The role of BECCS in providing negative emissions in Sweden under competing interests for forest-based biomass

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Abstract – Negative emissions are needed to meet climate mitigation targets and can be achieved through the capture and storage of biogenic CO_2 emissions (BECCS). Sweden holds a large potential for BECCS from the industry and heat and power sectors. This work provides a first assessment of how the conditions for BECCS in Sweden are impacted by competition for forest-based biomass from other sectors, in this work represented by production of transportation fuels. An optimization model is applied to study how demand levels for negative emissions and biofuels, and availability of forestry resources, influence the optimal system design considering the electricity, district heating and biomass sectors. BECCS and direct air capture technologies are available for investments in the model. The results show that biomass availability and biofuel demand have a large impact on the choice of negative emission technology, where high competition for biomass favours DACCS rather than BECCS. The available biomass is prioritized for use in fuel production and sets the upper limit for BECCS. In this work, CHP plants are more competitive for BECCS implementation than pulp mills, due to the energy penalty for CHP plants having a smaller impact on the overall energy system performance. The findings indicate that in addition to considering techno-economic assessments of individual technologies, it is important to take into account the system context in which they operate.

Nomenclature

Latin

C	Cost
D	Demand
I	Investment
q	Inflow of water to hydropower reservoir
R	Resource availability
TT	Length of timestep
x	Energy flow
y	Storage level
z	Storage charge/discharge

Greek

η	Conversion efficiency for plant p to energy carrier e
ε	Biogenic CO_2 captured-factor for plant p
κ	CO_2 usage-factor for plant p

Subscripts and superscripts

bat	Battery
ch	Charge of storage
dch	Discharge of storage
e	Set of energy carriers
p	Set of technologies/plants
s	Set of storages
t	Set of timesteps
U	Uranium

Abbreviations

BECCS	Bio-energy carbon capture and storage
BLG	Black liquor gasification
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CHP	Combined heat and power
DACCS	Direct air carbon capture and storage
FT	Fischer-Tropsch
HOB	Heat-only boiler
NET	Negative emission technology
SNG	Substitute natural gas
TES	Thermal energy storage

1 Introduction

Removal of CO_2 from the atmosphere by negative emission technologies (NET) is required, first, to offset emissions from hard-to-abate sectors and, later in the second half of the century, to achieve net-negative emissions and compensate the likely overshoot of the carbon budget and stabilize the climate at a temperature well below 2°C [1]. Bio-energy carbon capture and storage (BECCS) is one technology that can be deployed for CO_2 removal. In line with this reasoning, incentives specifically targeting capture of biogenic carbon is emerging e.g., Sweden launched a reversed auctioning system for negative emissions targeting 3-10 Mt CO_2 to be captured using BECCS in 2045 [2].

Negative emissions via BECCS could be achieved in Sweden by implementing CO_2 capture technology in the pulp and paper and/or heat and power sectors. Currently, the pulp and paper sector in Sweden emits around 22 $MtCO_2$/year and the heat and power sector emits at least 10 $MtCO_2$/year of biogenic CO_2, presenting interesting opportunities for large-scale BECCS deployment. In comparison, the total fossil CO_2 emissions from producing industries in Sweden are around 14 $MtCO_2$/year. However, the future potential for BECCS in these sectors is likely largely dependent on the future availability of and competition for biomass resources. Several other sectors – such as transportation and chemical manufacturing – indicate a continued or increased need for biomass to reduce their reliance on fossil resources.

Furthermore, utilizing forest-based biomass for climate mitigation purposes is controversial and discussions are ongoing about whether forests should be left to grow or utilized to provide the highest climate benefit [3]. In the Swedish context, forests are harvested to provide feedstock for wood products and pulp and paper production. Residues from these industries are utilized for heat and electricity generation, either at the industrial sites or in heat and power plants providing district heating to local communities and electricity to the grid.

If the availability of biomass for BECCS is limited, direct air carbon capture and storage (DACCS) is another emerging technology which could be implemented to generate negative emissions. DACCS captures CO_2 from the ambient air without the need for biomass combustion and is, in contrast to BECCS, location-independent and could be installed in regions with good access to low-cost energy and/or close to CO_2 storage locations, minimizing the demand for CO_2 transportation infrastructure.

However, the optimal choice of negative emission technologies depends on the system context in which they operate. Lehtveer and Emanuelsson [4] found that "impact to the whole system operation needs to be considered for well-grounded decisions" regarding implementation of negative emission technologies, and that the levelized cost of carbon on its own (often presented as the main indicator for choosing between CO_2 removal options) might be misleading from a system point-of-view.

Previous publications (see [5]–[7]) show the potential for BECCS in different Swedish industrial sectors, but do not consider any structural changes in these sectors, nor any changes in how the forest biomass resource is distributed between the sectors. Such reallocation of the biomass resource flows could potentially be a result of future technological and political developments that drives new demands for biobased materials, chemicals or transportation fuels. The aim of this work is to assess the role of BECCS from the pulp and paper and heat and power sectors in Sweden for meeting negative emission targets under conditions with different levels of forest biomass availability and future demands for biobased products in the transportation and industrial sectors.

