production would have to be compensated through additional energy production from other sources. In the case that insufficient renewables are available, bioenergy could be substituted by fossil fuels potentially negating the positive climate mitigation effect achieved through negative emissions. Secondly, as shown by the CareforParis scenario results, even in a stock accumulation scenario, the Austrian forest will become a net carbon source after 2100 partly due to aging forests and climate change. If the forest stands are not properly harvested and rejuvenated, their risk of breaking down in a few decades when they reach their saturation level is significantly increased (T. Ledermann, personal communication, May 3rd 2023). Hence, it needs to be carefully evaluated whether an extension of utilisation restrictions is desirable from a climate perspective.

BECCS provides a consistent and permanent opportunity for negative emissions with low risk of reversibility. The results have shown that a portfolio of both nature-based and technology-based solutions will be necessary to compensate for hard-to-abate emissions. Moreover, in case bioenergy production is expanding in the next decades, the potential for negative emissions from BECCS could even be larger. However, to transport the captured CO_2 a large-scale CO_2 transportation network will have to be implemented first. To allow for a sufficient time to scale up the required infrastructure, it is imperative that timely decisions will be taken to ensure BECCS' contribution to reaching climate neutrality by 2050.

The technical potential for BC amendment shows that BC could be another large contributor to negative emissions. However, due to its high cost both the techno-economic and the implementation potential were assessed at 0 Mt CO_2. Nevertheless, considerable cost reductions are possible in the future and, thus, BC should not be fully dismissed yet as a mitigation opportunity. As discussed, it is still to be determined, though, whether long-term environmental risks can be ruled out.

The implementation of the potential for BWB is associated with little to no adverse side-effects. Even though there is some risk of reversibility, this can be mitigated with close monitoring and by reusing timber construction materials after decommissioning. As shown, realising the potential for BWB also does not put increased pressure on feedstock competition and represents a highly cost-effective option. Hence, BWB constitutes a desirable opportunity for negative emissions.

As discussed, the carbon sequestration potential for soils is associated with considerable uncertainties. Moreover, there is a high risk of reversibility and due to sink saturation, the potential is limited in the long-term. Nevertheless, SCS poses significant environmental benefits, such as enhanced soil quality or improved water retention capacity. Moreover, through less intensive management, degraded soils can be restored to some extent. In addition, the applied measures for estimating the potential do not lead to any known adverse side effects. Hence, even though the potential for SCS is limited in the long-term, due to its many benefits it can represent a cost-effective mitigation option.

10.3 Recommendations

10.3.1 Recommendations for further research

Given the constraints discussed in the previous chapter (9), it is recommendable to integrate the research findings of this thesis into the wider energy system context to assess the implications of the implementation of the various NETs on the Austrian GHG balance. This could be done, for example, through the use of an Integrated Assessment Model (IAM). Furthermore, it is important to conduct a detailed life-cycle analysis specific to the Austrian context on each of the technologies to determine their net climate benefit and to trade off adverse environmental impacts against the achievement of negative emissions.

Given that BECCS and BC production compete for feedstocks, it would be important to conduct a more detailed assessment on the availability and the potential for future mobilisation of sustainable biomass specifically for the Austrian context. In addition, it would be advisable to assess the current use of each feedstock and potential future demands (both energetic and material uses) to allow for a more detailed evaluation of the constraints arising due to feedstock competition.

Since it was mostly not possible to determine cost estimates adapted to the Austrian context, an individual cost assessment should be conducted for each NET based on country-specific characteristics. To allow for comparability, the cost assessment should use the same assumptions on, for example, interest rate or scope of costs. This would enhance certainty which could be beneficial to promote investment in NETs.

10.3.2 Policy recommendations

It is imperative that timely decisions will be taken on an EU-level of how carbon credits will be allocated and whether it will be possible to claim credits for negative emission within the EU-Emission Trading System (EU-ETS) to enhance investment security. For example, it is not yet clear whether CO_2 captured in Austria, but stored in a foreign country can be credited towards Austrian climate targets.

