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A case study of the potential for CCS in Swedish combined heat and power plants

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Abstract

The global need to reduce anthropogenic CO_2 emissions is imminent and might be facilitated by carbon capture and storage (CCS) technologies. Sweden has a goal to reach net-zero emissions by 2045, where negative emissions – and bio-CCS (BECCS) in particular - have been proposed as an important strategy to reach this target at the lowest cost. The Swedish district heating sector constitutes a large potential for BECCS since there is a large number of relatively large biogenic point sources of CO_2 in the form of combined heat and power (CHP) plants burning biomass residues from the forest industry. This study provides a multi-level estimation of the impact and potential of CO_2 capture and negative emissions in 110 existing Swedish biomass or waste-fired CHP plants, located in 78 local district heating systems. Process models of CHP steam cycles give the impact of absorption-based CCS integration on CHP plant heat and electricity production. The propagation of the plant-level impact to the unit commitment of CHP plants in district heating systems is modelled, and the potential for CO_2 capture in each system is estimated. The results indicate that 45-70% of nominal steam cycle district heating generation is retained when integrating carbon capture, depending on the power-to-heat ratio; although the reduced heat output can be moderated by sacrificing electricity generation. In the district heating system context, CCS integration can lead to increased utilization and fuel use of CHP plants, in synergy with increased CO_2 capture, but might also lead to greater need for peak heat and/or electricity generation. The total CO_2 captured from the 45 CHP plants with modeled CO_2 emissions exceeding 150 kton/year could be sufficient to meet a proposed target of 3-10 Mton/year of BECCS by Year 2045.

Keywords: CCS; Negative emissions; District heating; Combined heat and power; Steam cycle

Nomenclature

BECCS	Bio energy carbon capture and storage
CCS	Carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District heating

1. Introduction

Climate change, caused by anthropogenic emissions of CO_2, requires urgent actions to limit the impacts of global warming. Carbon capture and storage (CCS) has been identified as an important part of achieving long-term CO_2 emission targets which, to comply with the Paris Agreement to limit warming to “well-below” 2°C, will most likely require net zero carbon emissions by around 2050, whereafter emissions have to become net-negative [1]. If applying CCS to biogenic emission sources (BECCS) and assuming the these are using biomass from biomass systems with a net growth in carbon stock, so-called “negative emissions” could be achieved. These can have two purposes: to offset residual emissions that are hard-to-abate in order to reach net-zero emissions; and, in the longer run, to obtain net-negative emissions. Compared to other negative emission technologies, BECCS has been found to be the most mature option in terms of technology [2].

In Sweden, a country with substantial biomass resources and a well-developed forest industry, the application of BECCS is especially interesting. Sweden has a goal to reach net-zero emissions by 2045, where negative emissions – and BECCS in particular - have been identified as an important possibility to reach this target at the lowest cost. A public inquiry [3] has proposed the contribution from BECCS to be 2 Mton/year in Year 2030 and 3-10 Mton/year by Year 2045, with the large span reflecting that it is not known how far other measures will contribute to the net zero target in 2045. Carbon emissions of 10 Mton corresponds to around one fifth of Sweden's current total greenhouse gas emissions from all sectors.

There is a large number of large point sources of biogenic CO_2 emissions in the Swedish energy and industry sectors, where CCS applications could be cost-effective [4]. In the heat sector, approximately 50% of the total annual heat demand for space heating and hot water is supplied from district heating (DH), where 40% of district heating deliveries are from combined heat and power (CHP) plants that combust biomass or municipal solid waste of partially biogenic origin. Implementation of BECCS at CHP plants could contribute to reaching the negative emissions target, and might also present a business case for the plants if economic compensation is granted for negative emissions [5]. Even though the economic incentives are lacking at present, BECCS is, for example, being considered for the DH system in Stockholm [6] and has been studied for the Helsinki DH network [7]. Thus, once the economic incentives are there it should be possible to establish full scale projects within a few years, considering that post-combustion carbon capture technology can be seen as commercially available. The Stockholm utility company Stockholm Exergi target Year 2025 for a full-scale implementation of CCS on their newest biomass-fired CHP plant. In addition to policy driven incentives there also seems to be an emerging market for negative emissions since several companies have declared that they will offset their emissions, in some cases also including historical emissions, as announced by Microsoft [8]. BECCS should be attractive for such compensation since other compensation schemes – typically from planting trees – have been questioned with respect to their actual climate benefit (e.g. lack of long-term guarantee of managing the planted trees).