2 Methodology

The work is based on optimization modeling of Swedish energy and industrial sectors, including electricity, district heating, and large-scale forest-based biomass users. The model captures the interaction between these sectors and cost-optimal pathways to meet demands for negative emissions and biofuel products under different scenarios. Section 2.1 describes the technologies and pathways considered to meet demands for negative emissions and biofuel products. Section 2.2 provides the model formulation, while Section 2.3 details the scenarios studied.

2.1 Technology descriptions and pathways

2.1.1 Negative emission technologies

Figure 1 gives an overview of the negative emission technologies included in the model with three options to capture and permanently store biogenic CO_2 emissions (BECCS) from pulp mills, CHP plants or heat-only boilers (HOB) producing district heating, as well as one pathway for CO_2 capture and storage through direct air capture (DACCS).

The Swedish pulp and paper mills consist of a mixture of pulp mills and integrated pulp and paper plants. In this work, we focus on the pulping process and assume that any paper production lies outside the system boundary. Kraft pulp mills emit CO_2 mainly from three point-sources of which two are most suitable for capture: the combustion of black liquor in the recovery boiler and the calcination process in the lime kiln. In this work, pulp mills with BECCS are assumed to capture 90% of CO_2 emissions from the recovery boiler and the lime kiln, using amine-based post-combustion absorption technology. The retrofit of BECCS is assumed to impact the energy performance of the mill, with reduced electricity generation and excess of forest residues, given that these energy resources must be used internally to drive the energy-intensive CO_2 absorption.

BECCS applied to CHP or HOB plants implies the capture of CO_2 from flue gases generated by combustion of forest residues in a boiler, using amine-based absorption with a 90% capture rate. The heat production efficiency from these plants is reduced when integrating BECCS, and in the case of CHP the electric efficiency is also decreased.

Two options for DACCS are considered in this work, operating at either low temperature (70-95°C) or high temperature (around 900°C) for sorbent regeneration. Different options to supply heat are possible [8], but in this work, both process options are assumed to be heated by electricity.

Costs for carbon capture are included in the model and listed in Appendix A. The capture cost for pulp mills is based on cost estimates for a mill that emits around 1.2 $MtCO_2$/year [6] while the CHP capture cost is based on the largest CHP plants in Sweden [5]. The transport and storage of CO_2 is not modeled, but a fixed cost of 40 €/tCO_2, based on the Northern Lights project [9], is included to account for costs associated with the CO_2 infrastructure needed.

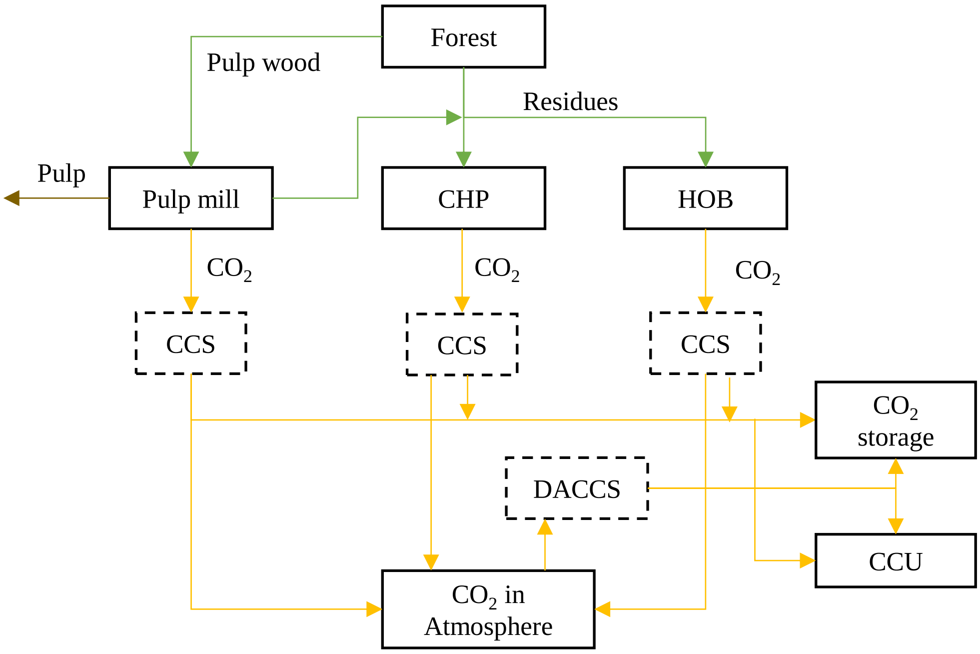

Figure 1. Negative emission pathways considered in this work. Electricity, district heating and biomass product energy carriers are omitted for clarity.

2.1.2 Biofuel production technologies

Figure 2 illustrates the pathways considered in the model for production of biofuels. Forest residues can be gasified in dedicated gasifiers to generate a set of different bio-derivates (syngas, substitute natural gas (SNG), Fischer-Tropsch (FT) diesel, or methanol). Black liquor gasification, and optionally syngas-upgrading, can be retrofitted to pulp mills to generate syngas or FT-diesel. Additionally, carbon capture and utilization (CCU) is included, in which captured CO_2 is reacted with hydrogen (supplied from electrolysis) to produce synthetic biofuels. Apart from an external demand for biofuels, the model must also supply any internal use of SNG for peak electricity production using biogas turbines or combined cycles. The biofuel demand is assumed to be an arbitrary mix of FT-diesel, methanol or jet fuels, and the model can select which fuel(s) to produce.

