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Large-Scale Implementation of Bioenergy With Carbon Capture and Storage in the Swedish Pulp and Paper Industry Involving Biomass Supply at the Regional Level

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Bioenergy with carbon capture and storage (BECCS) has been identified as a possible major contributor to efforts to reach ambitious climate targets through the provision of negative emissions–offsetting residual fossil emissions in “hard-to-abate” sectors and accomplishing net-negative emissions. The pulp and paper industry is the single largest consumer of biomass in Sweden, with many large point sources of biogenic CO_2 emissions that could be captured. This work investigates the biomass supply required for large-scale implementation of BECCS in the pulp and paper industry. Logging residues are considered as a fuel to supply the additional energy demand imposed by the capture plant, and the potential of these residues is evaluated in a case study that includes four pulp and paper mills located in regions of Sweden with different conditions for biomass supply. Two of the mills are located in southern Sweden, where there is strong competition for logging residues from the heating sector, and two of the mills are located in northern Sweden, where the competition is weaker. We show that implementing carbon capture at the four pulp and paper mills using regional logging residues to supply the additional heat demand required by the capture process (the reboiler heat demand) has the potential to capture around 4.6 Mt CO_2/year. The results also show that the fuel share of the capture cost, i.e., the cost to supply the reboiler heat demand with regional logging residues, is 22–30 €/tCO_2 captured, where the lower value corresponds to regions with weaker competition for logging residues (in this study, northern Sweden). In regions that have competition for logging residues, the possibility to increase the regional supply of logging residues to fuel the capture process while maintaining mill production output is limited, which in turn limits the possibilities to generate negative emissions via BECCS. In contrast, in regions with a low level of competition and strong availability of logging residues, there is an additional potential for logging residues to cover the additional heat demand required for CCS implementation.

Keywords: BECCS, bioenergy, carbon capture & storage, biomass supply, forest residual biomass, negative emissions, infrastructure

INTRODUCTION

Most of the IPCC scenarios that are in line with the Paris Agreement (IPCC, 2014; Rogelj et al., 2018) require negative emissions. Bioenergy with carbon capture and storage (BECCS) is typically considered a major measure through which to achieve these negative emissions. In general, negative emissions serve two purposes: 1) to offset residual fossil-fuel based emissions from hard-to-abate sectors; and 2) to establish the net-negative emissions required to compensate for a likely overshoot in emissions, so as to comply with the Paris Agreement. Recently, it has been proposed that the European Union (EU) should strive for climate neutrality by Year 2050 (EC, 2020). In this context, the EU has recently proposed to strengthen the European Framework for Climate in several ways, including a "commitment to negative emissions after 2050" (in a provisional agreement reached in April 2021 between the European Parliament and the Council on Climate Law Regulation[1]). It is likely that this will require BECCS to offset residual emissions before Year 2050 if climate neutrality is to be reached by that time-point.

Sweden has established a national target of achieving net-zero emissions by Year 2045, after which emissions should be net-negative. The Swedish climate policy framework defines this as a reduction of national emissions by at least 85% compared to the Year 1990 levels, and up to 15% reduction can be achieved by so-called supplementary measures. A recent public inquiry in Sweden (SOU, 2020) proposes bioenergy with carbon capture and storage (BECCS) as the major supplementary measure, suggesting BECCS targets corresponding to 1.8 Mton/year by 2030 and 3–10 Mton/year by 2045 (the latter large span due to the high uncertainty of the contribution of other measures on the longer term). The same public inquiry suggests a reverse auctioning system to incentivize investments in negative emission technologies (SOU, 2020). Sweden has favorable conditions for BECCS as shown by Karlsson et al. (2017) and Johnsson et al. (2020) but in spite of this, there is so far an "implementation gap" as concluded by Fuss and Johnsson (2021).

BECCS is based on relatively mature technologies where all parts of the capture, transport and storage chain have been demonstrated at large scale. The costs of carbon capture at industrial sites have been assessed (Leeson et al., 2017; Biermann et al., 2018; Garðarsdóttir et al., 2018; Johnsson et al., 2020). These costs are typically in the range of 40–100 €/tCO_2 depending on the process and including possibilities to utilize waste heat to power part of the capture process and the targeted capture rate. In addition, the conditions for a CO_2 transportation and storage infrastructure in the Nordic region have been analyzed by Kjärstad et al. (2016), who have shown that ship transport can be a favorable transport mode for CO_2 in the Swedish context, especially during a ramp-up phase. Garðarsdóttir et al. (2018) and Johnsson et al. (2020) have shown that capturing both biogenic and fossil CO_2 emissions from the largest industrial emission sources will confer a lower cost per tCO_2 captured than capturing only fossil-fuel emissions. This is because exclusively targeting fossil emissions would require capture from smaller emissions sources, which would drive up the costs. The largest biogenic emission sources in Sweden are found in the pulp and paper industry in the form of pulp mills. However, the analyses of a broad implementation of CCS carried out by Johnsson et al. (2020) and Garðarsdóttir et al. (2018) did not consider how carbon capture at sites of large users of biomass would impact the biomass supply, which is the focus of this work. Sanchez and Callaway (2016) have investigated the regional effects and optimal scale of BECCS in the United States context and have reported that a centralized BECCS infrastructure results in economy of scale, which is in line with the findings from techno-economic analyses illustrating that the specific capture cost (€/CO_2) will decrease with size of unit (e.g., Garðarsdóttir et al., 2018). However, for biomass-based industries, there is a tradeoff between economy of scale and the transport cost of the biomass, where an increase in scale implies mobilization of biomass transport over longer distances (de Jong et al., 2017).

