SCALING LAND-BASED MITIGATION SOLUTIONS IN SWEDEN

LAND-BASED MITIGATION NARRATIVE CO-DESIGN

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Short Summary of results

This narrative of a Swedish portfolio of selected Land-based Mitigation Technologies (LMTs) presents a possible future of deployment and upscaling in order to contribute to the country's climate policy targets. We base the analysis on a comprehensive literature review of scientific and grey literature, as well as interviews with key stakeholders active in this field. This report discussed general and policy context, land-use competition, climate risks, co-benefits and trade-offs of each LMT. Then economic implications and risks associated with upscaling are evaluated.

The shortlisted LMTs in the Swedish context are **BECCS**, **biochar** and **afforestation**. Among these, however, only biochar can be characterised as a specific land-based measure that can be upscaled in national, regional, and global terms. BECCS is the key negative emission technology (NET) in the portfolio, as it is expected to deliver a large share of the negative emissions needed for Sweden to achieve its 2045 target for net-zero emissions.

BECCS is expected to remove 1.8 Million tonnes CO_2-eq per year by 2030 and between 3 to 10 Million tonnes CO_2-eq per year by 2045. Biochar is considered as part of the increased carbon sink in forests and land category, which, in overall is expected to remove 1.2 Million tonnes CO_2-eq per year by 2030 and a minimum of 2.7 Million tonnes CO_2-eq per year by 2045. The above means that carbon removals between 9.4 and 16.4 would be reasonable to be assumed under this narrative by the year 2045.

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2. Acknowledgements

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3. Executive summary

Sweden's long-term strategy for reducing greenhouse gas emissions states that the country will have no net emissions of greenhouse gas by 2045 and should thereafter achieve negative emissions. As a result, the Swedish Government appointed in 2018 a commission for investigating how a "climate positive" future can be achieved for the country. The main task of the commission was to investigate three types of measures for negative emissions: (i) land-use, land-use change and forestry sector activities (LULUCF); (ii) Bioenergy with Carbon Capture and Storage (BECCS); and (iii) verified emission reductions (VER) in other countries.

This narrative of a Swedish portfolio of selected Land-based Mitigation Technologies (LMTs) presents a possible future of deployment and upscaling in order to contribute to the country's climate policy targets. We base the analysis on a comprehensive literature review of scientific and grey literature, as well as interviews with key stakeholders active in this field. This report discussed general and policy context, land-use competition, climate risks, co-benefits and trade-offs of each LMT. Then economic implications and risks associated with upscaling are evaluated.

The shortlisted LMTs in the Swedish context are **BECCS**, **biochar** and **afforestation**. Among these, however, only biochar can be characterised as a specific land-based measure that can be upscaled in national, regional, and global terms. BECCS is the key negative emission technology (NET) in the portfolio, as it is expected to deliver a large share of the negative emissions needed for Sweden to achieve its 2045 target for net-zero emissions. Biochar, although favoured for its diversity of co-benefits and co-products especially in the local context, will have a complementary role. Biochar can be scaled out (i.e., replication in different locations, countries and/or contexts and at varying scales), which is one of the reasons that it has been pursued in Sweden in spite of its somewhat limited applicability as well as the lower potential associated with the northern European climate. The wide applicability of biochar, especially in agriculture in developing countries, is of strategic interest for Sweden because of its international cooperation efforts and its commitment to investments in measures outside of Sweden to as to support pathways to negative emissions internationally as well as domestically.

BECCS is expected to remove 1.8 Million tonnes CO_2-eq per year by 2030 and between 3 to 10 Million tonnes CO_2-eq per year by 2045. Biochar is considered as part of the increased carbon sink in forests and land category, which, in overall is expected to remove 1.2 Million tonnes CO_2-eq per year by 2030 and a minimum of 2.7 Million tonnes CO_2-eq per year by 2045. The above mean that carbon removals between 9.4 and 16.4 would be reasonable to be assumed under this narrative by the year 2045. On average, this can be translated to 12.9 Million tonnes CO_2-eq per year, which is approximately equivalent to 25% of total greenhouse gas emissions in Sweden in 2019 (in CO2-equivalent terms, excluding LULUCF).

Stakeholders working with these LMTs highlight that in order for the emission removals to be delivered in line with the Swedish net-zero targets, there needs to be stronger incentives that would in turn create viable carbon markets. Sweden has a frontrunner status regarding BECCS implementation, but it is still unclear how investments on transportation and storage of carbon will be supported and by whom. At the same time, climate change is threatening Swedish forest species and might create cascading effects affecting biodiversity and biomass supply for BECCS and biochar upscaling.

4. Introduction

Sweden's long-term strategy for reducing greenhouse gas emissions states that "by 2045 at the latest, Sweden is to have no net emissions of greenhouse gases into the atmosphere and should thereafter achieve negative emissions. This means emissions from activities on Swedish territory are to be at least 85 % lower by 2045 at latest compared with 1990. Supplementary measures may count towards achieving zero net emissions, such as increased uptake of carbon dioxide in forests and land, investments in other countries or bioenergy with carbon capture and storage (BECCS). The effect of the supplementary measures shall be calculated in accordance with internationally agreed regulations (Ministry of the Environment 2020).

The Swedish Government appointed in 2018 a commission for investigating how a "climate positive" future can be achieved for the country. The main task of the commission was to investigate three types of measures for negative emissions: (i) land-use, land-use change and forestry sector activities (LULUCF); (ii) BECCS; and (iii) verified emission reductions (VER) in other countries (Ministry of the Environment 2020). The commission's investigation supported the previous claims that BECCS has large potential for helping achieve climate targets of the country.

The shortlisted LMTs in the Swedish context are BECCS, biochar and afforestation. Among these, however, only biochar can be characterised as a specific land-based measure that can be upscaled in national, regional, and global terms. Biochar can also be scaled out (i.e., replication in different locations, countries and/or contexts and at varying scales), which is one of the reasons that it has been pursued in Sweden in spite of its somewhat limited applicability as well as the lower potential associated with the northern European climate. The wide applicability of biochar, especially in agriculture in developing countries, is of strategic interest for Sweden because of its international cooperation efforts and its commitment to investments in measures outside of Sweden to as to support pathways to negative emissions internationally as well as domestically.

BECCS is a key NET in the Swedish context in reaching zero and negative emission targets, but the land use side is less relevant because so much land in Sweden is already managed and optimised for biomass supply and bioenergy. Consequently, the main issues of concern are related to biomass supply from existing production areas and the (non-land) issues associated with carbon dioxide transport and storage. Since CO_2 storage is expected to occur outside of Sweden (e.g., Norway) there are also some implementation issues that remain unresolved, in addition to other uncertainties associated with a new technology.

Afforestation is not a major issue in Sweden in and/of itself, but rather what is important is Forest Resource Management overall, as it will intersect with—and impact the relevance of—biochar, BECCS and other LMTs in various ways, since the forest resource in Sweden is overall by far the most strategic aspect of achieving climate neutrality. Therefore, the discussion below provides this broader context for Forests and BECCS, while the discussion around biochar follows more closely the notion of an LMT that can be scaled up in national, regional and global terms.

4.1 National policy context

Sweden has a total land area of 410 000 km^2 of which about 7% correspond to agricultural area and 68% to forest area, as presented in Table 1. Compared to other European countries, Sweden has one of the biggest shares of forest area.

Table 1: Total land area and distribution (SCB 2022).

Sweden land area	**410 000 km^2**
Forest area	68%
Agricultural area	7%
Open land	22%
Built area	3%

Energy in Sweden is supplied by renewable energy sources (e.g., wind, hydro, solar PV and biofuels) and imported nuclear fuels, biofuels and fossil fuels. More than half of the energy consumption in the Swedish industrial sector stems from the pulp and paper industry, which relies in the use of energy sources such as biofuels and electricity. Alternatively, the iron and steel industry, while consuming less energy than pulp and paper industry, makes extensive use of fossil fuels (Energimyndigheten 2022).

Sweden's final energy consumption in 2020 was about 355 TWh, of which about 136 TWh (38%) were consumed by the industrial sector. On the other hand, electricity consumption in 2020 accounted for 135 TWh_{el}, of which 47 TWh_{el} (35%) were consumed by the industrial sector (Table 2).

Table 2: Industry sector energy and electricity use in 2020 (Energimyndigheten 2022).