The investment costs, carbon conversion efficiencies and other energy in/outputs for each technology option is given in Appendix A. Gasification of forest residues in stand-alone processes and CCU processes typically generate excess heat that is assumed to be used for district heating. In addition to hydrogen, CCU also requires electricity that must be supplied internally in the model. Similar to the BECCS retrofit, the gasification of black liquor in pulp mills is assumed to reduce the output of forest residues, and to reduce the electricity generation so that electricity must instead be supplied to the mill.

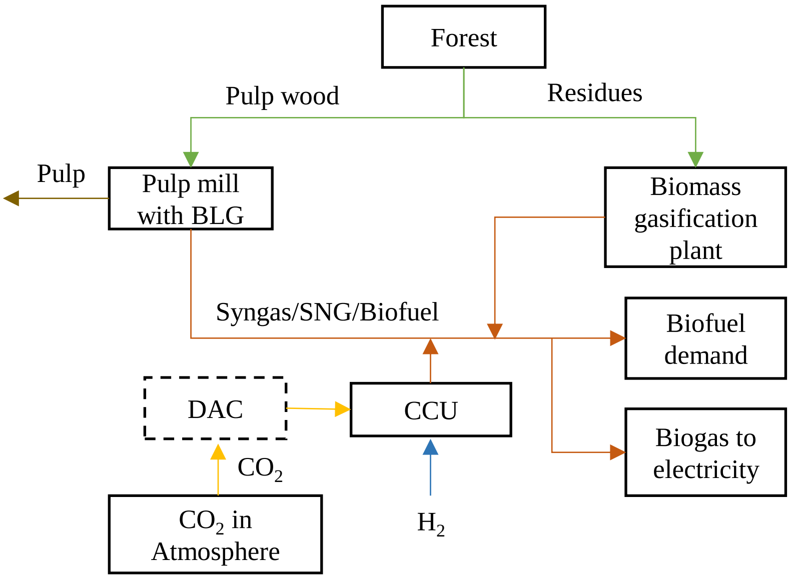

Figure 2. Biofuel production pathways considered in this work. Electricity, district heating and biomass product energy carriers are omitted for clarity. BLG, black liquor gasification.

2.1.3 Electricity and district heating technologies

Electricity can be generated by wind power, solar power, hydropower, biogas turbines or combined cycled, CHP plants, or nuclear power plants. District heating can be supplied by CHP plants, heat-only boilers, heat pumps, electric boilers, or industrial processes (pulp mills, gasifier plants, CCU plants, electrolysers). It is also possible to invest in storage capacity for electricity (Li-ion batteries), heat (seasonal thermal energy storage), gaseuos energy carriers (lined rock cavern). In Sweden it is common to incinerate municipal solid waste for heat and power generation, but this is not included in the model.

2.2 Model formulation

The model developed is a linear program that minimizes the cost of meeting a specified demand for negative emissions and demands for energy carriers (electricity, district heating, pulp and biofuels). The objective function of the model is given in Eq. (1) and minimizes the cost of investments and variable costs to supply the demands. Electricity and district heating demands must be met on an hourly basis [Eqs. (2) and (3)], while demands for pulp and biofuels must be supplied on an annual basis, Eq. (4). The use of forestry resources (pulp wood and forest residues) is limited by the annual availability, Eq. (5). Both CCS and CCU technologies are included in the model, and the BECCS target is given by the net balance of CO_2 captured and used, Eq. (6). The production level of technologies, and the storage level of a storage, cannot exceed the invested capacity, Eq. (7) and (8). Storage balances are given in Equations (9)-(11).

$$\min C_{tot} = \sum_p I_p C_p^{inv} + \sum_s I_s\, C_s^{inv} + \sum_p I_p\, C_p^{OMfix} + \sum_{p,t}(x_{p,t}\, C_s^{OMvar} TT + C_{p,t}^{start} + C_{p,t}^{part}) + \sum_t x_{Nuc,t}\, C^U + \sum_{p,t} CO2_{p,t}\, C^{CO2} \tag{1}$$

$$D_{el,t} + z_{bat,t}^{ch} \leq z_{bat,t}^{dch} + \sum_p x_{p,t}\, \eta_{el,p} \qquad \forall t \in T \tag{2}$$

$$D_{heat,t} + z_{TES,t}^{ch} \leq z_{TES,t}^{dch} + \sum_p x_{p,t}\, \eta_{heat,p} \qquad \forall t \in T \tag{3}$$

$$D_e \leq \sum_{p,t} x_{p,t}\, \eta_{e,p} TT \qquad \forall e \; in \; \{biofuel, pulp\} \tag{4}$$

$$R_e \geq \sum_{p,t} x_{p,t}\, \eta_{e,p} TT \qquad \forall e \; in \; \{pulpwood, forest\; residue\} \tag{5}$$

$$D_{BECCS} \leq \sum_{p,t} x_{p,t}\, \varepsilon_p TT - \sum_{p,t} x_{p,t}\, \kappa_p TT \tag{6}$$

$$x_{p,t} \leq I_p \qquad \forall t \in T, p \in P \tag{7}$$

$$y_{s,t} \leq I_s \qquad \forall t \in T, s \in S \tag{8}$$

$$y_{s,t+1} = y_{s,t} + z_{s,t}^{ch} - z_{s,t}^{dch} \qquad \forall t \in T, s \; in \; \{battery, TES\} \tag{9}$$

$$y_{s,t+1} = y_{s,t} + \sum_p x_{p,t}\, \eta_{s,p} \qquad \forall t \in T, s \; in \; \{H_2, syngas, SNG\} \tag{10}$$

$$y_{hydro,t+1} = y_{hydro,t} + q_t TT - x_{hydro,t} \qquad \forall t \in T \tag{11}$$

The production and consumption of each energy carrier by a plant is given by efficiencies ($\eta_{e,p}$), where a positive number indicates that the energy carrier is produced, and a negative number means that the energy carrier is consumed. Costs and efficiencies for all technologies are given in Appendix A.