The pulp and paper industry plays an important role in the biomass supply chain in Sweden and accounts for around 50% of the total energy use in the Swedish industry. The overwhelming majority of this energy is from the combustion of biomass in pulp and paper plants and combined heat and power plants (Energimyndigheten, 2019), with the latter type of unit burning biomass residues from the forest industry. Large pulp mills are the largest biogenic point sources of emissions, with several plants having yearly CO_2 emissions that exceed 1 million tonnes. Thus, these plants represent a large potential for cost-efficient BECCS. Capturing CO_2 will, however, lead to an increased onsite energy demand, assuming the same product output. It is likely that the pulp mills will try to cover this energy demand by combusting biomass, thereby increasing the demand for biomass. The energy demand could also, at least in part, be covered by changes in internal energy use and decreased generation of byproducts, such as electricity, district heating or biofuels, as discussed by Eliasson et al (2021), or by combusting additional waste products, mainly bark, which may be available onsite.

There are differing opinions and an ongoing debate as to whether utilizing forest biomass or leaving the forests as a carbon sink is the more-favorable option for combating climate change, as discussed by Berndes et al. (2018). In Sweden, frameworks for sustainable bioenergy use as a means to combat climate change have been proposed by government agencies (Black-Samuelsson et al., 2017). It is clear that the sustainability of bioenergy is case-specific and that many factors are important to consider, for example land use change and deforestation, forest growth and carbon sequestration, substitution effects, and long-term and short-term changes in the carbon stocks of products and living biomass. In Sweden, the rate of annual forest felling is lower than the annual growth rate and the standing volume has increased for at least the last 65 years, even as the forest industry has expanded (Naturvårdsverket, 2019). This supports the notion of a sustainable biomass out-take with respect to climate. The assortment of biomass used for bioenergy applications is

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[1] https://ec.europa.eu/clima/policies/eu-climate-action/law_en.

mainly made up of secondary byproducts from the forest industry (i.e., as the last step in a cascading use from long-lived products from saw timber, via pulpwood, to forestry residues used for energy purposes (SAPEA, 2021). However, the more-easily accessible shares of these biomasses are already utilized today. The potential for increased biomass out-take for energy purposes lies in the increased utilization of primary forest fuels, such as logging residues (tops and branches), which are a byproduct of forest harvesting. Utilization of logging residues for energy purposes has substituted for fossil fuel usage in the heating sector in Sweden for several decades (Werner, 2017). Combusting logging residues causes an immediate release of biogenic CO_2 into the atmosphere. However, the same CO_2 is released, albeit at a slower pace, if the residues are left to decompose in the forests (Hammar et al., 2015; Zetterberg and Chen, 2015). Gustavsson et al. (2017) have concluded that active forest management with high harvest levels and efficient forest product utilization provide greater climate benefits than reducing the harvest and storing more carbon in the forest.

This work aims to complement the existing techno-economic literature on (BE)CCS implementation, where previous works have mainly focused on the costs for CO_2 capture and represent the increased energy demand as a cost for steam. Here, the relationship between regional biomass supply systems and large-scale BECCS implementation is investigated, using the Swedish pulp and paper industry as a case study. The aims are to broaden the perspective on energy supply for BECCS by highlighting the required biomass supply system and to discuss how the infrastructure connects with decision-making at the site level. Specifically, the present work shows how BECCS implementation in Swedish pulp and paper mills influences the onsite energy system and the regional supply system for logging residues. Limitations related to the possibility that the logging residue supply may affect the ability to achieve negative emissions while maintaining the present product volume are explored. The work also presents and discusses the cost at which the additional biomass in the form of logging residues can be supplied.

METHODS

This work combines: 1) a site analysis of the heat requirement for post-combustion capture installations at pulp and paper plants, to estimate the increase in biomass demand at the site; and 2) a biomass-supply system analysis, to evaluate the regional biomass supply. To include regional and site-specific characteristics, four pulp and paper plants located in different parts of Sweden were chosen as case studies.

In this work, the term biomass is defined as a biogenic material that may be used either as a feedstock in a process or for energy purposes. Bioenergy, which is the subset of the biomass that is used for energy purposes, includes both refined fuels of biogenic origin and biomass assortments that are combusted without any refining steps. Logging residues refers to the specific type of bioenergy in residues from forest felling, such as branches and tops, which may be collected and combusted for energy purposes.

The investigated system includes the fuel supply system for the carbon capture process and the impact of the capture plant on the energy systems of the pulp and paper mills. While the electricity demand from the liquefaction of CO_2 is included in the analysis, an analysis of the CO_2 transportation and storage infrastructure is considered outside the scope of this work. Given that ship transportation is probably going to be the transport mode of choice for a future CCS system in Sweden, it seems likely that liquefaction of CO_2 will be the treatment mode for the captured CO_2 in the Swedish context. The bioenergy supply for the carbon capture plants is limited to waste product from forestry in the form of logging residues. Thus, it could be that a larger potential for BECCS implementation exists if other bioenergy assortments would be considered as well. The analysis of logging residue supply considers the present use and availability of logging residues in the regions investigated, and the results reveal the increased biomass demand required for implementation of BECCS, assuming that the product output from the pulp mills is maintained. Only bioenergy from forestry, in the form of logging residues, is considered. The possibility that the sites will reduce sales of present energy byproducts, such as electricity, heat or bioenergy fractions, to regional energy systems to cover the increased energy demand is not considered. This is motivated by the fact that this would increase the demand for a similar biomass assortment elsewhere. It should be noted that several sectors are likely to plan increased use of biomass as part of their strategy to combat climate change, which may result in increased competition for biomass resources. An analysis of the biomass demands from other sectors is outside the scope of the present work. In this work, logging residues are assumed to be carbon-neutral, based on the growth in carbon stock on the landscape level and the fact that conventional logging already generates the residues. Other possible environmental conflicts related to increased biomass use are outside the scope of this study.