Energy use	TWh	355
Industrial sector energy use	TWh	136
Electricity use	TWh_{el}	135
Industrial sector electricity use	TWh_{el}	47

4.2 Emission reduction goals and potential

By 2045, Sweden plans to reduce its emissions by 85%, compared to 1990. Thereafter, negative emissions should be achieved. The strategy envisioned by Sweden considers goals for the use of negative emission technologies (NET) and VER in other countries, as presented in Table 3. The baseline of emission reduction is 2030 and the projected emission reductions to 2045 consider two scenarios, one with lower and the other with higher carbon removals. BECCS is expected to remove 1.8 Million tonnes CO_2-eq per year by 2030 and between 3 to 10 Million tonnes CO_2-eq per year by 2045. Biochar is considered as part of the increased carbon sink in forests and land category, which, in overall is expected to remove 1.2 Million tonnes CO_2-eq per year by 2030 and a minimum of 2.7 Million tonnes CO_2-eq per year by 2045. The higher end of this category is uncertain, and therefore open to higher emission reduction. Verified reductions in other countries are expected to contribute to a reduction of 0.7 Million tonnes CO_2-eq per year by 2030. Further reductions to 2045 under this category are uncertain. Despite no other NET are considered in the national planning, Sweden is open to other NETs that could contribute to enhanced emission reduction.

Table 3: Sweden's projected emission reduction potential (Karlsson et al. 2020)

	2030	**2045**	
	Mtonnes CO_2-eq per year	Mtonnes CO_2-eq per year	
		Low	**High**
Increased carbon sink in forests and land (biochar included)	1.2	2.7	?
BECCS	1.8	3	10
Verified reductions in other countries	0.7	3.7	?
Other technologies for negative emissions	-	0	?
Total	**3.7**	**9.4 – 16.4**	

4.3 Biomass market outlook

Biomass is the main input for the implementation of BECCS and biochar in Sweden. Therefore, this section introduces biomass prices in the Swedish context. The average biomass price in 2020 was about 18.6 EUR/MWh. If a linear increase of price is assumed, then a biomass price around 20.2 EUR/MWh should be expected in 2022. If further projected to 2045, biomass price could be around 29.1 EUR/MWh (Martelius 2022). Given that the prices in 2045 are uncertain, it is relevant to consider a lower and a higher price boundary. Therefore, 14.6 EUR/MWh in the low biomass price scenario and 58.2 EUR/MWh in the high biomass price scenario could be reasonable to assume (Martelius 2022). A summary of the prices is presented in Table 4.

Table 4: Biomass price projections to 2045 (Energimyndigheten 2022; Martelius 2022)

Year	Units	Low	High
2020	EUR/MWh	10	31.1
2022	EUR/MWh	20.2	20.2
2045	EUR/MWh	14.6	58.2

4.4 Structure of the report

In the following sections, the narratives for the selected LMTs representing the Swedish portfolio are presented. After a short introduction to the general and policy context of each LMT, land-use competition, climate risks, co-benefits and trade-offs are discussed for each LMT. Then economic implications and risks associated with upscaling are evaluated. Finally, we close the analysis for each LMT with a concluding discussion summarizing outlook and future research. General reflections from the LMT narratives for Sweden are summarized in the final section of this report.

Engagement with stakeholders for the development of this narrative included actors at local and national levels, including public agencies and private actors, and was aimed at identifying some initial perceptions of the enablers and barriers for LMTs and measures in Sweden and the Nordic region. We included stakeholders with general knowledge on climate and/or sectoral issues (e.g. biomass and bioenergy sector stakeholders) but focused more on those with knowledge on the key LMTs that have been identified for our LMT portfolio. The stakeholder views were used as input in the development of the national LMT portfolio and narrative, as well as a commentary on future research directions and knowledge gaps that our project should cover. Stakeholder input has been used to validate modelling and case study assumptions, as well as for increasing our understanding of government strategies to create a well-functioning system for LMTs and NETs. Stakeholder input was gathered through one-to-one semi-structured interviews, a survey, as well as the first regional engagement workshop.

5. BECCS

5.1 Introduction

Bioenergy with carbon capture and storage (BECCS) is among the key mitigation technologies in most 1.5–2.0 oC compatible climate change mitigation scenarios. BECCS refers to a group of technologies used for capturing and storing carbon emitted from biomass combustion. Even though widely discussed in literature, actual BECCS implementation projects are few. Previous literature attributes this to the high upfront costs and the lack of strong policy drivers (Fridahl et al. 2020).

BECCS is a technology to achieve negative emissions, by sequestrating emissions resulting from biomass burning. As a result, BECCS has multiple benefits; it combines energy production (electricity and heat), with negative emissions. BECCS is a popular choice in integrated assessment models (IAMs) that optimize costs. Previous studies estimate that the median estimation in IAMs for the BECCS deployment for primary energy use production by 2050 is 46 % (Fridahl 2018). Out of 116 scenarios of the IPCC, 101 with a “likely” chance to stay below 2 oC include BECCS. In 67 of these scenarios, BECCS represents 20 % of the global primary energy by 2100 (Fuss et al. 2014).

BECCS is currently strongly pursued in Sweden by Stockholm Exergi, an energy company, which supplies the Stockholm region with electricity, heat, cooling, as well as provides waste management services. Stockholm Exergi is partially owned (50 %) by the municipality of Stockholm. The other owner of Stockholm Exergi is the Finnish energy company Fortum.

Among local authorities, Stockholm’s municipality is one of the actors that discuss the possibility of including BECCS as part of negative emissions portfolios that would help achieve their climate targets. But apart from Stockholm, many other Swedish municipalities ae interested in BECCS. For example, the climate policy knowledge network of Climate Municipalities (Klimatkommunerna in Swedish) has published material explaining how BECCS, among other technologies, can contribute to negative emissions .

In December 2019, Stockholm Exergi inaugurated a research facility in order to test BECCS, and in the autumn of 2020, the Swedish Energy Agency, approved a grant that gave the opportunity to Stockholm Exergi to expand the tests to additional technologies and processes. The target according to Stockholm Exergi is to get more robust results from operation of the small-scale demo, before proceeding with investments to a large-scale facility.

5.2 Policy context

Sweden’s carbon neutrality target has been translated in previous scenario studies to a net zero CO2 emissions target from 2045 to 2050, which in turn would need BECCS to achieve a maximum of 6.5 Mt negative CO2 emissions (equivalent to 10% of the emissions in 1990), with linear CO2 reductions between 2030 and 2045 (Millot, Krook-Riekkola, and Maïzi 2020).

The investigation also suggested the direction of complementing measures up to 2030 regarding increasing the impact of carbon sinks in terms of emission reduction. Among them, BECCS measures should aim for a reduction of 1.8 Mton CO2eq/year. After 2030 and with a comprehensive strategy in place, the potential emissions savings from BECCS up to 2045 could reach between 3 to 10 Mton CO2eq/year (Karlsson et al. 2020). For this goal to be met, it is projected that between 3 to 5 plants are in operation by 2045 (Karlsson et al. 2020).

One of the main policy instruments to assist implementation of BECCS and help realize Swedish goals on carbon neutrality is the so-called “Industrial Leap” (Industriklivet in Swedish), administered by the Swedish Energy Agency. BECCS is seen as a potential option for the Swedish energy intensive industries, such as the cement sector (Ministry of the environment & Government offices of Sweden, 2020). Previous case studies on the deployment of BECCS in the Swedish base industry recommend a wide set of actions in order to motivate BECCS investments; RD&D funding, governmental risk sharing and state funding to first-of-the-kind projects, support for niche markets through public/private procurement, market making for zero- and negative-CO2 products, as well as adaptation of infrastructure policies (Rootzén et al. 2018).

The Industrial Leap’s scope was amended in 2020 in order to facilitate supporting measures leading to negative emissions such as BECCS. The budget of the Industrial Leap has also been steadily increasing; from 30 million € in 2018, to 50 million € in 2019, and the government has proposed an increase by 60 million € for the period 2020-2022 (Ministry of the Environment 2020). As mentioned above, Stockholm Exergi received a grant for their industrial test project. A total of 10 million € was allocated to the promotion of negative emission technologies. This was the first economic incentive for test facilities for BECCS .

BECCS has an important role to play from a political perspective in Sweden’s case; developing this technology at full-scale will help Sweden maintain frontrunner status both at the climate policy arena, but also from an international business perspective according to some stakeholders (Christiansen 2020). In the budget proposition for 2021, the government discusses how NETs are important for strengthening businesses export ability and competitiveness at an international level. The Swedish Energy Agency suggests that a national centre for CCS should be developed, focusing among others on introducing an auctioning system for BECCS that would support operation of such plants already from 2022 . It is also recognized that Sweden should influence processes at the EU level in order to introduce policy instruments for BECCS that are cross-national.

However, the Swedish Climate Policy Council recommends that the creation of such incentives, as the ones discussed above, should be clarified in order to implement and scale up CCS in general, and more specifically BECCS, which currently seems to be necessary for certain types of emissions and for being able to reach negative emissions (Klimatpolitiska rådet 2019).

The storage of the captured CO2 emissions is planned to be underground. As of today, local storage is underexplored. An estimation indicates that the storage capacity in Sweden is about 3,400 Million tonnes of CO2, but these are not confirmed. Exploration for local storage is previewed for 2040. The option following would be international storage (Karlsson et al. 2020). Denmark and Norway have geological storage availability (Table 5). However, the current Swedish regulation severely limits the transportation and geological storage of emissions in other countries (Martelius 2022).