On a national level, the research findings can be used as a first estimate on the total potential for negative emissions to guide policy developments on which NETs to implement in order to compensate for the residual emissions from hard-to-abate sectors (between 13 and 23 Mt of $CO_{2\text{-eq}}$ by 2050). As shown in Figure 9, a combination of BWB, BECCS (via bioethanol production), SCS and AR/Forest Management depicts the most cost-effective NET portfolio leading to 25 Mt $CO_{2\text{-eq}}$ of negative emissions, that can be deemed feasible to implement. This portfolio can thereby effectively compensate for the residual emissions from hard-to-abate sectors. The assessment shows that a combination of both nature-based and technological solutions will be necessary for the lowest cost solution. However, before making any policy decisions it is critical to first quantify potential indirect effects from the implementation of NETs.

This analysis has further shown that BECCS presents a promising opportunity for Austria to complement its decarbonisation strategy. Thus, it is highly recommendable to revise the current law that prohibits the geological storage of CO_2 to allow for an early-on deployment of BECCS.

Public perception of NET can pose a major obstacle for the deployment of certain NETs such as BECCS or BC amendment (Buck, 2016). Hence, ensuring public acceptance can be critical for the adoption of NETs (Nemet et al., 2018). However, there is little knowledge on how to overcome these socio-political challenges, improve the framing of NET deployment and provide sufficient information to the public (Minx et al., 2018). In addition, research has been conducted, for example, in the UK (Shackley et al., 2011) or specifically Scotland (Howell et al., 2014) of how the public views the deployment of certain NETs, but similar studies are missing for the Austrian context. Hence, further research should be steered towards overcoming these knowledge gaps. This data will be critical to derive socially acceptable policy solutions.

Despite the considerable climate benefits to be achieved with the deployment of NETs, it is of utmost importance that NETs are not considered as a panacea for mitigating climate change but should rather be seen a complementary solution to compensate for hard-to-abate emission or for a temporary temperature overshoot in the case of an exceeded carbon budget.

