Comparative techno-economic analysis of BECCS and biochar in Sweden

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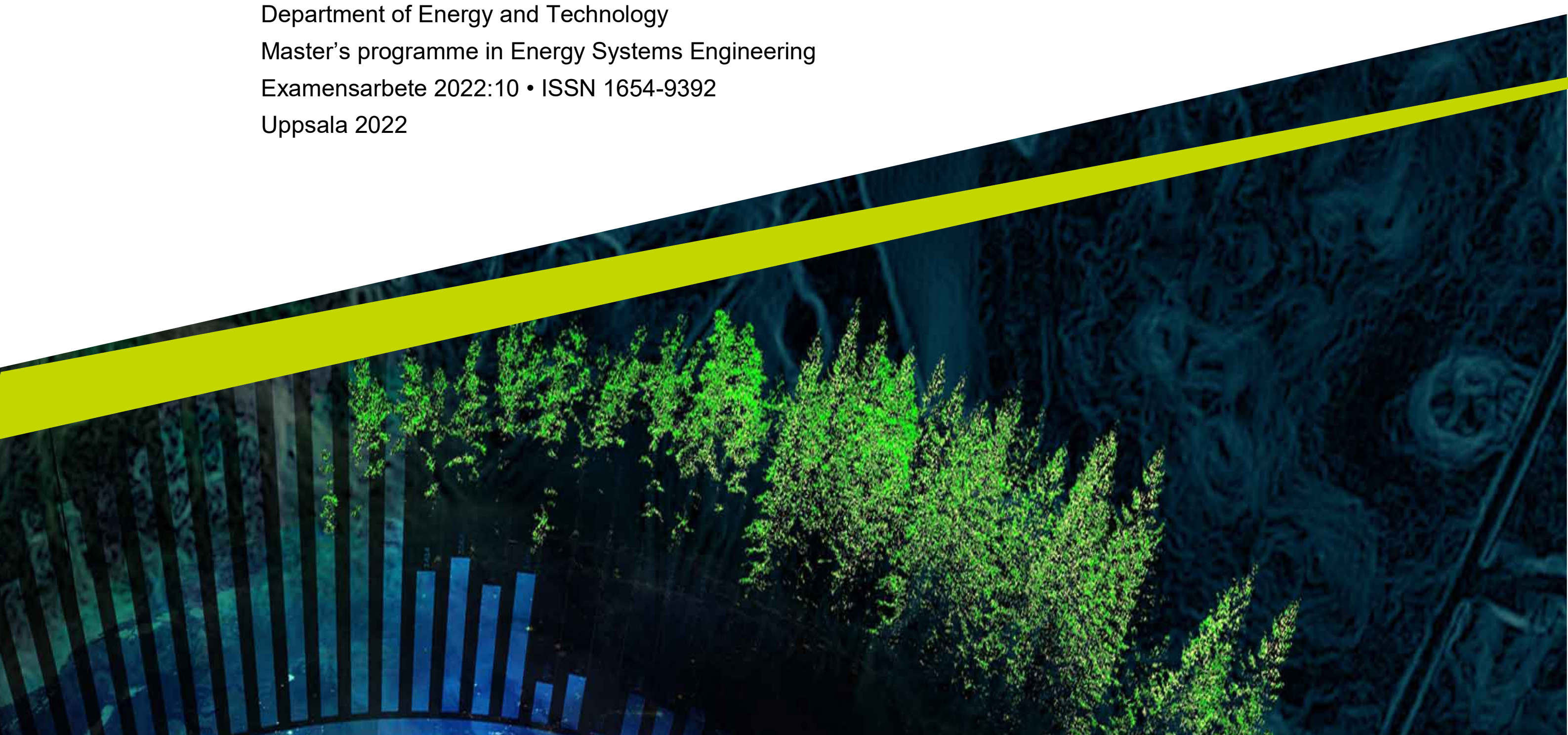
Degree project • 30 credits
Swedish University of Agricultural Sciences, SLU
Department of Energy and Technology
Master's programme in Energy Systems Engineering
Examensarbete 2022:10 • ISSN 1654-9392
Uppsala 2022



Comparative techno-economic analysis of BECCS and biochar in Sweden

Jämförande tekno-ekonomisk analys av BECCS och biokol i Sverige

Simon Martelius

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Credits:	30 credits
Level:	Master's level, A2E
Course title:	*Degree Project in Energy Systems Engineering*
Course code:	EX0724
Programme/education:	Master's programme in Energy Systems Engineering
Course coordinating dept:	Department of Energy and Technology
Place of publication:	Uppsala
Year of publication:	2022
Copyright:	All featured images are used with permission from the copyright owner.
Title of series:	Examensarbete (Institutionen för energi och teknik, SLU)
Part number:	2022:10
ISSN:	1654-9392
Keywords:	NETs, feasibility, cost-effectiveness, climate change-mitigation, CHP, carbon neutrality, bioenergy

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Abstract

Greenhouse gas emissions from human activity need to decrease for the Paris agreement goal of 1.5° C of global warming to be reached, and while emission reduction efforts remain the most important tool for combating climate change, it is increasingly evident that negative emission technologies (NETs) will play a key role reaching the climate targets of the Paris agreement. Two examples of NETs that are expected to contribute to the Swedish climate targets are bioenergy with carbon capture and storage (BECCS), and biochar production, which are technologies that both use biomass to generate energy while capturing carbon, making them potential replacements to traditional means of bioenergy production. In this report, the technical and economic conditions needed for BECCS and biochar to be able to compete with combined heat and power production (CHP) in Sweden is assessed through a literature study, stakeholder interviews, and a scenario based techno-economic net present value (NPV) analysis. The results of the analysis show that only the scenarios with the most favourable conditions for BECCS and biochar are able to achieve a higher net present value compared to CHP production. Ambitious CO_2 pricing and low system costs are identified as important variables for BECCS to outperform CHP economically. For biochar production, a high biochar selling price and low system costs are identified as important variables. Furthermore, low energy prices are shown to be beneficial to the economic performance of both BECCS and biochar when compared to CHP. Lastly, the effect of biomass availability on BECCS and biochar deployment is identified as a possible increasingly important factor to consider if the sustainability demands on biomass become more stringent and its number of competing uses increase. Care therefore needs to be taken to avoid the potentially harmful consequences on biodiversity if large scale deployment is to be successful.

Populärvetenskaplig sammanfattning

För att Parisavtalets 1.5-gradersmål ska nås behöver de globala koldioxidutsläppen nå en netto noll-nivå inom de kommande årtiondena. Samtidigt som rena utsläppsminskningar fortfarande är det viktigaste sättet att uppnå detta, så är det nu även allmänt erkänt att olika typer av negativa utsläpp kommer spela en viktig roll för att klimatavtalet ska kunna nås i tid.

Negativa utsläpp innebär att man på olika sätt minskar mängden koldioxid i atmosfären. Det flera metoder för detta, men koldioxidinfångning från luften och plantering av skog är två vanliga exempel.

I detta arbete undersöks BECCS och biokol – två olika tekniker som använder biomassa för att producera energi och samtidigt fånga in koldioxid – för att se vilken praktisk genomförbarhet de har i Sverige, samt hur ekonomiskt konkurrenskraftiga de är jämfört med traditionell kraftvärmeproduktion från biomassa (gemensam värme- och elproduktion från förbränning). Med hjälp av intervjuer med intressenter samt en litteraturstudie togs scenarier fram för olika förutsättningsnivåer för teknikerna. Dessa scenarier testades sedan i en tekno-ekonomisk modell för att undersöka hur ekonomiskt gångbart en investering i BECCS eller biokol är i de olika scenarierna. Samma beräkningar gjordes sedan för kraftvärmeproduktion, och resultaten för de negativa utsläppsteknikerna och kraftvärmeanläggningen jämfördes sedan.

De viktigaste resultaten:

Både BECCS och biokol kan endast prestera bättre ekonomiskt än kraftvärme i de mest gynnsamma scenarierna, vilket tyder på att nuvarande regleringar, kostnader, tekniska osäkerheter och policyincitament resulterar i förutsättningar som inte är gynnsamma nog för storskalig implementering.

Försäljningspriset av CO_2 har en större ekonomisk påverkan på BECCS än biokol, vilket troligen innebär att BECCS är mer känslig för utformningen av framtida klimatpolicy.

Försiktighet behöver iaktas för att undvika de potentiellt skadliga konsekvenserna på biologisk mångfald om storskalig implementering av teknikerna ska ske.

Executive summary

Biochar production and bioenergy with carbon capture and storage (BECCS) are two negative emission technologies (NETs) that are expected to be used globally as well as in Sweden to contribute to ensuring that the Paris agreement goal of 1.5°C of heating is reached. In this report, BECCS and biochar are analysed with the aim of making an assessment on the practical feasibility and economic trade-offs of BECCS and/or biochar deployment for energy production in Sweden until 2045. The study finds that only the most beneficial combinations of low system costs and high CO_2 and biochar pricing are able to make the NETs able to compete with conventional bioenergy production. To achieve these favourable conditions, an ambitious climate policy that involves stakeholders and the public will be of importance to ensure a high CO_2 pricing with stable investment conditions. Additionally, the lack of practical experience in BECCS and the remaining uncertainties in the material properties of biochar need to be addressed before large scale deployment can happen. To ensure that a sustainable usage of biomass is achieved in a future with an increasing biomass demand, the synergies and trade-offs of bio-based NETs – and other competing uses of biomass – need to be further studied.

Acknowledgements

This thesis was written at Stockholm Environment Institute (SEI) as a part of the LANDMARC project, which is an EU funded project with the purpose of contributing to an increased understanding of land-based negative emission technologies.

I would therefore like to start by thanking everyone at SEI – and in particular the people in LANDMARC – for making this experience such an enjoyable and insightful one.

Also, a special thank you to Maria, my supervisor at SEI. I feel so lucky to have had such a caring, supportive and engaged supervisor.

To all the stakeholders we interviewed as a part of the LANDMARC project, whose insights have been invaluable to this thesis as well as the project as a whole.

To Cecilia, my university supervisor, whose input and vast knowledge has been very helpful in finalising this thesis.

To Eileen, and all the other fellow interns at SEI. My thesis would not be the same without your support.

Last but not least to my family – Stefan, Kristina, Johan and Kaj: Thank you for all the love and encouragement.

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Abbreviations

NPV	Net Present Value
NET	Negative Emission Technology
SLU	Swedish University of Agricultural Sciences
DW	Dry weight
CHP	Combined Heat and Power
BECCS	BioEnergy Carbon Capture and Storage
Bio-CCS	See BECCS
CCS	Carbon Capture and Storage
DACCS	Direct Air Carbon Capture and Storage
EHR	Enhanced Hydrocarbon Recovery
NDC	Nationally Developed Contribution
CAGR	Compound Annual Growth Rate
CDR	Carbon Dioxide Removal

1€ = 10.486 SEK (Average over the first quarter of 2022 (X-rates 2022a))
1$ = 9.343 SEK (Average over the first quarter of 2022 (X-rates 2022c))
1€ = 1.123$ = 0.836 £ (Average over the first quarter of 2022 (X-rates 2022b))

1. Introduction

Greenhouse gas (GHG) emissions from human activity need to decrease in order for the Paris Agreement goal of 1.5°C of global warming to be reached. While emission reduction efforts remain the most important tool for combating climate change, it is increasingly evident that negative emission technologies will play a key role reaching the climate targets of the Paris Agreement (Roe et al. 2019).

To achieve this, the Swedish Riksdag (parliament) has passed a framework with the purpose of allowing for long-term and stable climate policy across party lines and terms of office (Regeringskansliet 2019). The framework states that Sweden should work internationally to limit the global temperature increase to 2°C, and make efforts to keep it below 1.5°C. Additionally, Sweden should have net zero GHG emissions by 2045, and after 2045 negative emissions should be achieved. To reach the 2045 net zero goal, the majority of today's GHG emissions need to be mitigated. However, some hard to abate emissions are expected to remain, which makes Negative Emission Technologies (NETs) necessary for Sweden to achieve its national climate goals (SOU 2020).

Two examples of NETs that are expected to contribute to the Swedish climate targets are Bioenergy with Carbon Capture and Storage (BECCS), and biochar production. Both of which use biomass to generate energy while capturing carbon, which makes them potential replacements to traditional biomass plants. BECCS has a higher energy and carbon capture efficiency than biochar production, but the transport and storage of the captured emissions is costly and requires large infrastructural solutions (Woolf et al. 2016). Biochar production generates less energy and negative emissions, but has the benefit of also producing biochar – a product with several additional values within agriculture and water management (Azzi & Sundberg 2022). While having different energy and mass balances, CO_2 storage permanence, deployment potentials, risks, and economic conditions; biochar, BECCS, as well as traditional bio-based Combined Heat and Power generation (CHP) all compete for the available biomass. Since CHP produces more energy compared to both BECCS and biochar, it is therefore the most profitable alternative of these three unless the captured carbon, or the additional values of the biochar product, is economically valued highly enough to make up for the loss in energy production (Woolf et al. 2016).

However, biomass is a limited resource with adverse impact on sustainability aspects such as land use, food prices, biodiversity, and water usage if overexploited. This highlights the importance of implementing NETs in a way that makes sure they contribute to net zero emissions, while also avoiding negative effects on other sustainability aspects (de Jong et al. 2017; Fajardy et al. 2018).

Additionally, neither biochar nor BECCS currently sees large-scale usage, which makes the future deployment of these technologies dependent on the policy incentives of today (Fridahl et al. 2020; SOU 2020; Söderqvist et al. 2021; Levihn 2022). Finding policies that creates the necessary conditions for BECCS and/or biochar to be deployed on a larger scale, while still considering the potentially harmful effects on biodiversity and energy production, is a challenge that needs to be met if these NETs are to successfully contribute to Sweden reaching its 2045 national emission targets.

1.1 Goal and purpose

BECCS and biochar are similar in that they both are NETs that use biomass to generate heat. However, characteristics such as energy and mass balances, investment and operating expenses, feedstock requirements, value chains, physical limitations, additional benefits, and potential side-effects differ between the two. This makes them similar enough to compare, but still distinct enough to potentially fill their own unique roles in a future NET portfolio. In this thesis, I analyse and compare BECCS and biochar with the aim of making an assessment on the practical feasibility and economic trade-offs of BECCS and/or biochar deployment in Sweden until 2045. To do this, I use the following three research questions:

1. Which are the main factors influencing the deployment of BECCS and biochar systems in Sweden?
2. What impact will changes in these factors have on the conditions for BECCS and biochar?
3. Under which technical and economic conditions can BECCS and/or biochar become viable for large scale energy production?