Table 5: Underground storage capacity (Karlsson et al. 2020)

	Storage capacity (Million tonnes CO_2)
Sweden	3,400
Denmark	22,000
Norway	94,600

In this sense, the regulation requires to be updated to allow local and international CO2 transportation and storage. Only if international storage infrastructure is not possible, local storage would be considered by Sweden. This could hinder BECCS development and risk meeting the 2045 goals (Martelius 2022).

5.3 Current land use and potential land-use competition

BECCS is likely to compete with other land-based activities, such as food production. This negative side-effect can be mitigated with agricultural intensification, but this approach could instead lead to biodiversity loss and increased biochemical flows. There are no specific studies quantifying these impacts for Sweden in the case of scaled-up BECCS, a research gap which is necessary to fill (Fajardy et al. 2019).

5.4 Climate risks and sensitivities

Negative emission technologies have been a topic for debate with regards to how their effects are modelled in IAMs. Previous studies express concerns on the feasibility of deploying such technologies large-scale. IAMs assume that large areas of arable land (e.g. double the size of India) will need to be available to provide biomass for BECCS. Area availability of such magnitude is unrealistic and would lead to significant loss of biodiversity and risks for food security (Christiansen 2020). There are yet no studies specific for such effects for the case of a Swedish implementation of BECCS.

However, as discussed by Swedish stakeholders, these risks may cause a big uncertainty, but as long as an offset claim has not been made on the affected land, the problems of that uncertainty can be minimized. There is indeed increased risk of disturbances from a changing climate, e.g. from pests (in Sweden the spruce bark beetle), storms, wildfires, drought etc. which means that storing carbon in forests is an uncertain climate mitigation strategy associated with risk. In that sense, permanent ground storage that biochar and BECCS offer are less sensitive to risks, however permanence is still an issue that needs to be clarified. Additionally, climate disturbances will affect the biomass availability, which will have indirectly negative impacts on other LMTs' deployment.

5.5 Co-benefits and trade-offs

Some estimations have been proposed for calculating the impact of BECCS in electricity production and energy use. According to national assessment, the capture and compression of 2 Mtonne CO_2 will increase the consumption of biomass by 0.6 TWh, meaning that about 0.3 TWh of additional biomass are needed per Mtonne CO_2 processed (Karlsson et al. 2020). Additionally, electricity consumption is predicted to increase too. It is estimated that an additional 0.2 TWh_{el} per Mtonne CO_2 captured and compressed will be needed (Karlsson et al. 2020).

Emission intensive sectors such as cement and iron and steel, could potentially reduce their emission with Carbon Capture and Storage (CCS). In the case of the cement industry, there are limited alternatives to decrease process CO_2 emissions given that in clinker production emissions are practically unavoidable. In the case of iron and steel, using CCS is an alternative to emission reduction (Karlsson et al. 2020). It has been estimated that a potential reduction of 12 Mton CO_2 could require about 22 TWh of energy. This translates to an energy requirement of about 1.8 MWh per tonne CO_2 to capture the emissions in these sectors (Karlsson et al. 2020).

BECCS may have impact on resource depletion, soil health, and biodiversity, since it can lead to monocultures for increased biomass yields. In fact, these negative side-effects have been identified as major limitations to the deployment of BECCS. Land use as well as water depletion associated with BECCS is according to previous studies a major concern (Fajardy et al. 2019). Nevertheless, implications of BECCS for the food, water, energy, biodiversity, and social systems nexus remain unclear at the regional/local scale.

There are mainly two routes currently discussed for BECCS; one via liquid biofuel production (biodiesel or ethanol) and the other via biomass conversion to heat and power (most often with direct pulverized combustion of biomass). Both routes imply the presence of co-benefits from implementing BECCS, since energy is produced, either as fuel or as electricity and heat. This means that implementation of BECCS could not only deliver negative emissions, but also help decarbonize other sectors, such as transport or heating sector.

However, there are some important risks connected to large-scale BECCS sustainability that can be summarized as follows (Fajardy et al. 2019):

- The industry's potential scale – IAMs estimate large-scale BECCS deployment being two thirds of the size of today's fossil industry by the end of the century,
- The reliance of large-scale BECCS on a significant quantity of sustainable biomass, and additionally water, land and nutrients,
- The possibility that BECCS deployment would encourage delays in mitigation action, and
- Missing the 2100 temperature target if BECCS potential to deliver negative emissions is not realized.

Additionally, stakeholder interviews highlighted the need for common accounting protocols and standards for negative emissions in order to be able to globally trade them in common markets.

On the other hand, the underground storage of the captured CO2 will require transportation to suitable geological locations. Considering that most of the storage capacity is international (Norway and Denmark), transportation is required to deliver the captured emissions. Two types of transport options considered by Sweden are boat transportation and pipelines.

Boat transportation is judged as a realistic option for the foreseeable future (Karlsson et al. 2020). Sweden could potentially make use of the Mälaren and the Vänern lakes, as well as the Baltic Sea to ship the captured CO2 to suitable underground storage in Norway or Denmark. One transport scenario considers the use of 4,000 tonne-capacity ships, able to travel about 1500 km in a one-way trip to Norway. Transportation cycle time would be around 200 hours (sailing at 12 knots and considering 70 hours in total for loading and unloading). In this case, one ship could do about 40 transport cycles per year, which represent a total of 160,000 tonnes of CO2/per year (Karlsson et al. 2020). A second transport scenario considers the use of a bigger ship, powered with LPG, with a capacity of 20,000 tonnes. In this case, about 800,000 Mtonne CO2/year could be potentially transported to international underground storage (Karlsson et al. 2020).

In contrast, pipeline transportation is considered less feasible, mainly due to the logistic implications of planning, designing and installing pipeline systems that connect the emitters and the potential storage sites, which already implies long distances (Karlsson et al. 2020). Along the same line, Swedish landscape conditions make a project like this unrealistic. First, the pipelines would need to cross hard rock, lakes and nature conservation areas. Secondly, a connection of the ground-level pipelines to the sea bottom would be needed, which represents increased costs. As a result, the emergence of such pipeline infrastructure would be dependent on state investment and would potentially require the creation of a state-owned company to oversee the piping system's operation (Karlsson et al. 2020).

5.6 Economic implications

According to the Swedish Goverment's investigation, which was recently published, the costs for BECCS should be expected to be within a range of 400 to 600 SEK/ton CO_2 with an additional cost of 150 to 300 SEK/ton CO_2 for the transportation to storage sites (including sites outside of Sweden). The storage itself is expected to cost between 100 and 200 SEK/ton CO_2. As presented in Table 6, the total cost would thus vary between 650 and 1,100 SEK/ton CO_2 (about 65 – 110 €/ton CO_2). The capital costs are expected to decrease by 30 % by 2045, but at the same time there is uncertainty regarding the long-term price trends for biomass supply, which could influence the overall cost of the technology (Karlsson et al. 2020).

Table 6: Forecast prices for BECCS stages (Karlsson et al. 2020).

	Low	High
	SEK/tonne CO_2	
Capture of CO_2	400	600
Transportation	150	300
Storage and safety	100	200
Total cost	**650**	**1,100**

Furthermore, Stockholm Exergi together with researchers have published their estimations for the costs and benefits of a potential large-scale implementation of BECCS for the case of Stockholm and the KVV8 plant. The calculations included a range on assumptions for potential costs for transport and storage and conclude that costs would range from 55 to 93 €/tonne CO2, which is somewhat lower, but within the same range with the costs indicated in the government investigation (Levihn et al. 2019).

The study concludes that BECCS is cost-efficient compared to many other abatement options, and abating 850 ktonne CO2/year (i.e. full scale implementation of BECCS at KVV8) would cost 47 – 79 million €/year for Stockholm Exergi. In order to manage the implementation of BECCS on one plant, Stockholm Exergi would have to increase the income by 10 %, according to the authors' calculations. With a profit at 120 million € (2016 values), this would mean reduced profit by 39 to 66 %. It should be noted that transferring cost to the consumers is not an option considered, because of the deregulated competitive heat market (Levihn et al. 2019).

Nevertheless, the municipality of Stockholm calculated the private and social costs of BECCS in the climate plan of 2017. The CO2 abatement potential through BECCS was estimated to be more than 2000 ktonne CO2/year. The private cost (cost for the municipality who owns 50 % of Stockholm Exergi) would then be 50 €/t CO2 and the social cost (for Sweden) was estimated at 120 €/t CO2. These numbers refer to a case where Exergi would have to be the sole investor on BECCS for KVV8, while in reality it is likely that State support would be required for realizing such an investment.

The cost competitiveness of the technology in the future is closely linked to carbon pricing as well as the potential to build a market for the negative emissions created. This is confirmed from our interviews with Swedish stakeholders, who discussed the need of a global market for negative emissions, in the same manner as the EU ETS. The carbon tax is not sufficient for doing any difference between fossil and renewable fuels.