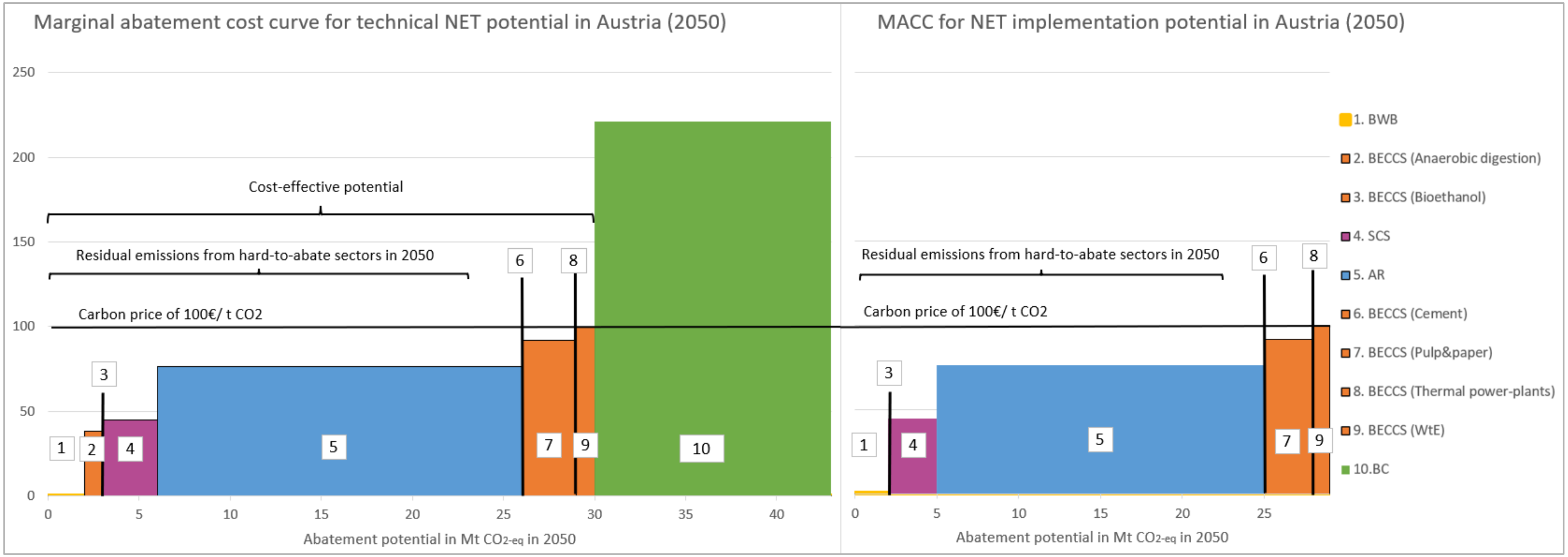


Figure 9. Marginal Abatement Cost Curves for the NETs. The MACC on the left refers to abatement potentials determined according to technical constrains, whereas the MACC on the right depicts the abatement options when considering implementation constraints. Negative emission options are ranked according to their abatement costs.

11. CONCLUSION

The aim of this research was to identify the potential for negative emissions in Austria from a technical, economic and implementation perspective. In addition, scenarios were developed to assess potential constraints resulting from feedstock competition for land-based NETs, including AR/Forest Management, BECCS, BC and BWB. To allow for a comprehensive assessment of the various NETs, potential trade-offs were qualitatively assessed according to the criteria determined by the EU CRCF.

As some of the NETs face limitations in respect to biomass availability, it was necessary to determine the domestic availability of sustainable biomass. This was done by conducting literature research. The results show that in a high biomass mobilisation scenario 5.5 Mt, 8.9 Mt and 1.1 Mt of feedstock can become available for bioenergy purposes from agriculture, forestry and biowaste, respectively. In addition, 4 Mt sawn wood are available for material use in the construction sector.

Building on these findings and by extracting additional data from both literature and expert interviews, the technical potential and abatement costs were quantitatively assessed. A carbon price of 100€ per tonne $CO_{2\text{-eq}}$ was used to determine the cost-effectiveness of the technical potential, also referred to as techno-economic potential. The total technical potential across all NETs for 2050 amounts 43.51 Mt $CO_{2\text{-eq}}$ whereas the techno-economic potential equals 30.18 Mt $CO_{2\text{-eq}}$ for 2050.

As a next step, scenario analysis was conducted to determine potential constraints for the deployment of biomass-based NETs. The results indicate that the main competition arises between BECCS and BC production. However, it has been shown that the potential for BECCS, which is primarily based on the current bioenergy production capacity, is mainly constrained by the availability of existing point sources rather than sustainable feedstock availability (except for BECCS via anaerobic digestion). Similarly, the potential for BWB is primarily constrained by technical limitations to the maximum WCS, as even in a scenario where the focus was put on maximising the forest carbon sink, sufficient sawn wood is available to supply the full technical BWB potential. Moreover, it was shown that pursuing a carbon stock accumulation scenario in forests significantly reduces the amount of biomass available for bioenergy purposes from forests.

The EU CRCF has defined compliance criteria to harmonise the accounting of carbon removal credits across the EU. These criteria include quantification, additionality, long-term storage and sustainability. By conducting a MCA, which was informed by literature review, each NET received a score that represents both the ease of compliance with the certification framework and potential trade-offs. The results show that whereas AR/Forest Management, BWB and SCS score high on sustainability in contrast to all other NETs, their carbon removals are associated with a relatively short permanence and a high risk of reversibility as compared to BECCS, BC and DACCS. Additionality was evaluated to be easily established for all NETs except for BWB and SCS due to their already existing widespread implementation. Quantification issues have been identified for BC, whereas BECCS, BWB and DACCS show rank high on this matter.

The results on feedstock competition were used to inform the discussion on the implementation potential of each NET. The implementation potential was determined by taking the TRL, upscaling constraints and infrastructure requirements into consideration through conducting literature research. The total implementation potential across all NETs amounts to 22.13 Mt $CO_{2\text{-eq}}$ and 29.06 Mt $CO_{2\text{-eq}}$ for 2030 and 2050 respectively. The cumulative implementation potential by 2050 was assessed at 284 Mt $CO_{2\text{-eq}}$.