1.2 Outline

In Chapter 2 “Method”, the methodology used in this thesis is detailed.
In Chapter 3 “Theory and background of BECCS and biochar systems”, the background and necessary context and theory needed for the rest of the report is provided.

Chapter 4 “The barriers and drivers to BECCS and biochar deployment” aims at answering the first two research questions by presenting the main drivers and barriers to BECCS and biochar deployment found in literature and from stakeholder interviews.

In Chapter 5 “Conditions needed for BECCS and Biochar deployment”, a techno-economic analysis on BECCS and biochar systems used for heat and power production is performed, with scenarios based on the narratives in the previous chapter. The results of the analysis shows the economic viability of BECCS and biochar for the different scenarios, thereby answering the third research question.

Chapter 6 “Discussion”, discusses the results, the strengths and weaknesses of the scope and method used, highlights identified knowledge gaps, and suggests areas that are of relevance for further research.

Chapter 7 “Conclusions”, summarises the results of the thesis based on the research questions.

2. Method

The first part of the project focuses on identifying the key drivers and barriers to BECCS and biochar deployment, and then assessing in which ways changes in them impact the conditions for BECCS and biochar deployment. This is done through a literature study and stakeholder interviews.

The interviews were held with nine stakeholders from a wide range of points of views within the NET area. They were kept relatively unstructured to promote a general discussion on the future of BECCS and biochar, instead of gathering answers to specific questions. Therefore, the insight gathered from the interviews is not regarded in this project as a complete picture of the current state of affairs, but rather a valuable addition to the drivers and barriers found in the literature study from the point of view of relevant stakeholders. Appendix 2 provides an anonymised list of the interviewees, along with their areas of expertise.

To answer the third research question, a techno-economic analysis is performed on BECCS and biochar production for scenarios of unfavourable, average or favourable sets of conditions. The scenarios are based on the findings from the first two research questions, and the purpose of them is to simulate different technical and economic conditions for the two technologies.

Because of the uncertain future of climate change, and which tools will be used to combat it, these different scenarios can be useful for analysing several possible outcomes. However, with the wide range of outcomes that may occur comes the challenge of constructing scenarios that span a sufficiently wide range of future developments while at the same time remaining focused enough to be able to draw conclusions.

Inspired by the Scenario Diversity Analysis (SDA) method (Carlsen et al. 2016), the scenarios will be designed to be as diverse as possible, resulting in a large scenario space. The scenario space is however limited to developments where BECCS and/or biochar are at least utilised to an extent where it has a non negligible impact on the Swedish climate targets. The extent to which these technologies will contribute will vary greatly depending on how the uncertainties of the drivers play out, which makes the scenarios focused enough to be relevant while still different enough to make the range of outcomes large.

As mentioned, the scenarios are formed to represent different future conditions for BECCS and biochar, spanning from unfavourable to favourable. The unfavourable scenario is inspired by a future development where the barriers identified in the literature study are the main factor determining the deployment speed, making the technical and economic conditions unfavourable for NETs in general, and in particular BECCS and biochar. Similarly, the favourable scenarios represent a development where the identified barriers are resolved, allowing for favourable technical and economic conditions for the technologies. The average scenario is defined as the mean of the variables in the two other scenarios.

Both BECCS and biochar have uses with various applications and within different value chains. All of these uses have different incomes and expenses depending on which feedstock is used and what products, services and benefits are being produced, which makes modelling them all unrealistic. Instead of accounting for all possible uses, the techno-economic analysis evaluates BECCS and biochar used for heat and power production. To make the results comparable to a baseline, the economic performance of BECCS and biochar is compared to Combined Heat and Power (CHP) plants for a given biomass. This particular usage of the technologies is chosen because of the comparatively large number of projects and initiatives already in progress (Levihn et al. 2019; Jakobsson 2020; Stockholm Exergi n.d.).

The produced biochar is assumed to be of sufficient quality to fulfill the EBC-Agro biochar standard (EBC 2022), meaning that it can be used for soil addition. To preserve its status as a NET, the biochar is also assumed to be used in a way such that the CO_2 locked in it remains for the full estimated duration. This, for example, means that biochar that is combusted to produce energy is excluded, since the carbon atoms are then released back into the atmosphere.

2.1 Modelling

A discounted net present value (NPV) analysis is performed to evaluate the economic performance of BECCS and biochar systems. The NPV is defined as the sum of the benefits minus the sum of the costs of a system over a period of time, and therefore reflects the value of a project that is expected to operate into the future. The NPV is therefore a commonly used metric for assessing the economic performance of investments in BECCS, biochar and CHP (Lehmann & Joseph 2015; Woolf et al. 2016; Linde 2017; Haeldermans et al. 2020). A positive value indicates a positive economic investment over the project lifetime, making an investment in it beneficial. A negative value – on the other hand – means that the costs outweigh the incomes, making the investment undesirable (Lehmann & Joseph 2015). Equation 1 shows the formula used to calculate the NPV.

$$NPV_{NET} = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+i)^t} \qquad 1$$

Where t is the time, N is the total time, C_t is the total costs at time t, B_t is the total benefits at time t, and i is the discount rate (Woolf et al. 2016).

The energy and mass balances of BECCS, biochar and CHP respectively are first defined and modeled. The unfavourable, average, and favourable scenarios are then defined by the deployment rates, as well as the carbon, biochar, feedstock, investment and operating prices. These scenarios are used as input in the NPV analysis to calculate a span of economic outcomes depending on the future conditions for BECCS and biochar.

The results for BECCS are then compared to a business as usual reference case – defined as using the same amount of feedstock used in the scenario, but in a regular biomass CHP plant instead of a BECCS/biochar plant – by subtracting the business as usual NPV from the NPV of the NET for each given scenario (see equation 2).

$$NPV' = NPV_{NET} - NPV_{ref} \qquad 2$$

This calculates the economic difference between maintaining an existing CHP plant and either retrofitting it with CCS technology, or replacing it with a biochar plant, with the same feedstock capacity. Note that since the amount and type of feedstock is the same in both NPV_{NET} and NPV_{ref}, equation 2 effectively removes the dependence on feedstock and deployment rates, making NPV' a value of the comparative economic performance between NETs and CHP systems per unit of captured carbon, for a given amount of feedstock. This makes NPV' a more generalised formula compared to NPV_{NET}, since conclusions can be drawn about the two NETs in comparison with CHP plants regardless of what type, and how much feedstock is used.

2.2 Delimitations

While there are many system types, methodologies, scopes and perspectives that could be included in an analysis of BECCS and biochar, delimitations will always be necessary.

In this report, only BECCS and biochar production used for the production of energy, carbon credits and biochar are considered. This means that Bioenergy with Carbon Capture and Utilisation (BECCU) is not included. One reason for this is to keep the analysis focused and straightforward in order to provide useful results. Another reason is permanence. Both BECCS and biochar are assumed to have a permanence of at least 100 years in this thesis (Söderqvist 2019; Puro.earth 2022), and the levels of negative emissions are expressed as the captured emissions expected to remain after 100 years. By including BECCU, various levels of permanence – some with doubtful claims of achieving negative emissions – would have had to be taken into consideration.

Sweden is the country that is being examined in this report. However, due to the international nature of many policies connected to climate, emissions and carbon capture, relevant international legislation is also included in the analysis. Furthermore, the BECCS value chain will likely require cooperation between Sweden and its neighboring countries, which means that other countries are included when discussing the practical implementation of BECCS. However, when international perspectives are considered, it is always within the context of BECCS and biochar deployment in Sweden.

Extreme events such as wars, natural disasters or major political shifts are not considered when determining the barriers and drivers. This includes the current war escalation in the Russo-Ukrainian war. However, while this is not included in the actual analysis, the severity and relevance of the ongoing conflict is hard to ignore. The Russo-Ukrainian war therefore has a section dedicated to it in the Discussion chapter, where the implications of the war on the conditions for BECCS and biochar are discussed using the results of the sensitivity analysis.

3. Theory and background of BECCS and biochar systems

This chapter provides the background and necessary context and theory needed for the rest of the report. Sections 3.1 and 3.2 are brief technical overviews of BECCS and biochar technologies, and sections 3.3 and 3.4 cover the current national targets and stakeholder commitments to NETs in general, and BECCS and biochar in particular.

3.1 Technical overview of BECCS

BECCS is an umbrella term for technologies that capture CO_2 emissions from combustion of biofuel and store them in geological formations. These can be broadly divided into pre- and post-combustion technologies.

With pre-combustion, the CO_2 is separated from the fuel before combustion (Gough et al. 2018). This is done through a gasification process (as per reaction 1) that converts the fuel into synthetic gas (commonly referred to as syngas), which is a gas rich in hydrogen and carbon monoxide.

$$\begin{gathered} 4CH + 2H_2O + O_2 \rightarrow 4H_2 + 4CO \\ \mathit{Fuel + water + oxygen \rightarrow hydrogen + carbon\ monoxide} \end{gathered} \qquad 1$$

The carbon monoxide is then converted to CO_2 and hydrogen in a shift reactor, where the carbon monoxide reacts with steam according to reaction 2. This further increases the hydrogen content of the gas and removes the carbon monoxide.

$$\begin{gathered} CO + H_2O \rightarrow CO_2 + H_2 \\ \mathit{Carbon\ monoxide + water \rightarrow carbon\ dioxide + hydrogen} \end{gathered} \qquad 2$$

The CO_2 is then separated from the gas and sent for geological storage, leaving a high purity hydrogen gas that can be used directly in a gas turbine, or further processed for other uses.

Post-combustion is applied – as the name suggests – after combustion, where the CO_2 is separated from the flue gas, and sent to a storage location. Unlike pre-combustion, little to no change is needed in the actual plant for post-combustion, which means that it can be retrofitted on existing power plants (Gough et al. 2018). This difference becomes a fundamental one when assessing practical feasibility and techno-economic aspects, since pre-combustion would require a new plant to be built, while post-combustion does not have that restriction. For this reason, only post-combustion will be assessed in detail in this project.

Different types of post-combustion technologies are mainly defined based on combustion conditions and what type of flue gas separation is used. The two most prominent methods of separation are wet scrubbing and membrane separation, with wet scrubbing likely being the most relevant and established of the two in the short to medium term (Zhao et al. 2010; Gough et al. 2018).

Wet scrubbing involves letting the flue gas come into contact with a solvent that reacts to the CO_2 in the gas in an absorber column. The solvent – now rich in CO_2 – is led away to a stripper column for regeneration, resulting in a high purity stream of CO_2 that only needs to be condensed before being ready to be sequestered, as well as a regenerated solvent that can be led back to the absorber column for flue gas CO_2 separation (Gough et al. 2018). Reaction 1 shows an example of a wet scrubbing process, which uses hot potassium carbonate as a solvent. The reaction occurs from left to right in the absorber column, and from right to left in the stripper column (Levihn et al. 2019).

$$\begin{gathered} K_2CO_3 + CO_2 + H_2O \rightarrow 2HCO_3^{-1} + 2K^+ \\ \mathit{Potassium\ carbonate} + \mathit{carbon\ dioxide} + \mathit{water} \rightarrow \mathit{bicarbonate} \\ + \mathit{potassium} \end{gathered} \tag{3}$$

The efficiency of the separation method depends on which solvent is used. However, significant leaps in solvent efficiency can only happen if radically different separation chemistries are found, which is unlikely in the short to medium term. Therefore, energy penalty improvements from technical advances in separation methods is only expected to happen incrementally (Linde 2017).

The higher the N_2 content of flue gas is, the more energy is required to separate the CO_2 from it (Abu-Zahra et al. 2013). If pure oxygen is used in the combustion the N_2 fraction is reduced drastically, which results in a flue gas with a high enough CO_2 purity to not require any CCS technology (Linde 2017). After condensation of the flue gas to remove moisture, the CO_2 is simply compressed and can then be transported to a geological storage location (Gough et al. 2018). Using pure oxygen in this manner is called oxyfuel combustion, and because of the high N_2 fraction in biomass flue gas, it can be beneficial to use it for BECCS application in particular

(Linde 2017). Figures Figure 1 and Figure 2 show simplified flowcharts over air fired and oxyfuel BECCS processes.

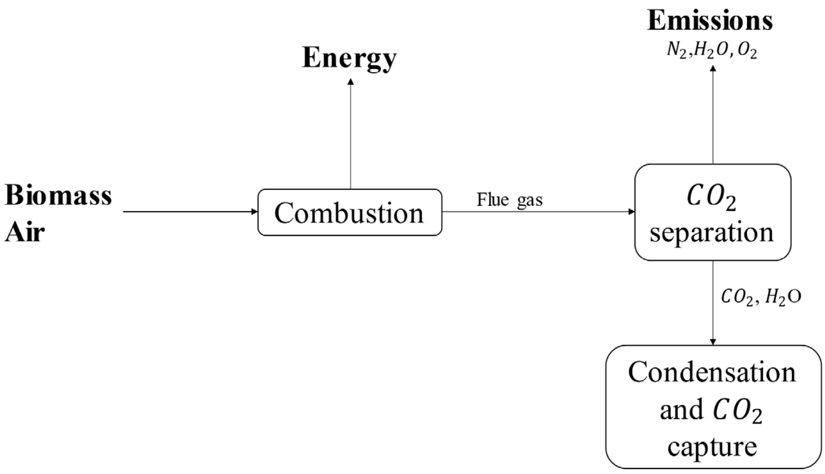

Figure 1. General overview of an air fired post-combustion BECCS system

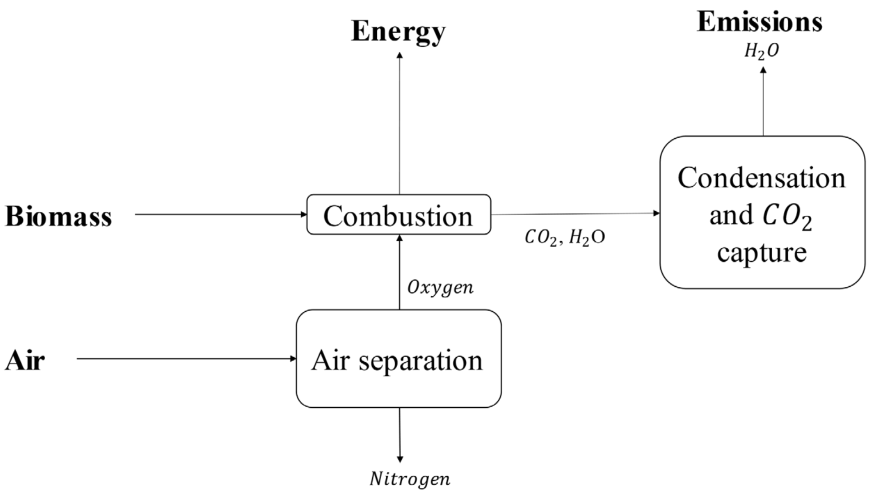

Figure 2. General overview of an oxyfuel post-combustion BECCS system

As Figure 2 illustrates, a gas with a high CO_2 purity only requires condensation and compression, and does not require a separation step such as the one in Figure 1. This makes the capture process significantly easier (Gough et al. 2018). While oxyfuel is a method of achieving this, gas flows with a sufficiently high CO_2 content for easy capture and storage can be found in several industrial processes such as the

CO_2 released from the fermentation process in ethanol production (Tanzer et al. 2021).