5.7 Risks associated with scaling up

Stakeholder interviews show there are technical, political, economic, and other risks that BECCS would have to overcome for scaling-up and becoming commercial. From the technical perspective, building and adapting existing CCS technologies to various industry types is one challenge, for example. From the political perspective, increasing interest and support for the technology is considered a challenge and from the economic perspective, introducing financial instruments and incentives for public and private investors at a wider scale is one of the main barriers. Finally, alleviating the public's concerns and spreading knowledge about the technology is another important challenge that the technology faces (Jakobsson 2020).

Another interview-based analysis stress that, in Sweden, both material and ideational factors support the role of negative emission technologies (NETs) – especially BECCS – as a way for the country to maintain a status of international frontrunner for battling climate change. However, financing BECCS and other NETs might be a challenge to the widely established "polluter pays" principle; rights and responsibilities for funding and implementing the technologies will shift to the society (Christiansen 2020). In other words, will the public fund private companies deploying BECCS in order to provide negative emissions? This would require strong public support, and, in any case, the potential risks should be discussed.

A remaining question is to what extent existing Swedish and international (UN, EU) climate policy instruments provide incentives for researching, developing, demonstrating and eventually upscaling BECCS in Sweden. It is possible that Swedish climate policy instruments would need to be reformed to deliver the desired effects when it comes to BECCS. It recommended that efforts to remove regulatory barriers continue and are complemented with demand-pull instruments. The existing policy mix needs to be reformed, in order to avoid risking substantial public expenditure on BECCS without succeeding with substantial deployment and diffusion of the technology (Fridahl et al. 2020).

5.8 Conclusion

BECCS is a key NET in the Swedish context, expected to deliver a large share of emission removals in line with the Swedish policy target to be a net-zero welfare country by 2045. This has led to Sweden being among the frontrunners of BECCS demonstration projects around the world, with planning for upscaling being at a relatively more advanced stage than other EU countries. Still, significant investments would be needed not just on the actual carbon capture and removal plants, but also in transportation and permanent storage of the carbon. There are technical, political, economic, and other risks that BECCS would have to overcome for scaling-up and becoming commercial, but there certainly is a technology that Sweden is placing at a central point in its LMT portfolio.

Negative emission accounting methods have been identified as an important knowledge gap according to interviews. Incorporating the time and lifecycle perspectives are two parameters which are also of interest when developing LMT portfolio narratives and modelling potential impacts. There is lack of a system in order to get reimbursed for negative emissions. How would a global market of negative emissions look like? Additionally, it should be further explored how countries should have their own systems/instruments to support biomass technologies. There is a policy gap for the large-scale implementation and storage of BECCS that is necessary to address.

6. Biochar

6.1 Introduction

Biochar is produced when plant matter is heated in a zero or low oxygen environment at relatively low temperatures (300 – 1000 °C) in a process called pyrolysis, when done in a zero oxygen environment (Saifullah et al. 2018; Hertsgaard 2014); or gasification, for low oxygen environments (Woolf et al. 2014). After the transformation, biochar can come in many forms such as sticks, pellets or dust (Hertsgaard 2014).

Biochar has many applications. According to the European Biochar Industry Consortium (EBI), biochar could be used to sequester carbon in soils (although a percentage of the char will decay) or it can be used in building materials (housing, asphalt) (Bier et al. 2020). If mixed into the soil, biochar enhances plant and crop growth and is said to have positive impacts on soil quality (Agegnehu, Srivastava, and Bird 2017; Agegnehu et al. 2016), although the long-term benefits in real world applications might be less than thought and might require further study (Jones et al. 2012). Additionally, biochar could be fed to livestock, thus enhancing soil quality indirectly (Gunnerund 2021). Sequestration potential varies according to assumptions such as availability of biomass and production efficiency, but is said to range between 1 and 3 Gigatons of CO_2 per year globally (Bier et al. 2020), also in a sustainable manner (Woolf et al. 2010).

Biochar is currently produced on small scale in Sweden and is used as a soil amendment in parks and tree plantations. However, these small quantities not accounted for in Swedish climate and emission reporting (Karlsson et al. 2020).

In terms of biochar production, The European Biochar Industry Consortium (2022) reported that about 20,000 tonnes biochar were produced in Europe 2021. Of this, Scandinavia represents 23% of overall production. Sweden participation in the Scandinavian biochar market represents about 75%, which translates in an estimated biochar production of 3,450 tonnes. If an average of 2,9 tonnes CO2 stored per tonne biochar is assumed, it can be estimated that about 10,000 tonnes of CO2 were stored in the biochar produced in Sweden (The European Biochar Industry Consortium 2022).

6.2 Policy context

Even though biochar deployment is currently limited, it is expected to play an important role in the Swedish mitigation strategy. For instance, biochar is mentioned in the Swedish National Integrated Energy and Climate plan (a plan to be delivered regularly due to EU regulation EU 2018/1999) and other studies speak of policy support to be expected (Azzi, Karltun, and Sundberg 2021).

On the local level, the city of Stockholm explicitly mentions biochar in its climate action plan of 2020 – 2023 (Stockholms Stad 2020), which lists increased use of biochar produced at local plants as one of the measures for reducing emissions and eventually leading to a climate positive municipality. According to an interview with Stockholm's municipality, the city is involved in several international initiatives building knowledge on issues related to implementation of negative emission technologies, such as biochar and BECCS, and even though land management is not directly under their sphere of influence, they are interested in the potential of negative emission technologies that can support the realization of their climate targets.

The potential emission savings per year by biochar deployment in Sweden are estimated to be less than 1 Mton CO2 up to 2045, but according to the recent Swedish Government's investigation the use of biochar as fertilizer is considered to be the technology which has the "[…] largest practical potential to contribute to negative emissions for Sweden by the middle of this century" (Karlsson et al. 2020). The report also recommends that investment support for biochar should continue through various programs.

The city of Stockholm has built a pyrolysis plant to turn park and garden waste into biochar with the funding of the Bloomberg Mayors Challenge fund (Bloomberg Cities Network 2021). There is a pilot plant in Högdalen annually producing 300 tons biochar from 1300 tons of garden waste (Gustafsson 2017). Five more plants are planned, which are expected to produce 7000 tonnes of biochar per year, thus sequestering 25,200 tonnes of CO2 per year[1]. Other cities and municipalities also have several pilot projects such as Länghem where a company works on carbon credit certification for biochar or Hällekis where a farm is producing biochar from waste. In addition, Swedish stakeholders are rather active in the research and development (R&D) sector when it comes to biochar. For instance, the energy and agriculture department of the university of Uppsala has a research programme on biochar as does KTH Royal Institute of Technology.[2] Some private sector players such as Envigas focus on making the process more efficient.[3] However, besides those pilot projects and early innovators, production and use of biochar is still in its early stages (Azzi, Karltun, and Sundberg 2021).

The Klimatkliv fund, administered by the Swedish Environmental Protection Agency, allows entities to compete for grants to implement emission reduction projects. In the past, Klimatkliv has financed biochar projects and the total budget in 2019 stood at SEK 1.5 billion (Ministry of Infrastructure 2020). As mentioned above, the Stockholm plant was financed by the Bloomberg Mayors Challenge fund, so international financing is available as well. Financing biochar deployment is also discussed under agricultural programs.

6.3 Current land use and potential land-use competition

Biochar applications and production facilities are in the beginning phase of its deployment, truly a niche technology (Geels 2010). Therefore, impacts on land use have seldom been investigated and historic data is lacking.

[1] https://nordregio.org/sustainable_cities/stockholm-biochar-project/
[2] https://www.biochar.abe.kth.se/
[3] All info from https://www.nordicbiochar.org/about-us/map/

Biochar is not considered a main technology to achieve negative emissions, but as a complementary measure that could contribute to Sweden's achievement of its objectives. Biochar potential is projected to be, in an optimistic scenario, up to 1 Million tonnes of CO2 stored per year, as long as economic measures and incentives accompany its market expansion. This would require employing at least 5.4 TWh worth of biomass (branches and park and garden waste) for the pyrolysis process, and about 500,000 tonnes of biochar would be produced as a result (Karlsson et al. 2020).

Like many LMTs, biochar might enter in competition with other LMTs for land and resources. To produce biochar, input materials in form of biomass is needed which might enter in competition with land for food growth (Tisserant and Cherubini 2019). However, (Dumortier et al. 2020) observe in their models that land-use change might even decrease, provided that the baseline lands produce higher yields (assumed 1% in their US case study) because of biochar applications (Dumortier et al. 2020).

6.4 Climate risks & sensitivities

Overall, there are not many studies investigating the impacts of climate change on biochar. Biochar production entails an "energy penalty", meaning that, in addition to the feedstock, between 2.5 to 3 TWh of additional biomass are needed in order to produce about 500,000 ton of biochar per year (Karlsson et al. 2020, 667). Azzi, Karltun, and Sundberg (2021) study Swedish biochar systems and report potential reduced biochar production capacities when heat demand (in combined systems where heat is used to heat homes/farms) varies according to weather patterns, depending on electricity demand and heat demand. This might be interpreted in the way that exceptionally cold or, conversely, mild winters will influence biochar production.