Overall, this research makes a valuable contribution to the literature on NETs, particularly because it addresses the lack of geographically specific assessments on a country level. While global or EU-wide potential estimates offer a rough indication on the total existing potential, they often lack the necessary details and fail to consider the implementation constraints specific to each country. The research findings highlight the considerable potential for a cost-effective implementation of NETs in Austria. It was further shown that nature-based solutions will be critical for achieving sufficient removals in the short-to-medium term. However, their relatively short permanence and their high risk of reversibility emphasise the importance of implementing a diverse NET portfolio to ensure continuous carbon removals, also in the long-term. Moreover, the cumulative potential highlights the importance for realising an early-on deployment of NETs as these technologies can make a considerable contribution to remaining within the fair share of the Austrian carbon budget.

12. REFERENCES

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13. APPENDICES

13.1 Appendix I. Description of Feedstock categories

Table 22 presents an overview of the feedstock categories discussed in this thesis and the respective feedstocks included in these categories.

Table 22. Feedstock categories and feedstocks included by Panoutsou and Maniatis (2021).

Feedstock category	**Feedstocks included**
Agriculture	
Cereal straw	cereal straw
Maize stover	leaves, stalks and empty cobs of grain maize plants left in the field after harvest
Oil crop field residues	dried stalks of rapeseed, sunflower and soy left in the field after harvest
Agricultural prunnings	Prunnings and cuttings of fruit trees, vineyards, olives and nut trees (primarily wooden residues) left in the field after cutting, mulching and chipping
Manure	Solid and wet manure produced in stables with a farm size over 100/200 Livestock Units (LU)
Sec. residues from agro-industries	Residues resulting from processing of crops into products incl. olive pomace and pits, cotton gin trash, almond shells, peach pits, etc.
Lignocellulosic crops	Fiber sorghum, kenaf, miscanthus, switchgrass, cardoon, poplar, willow produced from unused, abandoned and degraded land
Forestry	
Stemwood	Part of the tree stem from the felling cut to the tree top with the branches removed, incl. bark
Primary forest residues	Primary residues from pre-commercial thinnings and final fellings, mainly (thin) stems, branches, needles, bark, leaves, tree roots
Sec. forest residues & Post-consumer waste	By-products from wood industries (sawmill and other wood processing) incl. bark, sawdust, slabs, chips from coniferous and non-coniferous stemwood & sawdust, shavings and off-cuts from further processed timber products; Post-consumer wood (PCW) incl. woody material that is available at the end of its use as a wood product such as packaging materials, demolition wood, timber from building sites or used furniture
Biowaste	
Paper & cardboard	Paper and cardboard from sorting and separate sorting by businesses and households incl. fibre, filler and coating rejects from pulp, paper and cardboard production
Wood waste	Wood from the production of pulp and paper; wood from the construction and demolition of buildings; and separately collected wood waste from HH
Animal & mixed food waste	Animal and mixed wastes from food preparation and products
Vegetal waste	Vegetal wastes from food preparation and products
Municipal solid waste	Municipal waste, bulky waste, street-cleaning waste like packaging, kitchen waste, and household equipment except separately collected fractions

13.2 Appendix II. Ultimate analysis of feedstocks

Table 23 presents an overview of the various feedstock categories, the representative feedstocks used and the data found from ultimate analysis from literature research.

Table 23. Data on carbon content and fixed carbon content of each feedstock category.

			Ultimate analysis
Feedstock category	**Representative feedstock**	**Source**	Carbon in wt% db
Agriculture			
Cereal straw	Wheat	Nzihou (2020)	48%
Maize stover	n/a	Wojcieszak et al. (2020)	44%
Oil crop field residues	Rapeseed	Karaosmanoğlu et al. (2000)	45%
Agricultural prunnings	n/a	Duranay and Akkus (2021)	45%
Manure	Average cow, pig, chicken	Nzihou (2020)	48%
Sec. residues from agro-industries	Sugarcane bagasse	Nzihou (2020)	50%
Lignocellulosic crops	Miscanthus	Nzihou (2020)	50%
Forestry			
Stemwood	Spruce	Nzihou (2020), Robertson et al. (2012)	48%
Primary forest residues	Used wood class A	Nzihou (2020)	49%
Sec. forest residues & PCW	Used wood class B	Nzihou (2020)	51%
Biowaste			
Paper & cardboard	Average printing paper and cardboard	Zhou et al. (2022); Mitchell et al. (2013)	39%
Wood waste	Used wood class B	Nzihou (2020)	49%
Animal & mixed food waste	n/a	Chen et al. (2019)	42%
Vegetal waste	Fruit and vegetable waste	Lin et al. (2012)	43%
MSW	n/a	Nzihou (2020)	60%