However, since the BECCS systems analysed in this thesis are from combustion for energy production, the flue gases are not pure enough to be able to bypass oxyfuel combustion or flue gas separation. The increased cost of this type of BECCS means that the plants it is applied to need to be sufficiently large to be economically viable (SOU 2020). Therefore, the scale of BECCS in this analysis is limited to large power plants. While there is no hard limit to the minimum size required for a BECCS installation of this type to be feasible, a general rule of thumb of point emissions of at least 0.5 $MtonCO_2y^{-1}$ is used in the national case study of NETs launched by the Swedish government (SOU 2020), and is therefore also used in this analysis.

Because of the electricity needed in the CCS process, the net energy production of a plant with CCS technology will be lower than plants without it regardless of which method and feedstock is used. This energy penalty differs for each (BE)CCS system, but will largely depend on which type of separation method is used, and to what extent residual heat can be utilised (Gustafsson et al. 2021).

Since part of the electricity is needed in the separation of flue gas (or air in the case of oxyfuel), plants without heat production or recycling are impacted the most by the energy penalty. The overall efficiency of CHP plants is therefore less affected than that of a conventional power plant (Gustafsson et al. 2021), with different sources suggesting total energy penalties ranging from -3 to -7% (Gustafsson et al. 2021) to negligible (SOU 2020), or even slightly positive (Levihn et al. 2019), in systems where the residual process heat from the separation is utilised. Section 5.2 details the energy penalty used for this project's techno-economic calculations.

Due to the energy penalty and the transport and storage of the CO_2, the value chain energy balance becomes a more important factor to consider when evaluating BECCS compared to regular CHP or power production. An unfavourable combination of feedstock transport and moisture content, pretreatment energy costs and yield may result in a net negative value chain energy balance, which could threaten energy security when applied to a large scale energy system (Fajardy & Dowell 2018).

There are currently very few BECCS systems running, with only one large.scale BECCS plant in Europe (Bey et al. 2021).

3.2 Technical overview of Biochar

Biochar is a carbon rich product with uses including soil application, water management, and other environmental management applications. It is defined by the International Biochar Initiative (2018) as:

> … a solid material obtained from the carbonization thermochemical conversion of biomass in an oxygen-limited environments. In more technical terms, biochar is produced by thermal decomposition of organic material (biomass such as wood, manure or leaves) under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C). This process mirrors the production of charcoal, which is perhaps the most ancient industrial technology developed by humankind. Biochar can be distinguished from charcoal—used mainly as a fuel—in that a primary application is use as a soil amendment with the intention to improve soil functions and to reduce emissions from biomass that would otherwise naturally degrade to greenhouse gases.

A key property of biochar is its stability, which allows it to persist in soil for a much longer time compared to the residence time of the uncharred biomass (Lehmann & Joseph 2015). This characteristic is what makes biochar interesting as a NET, since the carbon stored in the biochar remains locked in for a long period of time with very little decomposing, which leads to carbon sequestration with high enough permanence to make it a potential NET (Lehmann & Joseph 2015; Smith 2016; SOU 2020). However, the permanence will vary depending on the characteristics of the biochar and the soil type, making the soil stability of biochar an uncertain variable that is difficult to evaluate because of the long timescales involved (Ding et al. 2017; Joseph et al. 2021). While it is difficult to find the exact permanence of biochar in soil, there is a sufficiently good understanding of it to be able to assume a permanence at centennial timescales (Wang et al. 2016; Söderqvist 2019; Puro.earth 2022). This makes its permanence shorter than the millennial time scale of BECCS (Bey et al. 2021), but still beyond the timeframe of the political targets such as those set out by the Swedish government (Regeringskansliet 2019). Along with the direct climate benefit of long term CO_2 sequestering by soil application of biochar, additional downstream environmental benefits such as reduced usage of fertilisers and soil N_2O-emissions may be attributed to it. These effects, however, have a relatively limited and highly uncertain climate benefit (Azzi 2021).

Biochar production is based on biomass pyrolysis, which is a thermochemical process that historically is well known and utilised for several purposes (Bey et al. 2021). Biomass pyrolysis can be defined as the "thermochemical decomposition of a fuel at elevated temperatures and without the addition of external oxygen" (Weber & Quicker 2018), and produces three products: permanent gases, condensable gases, and a carbonaceous solid residual, as well as residual heat that can be used for energy purposes (Woolf et al. 2010). The ratio of the three products primarily depends on the pyrolysis temperature, residence time, feedstock, and heating rate (Weber & Quicker 2018).

For biochar production, the primary focus is on the carbonaceous solid residue. This generally involves low heating rates and long residence times (Weber & Quicker 2018). The organic carbon content of biochar is the carbon that remains in the biochar after volatile components are excluded. Ths value increases with higher pyrolysis temperatures, approximately following the pattern of equation 3.

$$F_{C,daf} = 0.93 - 0.92e^{-0.0042T} \tag{3}$$

Where $F_{C,daf}$ is the organic carbon mass fraction on a dry, ash free mass basis, and T is the pyrolysis temperature in °C (Woolf et al. 2021). While higher temperatures generally lead to a higher carbon content – with temperatures well over 800°C needed to reach a $F_{C,daf}$ over 90% according to equation 3, the pyrolysis temperature for biochar production generally does not surpass 700°C in practice (Weber & Quicker 2018)

The pyrolysis gas is usually combusted in the pyrolysis plant to supply heat to the process (as well as useful residual heat), but there are examples of plants where the oil and/or the non-condensable gas is saved (Pyrotech 2020).

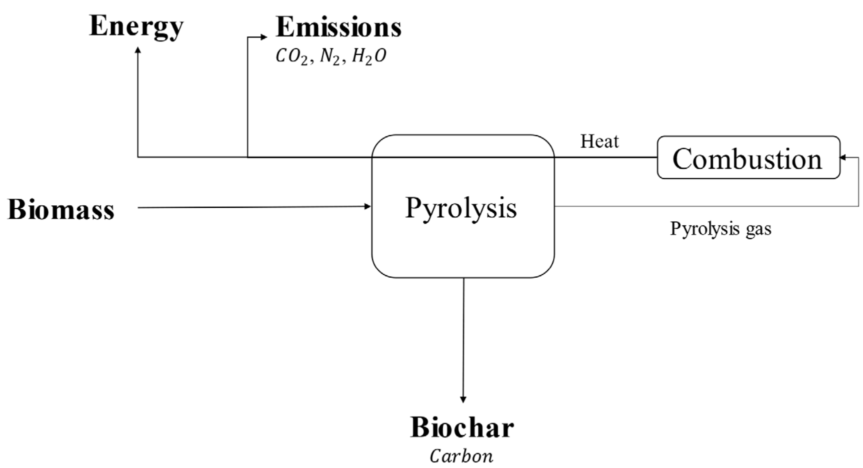

Figure 3. Overview of biomass pyrolysis for the production of biochar

Pyrolysis can be a part of a very simple or a technologically advanced system. An example of simple pyrolysis processes is the historical production of charcoal through charcoal piles, where biomass was combusted in a low oxygen environment such as a depression or under a layer of soil. This technique has been known and used by humans for thousands of years (Westerlund 1996).

One advantage of biochar production is that it can be applied at several different scales. Micro-scale cook stoves that produce biochar (Gitau et al. 2019) and large scale district heating plants are both possible examples of systems applicable to biochar production (Azzi et al. 2019), which makes it a technology that can be a part of a wide range of different circular flows and applied to many different waste streams (Cárdenas-Aguiar et al. 2022; Venkatesh et al. 2022; Zungu et al. 2022). However, in the simple cases of biochar production, the possibility to make use of the produced energy is limited or non-existent. There are however modern reactors that utilise pyrolysis to generate thermal (and sometimes electrical) energy, as well as by-products such as biochar and bio-oil (Biomacon 2020; Pyreg n.d.; Rainbow Bee Eater n.d.). Figure 3 shows a typical layout for an energy generating pyrolysis plant with biochar production, which represents the type of biochar system that is being analysed in this project. These types of plants can be found in over 100 installations across Europe, with sizes up to 5 000 ton of annual biochar production. The number of installations in Europe is expected to rise to around 150 in 2022, collectively capturing about 100 000 $tonCO_2y^{-1}$assuming that all produced biochar gets used for applications result in negative emissions (Lerchenmüller 2022).

A significant part of the energy in the feedstock is stored in the biochar, which means that the useful energy produced from the pyrolysis process is lower compared to combustion, but with the advantage of also producing biochar. In other words, most of the energy penalty for biochar production compared to combustion is the energy stored in the biochar. The amount of useful energy output and the energy content of the biochar varies depending on system configuration and feedstock characteristics, but in general twice as much biomass is needed for the same amount of heat from normal combustion (Woolf et al. 2014).

3.3 Current national emission targets

In June 2017 the Swedish parliament passed a framework with the purpose of ensuring long term and stable climate politics across party lines and terms of office (Regeringskansliet 2019). It states in law that the government's politics needs to be in line with the climate goals set in place by the framework, which means that future climate policy needs to be in line with it – likely making it highly formative for the future of BECCS and biochar. The framework outlines the actions Sweden is planning to take to fulfil the national and international climate goals.
These are to:

- Work internationally to limit the global temperature increase to 2 degrees celsius, and make efforts to keep it below 1.5
- Not have any net greenhouse gas emissions by 2045, and to achieve negative emissions after 2045
- Achieve at least 85% emission reduction within Sweden out of the total mitigation , which means that at most 15% of the reduced emissions can come from "supplementary measures". This corresponds to 10.7 $MtonCO_2e/y$.

These supplementary measures can be different types of NETs, but primarily reforestation, afforestation, soil carbon sequestration BECCS and biochar. Green investments outside of Sweden is also mentioned as a potential supplementary measure. This is not a NET, but rather a way of achieving emission reductions by contributing to verified reductions in other countries. An investigation was launched to come up with a strategy for how Sweden can use the supplementary measures to help achieve the climate goals defined in the framework. The resulting report, “The pathway to a climate positive future – strategy and action plan for achieving negative greenhouse gas emissions after 2045” (SOU 2020) (from here on referred to as “SOU2020:04”), is a roadmap to the 15% supplementary measures goal. In it, NETs that are expected to play a role in the coming decades are evaluated, and their possible contribution to the targets estimated. Table 3 summarises the road to 15% supplementary measures by 2045.

Table 1. Possible contribution of various NETs to achieve the national targets set by the Swedish parliament, and the total volume expected (SOU 2020).

	$2030\ [MtonCO_2e/y]$	$2045\ [MtonCO_2e/y]$
Increased carbon sink in forests and land	1.2	2.7-?
BECCS	1.8	3-10
Verified emission reductions in other countries	0.7	0-Very great
Other technologies	-	0-?
Total volume	3.7	10.7

Biochar is not presented as its own category in Table 1. Instead, it is included in the "Increased carbon sink in forests and land" category, with a potential of approximately 1 $MtonCO_2e/y$. Biochar is considered having a somewhat limited potential due to the small agricultural land area in Sweden compared to other countries. BECCS is believed to have a possible contribution of 3-10 $MtonCO_2e/y$ by 2045 (SOU 2020:90). Similarly to the national climate framework in Sweden, the EU has a goal written in law of reaching net zero, and eventually negative emissions in line with the Paris agreement (European Commision 2021).

3.4 Business and industry commitment

In 2015 the Swedish government established the fossil free Sweden initiative, which aims to facilitate a faster transition to fossil free business and industry, and ultimately reaching the 2045 national target. As a part of this initiative, business and industry sectors which combined cover around 70% of Sweden's territorial emissions have made roadmaps detailing the steps they plan on taking to reach the 2045 carbon neutrality goal (Fossil Free Sweden 2020). Fossil Free Sweden is an example of the practical initiatives taken as a consequence of the national target, which suggests that stakeholder involvement and interest depends on the overarching targets of the nation. While the commitments are not legally binding, they do provide goals for the businesses within the sector to work towards.

Table 2 lists the sector roadmaps and summarises their planned usage of CCS, BECCS and biochar. CCS is included because of the shared infrastructure with BECCS, which makes stakeholder interest in CCS relevant to BECCS.

Table 2. Summary of the business and industry sector roadmaps from the Fossil Free Sweden initiative rely on CCS, BECCS or biochar. Sectors where neither BECCS nor biochar are mentioned at all are not included. All of the roadmaps come from the Fossil Free Sweden website (Fossil Free Sweden n.d.). An asterisk(*) means that the technology is mentioned, but in a way that requires further clarification, which is provided in this section. Appendix 1 has a complete table with all roadmaps and clarifications included.

Roadmap	***CCS***	***BECCS***	***Biochar***
Cement industry	Yes	No	No*
Concrete industry	Yes	No	No
Construction and civil engineering sector	No*	No	No
Digitalisation consultancy industry	No*	No	No
Electricity sector	No	Yes	No
Fast moving consumer goods industry	No	No	No*
Gas sector	Yes*	No	No*
Heating sector	No	Yes	Yes
Mining and minerals industry	Yes	No	No*
Petroleum and biofuel industry	Yes	Yes	No
Steel industry	No*	No	No*

As we can see, BECCS plays a part in three roadmaps, and biochar is a part of one. The electricity sector, heating sector, as well as the petroleum and biofuel industry include BECCS in their plans to become carbon neutral by 2045, while the heating sector is the only sector that includes biochar production as a NET technology. However, the mining and minerals industry, and the steel industry include biochar for uses of biochar that do not result in negative emissions. The heating sector is therefore the only sector that intends to use both technologies.