Table 7: Biochar energy production and penalty (additional biomass) for the production of 500,000 ton biochar (Karlsson et al. 2020).

		Low	High
Energy production	TWh	2	4
Additional biomass required	TWh	2.5	3

Jahromi et al. (2020) in a case study in Tennessee, U.S. observe that biochar increases water retention in flooded sandy soil suggesting that biochar might be able to mitigate the impacts of heavy rainfall. Similarly, biochar has been observed to increase the health of soils by mitigating soil erosion, increasing soil porosity, and by improving soil consistency (Blanco-Canqui 2017). When it comes to flooding, biochar was observed to have water filtering qualities when applied in lab setting which potentially makes it appropriate to mitigate influx of metals, nitrates, phosphates and other substances in storm water (Reddy, Xie, and Dastgheibi 2014).

Another also unresearched issue is the impact of biochar on the reflectiveness (albedo) of the surfaces it is applied to which might change the temperature of the soil. However, initial studies suggest a saturation effect (applying more biochar over a certain threshold - going from 30 tonnes per ha to 60 tonnes per ha in the case study - doesn't affect the albedo) and propose to mitigate negative effects of the darkening of the surface by improved land management (Genesio et al. 2012). Other studies, in turn, see a reduction in climate mitigation potential by -30% in high solar irradiation contexts such as the Mediterranean (Bozzi et al. 2015).

6.5 Economic implications

Tisserant and Cherubini (2019) argue that biochar was one of the most affordable negative emission technologies (NET). But given the different biochar production pathways (high temperature, low temperature pyrolysis, gasification etc.) and the different input materials possibly used, cost and benefits vary from location to location and from context to context (Pratt and Moran 2010).

For instance, a study for Western and Northern Europe concluded a negative net present value (costs outweigh the benefits), while a positive net present value was found for sub-Saharan Africa (Dickinson et al. 2015). Nevertheless, Latawiec et al. (2019) found that costs for biochar production and application in Brazil for small farms largely outweigh the benefits. However, a case study in Canada modelled biochar production in combination with energy production and came to the conclusion that, provided that carbon sequestration can be monetised at 60 Canadian dollars per ton sequestered CO2 (about EUR 42), biochar applications could be profitable for farmers 12 years after investment (Homagain et al. 2016). Interestingly, the study identifies the pyrolysis process as having the biggest impact on overall costs (36%), thus pointing to the fact that efficiency gains in pyrolysis technology might increase the profitability of biochar applications.

Production cost of biochar vary widely depending on the technology used and the study parameters (Meyer, Glaser, and Quicker 2011). Slow pyrolysis in an earthen kiln was found to be the most expensive process (at 3,747 USD/tonne), while slow pyrolysis in a drum kiln was found to be producible at 41USD/tonne (Meyer, Glaser, and Quicker 2011).

In Sweden's national climate plan, Karlsson et al. (2020) refer to international biochar price for two types of biochar. On one hand, high quality biochar was found to be around 500 to 600 € per ton biochar. On the other hand, biochar for construction market price lies around 450 € per ton biochar.

Table 8: Observed market biochar prices (Karlsson et al. 2020).

	Low	High
	EUR/ton biochar	
High-quality biochar with low level of hydrocarbon	500	600
Biochar for construction soil	450	

The interviewed Swedish actors agreed that there are currently no economic incentives for biochar deployment in Sweden. Creating a market for biochar products from different feedstocks is also discussed in the Swedish Government investigation for a climate positive country. The investigation provides some estimations on potential costs for biochar used as fertilizer (0.9-2.8 SEK/kg CO2 or 0.1-0.3 €/kg CO2) (Karlsson et al. 2020).

6.6 Co-benefits and trade-offs

A technical factor that should be considered when accounting for emission storage in biochar is carbon stability, which is directly related to carbon permanence. Permanence refers to the amount of carbon that remains in the biochar sample after some time. It is desired that carbon performance in biochar is at least 100 years or more. The permanence of carbon in biochar obtained through slow pyrolysis at a temperature of around 450 oC , after 100 years, is about 80% (Karlsson et al. 2020).

Table 9 shows the carbon content and yields of biochar depending on the different production methods.

Table 9: Carbon content and yields of biochar depending on the different production methods (Meyer, Glaser, and Quicker 2011)

process type	typical process temperature	typical residence time	typical solid product yield on a dry wood feed-stock basis [in mass %]	typical carbon content of the solid product [in mass %]	typical carbon yield: (mass $_{carbon, product}$/ mass $_{carbon, feedstock}$)	reference
torrefaction	~ 290 °C	10– 60 min	61–84%	51–55%	0.67–0.85	16, 20
slow pyrolysis	~ 400 °C	minutes to days	≈ 30%	95%	≈ 0.58	16, 21
fast pyrolysis	~ 500 °C	~ 1 s	12–26%	74%	0.2–0.26	16, 17, 22, 23
gasification	~ 800 °C	~10 to 20 s	≈ 10%			15, 16
htc	~ 180–250 °C	1–12 h	<66%[b]	<70%[a]	≈ 0.88	12, 24
flash carbonization	~ 300–600 °C	<30 min	37%	≈ 85%	≈ 0.65	25

[a] The carbon content of 70% of the product indicated in Tsukashima[24] is related to the dry, ash-free product. [b] Lower solid product yields for htc at both shorter and longer residence times are reported by Libra et al.[12]

Studies on a Swedish farm (using model runs) point to the fact that a combined heat and pyrolysis installation on a farm (50 kW heat capacity) could save around 12 tonnes of CO2eq per year, or the equivalent of 1.5 average Swedish citizens (Azzi, Karltun, and Sundberg 2021). If half (12,500) of comparable Swedish farms (25,000 in total), were to use the investigated technology, around 125,000 tonnes of biochar could be produced, saving 0.3 million tonnes of CO2eq annually (Azzi, Karltun, and Sundberg 2021).

Biochar applications to soils do seem to have tangible benefits (see above) and some scholars make the connection between improved soil quality and crops yields (Palansooriya et al. 2019). In a meta review of published studies, (Biederman and Harpole 2013) come to the conclusion, that biochar increased "[…] aboveground productivity, crop yield, soil microbial biomass, rhizobia nodulation, plant K tissue concentration, soil phosphorus (P), soil potassium (K), total soil nitrogen (N), and total soil carbon (C) compared with control conditions." However, some studies nuance this picture and argue that biochar's impact on crop yield would depend on things factors like the pH value of the soil (moderate pH soils are already quite nutrient rich, therefore, biochar addition in moderate pH soils in temperate climates would yield less benefits) (Jeffery et al. 2017).

Regarding effects on the landscape, and since biochar is mostly used underground, impacts are expected to be negligible, except with a potential darkening of the soil. Furthermore, impacts on biodiversity have not been studied in depth. Experiments have shown that biochar applications have increased “biological activities” (Gałązka et al. 2019), but other studies came to the conclusion that different land management practices would have a larger impact compared to biochar (Hardy et al. 2019). There is, however, a positive impact on nitrogen emissions. According to a meta-analysis, N2O emissions could be 38 – 54 % lower if biochar was applied to soils and nitrate leaking might be reduced by 13 % (Borchard et al. 2019; Cayuela et al. 2014). Finally, studies show that application of biochar generally increased the capacity of soil to retain water (Fischer et al. 2019).

A study investigating a biochar pyrolysis unit on a Swedish farm reported several potential side effects based on model results: higher land use and negative impacts on human via a respiratory route (compared to purely electric heating) since combustion of biomass and the pyrolysis process can also generate harmful gases and air pollutants (Azzi, Karltun, and Sundberg 2019). Also, while not detecting any long term negative environmental impacts, (Gruss et al. 2019) observed short-term avoidance of biochar applied in fields for springtails (an insect) in laboratory tests due to a sudden increase in pH, suggesting some potential short term toxicity. Similarly, studies found that depending on the input materials used for the pyrolysis, biochar products might develop toxic properties (Godlewska, Ok, and Oleszczuk 2021).

Nevertheless, the Swedish Government’s investigation on carbon sinks concluded that more studies are needed on the effects of biochar on agriculture, carbon sequestration, and the environment taking into account the Swedish prerequisites (Karlsson et al. 2020).

One recently published Swedish study estimates the environmental impacts from biochar production using soil waste as feedstock. It is in the study that the increased demand for biomass would be met by harvesting residues from Swedish forestry. Even when emissions were included as a result of this direct change in land use (loss of forest ecosystem due to harvest compared to non-harvest), climate change impacts are low compared to other conventional heating fuels. With another set of assumptions about the availability of biomass, lower bioenergy availability for biochar production would lead to higher climate impacts. However, high stability of the biochar and low emission factors for electricity and biomass make the Swedish case unique and show large potential for emissions’ reduction (Enell et al. 2020).