Start-up and part load costs are calculated according to the work of Göransson et al. [10], and the electricity production from variable energy sources (wind and solar) are limited by hourly production profiles that represent variability in wind conditions and solar insolation. Investments in wind and solar power are limited by estimated potentials (e.g., max 10% of the land area is available for wind turbine installations).

2.3 Case study and scenarios

Sweden is used as a case study in this work. The timeframe of the study is around Year 2045, under the assumption that CO_2 emissions are net-zero and that fossil fuels are phased out, i.e., no fossil energy carriers or resources are included in the modelling. The Year 2020 installed capacity of hydropower and pulp mills is given as fixed capacities that cannot be expanded (it is unlikely that new pulp mills will be constructed in Sweden), although pulp mills can be retrofitted with CCS or black liquor gasification.

National energy balances and targets are considered as follows. Hourly profiles for electricity and district heating demand based on Year 2012 data are used. The annual electricity demand is scaled by a factor 1.5 compared to 2012 to account for an expected increase of electrification in the transport and industrial sectors. The annual demand for district heating is assumed to remain at 2012 levels, where building energy conservation measures are expected to offset increases in heat demand. There is no external demand for hydrogen in the model, rather, the hydrogen production matches the internal use in biofuel and electrofuel production processes.

The national availability of forest residues, the demand for biofuels, and the target for negative emissions are varied in levels according to Table 1. These levels are then combined to form 18 scenarios in total. The scenarios are given by low/medium/high (denoted L/M/H) levels of forest residue availability (first letter) and biofuel demand (second letter), e.g., “ML” indicates a scenario with medium forest residue availability and low demand for biofuels.

The low level of forest residue availability represents a scenario with low acceptance for the utilization of forest-based biomass for industrial and energy purposes, e.g., due to concerns about biodiversity or the general sustainability of biomass production. The medium level corresponds to the current level of biomass availability, and the high level represents a scenario with increased outtake of forest-based biomass [11].

Two levels for biofuel demand are included. The low level corresponds to a predicted demand for biofuels in the Swedish transportation sector [12], while the high level represents a scenario with a high demand, either driven by national targets and developments (e.g., with a low share of electrification in the transport sector) or by demands from other countries to export Swedish biofuels.

The negative emission target levels are based on SOU 2020:4 [2] for the low and medium levels. The high level for BECCS demand exceeds the proposed levels and represents a scenario in which Sweden “exports” negative emissions, which contribute to the abatement of CO_2 emissions in other countries or organizations.

Table 1. Demand and target levels for biofuels and negative emissions, and forest residues availability levels, used in combinations in the scenarios studied. The low, medium and high levels are denoted L, M and H in the text, respectively.

Demand/Resource constraint	**Low level (L)**	**Medium level (M)**	**High level (H)**
Forest residues availability [TWh/year]	25	50	100
Biofuel demand [TWh/year]	15	-	60
Negative emissions target [MtCO_2/year]	3	10	20

3 Results and discussion

3.1 Utilization of negative emission technologies

Figure 3 shows the modeled annual amount of CO_2 captured by industrial BECCS and DACCS in the studied scenarios for the three negative emission target levels, with the corresponding marginal cost of forest residues. BECCS is used for CO_2 capture in scenarios with low competition for biomass, i.e., high availability of forest residues and a low demand for biofuels (denoted HL and ML scenarios in Figure 3). With a high biofuel demand and/or a low availability of forest residues, biomass is allocated to gasification and biofuel production rather than BECCS. Thus, DACCS dominates the carbon capture and supplies both the negative emission target, as well as CO_2 needed for production of synthetic biofuels (CCU), resulting in levels of captured CO_2 that exceed the target levels for negative emission. CCU is needed for biofuel production in all scenarios with the 60 TWh biofuel demand, regardless of biomass availability and negative emission target levels, making forest residues a scarce resource. The high biofuel demand level might therefore be challenging to reach using only domestic forest-based biomass resources.

The ML-scenarios with medium availability of forest residues and a low biofuel demand are the only scenarios in which a mix of BECCS and DACCS is observed. The CO_2 capture from BECCS reaches approximately the same level for both the 10 Mt and 20 $MtCO_2$/year targets, indicating that the use of BECCS is maximized after forest residues are utilized to meet the biofuel demand, and that DACCS covers the remaining carbon capture required.