The cement, fast moving consumer goods, and the gas sectors all mention biochar, but do not include the NET as a part of their own roadmaps. They instead directly or indirectly mention biochar or pyrolysis and its usefulness in other sectors, or as a technology that might have uses within their own sector in the future.

Both the mining and minerals and the steel industries include biochar in their roadmaps to carbon neutrality, but not as a NET. Instead, they plan on using the biochar product as an energy source in parts of their processes as a replacement for fossil coal. The future biochar demand in the steel industry is estimated at 1-1.5 TWh. Note that biochar used to produce energy does not result in negative emissions, which - depending on the abundance of biochar - could lead to competition between negative emissions and energy production. This also means that the biochar described in these roadmaps does not match the definition of biochar (section 3.2), since it is not used for soil amendment or other environmental management applications. The characteristics and production of this "biochar"/bio-coal will however have similar characteristics to regular biochar, which likely makes its development relevant to the future of biochar in a similar way that CCS is relevant to the future of BECCS (see the description on Table 2).

The gas sector includes CCS as a potential technology in their roadmap, but states that it has a low priority compared to other alternatives. The steel industry mentions that CCS has been considered, but that it is not deemed relevant to them. The construction and civil engineering sector also mention CCS as a potentially useful technology, but not as a part of their own sector's roadmap to carbon neutrality.

Additionally, some sectors bring up deployment barriers for their planned technology. The electricity sector includes BECCS in their roadmap, but stresses that sufficient economic policy incentives are required to make it happen. The heating sector also includes BECCS in theirs, but highlights the transport and storage infrastructure of captured carbon as a barrier. Lastly, the steel industry mentions that the feedstock and process requirements to produce biochar with the characteristics they require is under investigation, and that the lack of knowledge of the properties of biochar is an uncertainty.

Notably, the digitalisation consultancy industry is the only sector to mention either technology in a negative light, emphasising the risk of over-reliance on CCS to possibly stand in the way of actual emission reduction efforts.

4. The barriers and drivers to BECCS and biochar deployment

In this chapter, the key drivers and barriers identified through the literature study and the stakeholder interviews are presented, followed by a discussion of their possible future developments.

4.1 System expenses and incomes

As described in section 3.1 the energy penalty of installing CCS technology on a heat and/or power plant results in a reduced energy production, which translates to less energy sales compared to if CCS had not been installed. Maximising the energy efficiency and minimising productivity and economic loss has therefore been identified as an important factor for stakeholders looking into BECCS implementation (Rodriguez et al. 2021). The loss in energy production becomes even more important for biochar production, since the energy penalty of it is higher than that of BECCS (Woolf et al. 2016)

On top of the economic loss from the energy penalty, the investment in the actual technology and its surrounding infrastructure is considerable. A challenge specific to BECCS is the need for the whole value chain/infrastructure to be in place from the beginning, which makes initial investments large and uncertain (Fridahl et al. 2020). As the number of BECCS systems operating increases, the capture and storage costs are expected to decrease. On the other hand, as the demand for biomass increases the feedstock price is expected to increase (Bey et al. 2021).

As covered in section 3.1, the captured CO_2 from CCS plants (which includes BECCS plants) is stored in geologic formations. The infrastructure and preparation of CCS storage locations is costly and takes considerable time (SOU 2020). This means that the cost of BECCS to a large extent depends on the cost of CO_2 transport and storage (Levihn et al. 2019). Additionally, not all geological formations are suitable for storage. In fact, places with an abundance of biomass rarely have suitable storage locations nearby, which means that CO_2 often will need transportation over large distances – and often across country borders - to be stored. This makes geological CO_2 storage a global issue (Fajardy et al. 2018).

Because of the early stages of development of the biochar industry, the costs of biochar production is highly volatile and uncertain, making it largely dependent on the method being used (Lehmann & Joseph 2015). For example, the economics of biochar still varies greatly depending on factors such as labour costs and degree of mechanisation, which makes estimation of costs per tonne CO_2 difficult to pinpoint, and likely to change in the future (Fuss et al. 2018). Since biochar is to be sold as a negative emission as well as a product with useful applications, the income of a biochar system will depend on the energy and carbon price, as well as the value of the benefits of the biochar product (Woolf et al. 2016).

Finding ways of compensating for the additional costs that come with BECCS and biochar is considered a significant barrier in research and among stakeholders (Fridahl et al. 2020; SOU 2020; Negem 2021; Interviewee A 2022; Interviewee B 2022; Interviewee D 2022; Interviewee E 2022; Interviewee F 2022). When comparing BECCS and biochar to traditional energy production the sources of income are the compensation received for the CO_2, as well as the sales of the biochar in the case of biochar production. These two incomes need to make up for the expenses if the NETs are to become economically competitive with CHP (Woolf et al. 2016).

4.2 Regulations and incentives

As established in section 4.1, neither BECCS nor biochar is economically viable without methods of compensating for the extra costs of the technology. In scenario making, a high CO_2-price can be seen as an indicator of ambitious climate action (IPCC 2014; Fuss et al. 2018:27). This could be from voluntary markets – of which examples such as Puro.earth (Puro.earth 2021c) already exist - and/or from regulations and policy incentives.

While the nature of the economic framework is up for debate, what remains clear from the literature study and stakeholder interviews is that the challenge of making BECCS and biochar economically viable is one of the largest – if not the largest – uncertainty for their future (SOU 2020; Interviewee A 2022; Interviewee B 2022; Interviewee C 2022; Interviewee D 2022; Interviewee E 2022; Interviewee F 2022).

Regulatory barriers are currently slowing down the deployment of NETs. This is especially evident for BECCS, where regulation currently prohibits or severely limits the possibility for transport and geological storage of carbon in the countries where storage is feasible for Sweden. Furthermore, establishing local storage sites in Sweden is expected to take many years, possibly not being ready until 2040. Relying on international storage will therefore be the only realistic option for

BECCS in the short to medium term, which emphasises the need for regulatory barriers to be lifted if the technology is to be widely used in Sweden (SOU 2020).

There are also very few, if any, incentives or policy in place supporting negative emissions today (SOU 2020), and the lack of standardised and widely accepted systems of accounting for and trading of negative emissions is a significant barrier to the deployment of NETs (Fridahl et al. 2020; Fajardy et al. 2021; Negem 2021; Rodriguez et al. 2021; Interviewee D 2022; Interviewee F 2022).

NETs are usually associated with large investments, land use changes, and long timeframes. This makes stable conditions as well as clear and predictable targets important to attract project owners (SOU 2020). The change in policy should therefore be clear, gradual and as predictable as possible for it to be successful in creating favourable conditions for BECCS and biochar.

As with most cases of early adopters of new technology, a certain degree of risk is inevitable initially. This will require decision makers to be daring and bear the risk until a stable market has been shaped if NETs such as BECCS and biochar are to become important components in the Swedish energy system (Fridahl et al. 2020).

4.3 Biomass availability

Biomass – being an attractive and renewable potential substitute to fossil fuels – is expected to play a vital role in climate change mitigation efforts in the EU and internationally (SOU 2020; European Commision 2021). However, the extraction of biomass impacts the biodiversity and the overall functioning of local ecosystems, and unless the production takes the value chain emissions the pre-existing natural carbon sinks into consideration, the emissions and ecosystem impacts may well result in it not being considered a renewable resource (Östman 2019). This makes the amount of biomass available for bioenergy dependent on how much can be extracted in a sustainable way, which in turn depends on the consensus regarding what is deemed sustainable (Andersen et al. 2021). The amount of biomass available for BECCS and biochar directly affects the extent to which they can be utilised (Bey et al. 2021), which means that the EU and national policy on biomass will have an effect on the future for BECCS and biochar.

Since Sweden has had large amounts of biomass available throughout history, the country has a long tradition of bioenergy usage. Today, Sweden has a large bioeconomy and several significant biogenic point emissions in the industry and energy sectors. The combination of rich bioenergy resources and already established infrastructure and knowledge of its usage makes Sweden a country ideally suited for BECCS, and to some extent biochar (SOU 2020). An estimation of the maximum additional domestically available biomass for bioenergy use in Sweden, when taking into consideration the todays criteria for sustainability, estimates an additional 41-59 TWh/y by 2030, and 56-79 TWh/y by year 2050 (Börjesson 2021). The biomass energy supply was 141 TWh in 2020 (Swedish Energy Agency 2022), which would mean that the roof of available bioenergy (assuming that Sweden's biomass imports remain on today's levels) is 220 TWh/y by 2050. However, the biomass available for bioenergy in the future will still largely depend on EU and national energy, forestry and agricultural policy (Börjesson 2021). For example, a report by The Swedish Society for Nature Conservation (Östman 2019) proposes a total bioenergy use of 132 TWh/y by 2040 to fit their more stringent definition of sustainable biomass, which includes a total halt in imported biomass for bioenergy. This would be a slight decrease from today's levels of 141 TWh/y. Figure 4 illustrates the historical bioenergy use in Sweden, along with the estimations made by Östman (2019) and Börjesson (2021) , as well as a linear approximation based on the bioenergy usage trend from 2010-2020 for comparison.

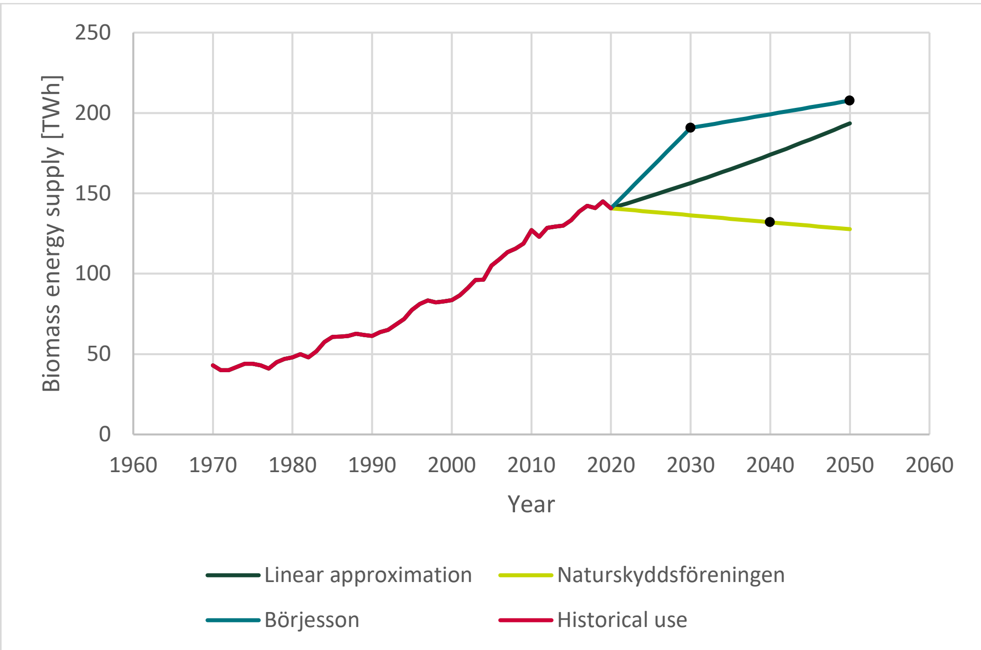

Figure 4. Historical bioenergy use in Sweden combined with future estimations made by The Swedish Society for Nature Conservation (Östman 2019) and Börjesson (2021), as well as a linear approximation based on the bioenergy usage trend from 2010-2020 for comparison. The black points are the data points from the estimations.

4.4 Technical maturity

Out of the widely established NETs, BECCS is considered having a comparatively high technical maturity. It is not deployed at scale yet, but readiness is moderate for deployment (Bey et al. 2021; Shahbaz et al. 2021; Lefvert et al. 2022). However, while technical factors rarely are mentioned as barriers for BECCS deployment, the lack of practical large scale examples can be considered a barrier, since unforeseen technical challenges may arise once the large scale technical and infrastructural systems start operating (Rodriguez et al. 2021). Because of this lack of practical experience, calling BECCS to be a “mature” technology may give the false impression of it being ready for large scale deployment. Furthermore, the large infrastructure that is needed for the transport and storage of the captured carbon makes deployment a large undertaking, causing long lead times (Interviewee D 2022). The lack of practical experience combined with the long lead times and complex infrastructure can therefore be considered a barrier to deployment of BECCS in the short to medium term.

The additional environmental benefits of biochar makes it an attractive technology from an environmental perspective. Its positive impact on soil health has the potential to contribute to a more sustainable and productive agriculture sector, while also generating energy and negative emissions (Ding et al. 2017; Enell et al. 2020). The environmental benefits of biochar can therefore be considered a potential driver for its deployment. However, the ways in which biochar interacts with soil, and how this interaction varies depending on the characteristics of the biochar and the soil type, is still partly uncertain (Tammeorg et al. 2017). While the overall effect of biochar to the soil water retaining capacity and microbial activity is expected to be positive (Fransson et al. 2020), several knowledge gaps remain (Bey et al. 2021). For example, in SOU 2020:04 biochar is considered a NET with a substantial realisable potential, but with the lack of information being a factor to bear in mind when assessing its usefulness (SOU 2020).

Because of these uncertainties, biochar and soil interactions is a prioritised area within the biochar research community. This uncertainty is biochar-soil interaction can therefore also be considered a barrier to large scale deployment until further research has been made (Bey et al. 2021; Interviewee B 2022).

These uncertainties are however not serious enough to hinder it from being considered a promising NET. For example, investment aid can be granted from the The Swedish Environmental Protection Agency “Klimatklivet”, which is an investment aid scheme for green transition technologies (Naturvårdsverket 2022a). Biochar is also part of the ongoing legislative process of including carbon dioxide removal (CDR) in the EU climate mitigation legislation (European Parliament 2021). In contrast to BECCS, biochar is also a technology that already sees commercial use in Sweden, primarily as a soil additive for urban landscaping (The City of Stockholm 2020).

4.5 Deployment potential

Since Sweden has had large amounts of biomass available throughout history, the country has a long tradition of bioenergy usage. Today, Sweden has a large bioeconomy and several significant biogenic point emissions in the industry and energy sectors. The combination of rich bioenergy resources and already established infrastructure and knowledge of its usage makes Sweden a country ideally suited for land based NETs such as BECCS and biochar (SOU 2020; Interviewee C 2022; Interviewee F 2022).