The main trade-off when it comes to biochar production is the competition between on the one hand energy and heat (generated by burning biomass) and on the other hand the different products which are technically feasibly using the pyrolysis or gasification pathways. Figure 1 gives an overview of different pathways.

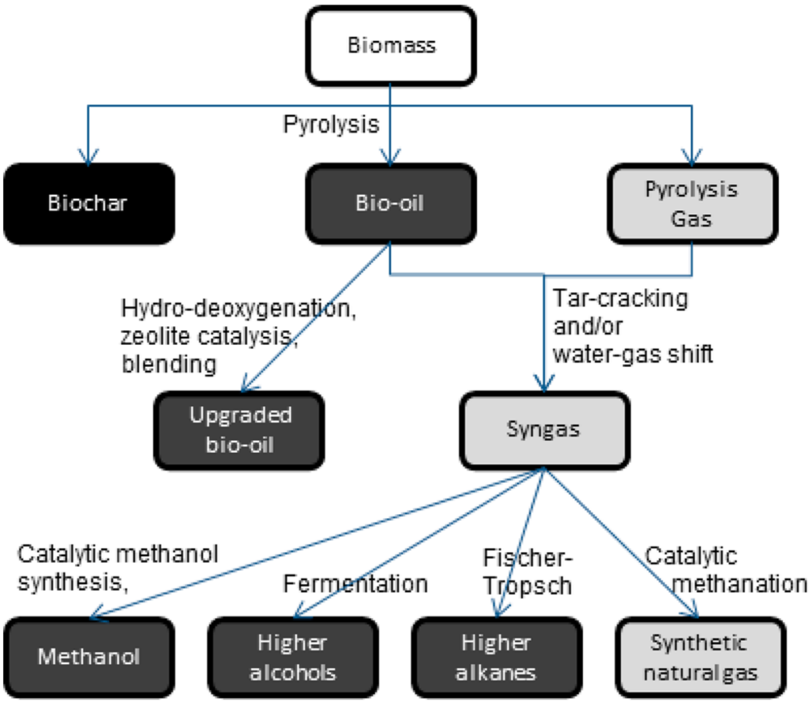

Figure 1: Biomass to bioproducts pathways. Source: Woolf et al. (2014).

As Woolf et al. (2014) have shown, the choice of heating temperature, input materials, the efficiency of the production site itself and the expected product to come out of the process have considerable impacts on biochar yields, heat generation and yields of other products (bio oils, syngas etc.). For instance, higher temperatures usually yield biochar high in carbon content (i.e. more carbon sequestration) (Zhao, Ta, and Wang 2017), which in turn reduces other fuel yields and increased energy demand as input (Woolf et al. 2014).

6.7 Risks associated with scaling up

One of the main risks of scaling of biochar it's its competition with cropland if biomass is grown especially for the purpose of converting it to energy and biochar, although increasing crop yields due to biochar application might offset this land-use change (Dumortier et al. 2020). Also, using waste biomass to produce biochar might offset the impact on land-use change, but the diverging lignite and moisture content of waste biomass could further complicate the picture of yield identified above (Tripathi, Sahu, and Ganesan 2016). Another risk might lie in the effect of biochar application of soil reflectivity and soil darkening.

There is interest in biochar from the perspective of a developing market, but as demand grows so should the supply grow as well. Ensuring profitable selling of heat and biochar is important not for just upscaling within Sweden but also outscaling to the rest of the world (Söderqvist, Norberg, and Turnstedt 2021). This was also confirmed in interviews, where the co-benefits from producing biochar through pyrolysis include the production of gas which can be used for running peak-power plants and support the grid when high capacity is needed. Ensuring the necessary grid capacity under peak loads has been a point of major discussions in the past years in Sweden, and according to recent reports the potential of biobased solutions has not been fully exploited.

6.8 Conclusion

Although currently deployed at smaller volumes, biochar will play a role in achieving Swedish climate policy targets, as a complementary measure with several co-benefits, such as soil productivity enhancement, as well as co-products, such as heat and electricity. Swedish municipalities have been active in exploring biochar implementation, but upscaling would require incentives and a stable market creation.

Climate risks and sensitivities are not well covered by the literature when it comes to biochar. Also quite surprisingly, there are few studies which take into consideration land-use change implications if biomass would be grown specifically for charcoal production. Moreover, investigating the issue of soil reflectivity (albedo) more in depth is another research gap. (Jakobsson, 2020). According to interviews, it is also important to connect to the Global Carbon Project in order to gain understanding about how biomass is increasing at the global level and how could this be utilized for biochar production.

7. Afforestation, Reforestation, Forest Management

7.1 Introduction

Sweden has more land under forest than any other country in the EU, with Sweden and Finland together accounting for nearly one-third of EU forests. Management of forests in Sweden has reached a high level of maturity and optimisation in environmental and socio-economic terms as a result of the high priority placed on the contribution to both carbon sinks and fossil fuel substitution. Markets for pulp and paper, wood products, and high-quality bioenergy products (e.g., wood pellets) have evolved continuously ever since WWII. There have also been a variety of major research and development efforts ever since the 1960s related to conversion of woody biomass, including biofuels, gasification, pyrolysis, and other platforms such that will be of strategic relevance for climate stabilisation and resilience. These efforts accelerated after the oil crises of the 1970s, with developments aimed not only at technological and market developments domestically but also to establish best practices within Europe and globally in some cases. Consequently, the forest resource base in Sweden is a pillar of land-based mitigation and negative emissions efforts not only in Sweden and the Nordic region but for the entire EU and to some extent in global terms as well due to international cooperation on technology and resource development.

At the same time, precisely because the use of forest resources is so mature and developed and is already high-performing in climate terms, it is difficult to talk about afforestation or reforestation as a major LMT in the Swedish context for several reasons. First, deforestation was extensive by the end of the 19th century, after which a continuous and comprehensive approach to reforestation and was later combined with an increasingly intensive management style that allowed high productivity for both standing biomass and extraction for wood products and bioenergy.

Second, since management has been oriented towards climate and renewable energy aims for so long, concerns have shifted somewhat to biodiversity and cultural impacts of intensive forest management, and therefore policy changes underway are expected to be more inclusive of wider societal aims even as climate mitigation and zero emission targets will receive high priority.

Third, as biomass and bioenergy markets because tighter and more competitive within the EU but at the same time Sweden and other countries are aiming to maximise domestic use rather than trade, there are greater linkages, synergies, and conflicts with portfolios of LMTs in Sweden and elsewhere in the EU, particularly in light of the new EU Forest Strategy that is under consultation and development (Aggestam and Giurca 2021). Therefore, rather than afforestation or reforestation, this LMT relates to Forest Management more generally, and will be analysed in this context, particularly emphasising the evolving forest policies and strategies. However, it is not possible to comprehensively cover such a broad set of issues for the Swedish case, so the discussion here is somewhat selective and is based on changes that are occurring at the margin and especially in relation to net zero emission goals that were established in 2016 (Regeringskansliet 2017).

7.2 Policy context

A long period of deforestation and/or neglect of forests into the 1800s eventually led to the Swedish Forestry Act of 1903, which began a century-long process of reforestation and establishing the basis for the modern and productive forest sector that is now the most important in the EU in many respects. The law was updated in 1993 to include ecological considerations and again in 2008 to incorporate social aspects, while the National Forest Programme of 2014 increased public participation in forest policies and strategies (Johansson 2016). The other main policy guidance for forests is found in the Swedish Environmental Code, which aims for sustainable use of forests across the three pillars of economics, ecology, and social elements (Riksdag 1998). The law was updated in 1993 to include ecological considerations and again in 2008 to incorporate social aspects, while the National Forest Programme of 2014 increased public participation in forest policies and strategies (Johansson 2016). The other main policy guidance for forests is found in the Swedish Environmental Code, which aims for sustainable use of forests across the three pillars of economics, ecology, and social elements (Riksdag 1998).

The significant efforts at reforestation have always been combined with an emphasis on commercial competitiveness in terms of high-quality wood and paper products and in recent decades, as bioenergy for heat and power production. Approximately two million of Sweden's 28 million hectares of forest, mainly in national forests and other public areas, are under protection such that any extractive or productive uses are aimed solely at ecological preservation and/or socio-cultural improvements rather than economic value. The Swedish Forest Agency (Skogsstyrelsen) interacts with many other government agencies at national and local level to manage forest resources in line with laws and guidelines. Sustainability certification of forests, covering more than 60% of forest area in Sweden, is provided through the internationally recognised guidelines of the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). Forest management is an integral element in implementing the measures to achieve negative emissions' targets (Karlsson et al. 2020).