13.3 Appendix III. Interview summaries

Date: May 3rd, 2023; 9:00-9:30

Interview partner: Thomas Ledermann

Role of Interviewee: Project Lead for the Care for Paris Study, Department Lead for Silviculture at the Austrian Forest Institute

Interview Summary:

The interview partner has mentioned that a growth of forest area was not looked at in their modelling project for Care For Paris. Nevertheless, it is expected thath the forest area will increase further. However, the growth rate is expected to decline. Most of the growth can be attributed to a natural expansion in mountaineous areas. The potential for afforestation in Austria is coonsiderably limited. Furthermore, there is competition between agriculture and forestry. Considering that agricultural productivity is expected to decline due to climate change, there is a need to increase agricultural production in Austria which puts increased pressure on land.

A study from the ETH Zürich was discussed which provided an estimate on the potential for Afforestation in Austria. However, the potential estimate for forest expansion in Austria was deemed to be highly unrealistic. The stock building scenario in the Care For Paris study shows an increase in total carbon stock primarily due to an increase of protected areas and a decrease in timber extraction. Austria is primarily spruce dominated. However, this scenario is also not really realistic, as it is important to make use of these forests and substitute fossil-based energy carriers. Moreover, as these forest stands grow they become more vulnerable to natural and human disturbances. Spruce is already at it its limits. Thus, these forest stands will break in a few decades when they reach their saturation level if they are not being harvested and rejuvenation is not taking place.

The scenearios are based on the underlying climate scenarios RCP 4.5 and 8.5. The RCP 8.5 was used because it is the more realistic scenario when looking at the current policies. Forest growth is dependent on the temperature. The maximum forest stock is dependent on the climate scenarios as the stock is slightly smaller when assuming a more pessimistic climate scenario.

As can be seen from the reference scenarios, for RCP 4.5 the carbon storage is higher in the period from 2050 to 2100. There is an optimal temperature range for forests. Stock growth can be attributed to the nitrogen input as well as to increasing CO2 concentrations in the air and increasing temperature. To enhance forest mangement practices that are better for carbon storage, political incentives will be necessary. There is a large share of private forest owners, which makes the implementation of forest management measures difficult. Considering that the forest growth in Austria has been natural, there are no associated costs.

Date: April 19th, 2023 15:00-16:00

Interview partner: DI Dr. Gerhard Soja

Role of Interviewee: Researcher at University of Natural Sciences (AT) & Senior Scientist at the Austrian Institute of Technology GmbH (AIT)

Interview Summary:

This interview aimed at discussing the potential for negative emissions through the deployment of biochar in Austria. The expertise of the interviewee lies in Biochar deployment and other soil management techniques. Biochar deployment is a reasonable strategy for the upcoming years, there is already the company called "Sonnenerde" which is producing biochar. However, currently biochar is not directly applied to soils but rather indirectly through using it as an admixture to animal feed. This not only improves carbon sequestration in soil but also animal health and leads to cost reductions. This will become considerably more important in the future. The admixture can contain around 1% of biochar.

There are several Synkraft plants in Austria which produce biochar, that has otherwise no use. This biochar can be used in the construction industry. The primary purpose of these plants is energy production, but biochar is a by-product (output of around 10%). A direct application to the soil is according to Mr. Soja not purposeful, as the C ratio of biochar itself is unfavourable to the soil. Moreover, without an additional benefit other than carbon sequestration, the economic viability is not given and not attractive for farmers. Thus, nitrogen addition through the intermediate step of farm manure or slurry enhances the economic feasibility and nutrient content of the soil. Another option lies in co-composting of biochar. However, in the longer term if there is sufficient financial incentive, he would not preclude that direct application can become an option.