However, in addition to the need for reduced carbon emissions, there is still a need for sustainably produced heat and electricity. Post-combustion CCS is an energy-intensive process that will impact the CHP plant performance, with reduced heat and electricity generation. There might, thus, be competing interests between generation of heat, electricity and negative emissions. On the other hand, the number of full load hours of Swedish CHP plants is generally low, and dictated by the district heating demand that varies seasonally. Integrating CHP plants with carbon capture might present opportunities for increased full load hours, both for CHP plants with CCS and for other units in the DH system. For instance, retrofitting a CHP plant with CCS might mean that other heat producing units in the DH system must compensate for the reduced heat output, and thereby get increased utilization.

The global potential of BECCS has been studied (e.g. [9]), as well as studies that have focused on the national potential in of BECCS in Japan [10] and South Korea [11]. The global potential for municipal solid waste to contribute to BECCS has also been estimated [12], along with a techno-economic screening of biomass-based power generation with BECCS [13]. However, there is little previous research on BECCS applied specifically to CHP plants [6], or the implications for district heating systems of retrofitting CHP plants with CCS.

This work evaluates the interaction of absorption-based CO_2 capture, district heating and electricity generation with respect to carbon reduction, plant performance and utilization. Process and system level perspectives are combined, to analyze how the heat integration may be implemented in existing CHP plants and district heating systems. For the existing Swedish capacity of CHP plants, the potential for and impact of carbon capture is evaluated on three energy system levels: 1) process level, i.e. the impact on CHP plant performance; 2) district heating system level, i.e. the impact on the operation of district heating networks; and 3) national level, aggregating the carbon captured from all DH systems in Sweden for comparison with national goals. Only CCS installations at CHP plants are considered, and no industrial sites or peak plants. Since the focus of this work is on the potential for CCS at CHP plants, we include all plants in Sweden, although some of the plants may be too small for implementing CCS at a reasonable specific capture cost. Also, this work does not include aspects on infrastructure for transport and storage of CO_2.

2. Method

Figure 1 gives an overview of the method. The work consists of process modeling of CHP plant steam cycles and modeling of the unit commitment of district heating systems. The results are finally aggregated to estimate the potential for negative emissions from CHP BECCS on national level. The process and system models are soft-linked and specific input for each plant and DH system is provided from a database. The database, available in [14], comprises information about 110 Swedish CHP plants that combust biomass or waste, located in 78 local district heating systems. The data include CHP plant heat and electricity production capacity, live steam conditions and year of commissioning; as well as the total annual heat delivery for each district heating system. The thermal capacity of the boilers ranges from 6.7 to 540 MW, and steam cycles have power-to-heat ratios in the range 0.1-0.65. The biogenic share of the waste is assumed to be 52% [15]. Given that some of the CHP plants included in the study are small and might not have economic incentives to install CCS, the total CO_2 capture from CHP plants with modeled emissions above 150 kton/year is also presented. The choice of 150 kton/year is arbitrarily reflecting that this corresponds to larger CHP plants for which some utility companies have shown an interest in CCS.

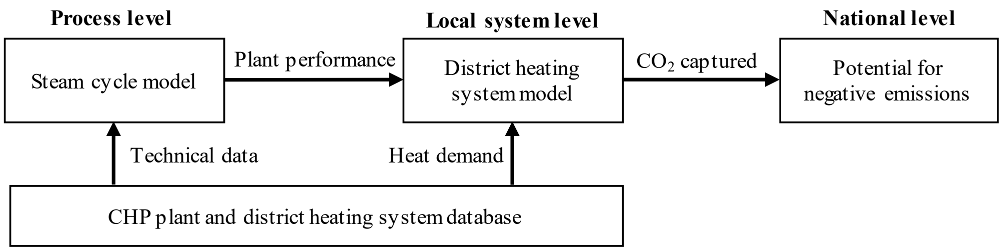

Figure 1. Method overview, indicating the levels of modeling, and their connectivity.