The CO_2 capture technology investments are reflected by the modeled marginal cost of forest residues, which increases strongly with competition for biomass independent of the negative emission target. BECCS technologies that are powered by forest residues are competitive for marginal costs of forest residues <40 €/MWh. Above this cost level, biomass is too scarce and costly to supply negative emissions from biomass combustion, and DACCS is deployed instead. That is, the competitiveness of BECCS technologies using forest residues as fuel have a strong sensitivity to low availability and high competition for biomass. DACCS is powered by electricity in this work, which is to a large extent produced by solar and wind power in the modeling scenarios, and is not as sensitive to the cost of forest residues. Figure 3 also shows that the marginal cost of forest residues is similar for the three levels of negative emission targets, indicating that CO_2 capture has a small impact on the biomass market in comparison to an increased biomass demand in other sectors.

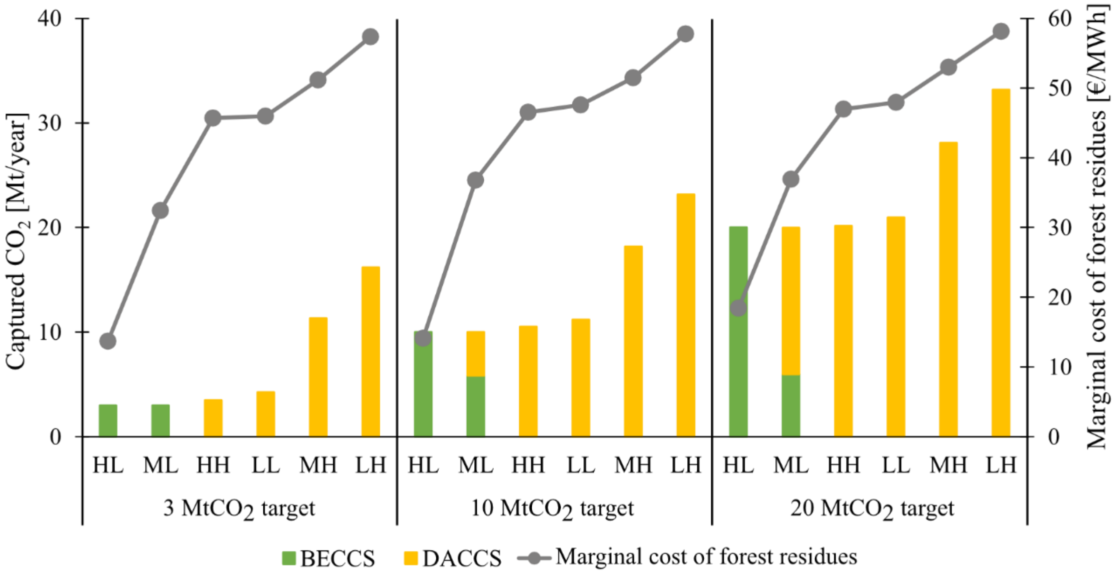

Figure 3. Annual CO_2 captured by BECCS and DACCS, and the marginal cost of forest residues for the modelled scenarios. The letters represent scenarios given by low/medium/high (L/M/H) levels (Table 1) of forest residue availability (first letter) and biofuel demand (second letter), e.g., "ML" indicates a scenario with medium forest residue availability and low demand for biofuels.

3.2 Biomass utilization pathway

Figure 4 displays the resulting biomass utilization pathways in scenarios with medium availability of forest residues and a 10 $MtCO_2$ negative emissions target, for the two biofuel demand levels. With the low biofuel demand level (15 TWh), forest residues are evenly distributed between CHP and gasification plants. A small amount of forest residues is converted to SNG in a gasifier plant to fuel biogas turbines for peak load electricity production. Both CHP-CCS and DACCS contribute to the negative emission target. Biomass is prioritized for use in biofuel production and the remainder is used for BECCS, due to alternative biofuel production pathways (CCU) being more expensive than biomass gasification and upgrading.

With the high biofuel demand level, the distribution of forest residues is strongly shifted towards gasification, and less than 1% of forest residues are allocated to CHP plants. However, the forest residues are not sufficient to cover the biofuel demand, and a DACCS and CCU pathway must be included to increase the carbon feedstock to meet the biofuel demand. With the strain on forest residue utilization, the negative emissions target is fully covered by DACCS, although 44% of the carbon captured is allocated to CCU and biofuel synthesis.