As established in section 3.1, efficient use of the BECCS applications that are being analysed are currently limited to large power plants. This is mainly due to the high investment cost, which makes large systems more effective economically. There is however no hard limit to the minimum size required for a CCS installation to be feasible, but a general rule of thumb of point emissions of at least 0.5 $MtonCO_2y^{-1}$ is used in SOU2020:04 (SOU 2020), and is therefore also used in this analysis. The total biogenic emissions from facilities exceeding 0.5 $MtonCO_2y^{-1}$ in Sweden is approximately 26 $MtonCO_2y^{-1}$, most of which can be found in the paper and pulp industry. Out of these emissions 3-10 $MtonCO_2y^{-1}$ is expected to be captured by BECCS systems by 2045 (SOU 2020). The storage of the carbon is expected to primarily be outside of Sweden since establishing local storage sites in Sweden is expected to take many years, likely not being ready until 2040. Relying on international storage will therefore be the only realistic option for BECCS in the short to medium term (SOU 2020), which could become a significant deployment barrier if international storage becomes financially, technically, or politically unfeasible.

While the transport and storage of BECCS is largely an infrastructural problem, one can make the argument that the storage of biochar to an extent is a societal problem. In order for it to be used, biochar and its applications need to be widely known by relevant stakeholders such as farmers, which in turn relies on training and knowledge sharing among them (Bey et al. 2021). However, since the deployment is limited by the demand of biochar, physical factors such as land area suitable for biochar application ultimately sets the upper limit . Due to the comparatively small amount of agricultulture in Sweden, the upper limit to the total biochar demand could be low compared to many other countries (SOU 2020). Yet the usefulness of biochar extends beyond use within the agricultural sector, which potentially increases the future demand for biochar. Some examples of alternative uses include the extensive usage of biochar within the urban landscaping sector (The City of Stockholm 2020), the creation of carbon neutral or negative building materials (Biokolprodukter 2021), stabilising of currently polluted soils (Söderqvist et al. 2021), and to increase the productivity and carbon sequestering of forests (Grau-Andrés et al. 2021). This makes the future demand of biochar potentially high enough for there to be a constant demand for it for the foreseeable future.

4.6 Public and stakeholder opinion

The public opinion on NETs in general, and BECCS in particular, has the potential to be a big driver or barrier to deployment. For example, the demand from customers (both private and businesses) for negative emissions is highly important to establish voluntary carbon markets, and the current lack of demand was identified as a "considerable barrier" in a study examining Swedish and Finnish company perspectives on BECCS (Rodriguez et al. 2021).

The public opinion also impacts the way in which policy is formed. In 2021 – for example - the debate on bioenergy from forestry gained much attention, with mutually exclusive narratives on the sustainability of the current use of forestry being advocated by different sides (Andersson 2021; van der Spoel et al. 2021). These narratives are also mirrored among the political parties in the Swedish government (see for example Dalunde & Holmgren (2022) and Polfjärd (2022).

In addition to the public opinion on issues related to BECCS and biochar shifting, decision makers need to consider the social aspects from the very beginning, since societal participation is vital for acceptance (Fridahl et al. 2020).

As established in section 3.4, all sectors that are part of the Fossil Free Sweden initiative except one that mention CCS, BECCS, or biochar have a positive view of the technologies, and eight sectors intend on using one or more of them to become carbon neutral by 2045. This could be considered a driver for both technologies, since the sector roadmaps show the general goals that the sector is striving to achieve.

A common critique of CCS and BECCS among opponents is that overly relying on an untested technology that may or may not work is irresponsible and dangerous, which the industry roadmaps have been criticised for (Lindahl 2020; Wronski 2021). Regardless, the general support of NETs among industries, businesses and in the stakeholder interviews indicate that some form of voluntary markets are likely to continue to exist even if policy incentives are unable to create sufficient incentives for NETs.

4.7 Possible futures for the drivers and barriers

In this section, possible developments of the conditions for BECCS and biochar are explored based on the findings in this chapter. While these developments are not to be regarded as predictions, they do provide context to the scenarios defined in section 5.2 by showing examples of what favourable and unfavourable conditions for BECCS and biochar could look like.

Possible future developments are first discussed for each factor separately. At the end of this section, the developments are categorised based on whether or not they would contribute to creating favourable or unfavourable conditions for BECCS and/or biochar (Table 3).

System costs - Both technologies have an energy penalty compared to CHP, which results in a loss in energy sales. The higher future energy prices are, the larger this loss would become. This is particularly notable in biochar production since the energy penalty is bigger compared to BECCS.

The investment and operating costs of both technologies is also considerable, as well as uncertain due to the early stages of development. This is an especially important factor for BECCS, because of the significant initial investments that need to be made due to its large scale and complex infrastructure.

Regulations and incentives - The current regulatory system and incentives are not sufficient to create a significant demand for NETs. If BECCS and biochar are to contribute to the national targets to the extent that is expected, national and international policy changes are needed.

Failing to find support by not lifting the current regulatory barriers, de-risking investments through transparent, stable and long term policies and incentives, or through other means creating a demand pull will likely lead to policy falling short of making BECCS and biochar attractive NET options. This would be a barrier to both BECCS and biochar deployment leading to unfavourable conditions for them. International cooperation is also necessary in particular to BECCS because of the complex and multinational transport and storage infrastructure necessary.

On the other hand, should the policy incentives and regulations succeed, they could help facilitate a rapid deployment of both technologies, thus becoming a major driver. This makes regulations and incentives crucial, as well as highly uncertain.

Biomass availability – While biomass is theoretically available to significantly increase the usage of bioenergy it is unclear to what extent it is politically and environmentally possible to utilise, since the future biomass available for energy purposes will largely depend on the EU and national energy, forestry and agricultural policies. Because of the reliance on bioenergy in Sweden, it can be assumed to be unlikely that the usage of biomass has decreased drastically by 2045. If a preservational approach to forestry is chosen in the future – as the one proposed by the Swedish Society for Nature Conservation – the available biomass decreases slightly compared to today's levels.

A lower biomass availability could lead to increased biomass prices and also less possibilities for BECCS and biochar to deploy, since they both require more feedstock to compensate for their energy penalties (assuming that the national energy demand increases or remains unchanged). This would possibly hinder the deployment speed of BECCS and biochar, but likely not stop it completely considering the existing reliance on bioenergy in Sweden. Due to the larger energy penalty of biochar compared to BECCS, a low availability of biomass could possibly impact biochar production more than BECCS.

However, the estimated upper limit to the biomass availability by 2045 is significantly higher than today's levels, which could contribute to lowering the biomass prices if utilised. This means that a large-scale expansion of BECCS and biochar is likely possible. That being said, whether or not an increased intensity and/or efficiency of biomass production from the Swedish forests and agricultural land can be considered sustainable remains up for debate.

Technical maturity – The theoretical technical maturity of BECCS is high, which makes it an attractive option compared to other NETs from a technical perspective. However, the lack of practical experience and long lead times may cause most of deployment to fall outside of the timeframe of this report. Biochar is also considered a comparatively mature NET, but the remaining uncertainties surrounding the usefulness and potential negative effects of the biochar product may hinder or speed up its future deployment speed depending on which findings are made in the near future.

Deployment potential – The conditions in Sweden are suitable for both BECCS and biochar because of the established bioeconomy, but because of the relative lack in agriculture the conditions are likely slightly better for BECCS. However, if the necessary international storage infrastructure for BECCS fails, Sweden will have to resort to local geological storage. If this were to happen, it would likely hinder the deployment of BECCS severely.

The large scale required to make the separation of flue gas or air – which is necessary in the applications analysed in this report – will also limit the deployment potential of BECCS.

The additional uses of biochar means that its application is not necessarily limited to use within agriculture, which means that the deployment potential of biochar may not be limited by the available agricultural land.

Public and stakeholder opinion – Public acceptance has the potential to be a driver and a BECCS and biochar depending on how successfully policy manages to include social aspects, and how opinions on forestry and climate ambitions shift on a societal level. The public and stakeholder opinion also matters to the formation and size of voluntary CO_2-markets.

CCS technologies are included in nine, BECCS in three, and biochar three out of the 22 fossil free Sweden roadmaps. Since CCS shares large parts of its infrastructure with BECCS, a large-scale deployment of CCS will also most likely help to facilitate BECCS.

A similar relationship can be found between the steel industry and biochar. Large amounts of bio-coal will be needed to replace the fossil coal used in the steel industry, which could help facilitate a large scale biochar production industry. However, depending on the biomass available, this might cut the amount of biochar available for negative emissions, possibly reducing its potential as a NET.

Table 3. Summary of the future developments that likely would lead to favourable/unfavourable conditions for BECCS and biochar.

Factor	**Unfavourable BECCS**	**Favourable BECCS**	**Unfavourable Biochar**	**Favourable Biochar**
System costs	-Investment and operating costs are higher than anticipated -Infrastructure investment cost too high -High energy and feedstock prices, and low CO_2 prices	-Low investment and operating costs -Low energy prices combined with high CO_2 prices	-Investment and operating costs are higher than anticipated -High energy and feedstock prices, and low CO_2 prices	-Low investment and operating costs -Low energy prices combined with high CO_2 and biochar prices
Biomass availability	-More rigorous sustainability demands on forestry and agriculture -Competing uses for biomass are more attractive	-Increased intensity and/or efficiency of forestry and agriculture	-More rigorous sustainability demands on forestry and agriculture -Competing uses for biomass are more attractive	-Increased intensity and/or efficiency of forestry and agriculture
Regulations and incentives	-Inadequate demand pull measures -Volatile economic conditions	-Lifting of regulatory barriers -Stable and predictable economic conditions -International cooperation -Ambitious carbon pricing	-Inadequate demand pull measures -Volatile economic conditions	-Stable and predictable economic conditions -Ambitious carbon and biochar pricing
Technical maturity	-Unexpected issues when deployed in practice	-No or few issues when deployed in practice	-Usefulness of biochar found to be low	-Additional values of biochar are found to be highly useful
Deployment potential	-Failure to establish CO_2 storage outside of Sweden -Separation technology remains expensive	-CO_2-storage is secured -Small scale BECCS becomes viable	-Lack of markets for biochar	-Several large markets for biochar are established -Medium to large scale biochar plants are viable
Public and stakeholder opinion	-Negative shift in public opinion on biomass or negative emissions -Failure to involve the public in policy making	-Stakeholder initiatives in CCS and BECCS pave the way for more deployment -Established voluntary CO_2-markets	-Negative shift in public opinion on biomass or negative emissions -NET-incompatible uses for biochar are prioritised	-Stakeholder initiatives in bio-coal and biochar pave the way for more deployment -Established voluntary CO_2-markets

5. Conditions needed for BECCS and Biochar deployment

In this section, a techno-economic analysis is performed with scenarios based on the narratives from section 4.7 in order to find suitable conditions for BECCS and/or biochar to become technically and economically viable.

5.1 System definition

As described in section 2, a discounted NPV analysis is used to evaluate the performance of BECCS and biochar systems. To calculate the NPVs defined in equations 1 and 2, the costs and benefits of biochar, BECCS and CHP systems are established. The NPV of each cost or benefit is then calculated separately and summed to find the total NPV of each system. Equation 4 shows the formula used to calculate the NPV for a given system,

$$NPV_{NET} = \sum_{i=0}^{N} NPV_i \qquad 4$$

Where NPV_i is the NPV for a specific cost or benefit, and N is the total number of costs and benefits of the system being evaluated. Equations 5, 6 and 7 apply Equation 4 to BECCS, biochar and CHP systems.

$$NPV_{NET\ BECCS} = \mathrm{NPV_e} + NPV_c + NPV_o + NPV_i + NPV_f \qquad 5$$

$$NPV_{NET\ Biochar} = \mathrm{NPV_e} + NPV_c + NPV_b + NPV_o + NPV_i + NPV_f \tag{6}$$

$$NPV_{NET\ CHP} = \mathrm{NPV_e} + NPV_o + NPV_f \tag{7}$$

Where

$\mathrm{NPV_e}$ = NPV of energy sales

NPV_c = NPV of carbon sales

NPV_b = NPV of biochar sales

NPV_o = NPV of operating cost

NPV_i = NPV of investment cost

NPV_f = NPV of purchased feedstock

Applying equation 2 to equations 5 to 7 we get expressions for the NPV relative to the business-as-usual case. In the BECCS calculations, note that only the CCS technology and its related infrastructure are assumed to have an investment cost since BECCS is retrofitted on already existing CHP plants.

$$NPV'_{BECCS} = NPV_{NET\ BECCS} - NPV_{NET\ CHP} = \Delta\mathrm{NPV_e} + \Delta NPV_c + \Delta NPV_o + NPV_{\{i\ CCS\}} \tag{8}$$

$$NPV'_{Biochar} = NPV_{NET\ Biochar} - NPV_{NET\ CHP} = \Delta\mathrm{NPV_e} + \Delta NPV_c + \Delta NPV_b + \Delta NPV_o + NPV_i \tag{9}$$

Equations 5 - 9 were used to calculate the overall economic performance of BECCS and biochar systems applied to the Swedish district heating sector up until 2045. The next section presents the input parameters used for the calculations and highlights the key assumptions made when choosing them.

5.2 Scenarios

In this section, the rationale behind the scenarios used in the techno-economic model are motivated using the findings in chapter 4, and section 4.7 in particular. Table 4 shows the variables that define the scenarios, and how these variables will differ between scenarios.

Table 4. Scenarios to be used in the techno-economic analysis. The average scenarios are defined by input values that are the average of the low and the high values. For further information on the scenarios, see chapter 2.

Scenario	*CO_2 price*	*Biochar price*	*Deployment rate*	*Feedstock price*	*System costs*
Unfavourable biochar	Low	Low	Low	High	High
Average biochar	Average	Average	Average	Average	Average
Favourable biochar	High	High	High	Low	Low
Unfavourable BECCS	Low	N.a	Low	High	High
Average BECCS	Average	N.a	Average	Average	Average
Favourable BECCS	High	N.a	High	Low	Low

Carbon price

As established in section 4.2, a high CO_2 price can be seen as an indication of ambitious climate action. Furthermore, since the sales of CO_2 is a vital part making BECCS and biochar economically viable, a high estimation of the future carbon price is used in the favourable scenarios, and a low price is used in the unfavourable ones.

Biochar price

The biochar selling price has a high estimation in the favourable biochar scenario, since it is assumed that ambitious and successfully implemented policy will lead to incentives specifically aimed at NETs with additional values such as biochar production. This assumption is based on the national NET case study for Sweden (SOU 2020), where NETs with additional values are to have a high priority.