Another benefit of biochar application lies in the enhancement of the soil water retention potential. This could be an option for Lower Austria, as there is little animal husbandry. Direct application would be more likely in this area, however, also only via co-composting. There are considerable amounts of waste that could potentially be used for biochar pyrolysis. So, there is no need to specifically grow biomass for the sole purpose of pyrolysis. Waste feedstocks include e.g. cherry pits, nutshells or sunflower seed shells. There is also considerable potential for biowaste from private households. In respect to wood waste, there are also significant amounts of sawdust that cannot be utilised otherwise. There is competition of biomass with pyrolysis and biogas. However, biogas production produces considerable amounts of digestate that can still be pyrolyzed. Another potential feedstock is sewage sludge with high phosphor content. Retrieving phosphorous from sewage sludge requires significantly higher effort than pyrolysis.

Biochar will always be only a small contributor to the total soil carbon sequestration potential. If we are assuming that the 4 per mille objective represents the carbon sequestration potential of soils, biochar can contribute around 20 to 30% to this potential, but from a very optimistic perspective. This requires strong political incentives and favourable legislation. Legislative framework conditions for the application of biochar in agriculture are more favourable in Austria than in Germany.

Date: April 27th, 2023 10:00-10:30

Interview partner: Gerald Dunst

Role of Interviewee: CEO at Sonnenerde GmbH (Biochar production plant)

Interview Summary:

This interview aimed to discuss the potential for negative emissions through the deployment of biochar in Austria. The interviewee, an expert in biochar production, provided valuable insights on the topic.

The interviewee stated that the potential for biochar is enormous and depends solely on the technology deployed. Currently, the biggest challenge lies in the expensive electricity prices. Gasification plants also produce biochar, but they can do so at a lower cost due to the affordable electricity prices. As a result, the produced biochar can be distributed almost for free. However, this biochar is of lower quality and cannot be mixed into the soil or substrate, making the future of pyrolysis uncertain.

Sonnenerde is constructing a new plant capable of producing 2000 tons of plant biochar annually. The plant exclusively uses waste materials, primarily tree and shrub cuttings. They are also planning to use paper sludge as they get paid for its disposal, making it a near-zero-cost resource. The interviewee mentioned that biogas residues from anaerobic digesters should not be used, as it is better to compost them to retain nitrogen. However, it is technically possible to use them.

The interviewee predicted that pyrolysis will likely replace combustion in the future. The expansion of pyrolysis is mainly dependent on the price it can achieve. Currently, there is still much untapped potential for using residual materials, but there are difficulties in collecting them. The previous plant used spelt and sunflower husks, but the price has significantly increased. The current plant is designed to pyrolyze any type of raw material.

Regarding the use of raw materials, the main competition lies with composting and heating plants. The woody part of tree and shrub cuttings is best suited for pyrolysis, while the remaining part is suitable for composting. In the past, there was high competition between biogas plants and composting, but the preference for wetter materials in biogas production and drier materials for composting reduced the competition.

There is a European Biochar Certificate. Sonnenerde produces biochar in the highest quality grade, which gasifier char cannot achieve. Therefore, this biochar is not suitable for increasing carbon content in the soil. Plant biochar is not directly applied to fields; it is marketed as a substrate for urban tree planting or private raised beds. For agriculture, there is “Güllekohle” (for manure treatment and nitrogen binding) or feed charcoal (for animal health, which indirectly brings the biochar to the fields through manure). To be directly applied, the price would need to decrease by a factor of ten. It is expected that plant charcoal will become cheaper with increased capacities.

Demand is rising, and the market is growing significantly, but there is competition with gasifier char. However, there is a legal curiosity as gasifier char goes into animal feed, and plant charcoal is used for substrate preparation, leading to price competition. The market will only see significant growth when the prices of biochar decrease significantly and when carbon certificates/CO2 prices increase substantially. Currently, certificates are sold for about €200 per tonne of CO2, which is still too expensive for farmers. Demand is present among farmers, but only when the economic situation for farmers is favourable.