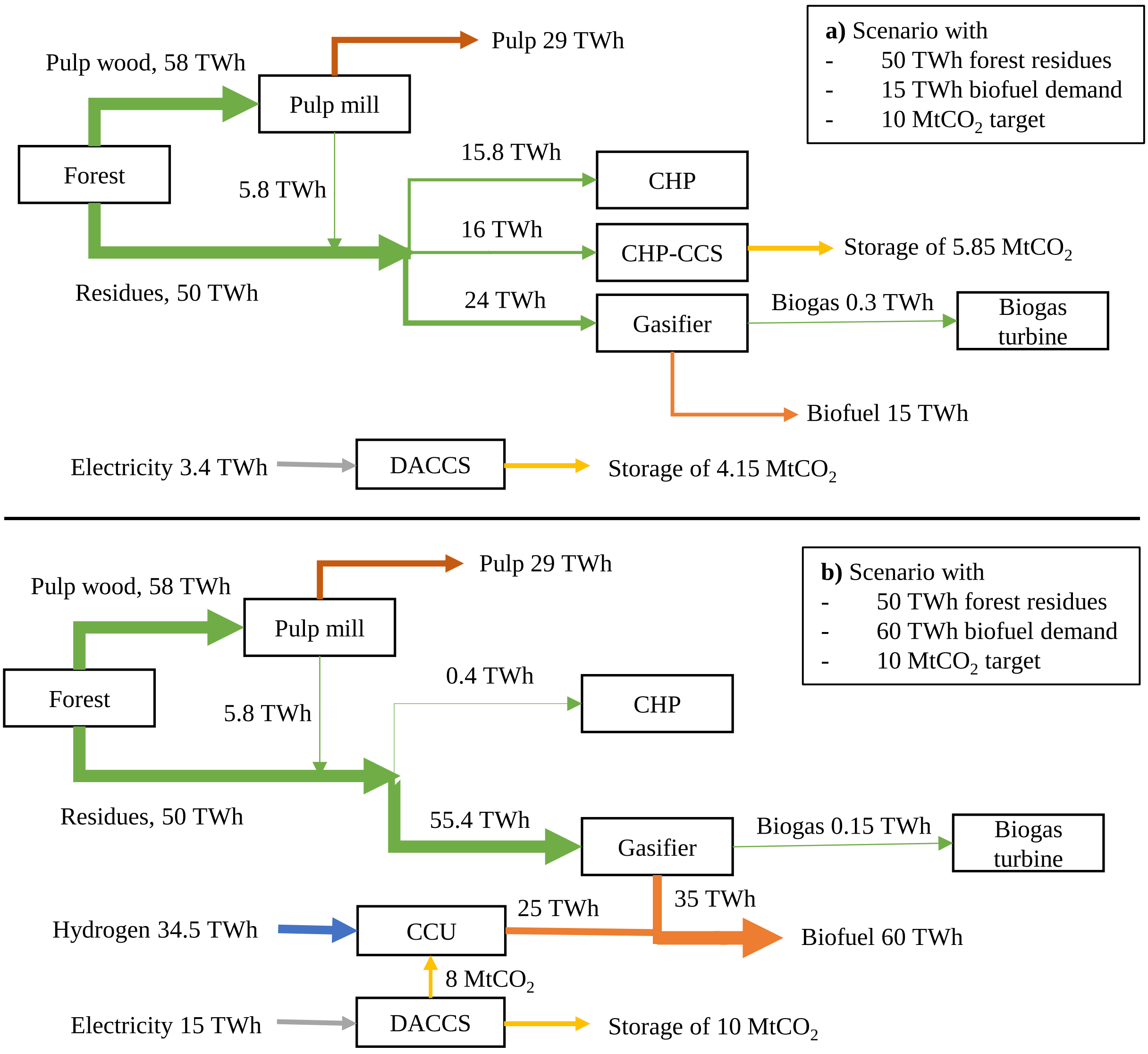

Figure 4. Biomass utilization pathways in scenarios with medium forest residue availability (50 TWh) and a 10 $MtCO_2$ negative emissions target. a) Low biofuel demand. b) High biofuel demand. Electricity and district heating energy carriers are omitted for clarity.

3.3 The choice of BECCS technology: Pulp mill-CCS vs. CHP-CCS

In the scenarios in which BECCS technologies are invested in, CHP plants with CCS is the only BECCS option that is competitive with the input data in Appendix A. Pulp mill capacity is available in all scenarios, but the model does not choose to retrofit pulp mills with CCS, nor with black liquor gasification. Pulp mill-CCS is not implemented, even in scenarios where biomass is redistributed away from CHP plants, and CHP-CCS is no longer a competing BECCS option, and despite the fact that large biogenic CO_2 flows are still being emitted from the pulp mills in these scenarios. HOB plants are not competitive in any scenario, with or without CCS, and are excluded from further analysis.

The preference for CHP-CCS over pulp mill-CCS in this work is at first glance unexpected given that pulp mill-CCS is generally estimated to have a lower cost of capture than CHP plants equipped with CCS, due to economy-of-scale and operating patterns: most pulp mills in Sweden have larger CO_2 emissions than CHP plants, and pulp mills generally have a higher utilization factor, operating year-round, compared to CHP plants that tend to operate on a seasonal basis following the heat demand, leading to lower utilization factors and higher specific capital costs.

The cost of operating CCS favors CHP-CCS in this work. Implementation of carbon capture is in the modeling assumed to reduce the output of product energy carriers. For pulp mills this implies that forest residues are consumed internally to provide process heat to the capture process, and that no electricity is supplied to the grid. Given the scarcity of biomass resources observed in the scenarios, the loss of valuable forest residues as a plant output is discouraging for pulp mill-CCS. That is, the system cost of pulp mill-CCS can be high if forest residues are a limited resource. A sensitivity analysis in which the energy penalty of pulp mill-CCS is lowered shows that, for the CCS cost levels applied in the modeling, the pulp mills must retain nearly all electricity and forest residue outputs when retrofitting CCS (i.e., same performance as a mill without CCS) to be competitive compared to CHP-CCS.

CHP plants, on the other hand, lose some production of electricity and district heating when retrofitting CCS. The supply of district heating is not limiting for CCS implementation, as district heating is generated as a by-product in gasifiers and CCU processes. Occasionally the marginal cost of district heating is zero, indicating that heat is available in excess quantities. Heat supply being the primary objective of CHP plants, the retrofit of CCS is of small consequence for CHP plants as long as forest residues are available to an acceptable cost. As the competition for biomass increases, dedicated heat production from CHP and HOB plants is outcompeted by industrial excess heat sources, which strongly reduces the potential for BECCS applied to CHP plants. These results also imply that it is of high value for new industrial processes to take advantage of polygeneration and sector coupling opportunities to increase competitiveness in future decarbonized energy systems, and might be a reason that pulp mill-CCS has low competitiveness in the model results, as the CCS integration reduces the sector coupling potential and system integration of pulp mills, with only heat and pulp production left.