Case Studies

Four chemical pulp and paper mills, presented in **Table 1**, were selected as case studies. These mills are among the largest emitters of biogenic CO_2 when one considers all industrial sites in Sweden, including heat and power plants. For all the studied mills, >97% of the total site emissions are biogenic, meaning that almost all the captured carbon could be considered as negative emissions. **Table 1** shows the site CO_2 emissions, bioenergy use, district heating output, amount of sold electricity, and the county in which the site is located. The plants are named according to their current yearly bioenergy use in GWh. Since two of the mills have very similar bioenergy use, the one located furthest to the north, in Östrand, is denoted as the “3-GWh plant, North.” Data for all the sites, except the 4.7-GWh plant, are taken from the Chalmers Industrial Case Study Portfolio (see Svensson et al., 2019 for more information) and are for Year 2016. As the 4.7-GWh plant expanded their production capacity between 2016 and 2018, updated data for that site from 2018 are taken from the Swedish Forest Industries environmental database (Skogsindustrierna).

TABLE 1 | General information about the selected case study plants. Most of the data were collected from the Chalmers Industrial Case Study Portfolio (ChICaSP), and in the case of the 4.7-GWh plant from the Swedish Forest Industries environmental database.

Site	CO_2 emissions [kt/year]	Fossil emissions [%]	Bioenergy use [GWh/year]	DH delivery [GWh/year]	Sold electricity [GWh/year]	County
5.3-GWh plant (Södra Cell Mönsterås)	1,834	1.26	5,308	336	203	Kalmar
3-GWh plant (Stora Enso Skutskär)	1,826	0.04	3,013	0	299	Uppsala
3-GWh plant, North (SCA Östrand)	1,166	2.72	2,963	173	0	Västernorrland
4.7-GWh plant (Södra Cell Värö)	1,731	0.48	4,670	365	302	Halland

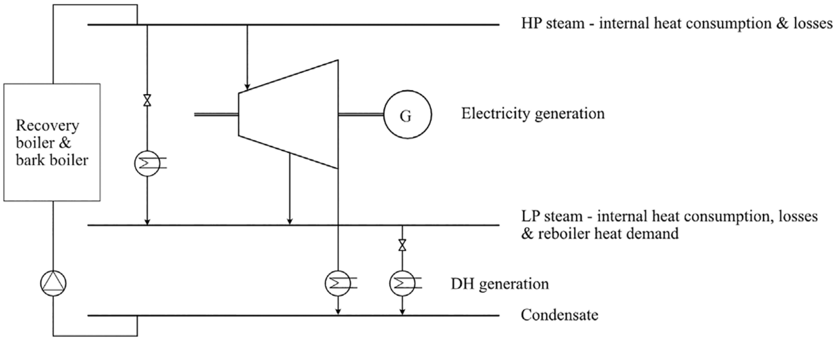


FIGURE 1 | Simplified steam system considered for the mill energy system calculations. Steam is generated in the recovery boiler and bark boiler on site. The steam is used at different pressure and temperature levels depending on the process requirements. High-pressure (HP) steam that is not consumed by the process is run through a steam turbine to generate electricity and is extracted at the pressure appropriate to its application in the process. Low-pressure (LP) steam is considered to be used for the capture process in this work. District heating (DH) is generated by condensing expanded steam from the turbine and LP steam header. Note that IP/MP pressure headers not shown in the figure are present in the plants' energy systems—they are excluded in the figure as they are not considered in this work..

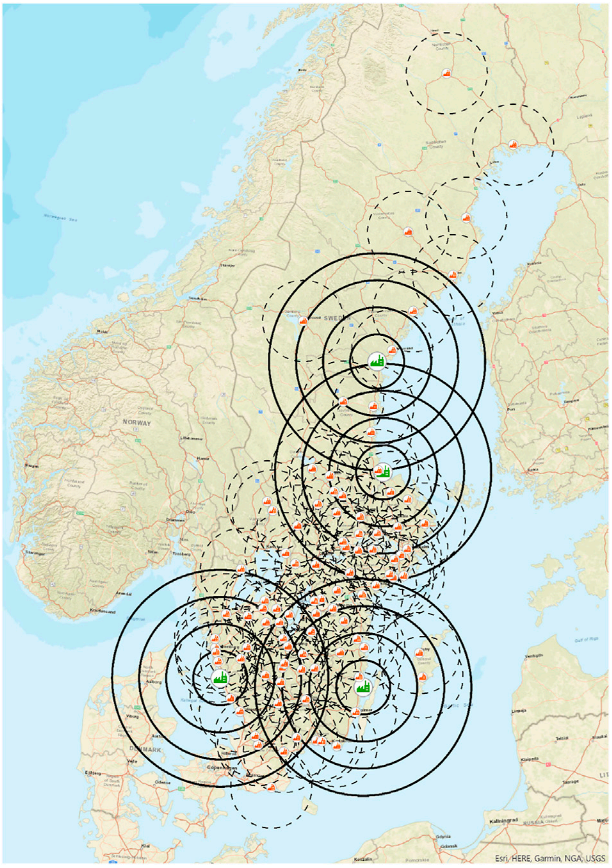
Site Energy System Analysis

The amount of biomass in the form of pulpwood currently used by the sites is unknown in energy terms and is calculated based on the output of product, which is converted to input of feedstock using the conversion factors from Ervasti (2016), where 1 tonne of unbleached sulfate pulp corresponds to around 4.45 m^3 of feedstock. The feedstock is then converted into energy values using the heating values from Ringman (1995), where 1 m^3 of pulpwood has a heating value of 1.1 MWh/m^3.

The additional heat demand for separating CO_2 is covered by the combustion of logging residues in a steam boiler. The specific heat requirement for capture is assumed to be 3,700 kJ/kgCO_2 based on modeling work performed by Garðarsdóttir et al. (2018). The heat demand is estimated for the absorption of CO_2 in monoethanolamine (MEA)-based solvent. Although other carbon capture technologies may be more efficient, absorption of CO_2 in an MEA-based solvent is considered the benchmark technology. An absorption-based capture technology may be implemented as an end-of-pipe solution with little modification to the existing plant, which is beneficial in terms of the near-term implementation reaching the proposed level of 1.8 Mt of biogenic carbon captured by Year 2030. The estimation is based on capturing 90% of the CO_2 from the recovery boiler and the lime kiln in the plants (which together make up approximately 90% of the site emissions). Thus, the captured CO_2 corresponds to 81% of the total site emissions.