Raw materials are currently not a problem. There is still much long-term potential for their use in pyrolysis. Potential raw materials exist in residual materials from the saw, furniture, and paper industries, anywhere cellulose is present.

Regarding the political framework, there are only standard economic support measures covering investments. In Austria, there are no subsidies for plant charcoal production. In other countries like Norway and Sweden, there are subsidies covering 50% of the investment in biochar plants, putting Austria far behind in this aspect. The legislative discrepancy between feed charcoal and charcoal allowed in soil application needs to be resolved as soon as possible. There is the European Biochar Certificate, ÖNORM, and fertilizer regulations. Currently, in organic farming, feed charcoal is not allowed, and this should be addressed. Otherwise, plant charcoal can be used throughout Europe. There is a positive list of raw materials that can be used for each respective quality grade.

Regarding the sale of certificates, there are Carbon Future and Puro Earth, which are trading platforms that buy certificates from Sonnenerde and sell them to customers. These certificates certify how much CO2 is sequestered by biochar in the product.

Biochar is not solely applied to agriculture due to its price. Austrian soils are highly nutrient-depleted. Applying 10 tons of biochar per hectare can significantly improve the soil, but applying more is likely not beneficial and too costly.

Date: April 26th, 2023 15:00-16:00

Interview partner: Alfred Teischinger

Role of Interviewee: Professor at University of Natural Resources

Interview summary

Compared to other Negative Emission Technologies, Building with wood is a technology that can be relatively quickly implemented. The 2 main feedstocks used for building with wood are cross laminated timber and glue laminated timber. Related capacities in the sawn mill industries have been built up in the last couple of years. Austria is a small country and we have a big export share for timber.

In their study on the potential for BWB, they defined what counts towards wood construction. Simply said 1m^3 translates into 1t CO_2. According to Mr. Teischinger a doubling of the wood construction share of the total built volume is realistic, but already quite optimistic. This is due to both technical limitations and limited feedstock availability. It is sometimes argued for even 50%, but that cannot be considered realistic.

There is significant potential for multi-storey residential buildings as the current share is quite low with only around 5%. This could be scaled up to 30/40%. Every building category has different wood construction shares, and some have more potential than others. Currently there is 1.5-2 Mm^3 wood demand per year. When doubling this share, we arrive at roughly 3 Mm^3 wood. The speed of growth can be partly read from the trend analysis. 3 Mm^3 timber used in buildings require at least double the amount of round wood. Out of the total annual forest increment not everything can be used for construction, because some of the wood is not of high enough quality or spruce or goes into other sectors. There is still potential to import from other countries. There is also more and more wood that is being used within Austria rather than being export. Thus, there is a considerably higher reserve than we currently have due to high exports.

Date: May 16th, 2023 14:30-15:15

Interview partner: Dr. Rappold

Role of Interviewee: Responsible for Wood Initiative (Holzinitiative) at Ministry for Forestry and Agriculture, Austria

Interview summary

The interview with Dr. Rappold discussed a different approach to estimating the timber construction share, particularly in the context of multi-story timber buildings. Currently, the timber construction share stands at 5% based on an industrial study. Driven by the proHolz study, the goal is to advance the share of timber construction in multi-story buildings.

The aim is to increase the timber construction share to 15% by 2030. To achieve this, there is a need for investment support specifically targeted at multi-story timber construction. The focus is on urban areas for densification and redevelopment rather than expanding to new areas. A realistic target is a 1% annual increase in timber construction, but this is strongly influenced by the economic situation of the construction sector. Efficient use of wood in construction is emphasized, promoting the use of less material per area. The intensity of timber usage lacks sufficient data and is dependent on the construction technique, whether it is lightweight or solid timber construction.

Comparing costs holistically, timber construction is on par with concrete construction. In some cases, considering externalized costs, timber construction can even be more cost-effective. Data and statistics related to timber construction can be found in sources such as the Holzzentralblatt, Waldbericht 2023, and other reliable references.

Sustainable timber usage is emphasized, utilizing timber resources sustainably to meet demand while also considering the unused growth from previous years. The potential of wood for construction depends on evolving technologies, such as the potential use of hardwoods in the future.