Additionally, a high biochar product price indicates that the remaining technical uncertainties regarding its usefulness have been clarified, and that the usefulness has been proven to be large. This is the case for the favourable biochar scenario since technical maturity is not assumed to be a barrier in the favourable conditions (section 4.7).

In the unfavourable biochar scenario the selling price is low, which can be seen as an indication of policy prioritising NETs or supplementary measures with less of a potentially negative impact on biodiversity, or the additional benefits of biochar being smaller than first anticipated.

Deployment rate

If the conditions for BECCS and biochar are unfavourable the deployment rate is expected to be low. Therefore, both BECCS and biochar have low deployment rates in the unfavourable scenarios and high deployment rates in the favourable scenarios.

Feedstock price

As established in sections 4.3 and 4.7, a high feedstock price combined with otherwise unfavourable BECCS and biochar – such as low CO_2 and biochar prices – likely has a negative impact on the economic performance of BECCS and biochar compared to CHP. A high feedstock price is therefore used in the unfavourable scenarios, and a low price is used for the favourable scenarios.

System costs

The system costs include the investment and operating costs, as well as the cost of the additional surrounding infrastructure used for BECCS and biochar. High system costs are therefore unfavourable to the economic performance of them.

5.3 Input parameters and quantification of the scenarios

In this section, the input data used in the NPV analysis are detailed, along with the sources and assumptions used. Some key assumptions that require a more thorough derivation are presented in individual subsections later in this section.

5.3.1 CHP parameters

Table 5 contains the parameters used in the techno-economic analysis that are related to CHP.

Table 5. The parameters used for the NPV calculations that were associated with CHP

Parameter	**Unit**	**Min**	**Avg**	**Max**	**Sources and assumptions**
CAPEX	K€/MW	402	402	402	(GREBE 2017)
O&M	% of CAPEX	3.5	3.5	3.5	Average between the span of 1-6% of OPEX proposed in (GREBE 2017)
Power efficiency	%	36.2	36.2	36.2	Average of the CHP processes in Linde (2017)
Thermal efficiency	%	51.0	51.0	51.0	Average of the post-combustion processes in Linde (2017)
Installed capacity per yearly emission	$MW/MtonCO_2y$	567.2	567.2	567.2	Installed capacity of Igelska Kraftverk (Söderenergi 2019), divided by the biogenic emissions of the plant (Naturvårdsverket 2022b)

5.3.2 BECCS parameters

Table 6 contains the parameters used in the techno-economic analysis that are related to the BECCS value chain.

Table 6. The parameters used for the NPV calculations that were associated with CCS

Parameter	***Unit***	***Min***	***Avg***	***Max***	***Sources and assumptions***
CO2 sequestration 2022	$MtonCO_2$	0.0	0.0	0.0	See "BECCS annual CO_2 sequestration" below
Cumulative CO2 sequestration 2045	$MtonCO_2$	0.8	1.4	2.0	See "BECCS annual CO_2 sequestration" below
CCS cost	€/tonCO_2	82.8	128.9	175.0	See "CCS cost" below
Power energy penalty	%	-24	-24	-24	Average of the post-combustion processes in Linde (2017)
Thermal energy penalty	%	-10.3	-10.3	-10.3	Average of the post-combustion processes in Linde (2017)
Carbon capture efficiency	%	86	86	86	(Woolf et al. 2016)

BECCS annual CO_2 sequestration

The minimum value is calculated based on the assumption that Sweden is unable to secure storage of the carbon outside its borders, which would require national storage knowledge and infrastructure to be established. The process of establishing national geological storage of captured carbon is estimated to take until 2040 to be completed (SOU 2020), until which the deployment of BECCS is likely to be severely hindered. The deployment rate is therefore assumed to be zero until 2040, and 0.18 $MtonCO_2y^{-1}$ between 2040 and 2045. 0.18 $MtonCO_2y^{-1}$is the deployment rate between 2020-2030 stated in SOU. This value is averaged out over the 2022-2045 time period for calculation purposes, which gives an average deployment rate of 0.036 $MtonCO_2y^{-1}$. The maximum annual CO_2 sequestration is the total emissions of the biogenic point emitters over 0.5 $MtonCO_2y^{-1}$ in the heating sector multiplied (Naturvårdsverket 2022b) with the carbon capture efficiency stated in Table 6. In reality, deployment will not begin in 2022, but rather in 2025 at the earliest (Stockholm Exegy 2022). The upscaling will also most likely follow the pattern of an S-curve and begin slowly, followed by an acceleration, which is eventually followed by a plateau (Cherp et al. 2018). However, because of the early stages of deployment as well as for calculation purposes, no assumptions are made on the shape of the S-curve, or at which point on it we will be in 2045. Instead, the upscaling is averaged over the 2022-2045 timespan, and approximated to be linear.

CCS cost

While the cost of BECCS remains uncertain, an estimation of the CCS price of a large scale BECCS plant in Stockholm, Sweden found the total price to be between 66 and 100 eur/ton CO_2, considering capital investment, operating costs as well as transport and storage of the captured carbon (Levihn et al. 2019). A global analysis of the cost of BECCS for combustion done in 2021 presented a price range between 82-268 $€/ton\mathrm{CO_2}$, not including transport and storage (Bey et al. 2021). The value used in this analysis is the mean of these two ranges.

5.3.3 Biochar parameters

Table 7 contains the parameters used in the techno-economic analysis that are related to the biochar value chain.

Table 7. The parameters used for the NPV calculations that were associated with biochar

Parameter	***Unit***	***Min***	***Avg***	***Max***	***Sources and assumptions***
CO2 sequestration 2022	$Mton\mathrm{CO_2}$	0.0131	0.0131	0.0131	See "Biochar annual CO_2 sequestration" below
Cumulative CO2 sequestration 2045	$Mton\mathrm{CO_2}$	0.18	0.58	1.8	See "Biochar annual CO_2 sequestration" below
CAPEX	$€/ton\mathrm{CO_2}$	77.5	198.2	318.9	A span of 77.5-106.3 eur per annual production of biochar (Haeldermans et al. 2020). 106.3 was multiplied by 2 to find the maximum value, and 77.5 was divided by two to find the minimum
O&M	% of CAPEX	10	10	10	O&M was assumed to be 10% of OPEX
Biochar price	€/ton (DW)	95.4	677.1	1258.8	See "Biochar price" below
Power efficiency	%	7.5	7.5	7.5	See "Energy and mass balance for biochar production" below
Thermal efficiency	%	47	47	47	See "Energy and mass balance for biochar production" below
Biochar net carbon sequestration	$TonCO_2$ $/ton$ $biochar$ (DM)	2.92	2.92	2.92	See "Biochar net carbon sequestration" below
Biochar production	% of feedstock (DM)	28.5	28.5	28.5	See "Energy and mass balance for biochar production" below

Biochar annual CO_2 sequestration

Deployment at 2020 based on the 2021 Biochar Market Report (Lerchenmüller 2021), where the biochar production in Europe 2020 was 17000 t, which is equal to 39950 ton CO_2 sequestered for at least 100 years (see the Biochar stability parameter in Table 7). In the 2022 biochar Market Report, Scandinavia represents 23% of total biochar production (Lerchenmüller 2022). This percentage is assumed to be the same for 2020. Sweden - being the major biochar producer in Scandinavia – was assumed to represent 75% of the Scandinavian biochar production, which would be equal to a yearly biochar production of 4499 ton in 2020.

The production of biochar in the EU between 2010 and 2020 increased from around 2000 to 17000 tonnes, which represents a compound annual growth rate of 24%. CAGR is the average growth rate over a period of time, and a CAGR of 24% is assumed to be the maximum percentual growth rate until 2045. Similarly, the minimum and average growth rates were assumed to be 50% and 75% of the 2010-2020 CAGR respectively.

Biochar price

The future biochar price is highly uncertain, and largely depends on the effectiveness of the product in its various potential applications. In a price estimation done for the Swedish region of Öresund a price range of 363 to 1612 eur 2022/ton biochar depending on application and potential demand was found (Söderqvist et al. 2021). However, the vast majority of potential demand in this analysis was for using biochar as soil improvement, for which the price range was estimated at 954 to 1049 eur 2022/ton. An estimation of the Swedish biochar price done in 2020 proposes a price range of 477 to 1383 eur 2022/ton (Gahne & Martelius 2020), and in Haeldermans et al. (2020) the minimum selling price for biochar in Belgium using wood waste is estimated to be 562 eur/ton. The minimum price was set as 20% of the current lowest value to reflect a drastic reduction in biochar demand in the case of limited additional benefits. Similarly, the maximum price was set to 20% above the maximum current estimate to reflect considerable additional benefits.

Energy and mass balance for biochar production

In Azzi et al. (2019), four plant configurations for biochar production are analysed, with thermal efficiencies ranging from 31 to 48%, power efficiency from 0 to 18% and biochar yield from 21 to 36%. These four plant types are assumed to be deployed at equal measure, meaning that the average thermal efficiency, power efficiency and biochar production of the biochar production plants is assumed to be an average of the configurations.

Biochar net carbon sequestration

The biochar stability is commonly defined as the amount of CO_2 removed from the atmosphere over a 100-year period, and is also the definition used in this report. The value of 2.92 used in these calculations is the average net carbon sequestration of the two Swedish biochar producers for Puro.earth (Puro.earth 2021b; a). Puro.earth uses the methodology by Woolf et al. (2021) to calculate the biochar stability combined with a value chain life cycle analysis to find the net sequestration (Puro.earth 2022).

5.3.4 Universal parameters

Table 8 details the parameters used in the techno-economic analysis that are not specific to BECCS, biochar or CHP.

Table 8. The parameters used for the NPV calculations that were universal among all technologies

Parameter	***Unit***	***Min***	***Avg***	***Max***	***Further information***
Discount rate		0.05	0.05	0.05	See "Discount rate" below
Plant availability	h/y	7446	7446	7446	All plants analysed were assumed to be in production 85% of the year.
Biomass price 2022	€/MWh	20.2	20.2	20.2	See "Biomass price" below
Biomass price 2045	€/MWh	14.6	29.1	58.2	See "Biomass price" below
Carbon price 2022	€/MtonCO$_2$y	48.9	48.9	48.9	See "CO_2-price" below
Carbon price 2045	€/MtonCO$_2$y	54.4	117.9	181.4	See "CO_2-price" below
Heat price 2022	€/MW	83.2	83.2	83.2	Price trend from 1993-2018 (Swedish Energy Agency 2022) assumed to continue linearly to 2022
Heat price 2045	€/MW	117.3	117.3	117.3	Price trend from 1993-2018 (Swedish Energy Agency 2022) assumed to continue linearly to 2045
Electricity price 2022	€/MW	28.8	28.8	28.8	Average price in 2022 for customers with variable price agreements (SCB 2022).
Electricity price 2045	€/MW	56.9	56.9	56.9	Linear continuation of the yearly average electricity price between 2013-2022 for customers with variable price agreements (SCB 2022)
Feedstock energy content	MWh/ton feedstock (DW)	15	15	15	Average taken between the LHV of pellets, wood chips and forest residue (Strömberg & Herstad Svärd 2012)

Discount rate

As with most long term investments, the discount rate becomes an important factor. This holds especially true when dealing with the economics of climate change, where investments done today may result in future avoided damage worth several times more than the initial investment (Giglio et al. 2021).

Biomass price

The average biomass price for combustion was 18.6 €/MWh in 2020 (Energimyndigheten 2022). Assuming a linear continuation of the price trend from 1993 to 2020, the biomass price in 2022 is 20.2 €/MWh, and in 2045 29.1 €/MWh. To take into consideration the uncertainty of the future biomass supply, the estimated 2045 value was multiplied with -50% or + 100% to find the maximum and minimum biomass prices.

CO_2 price

In 2045 the minimum value is the CO_2price corresponding to the least ambitious IPCC WG III AR5 atmospheric CO_2 target (650-720 ppm), and the maximum value represents the most ambitious target (430-480 ppm). The 2022 price is the average estimated 2020 CO_2 price plus the price change between 2020 and 2022 assuming a linear price change from the 2020 to the average 2045 price (IPCC 2014). The carbon price is assumed to be the same for both BECCS and biochar. This assumption may or may not hold true depending on to what extent future carbon markets take into consideration factors such as sequestration permanence, working conditions, calculation uncertainties and other differences between NET value chains.

5.4 Results of techno-economic modelling

Figure 5 shows the economic performance of each system and scenario when not compared to the CHP reference system. Heat sales is the main source of income for both NETs, but in the favourable BECCS scenario the carbon sales become almost equally important. For biochar systems, the sales of biochar is more important than carbon sales to their economic performance. While Figure 5 suggests that both technologies are viable even under average conditions, it is also slightly misleading to analyse on its own. In reality most BECCS and biochar systems will replace an already existing CHP plant which means that the system needs to perform on a similar level or better economically after the NET investment for it to be a viable investment for project owner. The net NPV is positive for both technologies in the average and favourable scenarios (Figure 5) , which would suggest that BECCS and biochar systems under the conditions set in these two scenarios can be profitable. However, looking at the NPV relative to the reference system (see equation 2) makes the profitability less obvious (Figure 6). While Figure 5 shows the proportion of the various incomes and expenses in BECCS and biochar systems, Figure 6 gives a more accurate representation of the NPV of the investment since it presents the NPV' (equation 2).