A sensitivity analysis indicates that the carbon capture cost (CAPEX and fixed OPEX) for a pulp mill CO_2 capture plant must be reduced to around 13-25 €/tCO_2 (compared to the assumed cost of 50 €/tCO_2, Appendix A) to be competitive compared to CHP-CCS. The CHP-CCS plant can handle a slight cost increase and still be competitive in relation to pulp mill-CCS.

3.4 Model limitations and further development

The model provides a first assessment of the relative future competitiveness of negative emission technologies in a Swedish system context. Simplifications and assumptions are made, which limit the accuracy of the model and resulting output values should only be seen as indicative. However, the main principles should remain valid as the model captures the relative dependencies between technology options and sector pathways.

Simplifications include that the modeling does not consider costs associated with transport, infrastructure and transmission grid bottlenecks that are needed to integrate the different processes. DACCS and CCU processes imply a high degree of electrification that require adequate grid connection capacities. Furthermore, it is assumed that processes are located in such a way that, for example, all excess heat from processes can be used for district heating (i.e., are located close to a district heating network). Local biomass availability and biomass transport costs might contradict such arrangements and limit the polygeneration benefits that are observed in this work. An increased spatial resolution in the model would provide an understanding of how these factors might impact the optimal system design.

Assumptions regarding the costs and technical performance of the technologies considered have also been made. Costs for BECCS and DACCS can be expected to vary depending on location, plant scale and access to energy carriers, but these variations are difficult to account for in linear models. The relatively low technical maturity of DACCS processes further increases the uncertainty of cost estimations. However, the modeling shows that the cost of DACCS can be increased by a factor 5 without significantly loosing competitiveness and suggests that biomass scarcity has a stronger influence on the results than the cost of DACCS.

The options for negative emission technologies might be expanded. For instance, there might be opportunities to capture CO_2 from gasification processes, which have not been considered in this work, but could contribute to meet negative emission targets. Increased demands for biomass could also emerge from other users than included here. Although this is not modelled explicitly, the results for the high biofuel demand scenarios can also give insights regarding high demand for other biobased products.

4 Conclusion

This work provides an energy system-oriented assessment of the role of Swedish pulp mills and district heating plants (CHP and HOB plants) in providing negative emissions in scenarios with different levels of competition for forest-based biomass residues. An optimization model is developed to study investment and dispatch trends. The results show that biomass availability and biofuel demand have a large impact on the choice of negative emission technology, where high competition for biomass favours DACCS rather than BECCS. The available biomass is prioritized for use in fuel production and sets the upper limit for BECCS.

With low competition for biomass, CCS at CHP plants is a competitive negative emission technology. The reduced energy performance of pulp mills with CCS prevents investments due to the high system cost of reduced output of forest residues and electricity from the pulp mills when retrofitting CCS. Thus, the work highlights the importance of considering system interactions when large scale negative emission systems are designed - it is not sufficient to only consider the techno-economic assesments of individual technologies.

Acknowledgments

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Appendix A – Technology data

The input data is mainly based on Danish Energy Agency Technology Catalogue [13]. DACCS data are obtained from Lehtveer and Emanuelsson [4].

Table A1. Conversion efficiencies for technologies. A negative efficiency means that the energy carrier is consumed. The calculation basis for pulp mills is 1 MWh pulp wood. Renewable energy technologies (wind, solar, hydro) have efficiencies of 1 MWh electricity/MWh input energy (not included in the table).

Technology	η_{el}	η_{heat}	$\eta_{forestresidue}$	η_{H2}	η_{syngas}	η_{SNG}	η_{FT}	η_{pulp}
Pulp mill	0.10	0.10	0.10	0	0	0	0	0.50
Pulp mill CCS	0	0.10	0	0	0	0	0	0.50
Pulp mill BLG to syngas	-0.05	0.10	0	0	0.15	0	0	0.50
Pulp mill BLG to syngas, CCS	-0.15	0.05	0	0	0.15	0	0	0.50
Pulp mill BLG to FT	-0.05	0.10	0	0	0	0	0.10	0.50
Pulp mill BLG to FT, CCS	-0.15	0.05	0	0	0	0	0.10	0.50
CHP	0.35	0.60	-1	0	0	0	0	0
CHP CCS	0.25	0.50	-1	0	0	0	0	0
HOB	0	0.95	-1	0	0	0	0	0
HOB CCS	0	0.65	-1	0	0	0	0	0
HP	-1	3	0	0	0	0	0	0
EB	-1	1	0	0	0	0	0	0
DACCS LT	-1	0	0	0	0	0	0	0
DACCS HT	-1	0	0	0	0	0	0	0
GT	0.42	0	0	0	0	-1	0	0
CCGT	0.62	0	0	0	0	-1	0	0
Nuclear power	0.33	0	0	0	0	0	0	0
CCU Jet fuel, electricity-based	-1	0.30	0	0	0	0	0.50	0
CCU Jet fuel, H_2-based	0.01	0.17	0	-1	0	0	0.73	0
CCU Methanol	-1	0.25	0	-0.72	0	0	0.63	0
Electrolyser SOEC	-1		0	0.82	0	0	0	0
Electrolyser PEM	-1	0.17	0	0.68	0	0	0	0
Gasifier Methanol	0.02	0.22	-1	0	0	0	0.63	0
Gasifier FT	0.02	0	-1	0	0	0	0.28	0
Gasifier SNG	0	0.20	-1	0	0	0.70	0	0
Gasifier Syngas	-0.02	0.05	-1	0	0.85	0	0	0
Biogas SNG	-0.02	0.19	0	-0.87	-1	1.68	0	0
Syngas SNG	-0.03	0.03	0	0	-1	1	0	0