The BECCS heat demand onsite leads to an increased bioenergy demand, which is considered to be supplied by the logging residues. The heat demand was considered to be supplied by the existing steam network and the corresponding demand for logging residues was calculated for each individual case based on available data regarding the energy system of the plant (i.e., steam headers and their respective temperatures and pressures). The ratio of the enthalpy drop of the steam run through the reboiler to the enthalpy increase over the high-pressure boiler determines the bioenergy demand to generate the 3,700 kJ/kgCO_2 required in the reboiler.

The steam system with the considered components is illustrated in **Figure 1**. The site energy system analysis was performed using spread sheet heat balance calculations based on the temperature and pressure levels in the steam system. In all cases, the steam network includes a high-pressure boiler and a steam turbine, with extractions for the mill steam demand. A condensation pressure of 0.75 bar was assumed, since all four investigated pulp and paper mills deliver heat to local district heating networks. It should be noted that there are intermediate and/or medium pressure steam headers present within the site steam networks not affected by the implementation of carbon capture and, thus, they are excluded from **Figure 2**. The heat demand of the capture unit is covered by using steam at around 4 bar, corresponding to the LP steam header in the investigated pulp mills. Additional logging residues are combusted if the addition of a capture unit results in a lack of steam in the present configuration. Waste heat, if available, is utilized at



Esri, HERE, Garmin, NGA, USGS

FIGURE 2 | Considered biomass uptake areas for the four pulp and paper mills in the study, as well as the heat and power plants that use logging residues as fuel. The radius of each uptake area was set to 200 km based on current transportation patterns of logging residues by truck.

the pressure levels of the capture unit. Additional biomass combustion is assumed to increase the level of electricity production, since the amount of steam that is run through the steam turbine(s) increases. The extent of the increase in electricity production is determined by the enthalpy drop over the turbine, as well as by the increase in steam mass flow that is run through the system due to the increased demand from the capture plant. The produced electricity is primarily used to power the liquefaction plant; any excess electricity can be sold to mitigate the additional costs imposed by the increased demand for biomass.

The increased electricity demand for the capture plant is assumed to consist primarily of the demand for treatment of the CO_2 stream after separation from the solvent and is calculated based on the amount of CO_2 being liquefied. The considered liquefaction plant comprises an ammonia refrigeration cycle. The electricity demand for compression in the liquefaction plant is calculated by modeling the electricity demand for the compression train after the capture plant. The modeled compression train consists of three compression stages with intercooling and knockout drums between the compressors. The calculated electricity demand for the compression train is then scaled up to represent the demand for the entire liquefaction plant, as described by Deng et al. (2019). Liquefaction for the treatment of the CO_2 stream was chosen because ship transportation is likely to become the transport mode of choice in the Swedish context. This is due to its favorable cost profile, especially during a ramp-up phase, as demonstrated by Kjärstad et al. (2016), as well as the choice of ships as a means of transportation in the Norwegian CCS project Longship (CCS Norway).

Biomass Supply Evaluation

Current biomass transport intensities to the four mills were evaluated based on transportation data provided by Biometria,[2] which is an organization that measures, collects and reports statistics on forest biomass including transportation, thereby facilitating transport intensity studies.

The logging residue uptake areas considered for the pulp and paper mills, as well as the biomass-fired heat and power plants using logging residues are shown in **Figure 2**. As demand for logging residues is increased following BECCS implementation in the four pulp and paper mills, the supply can be evaluated by calculating the logging residue potential in an area of 200-km radius around the mills (concentric circles around the green sites in **Figure 2**), and deducting the amounts already used by heat and power plants. As the radius is expanded, more logging residue potentials will appear, although there will also be increased competition for the same resource from local heat and power plants within the uptake area. Longer transport distances will also increase the delivery cost. An initial stochastic simulation was carried out to establish the maximum radius of the heat and power plant uptake area. The uptake area radius should be set to correspond to the actual average road transport distance, which in Year 2018 was 62.7 km for logging residues (Asmoarp et al., 2020). This results in a maximum radius of 75 km in a circular uptake area when considering a winding factor of 1.25 and assuming that logging residue objects are evenly distributed within the uptake area.

The availability levels of logging residues in different regions of Sweden were analyzed using the tool Forest Energy Atlas (Natural Resources Institute Finland), which is based on analyses carried out by the Swedish Forest Agency (Skogsstyrelsen) and the Eureka simulation model for long-term forest management (Wikström et al., 2011). The values for logging residue potential are expressed in MWh to better relate to the energy needed for the BECCS process and is converted from oven dry tonnes (logging residues with no moisture content) to MWh with a conversion factor of 4.81 MWh/odt. The present level of fuel use at each district heating plant is analyzed using delivery statistics provided by Energiföretagen (2020), and the increased demand for logging residues at the pulp mills as a result of capture installations is assumed to be filled by regional unutilized logging residues from within the respective uptake areas. When the uptake area for a pulp and paper mill overlaps with

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[2] An organization owned by member companies within the forest industry. www.biometria.se.