The forest sector in Sweden is dominated by small owners/managers, mainly the 200,000 or some families that own on average 50 hectares of forest. There are also some private and nationally-owned forests, as shown in Figure 2. It is important to note that "ownership" of forests does not allow these actors full control over forested land and forest resources: as in most countries they must follow the environmental regulations and institutional guidelines established by the Forestry Act and the Environmental Code and any additional guidance at local or national level. In terms of recreational use of forests, areas that are not under production or extraction are generally subject to the principle of Allemansrätt, under which citizens or residents may walk or visit land and forest anywhere as long as they respect these areas and do not disturb or remove trees, plants, or animals.

The forestry sector is largely self-supporting in Sweden because of the relatively stable commercial value of timber extracted and the associated economic linkages and sectors. There may be some funds available where additional measures in the forest sector are needed to fulfil climate policy aims associated with net zero emission goals. However, there is no general or systematic way to specify these financial support mechanisms without reference to implementation in particular contexts and locations.

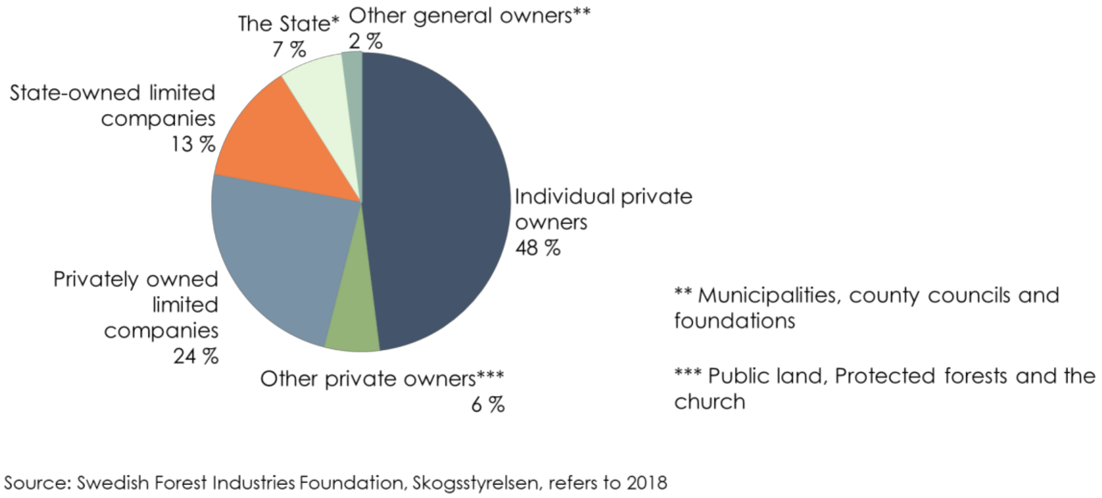

Figure 2: Ownership of forests in Sweden.

7.3 Current land use and potential land-use competition

Forests currently occupy around 28 million hectares or 70% of land area in Sweden, of which around 22 million hectares can be considered productive or potentially available for extraction and/or production. The long process of forest restoration that started in the early 1900s has resulted in nearly a doubling of land under forest while the quality and productivity of forest land has also increased several times over. As the management of Swedish forests is somewhat decentralised due to the ownership structure, there are some variations in management approaches but in general the model aims to combine the three pillars of sustainability. It is unlikely that the amount of land under forest will change significantly in the coming decades, but rather the management practices may change and the balance between production and conservation may shift as some additional emphasis is placed on biodiversity and ecosystem services (including cultural ecosystem services).

The most important single contributor to Swedish climate targets is thus essentially the forest resource base, as it provides carbon sequestration and fossil substitution alongside all the other benefits associated with forests. The comparison across the land sectors in Table 10 shows that other land types are net sources of emissions while managed forest land provides a considerable share of Sweden's overall net positive GHG balance. The key metric in current practices relates to net growth, which continues to be positive, i.e., the growth in Swedish forests continues to outweigh the amounts harvested and/or removed (Ministry of the Environment 2020).

Table 10: Historical and projected net emissions (+) and net removals (-) of GHG from land sectors in Sweden (million tonne CO2-equivalents). Source: Ministry of the Environment (2020)

	2015	2020	2025	2030	2035	2040
Afforested land	-0.8	-0.9	-0.9	-0.9	-0.9	-0.9
Deforested land	4.0	2.9	2.9	2.8	2.8	2.7
Managed forest land	-42.9	-43.1	-46.5	-44.5	-45.4	-47.4
Managed cropland	4.3	4.7	4.6	4.6	4.5	4.5
Managed grassland	0.2	0.3	0.3	0.3	0.3	0.3
Managed wetland	0.2	0.2	0.2	0.2	0.2	0.2
Total	**-34.9**	**-35.9**	**-39.3**	**-37.4**	**-38.4**	**-40.4**

Land competition is not a major issue in the context of the Swedish forestry sector, but it does affect decisions about the replication or expansion of particular forestry measures, in a few ways. First, forest measures that are expected to result in reduced agricultural land (which is already small by comparison) and/or increased food imports will normally not be prioritised, for reasons of national health and food security or safety but also because imports may have a higher climate impact. Second, commercial development for non-land activities (i.e., housing, commercial sector, etc.) also tends to get lower priority except for remote areas in the north where additional infrastructure and development is needed for quality-of-life improvements. Finally, social, and cultural factors are increasingly being considered in the choice between intensive harvesting practices (e.g., clear-cutting) vs. low-impact solutions to forest management, particularly in the context of indigenous peoples in northern Sweden or areas where cultural values are more strongly incorporated into regional guidelines. This last point connects also to the central debate around greater emphasis on biodiversity, ecology, and nature rather than productivity and climate stabilisation targets.

7.4 Climate risks & sensitivities

According to an existing study of the Swedish Environmental Protection Agency, afforestation of previously abandoned arable lands could have a positive effect for climate due to their contribution to emission absorption and substitution, and also pose negative effects due to intense cultivation with short time for rotation and the risk of monocultures could limit tree species growth (Karlsson et al. 2020). Other potential risks associated to afforestation concern biodiversity impact (Karlsson et al. 2020).

There needs to be a larger awareness of the importance of biological systems to enable a fossil-free future, according to Swedish stakeholders. This includes aspects related to energy and material but is broader than that and includes poverty alleviation, food provision and a broad set of factors related to sustainable development in general. A key general advantage of managed forests, compared to unmanaged, is a decrease in risks of fire and other damages and that it allows for more adaptation opportunities, i.e., in response to changing climate conditions.

7.5 Economic implications

The forest sector is highly cost-competitive and thus the current issues relate primarily to the trade-offs with other societal aims beyond climate rather than cost-competitiveness of forest measures. In particular, any marginal costs associated with measures in the forest sector have to be analysed for specific implementation and in connection to particular scenarios and pathways.

The costs are generally negative for a variety of measures in the forest sector but the maturity of the sector and the integration of forest management with downstream products and markets means that different changes in management could have varying cost implications and need to be analysed in particular cases and/or locations within future scenarios.

7.6 Co-benefits and trade-offs

The main issue that has emerged in forest resource management in Sweden is that the intensive production systems that have been used have raised some concerns with biodiversity and to some extent cultural issues. A number of approaches have been considered to improve biodiversity, including increasing the area of protected forest, lengthening the harvest cycle, and diversifying the structure of forest plantings (mixed leaf/forest case), as shown in Table 11. Among these options, increased forest protection would increase carbon sequestration capacity the most in the near to medium term, while also supporting biodiversity aims. The loss of production would also reduce the amount of biomass substituting for fossil fuels but the estimate of the resulting change in GHG emissions depends on the timeframe and substitution scenario used and therefore cannot be specified without further disaggregation. Lengthened harvest cycle initially provides greater removal but declines over time by 2045, due to the differing sequestration and growth capacities for younger vs. older forest stands. Increased production methods for forest resources would result in 3.1 million tonnes of additional CO2 removal by 2045, similar to the low case of increased forest protection and more than the high case of lengthened harvest cycle. It must also be noted that some of these scenarios can change significantly over the entire lifecycle of the trees, which can be up to 100 years, but the results are only shown until 2045 because of the net zero emission target.

Table 11: Measures for changing carbon management in Sweden via forest management practices. Source: Statens Offentliga Utredningar (2020)

	Area applied (Million hectares)	Net CO2 removal (million tonnes CO2/year)		Change in harvesting (2020-45)		Effect on Biodiversity	Effect on Fossil Substitution
		2030	2045	million m^3	percent	2045	2045
Increased forest protection (high case)	4.5	12	13	-17.0	-23%	+	-
Increased forest protection (low case)	0.5	1.3	3.1	-2.0	-2.5%	+	-
Lengthened harvest cycle (high case)	3.8	4	2.9	-2.0	-3%	+	-
Lengthened harvest cycle (low case)	0.5	0.2	0.1	-0.1	-0.1%	+	-
Mixed leaf/forest	5.5	2.2	4.5	-4.0	0%	+	-
Increased production methods	varies	2.8	3.1	2.0	2%	-	+

7.7 Risks associated with scaling up

Afforestation is already a very upscaled LMT in Sweden and there are not many risks associated with further scaling up. However, when large areas are populated with poorly adapted to the local environment species, negative environmental consequences have been observed (Cao et al. 2010). As previously mentioned, the risk of monocultures limiting tree species growth has been discussed in the Swedish context. Another issue could be that the increase of forest areas and subsequent decrease of open areas, especially pasturelands, can lead to species extinction. Furtheromore, reduction in the available grazing land could lead to decreasing numbers of grazing animals and therefore to decreaded food production. A final risk of uncontrolled expansion of afforestation as an LMT might lead to loss of high biological or cultural heritage sites in the country (Svensson 2018).