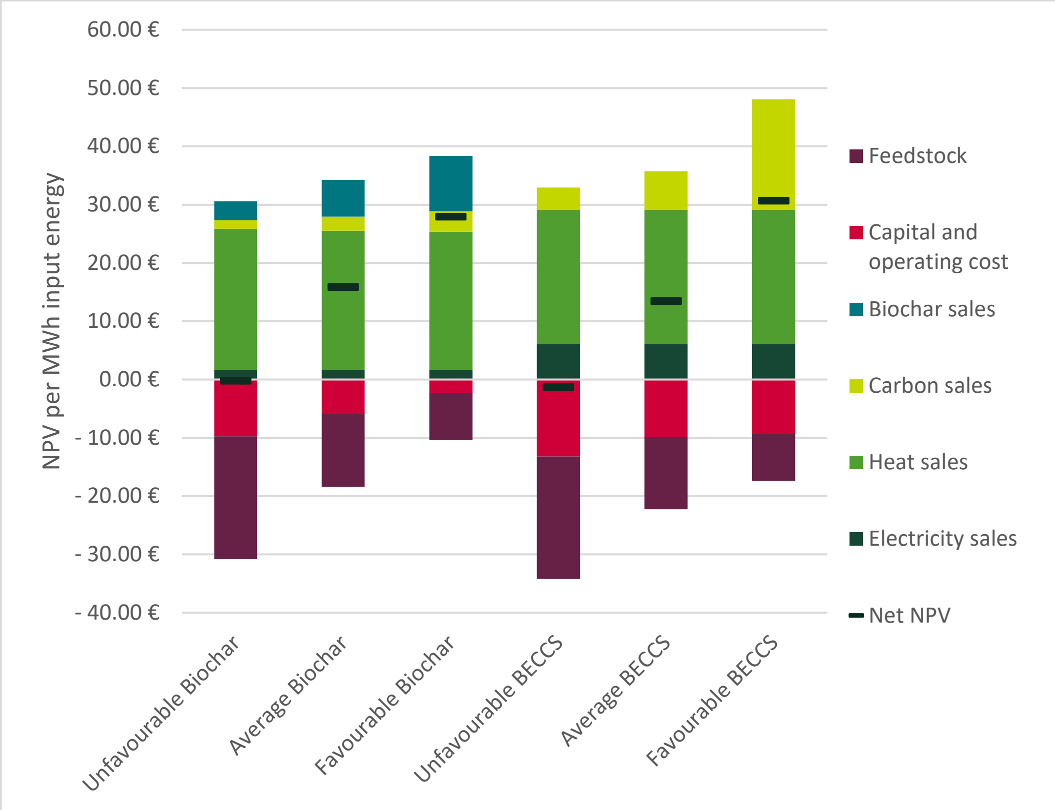

Figure 5. NPV of BECCS and biochar systems. Each income and expense are expressed per MWh of input energy to the systems.

Replacing a CHP plant with a pyrolysis plant or retrofitting it with a CCS system, results in a net loss in both the unfavourable and the average scenarios (Figure 6). The effect of the energy penalty can be noted in the negative heat and electricity sales, since they show that the energy sales are lower in the NET systems compared to the reference ones. We do see that if the biochar price and the CO_2 price is high enough, BECCS and biochar become profitable. Profitability is only reached in the favourable cases which reflects the picture painted in the literature study as well as in the stakeholder interviews, where the need for more robust economic incentives for these technologies is highlighted as the most important factor in making NETs attractive.

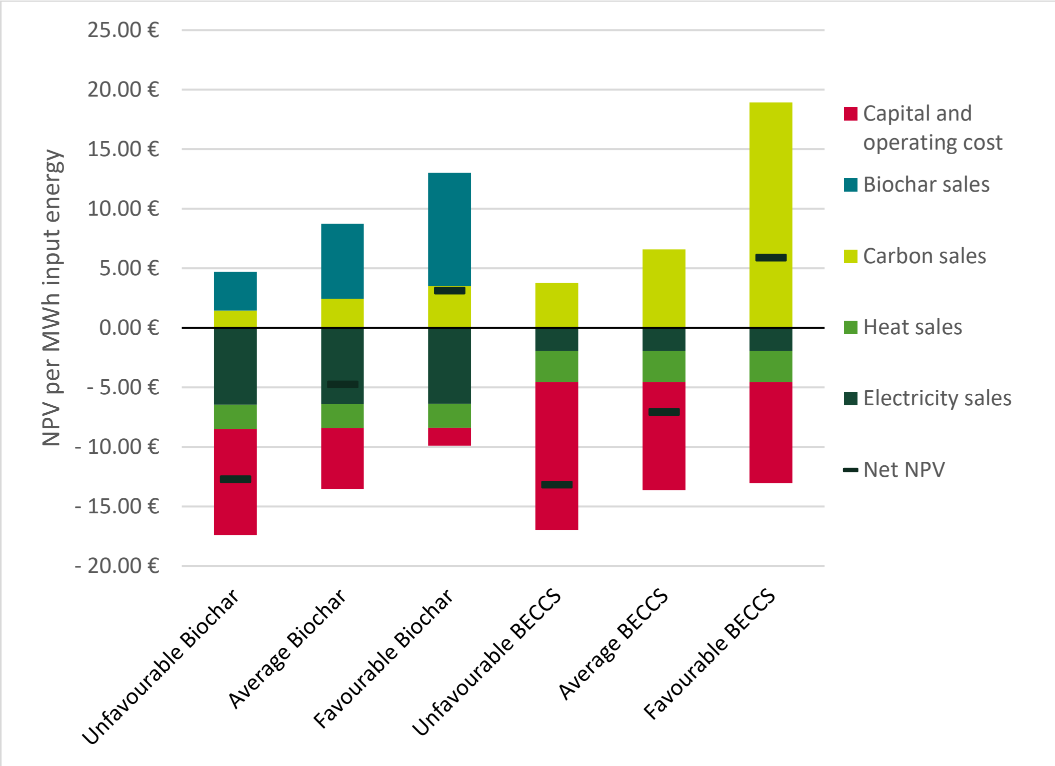

Figure 6. NPV of BECCS and biochar systems relative to the reference case of maintaining a CHP plant with the same feedstock volume. Each income and expense are expressed per MWh of input energy to the systems

Table 9 shows the total loss in installed energy capacity of BECCS and biochar for all six scenarios, compared to if the same amount of feedstock was instead used for generic CHP. It also shows an estimation of how much extra feedstock would be required to compensate for this loss assuming that CHP is used for the energy compensation.

Table 9. Total installed capacity loss and additional feedstock needed to compensate for it and retain the same installed energy capacity assuming that CHP with the plant availability in Table 8 is used for the compensation. MW el is the change in electrical installed capacity, and MW th is the change in the installed thermal energy capacity

	MW el	MW th	MW	Extra feedstock needed [TWh]	Percent of 2020 bioenergy use
Unfavourable Biochar	-14	-125	-139	1.2	0.8
Average Biochar	-46	-411	-457	3.9	2.7
Favourable Biochar	-144	-1280	-1424	12.2	8.6
Unfavourable BECCS	-56	-124	-180	1.5	1.1
Average BECCS	-97	-213	-309	2.6	1.9
Favourable BECCS	-137	-302	-439	3.7	2.7

5.5 Sensitivity analysis

A sensitivity analysis was performed on the techno-economic model to gain a more solid understanding of the impact that the individual parameters have on the NPV′ of BECCS and biochar systems respectively. Table 10. shows which parameters were analysed. The sensitivity was performed on the average scenarios, and all parameters were varied from -50% to +50% of the original value found in Tables Table 5 to Table 8.

Note that the electrical and thermal energy *penalties* for biochar are recalculated from the “Power efficiency” and “Thermal efficiency” that were used as the actual input in the model. This is done to make the results of the sensitivity analysis comparable between BECCS and biochar, since the energy balance of BECCS is expressed in terms of the energy penalty.

Table 10. List of the parameters used in the sensitivity analysis

Parameter	BECCS	Biochar
Discount rate	X	X
Electricity price	X	X
Heat price	X	X
Carbon price	X	X
CCS cost	X	
Electrical energy penalty	X	X
Thermal energy penalty	X	X
Biochar production cost		X
Biochar selling price		X
Biochar yield		X

Figure 7 shows the change in NPV´ for BECCS when varying the parameters in Table 10. It shows that the CCS cost is the parameter with the highest impact on the overall results. The carbon price and discount rate have larger impacts, while the energy prices and penalties are the least sensitive parameters.

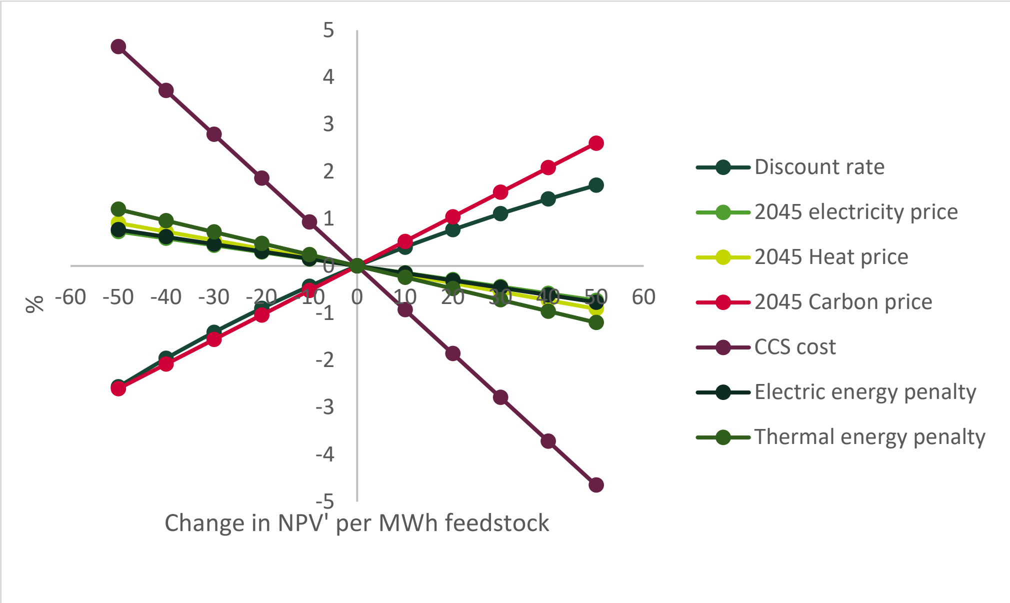

Figure 7. The results of the sensitivity analysis on the BECCS system

Figure 8 shows the change in NPV´ for biochar production when changing the parameters in Table 10. We can see that the biochar price is the parameter with the highest sensitivity. Most other parameters show a similar level of sensitivity, but the electric energy penalty, the biochar production cost, and the electricity price are slightly more sensitive compared to the others. The two least sensitive parameters are the heat price and the thermal energy penalty.

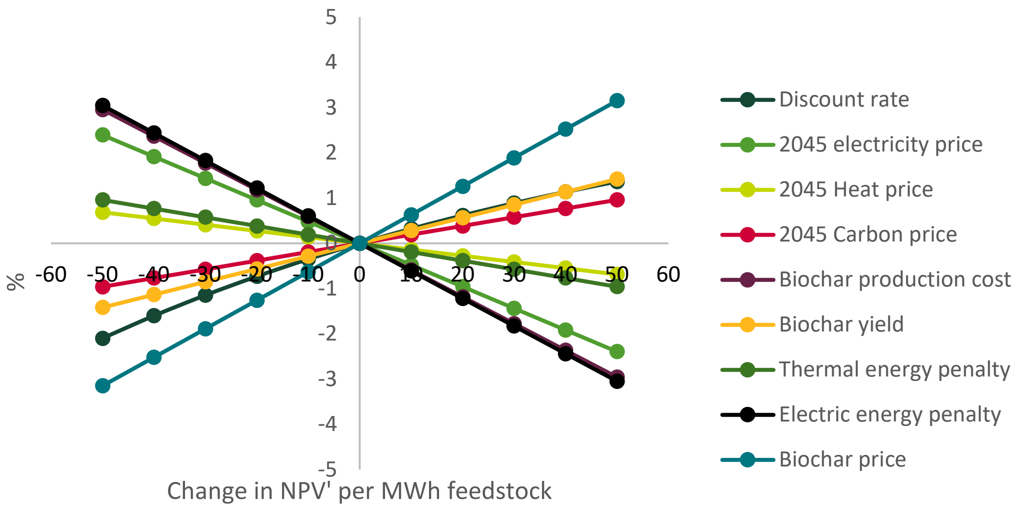

Figure 8. The results of the sensitivity analysis on the biochar system

6. Discussion

Based on the results of the techno-economic analysis performed in this study, both BECCS and biochar are able to economically outperform CHP in the scenarios with favourable conditions. This goes in line with the findings in chapter 4, where the current conditions for BECCS as well as biochar are found among both stakeholders and in literature to be insufficient to make them viable enough for large scale deployment.

From Figure 6 it is clear that the CCS cost is a major expense for BECCS plants in all three scenarios, and therefore a significant contributor to BECCS only being profitable in the favourable scenario. This expense could be alleviated through policy aimed at reducing the costs associated with CCS, which is what is seen today in investment aid schemes. However, these types of supply push measures are expected to eventually be replaced by more demand pull measures as the policy shifts more towards becoming technology neutral, and carbon markets become established (SOU 2020). This highlights the importance of a reduction in BECCS capital, operating, transport and storage costs going forward if BECCS is to become an established NET in Sweden. As BECCS becomes more common and the surrounding infrastructure more established, the system costs are expected to decrease. However, if the costs associated with the CCS technology for some reason are unable to decrease going forward, other NETs may become more economically viable.

The biochar production cost has a similar – albeit slightly smaller – impact on the profitability of biochar plants to the one that the CCS cost has on BECCS plants. However, due to the large variability between individual biochar systems, the uncertainty of the biochar production cost is large. For this reason, a vastly different CAPEX is used in each of the three scenarios.

6.1 Comparing the results of the literature study to the techno-economic analysis

The findings from the literature study and stakeholder interviews are generally supported in the techno-economic analysis. For example, the energy prices play a more important role in biochar systems than for BECCS systems, due to the fact that the energy penalty is larger when producing biochar. This is also evident in the sensitivity analysis where the electric energy penalty is one of the parameters with the highest impact on the profitability of biochar production.

According to literature and stakeholder interviews, the CO_2 price also plays an important role in making both NETs profitable, which is also supported by the modelling results. However, the CO_2 price is significantly more important to the profitability of BECCS than to biochar – as seen in Figure 6 – due to fact that the only source of income for BECCS is the carbon sales, while the income for biochar is split between sales of carbon credits and the biochar product. In fact, the results in Figure 6 indicate that the biochar price is more important to the profitability of biochar production than the carbon price. This pattern is further confirmed in the sensitivity analysis, where the carbon price is one of the parameters with the largest impact on BECCS profitability, and where the biochar selling price has a similarly large impact on biochar profitability.

From chapter 4 we learn that the CO_2 selling price, public and stakeholder opinion, investment stability, and policy incentives are deemed to be key factors contributing to the future conditions for both BECCS and biochar among stakeholders and in literature. For BECCS specifically, the regulatory and cost effectiveness of the CO_2 transport and storage, and the lack of practical experience are also of importance. For biochar production, on the other hand, the extent to which the biochar becomes a useful product and finds applicable markets is important.