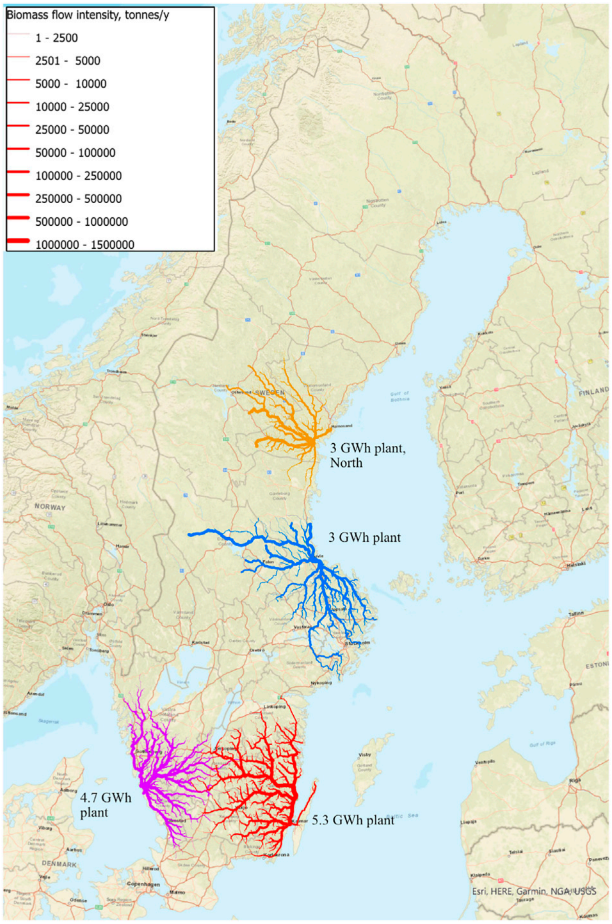

FIGURE 3 | Yearly biomass transport intensities (in tonnes) along the transportation routes currently used by the four pulp and paper mills investigated in this work.

that of a heat and power plant, availability proportional to the size of the overlap is subtracted from the amount of logging residues that can be used by the pulp and paper mill. The evaluations are made for each pulp mill individually, since the demand from the heat and power plants is known whereas the biomass demand from the pulp mills is added in our analysis as a result of BECCS implementation. Competition between the pulp and paper mills for the additional biomass required for BECCS is not considered, i.e., the overlap of uptake areas is not considered. This is because it is likely that BECCS will not be implemented at the four plants at the same time.

Biomass Supply Cost

The supply costs for logging residues were calculated using survey-based cost data presented by Brunberg (2013). Costs in SEK/m^{3}s were converted to €/MWh using a conversion factor for logging residues with 45% moisture content of 0.85 MWh per 1 m^{3}loose (Ringman, 1995) and an exchange rate of 10.18 SEK/€. The cost values for road transportation were differentiated based on the specific transport distance using an hourly cost of €99 (Enström et al., 2021) and an empirical equation for distance-specific average driving speed (Ranta and Rinne, 2006; Eriksson et al., 2014). Moreover, a fixed terminal time of 1.5 h per turn was added to reflect loading, unloading and measurement activities, and an average capacity of 90 MWh per turn was assumed. All the cost values were converted to the present situation using an index (T087SÅ17) for cost development for forest raw materials (Statistics Sweden, 2021).

RESULTS AND DISCUSSION

First, the current biomass usage levels for the four pulp and paper mills are presented, followed by a demonstration of how CO_2 capture with BECCS increases the biomass demand and influences the energy system of the pulp and paper plants. Lastly, the costs to supply the mills with the required biomass demand for BECCS from regional logging residues are shown.

Current Biomass Use

Figure 3 gives the current yearly biomass transport intensities (in tonnes) along the transportation routes used by the four pulp and paper mills investigated in this work, as obtained from the transportation data provided by Biometria (*Biomass Supply Evaluation* section). The biomass uptake areas for the pulp mills consist of high-density transportation routes that branch out to several, lower-density routes into the inland forests. **Figure 4** shows the biomass purchased by the plants during the period 2010–2018. The owners of the 4.7-GWh plant expanded their mill between 2016 and 2018, almost doubling the production capacity. This is reflected by the near doubling of the biomass intake in this period.

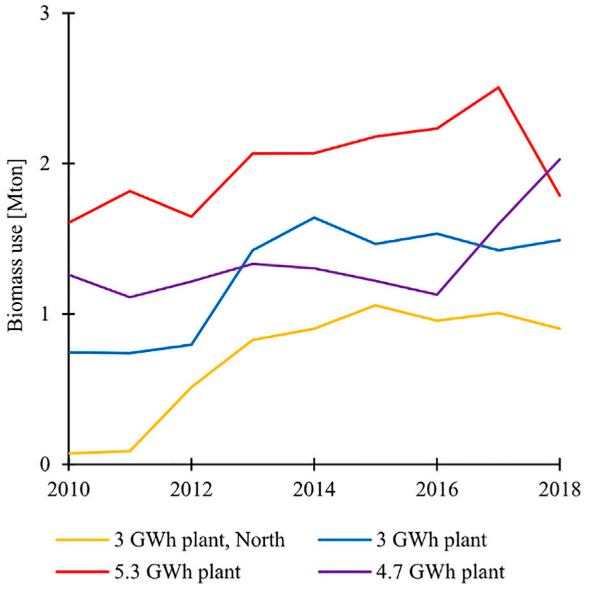

FIGURE 4 | Biomass usage levels for the pulp mills investigated for the period 2010–2018, based on transportation data.