7.8 Conclusion

Sweden has the most forest land among EU countries and has a long history of forest policies. In the Swedish context, the LMT generally referred to as afforestation or reforestation is more related to forest management more generally. The significant efforts at reforestation have always been combined with an emphasis on commercial competitiveness in terms of high-quality wood and paper products and in recent decades, as bioenergy for heat and power production. A key general advantage of managed forests, compared to unmanaged, is a decrease in risks of fire and other damages and that it allows for more adaptation opportunities, i.e., in response to changing climate conditions.

There are relatively few major research gaps in general terms since there has been intense analysis and research on Swedish forest resources and management for several decades. However, in light of the critical role of forest management and/or afforestation/reforestation for climate aims in the EU and globally, there are no doubt a variety of research gaps that could be identified depending on the particular focus in the research programme and the interactions with other LMTs. One research gap is associated simply with the uncertainties associated with future climate change impacts as well as with the effects of changing climate policies in relation to net zero emission goals, i.e., feedbacks and interactions during the next decade or so as efforts are intensified to reach climate neutrality.

8. Final reflections

In this analysis, we focused on BECCS, biochar, and afforestation (or rather forest resource management) as the selected LMTs comprising the Swedish portfolio. BECCS is the key NET in the portfolio, as it is expected to deliver a large share of the negative emissions needed for Sweden to achieve its 2045 target for net-zero emissions. Biochar, although favoured for its diversity of co-benefits and co-products especially in the local context, will have a complementary role.

A recent comprehensive government investigation showed that BECCS is expected to remove 1.8 Million tonnes CO_2-eq per year by 2030 and between 3 to 10 Million tonnes CO_2-eq per year by 2045. Biochar is considered as part of the increased carbon sink in forests and land category, which, in overall is expected to remove 1.2 Million tonnes CO_2-eq per year by 2030 and a minimum of 2.7 Million tonnes CO_2-eq per year by 2045. There are still high uncertainties of course, and the country is open to any other NET that could contribute to enhanced emission reduction.

The above mean that carbon removals between 9.4 and 16.4 would be reasonable to be assumed under this narrative by the year 2045. On average, this can be translated to 12.9 Million tonnes CO_2-eq per year, which is approximately equivalent to 25% of total greenhouse gas emissions in Sweden in 2019 (in CO2-equivalent terms, excluding LULUCF)[4].

Stakeholders working with these LMTs highlight that in order for the emission removals to be delivered in line with the Swedish net-zero targets, there needs to be stronger incentives that would in turn create viable carbon markets. Sweden has a frontrunner status regarding BECCS implementation, but it is still unclear how investments on transportation and storage of carbon will be supported and by whom. At the same time, climate change is threatening Swedish forest species and might create cascading effects affecting biodiversity and biomass supply for BECCS and biochar upscaling.

[4] According to Sweden's 2021 National Inventory Report (p23) submitted to the UNFCCC, Sweden emitted 50.9 MtCO2e of GHG emissions in 2019.

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ANNEX III

OVERVIEW OF INPUT TABLES FOR SIMULATION MODELLING PER COUNTRY

This project has received funding from the European Unions' Horizon2020 Grant Agreement No 869367

5. Sweden

5.1. Qualitative storylines by identifying measures and actions from interviews for each LMT scenario

Sweden LMT 1: BECCS

	1. Wishes of the future for the LMT: include timing	2. How to achieve the wishes • Who pays? • Who implements?	3. Target/Actions • Policies, strategies, projects
Scenario 1: " Favourable" **Stakeholder representations:** big Private stakeholders, small participants, government	By 2045: • Low investment and operating costs • Low energy prices combined with high CO2 prices • No or few issues when deployed in practice (technology maturity) • CO2 underground storage is secured • Small scale BECCS becomes viable • Broad investment support nationally and from the EU • Ambitious climate policy framework requiring negative emissions for net zero targets	• Payment: established voluntary CO2 markets • Payment: government investment • Implementation: private actors including power generators and pulp and paper industry, shipping industry and international underground storage providers	• Lifting of Regulatory barriers • Stable and predictable economic conditions • International cooperation • Ambitious carbon pricing

Scenario 2: "Unfavourable" **Stakeholder representations**: Big Private stakeholders, government	By 2045: • Investment and operating costs are higher than anticipated • Infrastructure investment cost too high • High energy and feedstock prices, and low CO2 prices • Failure to establish CO2 storage outside of Sweden • Negative shift in public opinion on biomass or negative emissions • Competing uses for biomass are more attractive • Lack of investment support nationally and from the EU	• Payment: government and EU investment • Implementation: private actor in power generation sector, local underground storage providers	• Policies in place are half way to include demand pull measures for the technology • Still on-going plans to involve the public in policymaking • More rigorous sustainability demands on forestry and agriculture

Sweden LMT 2: Biochar

	Wishes of the future for the • include timing	1. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	2. Actions • policies, strategies, projects
Scenario 1: "Favourable " **Stakeholder representations:** Agricultural stakeholders (farmers), carbon market intermediaries, industrial participants	By 2045 • Low investment and operating costs • Low energy prices combined with high CO2 and biochar prices • Additional values of biochar are found to be highly useful • Medium to large scale biochar plants are viable • Ambitious carbon and biochar pricing • Heating providers switch to biochar • Knowledge sharing among cities promotes use of biochar for urban gardening projects	• Several large markets for biochar are established and for their carbon credits • Payment: voluntary markets • Implementation: municipalities (use) and private operators (production)	• Established voluntary CO2 markets • Stakeholder initiatives in bio-coal and biochar pave the way for more deployment
Scenario 2: " Unfavourable" **Stakeholder representations**: small producers, local producers, policymakers	By 2045 • Investment and operating costs are higher than anticipated	• Implementation: Small pilots • Dependent on private investment decisions and/or municipal funding	• Lack of markets for biochar • NET incompatible uses for biochar are prioritised

	• High energy and feedstock prices, and low CO2 prices • Negative shift in public opinion on biomass or negative emissions • Usefulness of biochar found to be low • Competing uses for biomass are more attractive • Lack of interest from municipalities to implement biochar initiatives.		• More rigorous sustainability demands on forestry and agriculture

5.2. Quantitative storylines: pace of implementation for each LMT

	Current situation (baseline)	**SCEN-" Favourable "** **SH perspective:** Stakeholder initiatives in CCS and BECCS pave the way for more		**SCEN-" Unfavourable "** **SH perspective:** Negative shift in public opinion on biomass or negative emissions	
Year	Now (Karlsson et al. 2020)	2030 (change relative to the current situation) (provide sources)	2050 -> **2045** (change relative to the current situation) (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 -> **2045** (change relative to the current situation) (provide sources)
LMT 1: BECCS	0 CO2 emissions captured and stored [1]	Deployment rate would be 0.535 Mton CO2/y: 2 Mtonnes CO2-eq per year [1] are captured and stored	Deployment rate would be 0.535 Mton CO2/y: By 2045	Deployment rate would be 0.08 Mton CO2/y: 0.5 Mtonnes CO2-eq per year [1] are captured and stored	Deployment rate would be 0.08 Mton CO2/y: By 2045

[1] https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2020/01/sou-20204/

			10 Mtonnes CO2-eq per year [1] are captured and stored		around 2 Mtonnes CO2-eq per year [1] are captured and stored
LMT 2: Biochar	0.001 Mtonne CO2-eq per year mitigated [2]	Deployment rate would be 0.078 Mton CO2/y: 0.7 Mtonne CO2-eq per year are mitigated [2]	Deployment rate would be 0.078 Mton CO2/y: By 2045 1.8 Mtonne CO2-eq per year [1] are mitigated	Deployment rate would be 0.0078 Mton CO2/y: 0.07 Mtonne CO2-eq per year are mitigated [2]	Deployment rate would be 0.0078 Mton CO2/y: By 2045 0.18 Mtonne CO2-eq per year are mitigated [2]

[2] https://stud.epsilon.slu.se/18289/1/martelius-s-2022705.pdf and https://www.biochar-industry.com/2022/european-biochar-market-report-2021-2022-available-now/ and https://bitrix24.tbm.tudelft.nl/~DlvW7