6.2 Limitations of this study

When comparing BECCS and biochar performance of a specific task under the same conditions – as has been done in this report – some unique characteristics of the two NETs are ignored. To conclude that BECCS is the superior technology would therefore be to ignore the many applications where biochar production is a possible solution and BECCS is not. The ability for biochar production to operate at different scales, and access previously unused waste streams makes it a complex NET with many applications (Interviewee A 2022), and the application that is analysed in this study is only one of them. Similarly, to say that the separation cost of BECCS limits its deployment potential ignores the cases where separation is not needed (Lask et al. 2021), which enables BECCS to be used in other sectors and for other purposes than the ones that were examined here. Furthermore, the theoretical possibility to combine BECCS and biochar production by applying CCS to the pyrolysis plant may lead to many future synergy possibilities between the two NETs.

In other words, while relevant and important findings can be made from assessing BECCS, biochar and other NETs comparatively in the way that was done in this project, other relevant and important findings can be made if basing the analysis on the differences between the NETs instead.

The timeframe of the analysis was chosen to be 2022-2045. The two primary reasons for this is the fact that 2045 is the year where Sweden plans on becoming carbon neutral (Regeringskansliet 2019), and the long lead times of BECCS deployment making it necessary to use long timeframes. However, in the techno-economic analysis, the time between 2022 and 2045 was not modelled in detail. Instead, the model input values were approximated at 2022 and 2045, and assumed to change linearly between the two data points. This likely primarily affects the results for BECCS because of its long term and irregular deployment patterns. The Unfavourable BECCS scenario is an example of this since the deployment rate is based on the assumption that the first BECCS installations happen in 2040, but where the calculation only considers the deployed capacity at 2022 and 2045 and assumes a linear development.

Furthermore, performing calculations based on assumptions on future developments also makes it more difficult to draw decisive conclusions, since the modelling of future developments is inherently uncertain. To counter this, the unfavourable and favourable scenarios were designed to be as far apart as possible, thereby covering a large range of outcomes, but there is no way of knowing for sure if the actual course of events will be covered in any of the scenarios.

An example of this uncertainty is the Russo-Ukrainian war, that in the middle of the writing of this thesis was further escalated when Russia launched a large-scale invasion of Ukraine on the 24 of February 2022. This development is a stark reminder of how unexpected events may happen at any time, which is something that a scenario based analysis on future developments struggles to take into consideration. While it is impossible to tell the long term effects of the development of this war, the reduced access to Russian gas has led to drastically increased energy and biomass prices in Europe, which are expected to remain high for at least the coming few years (Elliott 2022; Millard 2022). Based on the sensitivity analysis, increased energy prices would further disincentivize both BECCS and biochar, since the additional cost of the energy penalty is increased. If the usage of NETs such as BECCS and biochar increases, the need for having a sufficiently high carbon price to compensate for this loss therefore increases. This further emphasises the need for public inclusion as well as stable and transparent terms when making policy, if BECCS and biochar are to become established under conditions with high and volatile energy prices.

6.2.1 The environmental effects of BECCS and biochar deployment

Ambitious climate policy in terms of high carbon pricing, favourable economic conditions for BECCS and/or biochar, or a high reliance on NETs in general, is not necessarily equivalent to a climate policy that successfully deals with the complexities of climate change mitigation in general. For example, the favourable scenarios used in this project will result in an increased amount of pressure being put on the Swedish forests and agricultural land, as can be seen in Table 9.

As Table 9 shows, the national loss in energy production capacity would be reduced by approximately 457 MW for biochar and 309 MW for BECCS, if they were to be deployed to the extent defined in the average scenarios. To compensate for this energy loss, approximately 3.9 and 2.6 TWh of additional biomass would be required for biochar and BECCS respectively. This gives an idea of the approximate biomass volumes that are at stake for large scale BECCS and biochar deployment for energy production if biomass is used as the only substitute for the lost energy.

As established in section 4.3, the highest current estimate of the availability of biomass for energy usage in 2045 is at 79 TWh/y. Therefore, 2.6 plus 3.9 TWh (or 3.7 plus 12.2 TWh in the favourable scenarios) of additional biomass usage is not unrealistic, but neither negligible considering the many competing uses of biomass. If the future bioenergy use proposed by The Swedish Society for Nature Conservation becomes reality, the biomass availability would be 130 TWh/y, which is lower than today's usage of 141 TWh. This would likely result in the national energy penalty being hard to ignore. However, one factor that is not considered in this analysis is the increased land productivity from biochar application. If this effect had been included, the net energy penalty of biochar production would likely have been smaller due to the increased biomass production from the biochar product. This effect was not considered since the extent of it remains uncertain (Tammeorg et al. 2017).

However, while it was not included, this effect demonstrates how the upgrading of low grade biomass to biochar complicates comparisons between BECCS and biochar, since biochar is a material with uses that are more highly valued than that of the input material. It also illustrated how the net environmental effects of implementing a NET can be complex, difficult to quantify, and dependent on which downstream effects are included in the analysis.

This reasoning can be further nuanced by considering the fact that climate change itself has a major environmental impact, which means that the negative effect of an increased biomass usage may be partly or wholly compensated by the reduced intensity of the greenhouse effect as a consequence of using it. This, however, would depend on the societal importance of the service or function the harvested biomass is used for, which requires one to assess which uses of biomass are important, and which are not. Is the service, product or function that requires biomass necessary to a functioning society? Or would its decommissioning– with the consequence being a reduced biomass extraction – result in a net benefit to society, and the longevity of life on our planet?

6.3 Further research

BECCS and biochar are technologies that have a certain degree of overlap in their areas of application. However, they do also fill niche uses that are not in competition with each other (Levihn et al. 2019). While these are mentioned when possible in this report, the techno-economic analysis is still based on the premise that both technologies are replacing CHP specifically. Comparative NET studies are expected to become increasingly important to ensure that the future portfolio of NETs that are used as efficiently as possible while minimising their negative effects (Amann & Hartmann 2019). To include the synergies and trade-offs between BECCS and biochar, the modelling software "LEAP" was considered for use during the planning stages of this thesis. LEAP is an integrated modelling software for energy system and resource planning, and can be used to approximate energy balances, emissions and resource extraction of an economy. By modelling the Swedish energy system and bioeconomy, and deploying BECCS and biochar to study the consequences, the synergies and trade-offs from a co-deployment of BECCS and biochar could be studied. This idea was abandoned due to time constraints, but future studies using econometric modelling of energy and natural resources would likely allow for further progress to be made in understanding the effects of a BECCS and biochar co-deployment.

The idea off creating a model that accounts for the synergies and trade-offs could be expanded upon by mapping and including different biomass resources, other applications of BECCS and biochar, other NETs such as afforestation and reforestation, as well as competing uses of biomass, in the model. Being able to identify the circumstances where BECCS or biochar impedes the effects of afforestation, or to what extent biochar based steel production affects the NET potential of biochar depending on biomass availability, are questions that need to be answered in order to find the optimal use of a given amount of biomass. This becomes particularly important when considering the uncertainty of future biomass availability (European Commision 2021; Dalunde & Holmgren 2022; European Parliament 2022; Polfjärd 2022), and should therefore be the subject for further research.

7. Conclusions

In this thesis, the aim was to assess the practical feasibility and economic trade-offs of BECCS and/or biochar deployment in Sweden until 2045. To do this, the following research questions have been studied:

1. Which are the main factors influencing the deployment of BECCS and biochar systems in Sweden?
2. How will changes in these factors impact the conditions for BECCS and biochar?
3. Under which technical and economic conditions can BECCS and/or biochar become viable for energy production?

To answer the first two questions, a literature study was conducted and stakeholders were interviewed. The identified primary factors to the deployment of both technologies are the system costs, biomass availability, regulations and incentives, technical maturity, deployment potential, as well as the public and stakeholder opinion.

Higher than anticipated investment, operating and infrastructure costs, rigorous biomass sustainability regulation or competing uses of biomass, volatile economic conditions and unambitious CO_2 pricing, unexpected issues arising due to lack of practical experience of large scale deployment, lack of available CO_2 storage or biochar applications, as well as a negative shift in opinion on negative emissions or biomass extraction are key changes indicative of unfavourable conditions for both BECCS and biochar.

Similarly, low costs, an increased intensity or efficiency of agriculture and forestry, stable economic conditions and ambitious CO_2 pricing, the securing of CO_2 storage and biochar applications, and further expansion of voluntary CO_2 markets are key changes indicative of favourable conditions.

To answer the third research question a scenario based techno-economic analysis was performed with scenarios representing favourable, moderate and unfavourable deployment conditions. Based on the results of this analysis, only the most beneficial scenarios for BECCS and biochar are able to support them enough to achieve a higher NPV compared to conventional combined heat and power production. The results suggest that both ambitious CO_2 pricing and low capital and operating costs are needed for BECCS to outperform CHP economically. For biochar production, a high biochar selling price and low system costs are necessary.

The energy prices have a higher impact on the NPV of biochar production compared to BECCS, with high prices being disadvantageous and low prices are advantageous to overall biochar profitability. Similarly, the CO_2 pricing has a bigger impact on BECCS than on biochar production.

If BECCS and biochar are not compared to a reference technology, their NPVs are above zero even under moderate – and even under unfavourable – conditions, which suggests that alternative uses of the NETs may still be economically attractive in some cases even in future developments where insufficient policy or technical uncertainties stop BECCS and biochar from replacing CHP at a major scale.

The effect of biomass availability on BECCS and biochar deployment is identified as a possible increasingly important factor to consider if the sustainability demands on biomass become more stringent and its number of competing uses increases. To ensure that the future portfolio of NETs used in Sweden and globally are used efficiently and with minimal negative impact, further research in the synergies and trade-offs of a co-deployment of NETs is suggested.

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Appendix 1 – Detailed breakdown of the mentions of BECCS or biochar in fossil free Sweden

Table 11. Summary of the mentions of BECCS and biochar in the business and sector roadmaps from the Fossil Free Sweden initiative. The search words used were "BECCS", "CCS", "Bio-CCS","Biokol","Bio-kol","Pyrolys", and " Kol ". All the roadmaps come from the Fossil Free Sweden website (Fossil Free Sweden n.d.)

Roadmap	**BECCS**	**Biochar**
Aggregates industry	No	No
Agricultural sector	No	No
Automotive industry – heavy transport	No	No
Automotive industry – passenger cars	No	No
Aviation Industry	No	No
Cement industry	No, but reliance on CCS	No, but a mention of refined waste-derived fuel and carbon negative cement (CCU) occurs.
Concrete industry	No, but reliance on CCS	No
Construction and civil engineering sector	No. CCS is mentioned but not as a part of the sector's roadmap	No
Digitalisation consultancy industry	No but CCS is mentioned as a technology to preferably avoid	No
Electricity sector	Yes. The need for economic policy incentives is highlighted.	No

Fast moving consumer goods industry	No	Yes, but not mentioned as a part of their roadmap. It is instead encouraged as an opportunity for the agricultural sector to create a carbon sink
Food retail sector	No	No
Forest sector	No	No
Gas sector	No, but CCS (not prioritised though)	Yes, but not as a part of the roadmap. Biochar is mentioned as positive aspect of gasification. Pyrolysis of waste products to produce bio-gasol is mentioned as a possible future technology
Heating sector	Yes, makes negative emissions possible. Infrastructure for transport and storage of captured carbon is seen as a barrier. A carbon sink of 5 million tonnes per year is achieved by 2045 by using BECCS and biochar.	Yes, needed to reach negative emissions. The sector calls for state support for BECCS and biochar research. A carbon sink of 5 million tonnes per year is achieved by 2045 by using BECCS and biochar
Heavy road haulage industry	No	No
Maritime industry	No	No
Mining and minerals industry	No, but reliance on CCS	Yes, for heating along with bio-oil
Petroleum and biofuel industry	Yes, reliance on CCS and BECCS	No
Recycling sector	No	No
Ski resort sector	No	No

Steel industry	No. CCS mentioned but not considered relevant	Yes, reliance on biochar. High quality biochar is planned to be used as a replacement for fossil coal. Biochar demand is estimated at 1-1.5 TWh. Feedstock and process requirements to produce the biochar is under investigation. May also be used as a replacement of coke, but less likely

Appendix 2 – Stakeholder interviewee list

Interviewee A, Industry and academia representative. Works with large project planning at an industry and is also an industrial PhD student. They have worked with, for example, biogas and waste sorting before starting to work with biochar and carbon sinks, which is their current area of expertise within the company. Specifically, biochar and BECCS are of interest.

Interviewee B, Environmental NGO Climate investigator - The interviewee works as a climate investigator at a major environmental organisation. Currently, the interviewee primarily works with policy incentives, and is now developing an ecologically sustainable tax reform (which includes a biogenic carbon tax). They have previously worked with LMTs and negative emissions.

Interviewee C, Industry representative - The interviewee works with producing biochar performing pre-studies. The biochar production is following the European biochar certificate and uses biomass waste products. Since 2019, they retrofit grates so they can produce biochar using pyrolysis.

Interviewee D, Local authority representative - The interviewee works with NETs, assessing them from the perspective of a Swedish municipality, and promoting deployment in the city. The municipality works with maintaining and increasing the existing soil carbon levels.

Interviewee E, Independent negative emission advisor - The interviewee works as a negative emission advisor, with a focus on business engagement in negative emissions and other climate contributions. They have a background in working at NGOs with policy on carbon sequestration but is currently focusing exclusively on negative emissions.

Interviewee F, Bioenergy and negative emission expert - The interviewee has previously been working in the (bio)energy and the waste sector, and has been involved in developing policy targets and strategies for negative emissions. They were involved in starting - and is currently the CEO of - an organisation promoting better terms and conditions for carbon sinks and negative emission technologies.

Interviewee G, Forest industry representative - The interviewee is a forest industry expert with particular focus on international issues. Aware of the division into nature-based removals and technology-based solutions. This interview focused on forestry related LMTs.
Interviewee H, Government agency - The interviewee works at a governmental agency and is a climate change expert with particular focus on the land use sectors. In terms of the role of the land use sector in climate change mitigation, the interviewee reflects on how this is a difficult topic politically and in public discussions because the debate is so very polarised.
Interviewee I, Land use consultant/independent expert - The interviewee has worked internationally for quite some time and with focus on land use governance, including forestry and agriculture. Has worked on issues related to REDD and also climate-smart agriculture, a concept aimed at finding synergies between food production and climate change mitigation. More recently, they have focused more on aspects related to forest industries in the Northern hemisphere, especially the Nordic region but also Ireland, Canada and the EU. Has helped develop sustainability strategies and action plans for forest industry companies.

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