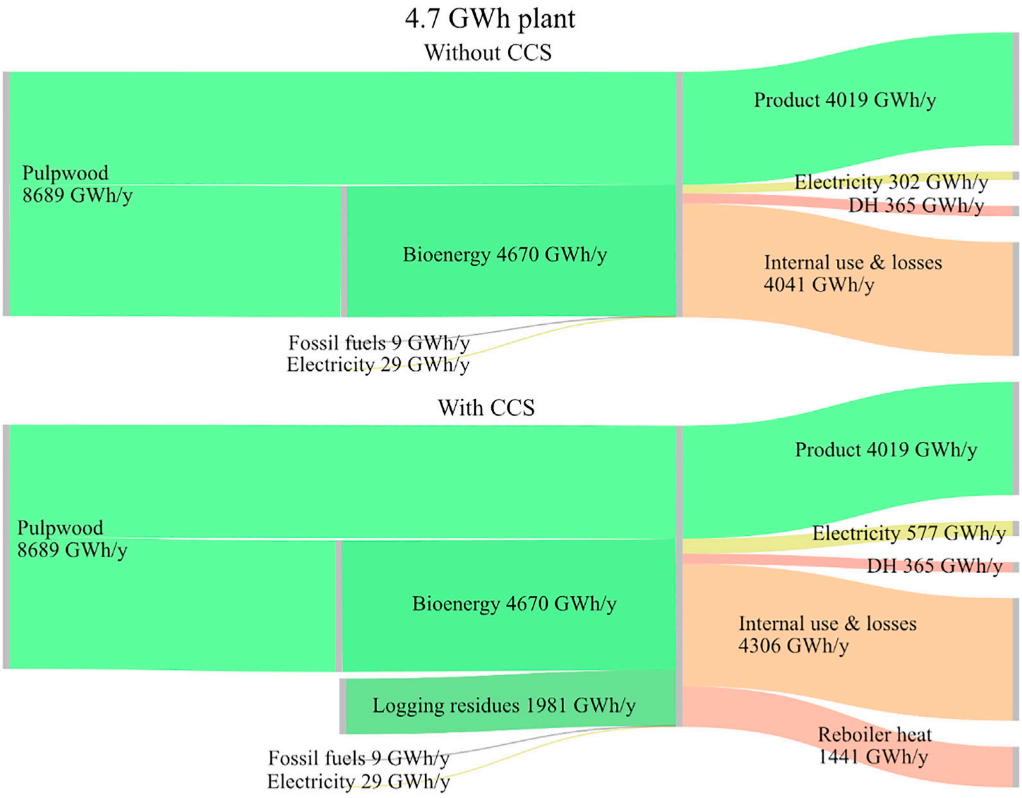

FIGURE 5 | Energy balance for the 4.7-GWh plant without and with CCS implementation. The amount of pulpwood used by the site is maintained and the heat demand in the reboiler is covered using logging residues. The level of electricity production increases and the electricity output with CCS included corresponds to the existing production plus the excess electricity (over what is required for liquefaction of the captured CO_2.) that can be sold.

Impacts on Site Energy Systems of BECCS and Logging Residue Availability

Figure 5 shows the energy balances for the 5.3-GWh plant before and after CCS implementation with maintained product and district heating outputs, as obtained from the heat balance calculations (*Site Energy System Analysis* section). Energy balances for the other studied mills are available in the **Supplementary Materials**. As indicated above, the pulp and paper industry – including the pulp mills of this study—collects and uses large amounts of biomass for the purpose of generating energy and, thus, has considerable potential for achieving negative emissions through BECCS. However, the energy requirement for powering CO_2 capture units entails a significant additional biomass demand, under the assumptions that there is no change in the output of products or district heating and that no energy-efficiency measures are applied in the plant energy system. The energy balance shown in **Figure 5** assumes that logging residue availability is not a limiting factor, i.e., only describes the potential for BECCS. The amount of logging residues that would need to be supplied to cover the reboiler heat demand due to BECCS implementation at the 5.3-GWh plant is around 42% of the bioenergy use of the plant without CCS, which is greater than what is available within the uptake area shown in **Figure 2**. Electricity output from the mill is increased, even when accounting for the electricity demand from the liquefaction plant. The results in **Figure 6** are based on the biomass supply evaluation and show the net amount of logging residues available in the different uptake areas, i.e., the total logging residues minus the amount already being used by the heat and power plants in each uptake area (cf. **Figure 3**). Note that the pulpwood currently used by the pulp mills is not included in **Figure 6**, as this represents a different assortment of biomass. The black bars in **Figure 6** for the 3-GWh plant represent the availability with the demand from a large heat and power plant owned by Stockholm Exergi included. Excluding this plant is motivated by the fact that it does not rely on local or regional biomass supplied via trucks but instead sources its fuel from more distant locations (including from foreign countries) using railway and sea transports. The present biofuel demand in the district heating sector is considerably lower in northern Sweden (3-GWh plant, North) than in southern Sweden (4.7-GWh and 5.3-GWh plants), which leads to larger net availability of biomass in the northern parts of the country.

CO_2 Capture Potential and Costs

Table 2 shows the CO_2 capture potential, based on the site energy system analysis and the biomass supply evaluation, for each

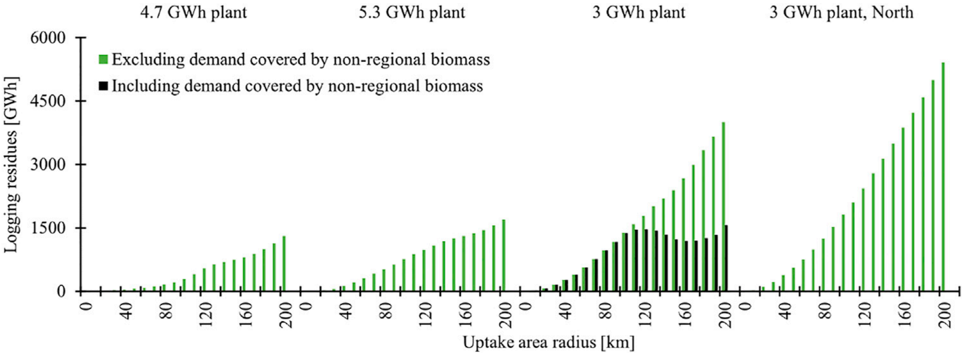

FIGURE 6 | Excess logging residues available for use (potential minus the demand from heat and power plants) at the four pulp and paper plant sites as a function of the radius of the uptake area. The increased net availability for the sites located further north (3-GWh plant and 3-GWh plant, North) is primarily due weaker competition from local heat and power plants.

TABLE 2 | Captured CO_2 levels for the studied sites resulting from BECCS implementation for the three ways of assessing capture potential: 1) Site potential, when capture is limited only by available CO_2 emissions; 2) Logging residue potential, when capture is only limited by available logging residues in the 200-km-radius uptake area; and 3) Combined potential, when capture is limited by either of the two previous options.