BLG, Black liquor gasification; SOEC, Solid oxide electrolysis cell; PEM, Polymer electrolyte membrane; LT, Low temperature; HT, High temperature; HP, Heat pump; EB, Electric boiler; GT, gas turbine; CCGT, Combined cycle gas turbine.

Table A2. Technology cost data. Fuel costs are not included in Variable OPEX, but implicitly determined as marginal values by the model.

Technology	CAPEX[a] [k€/MW]	Fixed OPEX[a] [k€/MW]	Variable OPEX [€/MWh]	Start cost [€/MW]	Part load cost [€/MWh]	CCS cost[b] [€/tCO_2]	Start time [h]	Min. load [%]
Pulp mill	0	0	0	0	0	-	-	-
Pulp mill CCS	0	0	0	0	0	43	-	-
Pulp mill BLG to syngas	286	0	0	0	0	-	-	-
Pulp mill BLG to syngas, CCS	286	0	0	0	0	51.6	-	-
Pulp mill BLG to FT	410	0	0	0	0	-	-	-
Pulp mill BLG to FT, CCS	410	0	0	0	0	51.6	-	-
CHP	368	10.3	0.56	19.9	0.66	-	12	35
CHP CCS	888	10.3	0.56	19.9	0.66	-	12	35
HOB	466	29.3	0.70	0	-	-	-	20
HOB CCS	986	29.3	0.70	0	-	-	-	20
HP	1590	0.3	0.53	0	-	-	-	10
EB	50	0.9	1.00	0	-	-	-	-
DACCS LT	880	0	35.2	0	-	-	3	-
DACCS HT	533	0	19.6	57.0	1.9	-	12	35
GT	196	3.3	0.29	8.48	0.21	-	-	30
CCGT	578	8.1	0.50	26.6	0.31	-	6	30
Nuclear power	1574	50.7	0	132	0.33	-	24	70
Solar PV	450	7.8	1.10	0	-	-	-	-
Wind power, onshore	1389	12.6	1.10	0	-	-	-	-
Wind power, offshore	2594	36	1.00	0	-	-	-	-
CCU Jet fuel, electricity-based	950	0	17.5	0	-	-	-	-
CCU Jet fuel, H_2-based	803	0	8.54	0	-	-	-	-
CCU Methanol	1424	33.4	6.27	0	-	-	-	-
Electrolyser SOEC	1342	0	0	0	-	-	-	-
Electrolyser PEM	450	0	0	0	-	-	-	-
Gasifier Methanol	1336	23.9	13.6	0	-	-	-	-
Gasifier FT	1021	29.0	0.30	0	-	-	-	-
Gasifier SNG	1500	24.1	1.60	0	-	-	-	-
Gasifier Syngas	1100	16.2	2.00	0	-	-	6	20
Biogas SNG	1008	40.3	4.84	0	-	-	-	-
Syngas SNG	245	8.6	0	0	-	-	-	-

BLG, Black liquor gasification; SOEC, Solid oxide electrolysis cell; PEM, Polymer electrolyte membrane; LT, Low temperature; HT, High temperature; HP, Heat pump; EB, Electric boiler; GT, gas turbine; CCGT, Combined cycle gas turbine.

a. Per MW energy carrier marked with (-1) in Table 2, or per MW pulp wood in the case of pulp mills.
b. For pulp mills, the capital expenditures of CCS are included as a fixed cost [€/tCO_2] based on Johnsson et al. [6] rather than as part of the CAPEX, as is the case for the other CCS technologies.

Table A3. Negative emission factors and CO_2 usage factors for BECCS, DACCS and CCU processes. Pulp mills, CHP and HOB plants are assumed to capture 90% of the generated emissions.

Technology	Negative emission factor	CO_2 used-factor	Unit
Pulp mill CCS	0.18	0	$tCO_2/MWh_{pulpwood}$
Pulp mill BLG to syngas, CCS	0.11	0	$tCO_2/MWh_{pulpwood}$
Pulp mill BLG to FT, CCS	0.11	0	$tCO_2/MWh_{pulpwood}$
CHP CCS	0.36	0	tCO_2/MWh_{fuel}
HOB CCS	0.36	0	tCO_2/MWh_{fuel}
DACCS LT	1.20	0	tCO_2/MWh_{el}
DACCS HT	0.65	0	tCO_2/MWh_{el}
CCU Jet fuel, electricity-based	0	0.16	tCO_2/MWh_{el}
CCU Jet fuel, H_2-based	0	0.24	tCO_2/MWh_{H2}
CCU Methanol	0	0.15	tCO_2/MWh_{el}

BLG, Black liquor gasification; LT, Low temperature; HT, High temperature.

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