	Site potential	Logging residue potential		Combined potential	
Site	CO_2 captured [kt/year]	Logging residues [GWh/year]	CO_2 capture potential [kt/year]	CO_2 captured [kt/year]	Share of site emissions [%]
5.3-GWh plant	1,486	1,702	1,209	1,209	66
3-GWh plant	1,479	4,003	2,895	1,479	81
3-GWh plant, North	944	5,408	3,896	944	81
4.7-GWh plant	1,402	1,307	925	925	53

of the four pulp mills and for three different ways to estimate the capture potential: 1) the site potential, which describes the amount of CO_2 that can be captured, assuming a 90% capture rate and capture being implemented on the lime kiln and recovery boiler of the pulp mills with maintained product output. In short, this capture potential describes the amount of CO_2 that can be captured assuming 81% capture rate of total site emissions and free access to bioenergy to cover the reboiler heat demand; 2) the logging residue potential, which shows the amount of regional logging residues available and the potential for CO_2 capture if all of these logging residues can be utilized for CCS and the amount of CO_2, i.e., the site emissions, is not a limiting factor; and 3) the combined potential, which describes the CO_2 capture potential where both the availability of CO_2, i.e., emissions from the sites. and the logging residues within the uptake areas are considered. In essence, the combined potential shows the capture that can be achieved at the sites when limited to which of the site and the logging residue potential is the lowest. Regarding this combined potential, the amount of available logging residues limits the amount of CO_2 that can be captured for the two sites located in southern Sweden (i.e., the 4.7-GWh and 5.3-GWh plants), since the logging residue potential for carbon capture

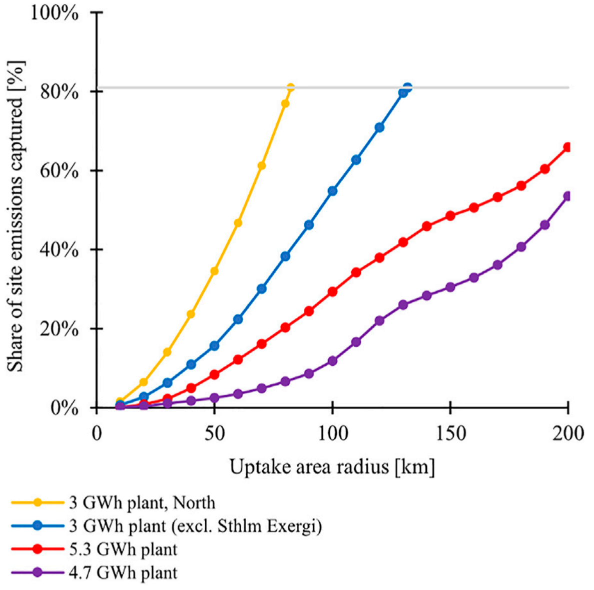

FIGURE 7 | Shares of site emissions that can be captured using all available logging residues at different radial distances from the four pulp mills. The gray line indicates the site potential of 81% CO_2 captured from the sites.

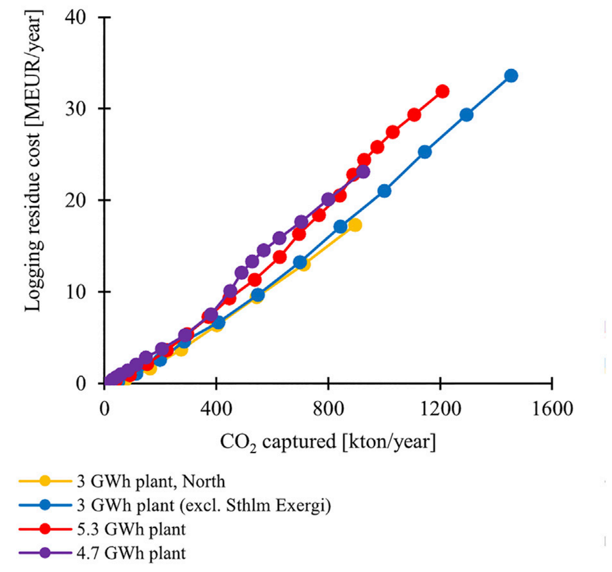

FIGURE 8 | Costs for regional logging residues in M€/year at the studied sites as a function of the amount of CO_2 captured annually.

is much lower than the site potential in terms of the amount of carbon that can be captured.

Figure 7 shows the share of site emissions that can be captured as a function of the radius of the pulp mills' uptake area for logging residues. The results consider the available logging residues in the 200-km-radius uptake area, as well as the competition from heat and power plants. The limitation on the ability to capture CO_2 set by the availability of regional logging residues becomes evident in **Figure 7**, as the lines for the 4.7-GWh and 5.3-GWh plants do not reach the horizontal gray line, meaning that the site potential for capture cannot be reached using the net available logging residues within the assumed 200-km-radius uptake area. For the 3-GWh and 3-GWh, North plant the opposite can be seen, the site potential of capturing 81% of emissions is reached using logging residues well within the 200 km radius uptake area. The cost to supply logging residues to the sites as a function of the amount of CO_2 captured is shown in **Figure 8**. The increased heat demand from CCS implementation cannot be fully met using logging residues from within the uptake areas for the 4.7-GWh and 5.3-GWh plants, and the marginal cost of logging residues for these sites indicate a price for imported biomass that could be used to facilitate full capture. The specific cost for logging residues, i.e., the cost to satisfy the reboiler heat demand with logging residues to capture a given amount of CO_2 varies in the range of 22–30 €/tCO_2 captured, which corresponds to a steam cost of 13–17 €/tonne of steam. These costs are in a similar range albeit on the lower side of the steam cost of 17 €/tonne of steam used by Garðarsdóttir et al. (2018). Since the change in cost of logging residues is influenced by the transportation distance, a larger amount of fuel can be supplied to the sites further north at a lower price, yielding lower fuel costs for the same amount of carbon captured, as can be seen in **Figure 8**. The costs presented are based on truck transportation of regional logging residues. However, depending on regional conditions it could be feasible to use other transportation modes such as ship or railway, in combination with truck transport to terminals or harbors to transport large volumes of logging residues regionally. The cost effectiveness of these alternatives would need to be investigated. Additionally, the costs presented do not consider any energy efficiency measures or attempts for optimal heat integration of the carbon capture plant with the pulp mill. Hence, it is possible that the demand for logging residues, and thus the costs for supplying the reboiler heat demand could be lowered. Leeson et al. (2017) presented costs of around 50 and 52 €/tCO_2 (56.4 and 59.0 $/t$CO_2$, respectively) from two references for CO_2 capture from pulp and paper mills. With capture costs in these ranges, a fuel cost for reboiler heat of 22–30 €/tCO_2 does not seem entirely unreasonable, since the cost for reboiler heat is a large part of the operational expense (OPEX) for carbon capture using MEA absorption. It is also important to note that assessing locations for BECCS implementation should consider the infrastructure for CO_2 transportation and storage, to derive a complete picture of the entire system cost. Yet, many of the Swedish pulp and paper mills are located along the coastline, which facilitates ship transportation to storage locations offshore, such as in the North Sea.

The results of this work reveal that from the perspective of the biomass supply system, BECCS implementation is favorable in less-populated and remote areas, where the competition for low-value biofuels for steam generation from the industrial and domestic heating sectors is lower, leading to overall greater net biomass availability, lower transportation distances, and lower biomass costs. In densely populated and industrialized regions, such as southern Sweden where two of the pulp and paper mills are located (the 5.3-GWh and 4.7-GWh plants), the competition for biomass is higher. This means that BECCS will be in direct conflict with other uses, in this case district heating generation via biomass-fired plants (for which the production units may also implement CO_2 capture). In these areas, BECCS is limited by the bioenergy supply rather than being defined by the size of the biogenic CO_2 source. The results indicate (as mentioned in the *Introduction*) that the potential for increased biomass use is case-specific, varying between regions. One solution to lowering the demand for logging residues is to modify the process by, for example, introducing energy-efficiency measures or reducing product or energy outputs to free up heat for use in the capture plant. Other alternatives include designing the capture plant for partial capture, i.e., to have lower capture rates, so as to adapt the volume of CO_2 captured to the amount of available logging residues in the region (as shown in Table 3), or expanding the inter-regional biomass supply infrastructure, to match the biofuel demand in the south of Sweden with the supply in the north. Such infrastructure could for example be ship or rail transportation which could potentially facilitate cost-effective long-range transportation. Moreover, using a combination of other biomass sources, such as small-diameter trees, stumps and low-quality round wood, could also be considered.

Implementation of capture in the four mills while considering the amount of available logging residues would result in an annual capture of biogenic carbon of around 4.6 Mt, which would satisfy the proposed BECCS targets for Year 2030 and the lower bound for the Year 2045 target set in public inquiry SOU 2020:4 (SOU, 2020) by quite a large margin. This will require an increase of 6.4 TWh/year in biomass use for energy purposes for the four pulp mills if the output of the mill is maintained. The increased combustion of logging residues to supply the capture plant with energy will lead to additional biogenic CO_2 emissions. However, due to the large amount of emissions captured at the mills and the reasons discussed in the introduction that motivate the assumption of logging residue use being carbon neutral, these emissions are not quantified or included in the analysis. It should be safe to assume that the total potential for BECCS in the Swedish pulp and paper industry is large. There are 29 pulp and paper mills in Sweden emitting over 100 ktCO_2 yearly, many of which are located in the northern parts of the country where this work shows that the potential to use regional logging residues to fuel the capture plant is large. The total yearly CO_2 emissions from these 29 mills are around 22 Mt, putting an upper limit on large scale BECCS from the existing Swedish pulp and paper industry and indicating a large potential, given that the energy demand can be satisfied and that the transportation and storage infrastructure to handle these CO_2 volumes is developed.

In a future economy with stricter restrictions on fossil fuel use, it is highly likely that other sectors will compete for forest biomass resources, thus lowering the potential for BECCS powered by logging residues. This complicates the picture, since we here assume that the competing demand arises only from large users of logging residues for energy purposes, i.e., heat and power plants. With increased interest in biomass as a means to combat climate change, additional uses of biomass, such as production of fuels from solid biomass for use in road transportation or aviation or the use of biomass to substitute fossil fuels for heat generation in industrial processes, could be competing for the same resource. These potential developments point to biomass supply being a limiting factor for BECCS in the future. As indicated above, there is also an increased interest in CO_2 capture within the Swedish district heating sector, which is mainly using biomass residues as a fuel. Stockholm Exergi has concrete plans for implementing CO_2 capture in their largest biomass fired Combined Heat and Power plant in Stockholm. Thus, it is also possible that the potential development of BECCS in Sweden could take place in industry sectors other than the pulp and paper industry. When comparing low carbon technologies, it is important to consider the costs and potential climate benefit of the alternative use of biomass.

CONCLUSION

This work evaluates the biomass demand associated with large-scale implementation of BECCS in the Swedish pulp and paper sector, as exemplified by the capture of emissions from four large pulp mills. The results show that implementation of capture in the four pulp mills will lead to significant levels of negative emissions, around 4.6 Mt yearly (around 9% of the Swedish domestic GHG emissions). However, there are important differences in the competition for and the availability of the regional biomass supply. Population density is an important factor as it, together with the degree of utilization of bioenergy in the energy sector, decreases the availability of regional biomass, primarily as a consequence of increased competition. Thus, in addition to overcoming the barriers of high capital and operating expenditures for carbon capture and the current lack of incentives for negative emissions technologies, the infrastructure for supplying biomass is a limiting factor that needs to be considered in making decisions regarding the locations of carbon capture sites. Regional logging residues can, however, be used and supplied at reasonable cost, i.e., 22–30 €/tCO_2 captured, as a means of facilitating negative emissions via BECCS. Nevertheless, increased competition for biomass resources from other sectors is likely, i.e., the willingness to pay and, therefore, the costs are likely to increase as well. In addition, inter-regional infrastructures for biomass and/or transportation of CO_2 should be planned in a concerted fashion, and costs for the entire CCS chain, including the energy supply systems, should be taken into consideration.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SK performed the site energy system analysis. AE contributed with the biomass supply system analysis and cost estimations. FN and FJ contributed input to the site energy system analysis. All authors discussed and analysed the results and contributed to the writing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.738791/full#supplementary-material

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