2.1. Process models of CHP steam cycles with carbon capture

Steady-state process models of CHP plants simulate the impact on steam cycle performance of integration with carbon capture. Five types of steam cycle models with different power-to-heat ratios (alpha values) are developed in Ebsilon Professional, to represent the range of CHP plants in the database. Figure 2 gives a schematic overview of the modeled steam cycle design, where A-E mark steam extractions that differentiate the five type models. The model components include a steam boiler that generates steam with a given temperature and pressure, that is expanded in a steam turbine for generation of district heating and electricity. The steam turbine is modeled with 1-5 stages depending on the alpha value of the CHP plant, where the number of extractions and steam cycle complexity increase with alpha value. Plants with low alpha values are modeled with only extraction A; if necessary using the steam turbine bypass to further lower the alpha value. Plants with slightly higher alpha values have extractions A and B; and so on, so that the plants with the highest alpha values are modeled with all extractions, A-E.

District heating is generated in the backpressure condenser, and where applicable also in the extraction condenser, the bypass condenser and/or the flue gas condenser. Boundary conditions for the district heating water are set to 40°C for the return temperature and 90°C for the supply temperature.

The carbon capture plant is assumed to be a post-combustion absorption-based unit that requires heat at a temperature of 120°C for the reboiler, and is represented by a heat sink in the model. A heat load of 3.8 MJ/kg CO_2 captured is chosen based on the conditions for biomass or waste-fired CHP plants and 90% capture rate from a flue gas CO_2 concentration of 13-15% [16]. For conventional cogeneration operation of the steam cycle, steam is extracted from the CHP plant steam turbine at 6 bar to meet the reboiler heat demand. Alternatively, the steam cycle can be operated as a heat-only plant by bypassing the turbine; in which case steam for the CCS reboiler is throttled directly from the live steam flow.

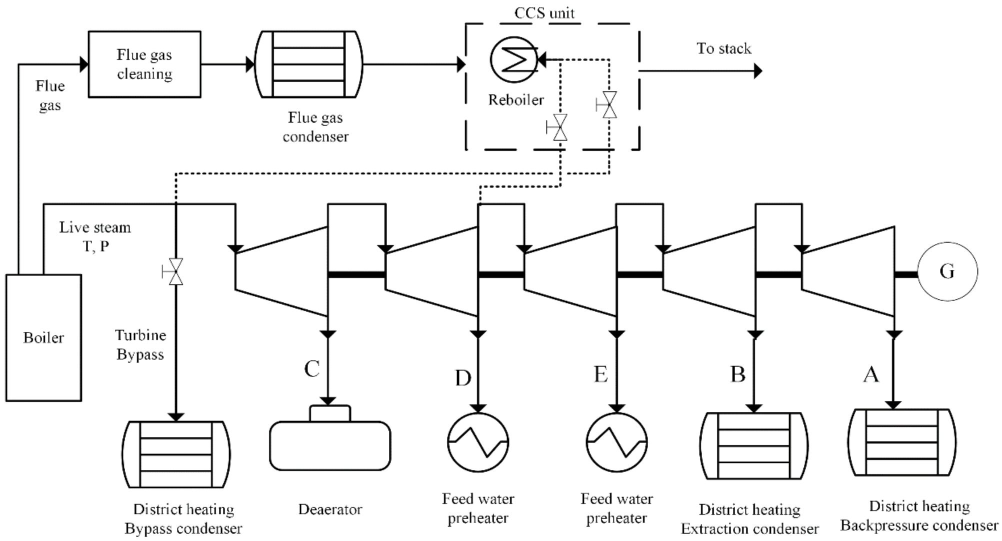

Figure 2. Simplified process schematic of a combined heat and power plant, focusing on the turbine train with steam extractions, and the flue gas train including the CO_2 absorption unit. Letters A-E indicate the possible extractions that are added to the process model to increase the power-to-heat ratio. The CCS reboiler extraction point is adjusted to match 6 bar.

Each of the 110 CHP plants in the database are simulated with the steam cycle model that best matches the steam cycle design alpha value; for operation with and without the steam extraction to the CCS reboiler. Input values for live steam temperature and pressure and boiler thermal capacity are given for each specific plant. The simulated output includes the plant heat and electricity generation, and mass flow of CO_2 captured.

2.2. District heating system unit commitment model

The DH system unit commitment model is a spreadsheet tool that, based on a determined merit order, finds the operation of CHP plants in each DH system with hourly resolution. The model inputs are: an hourly heat demand profile for each system, spanning a year; a mapping of which CHP plants that are located in each DH system; and the resulting performance data from the steam cycle process simulations for each CHP plant. In the case where CCS is implemented, the plant performance input data represent plant operation with CCS, obtained from the process simulations. Heat from CHP plant flue gas condensers is included where applicable, as well as industrial excess heat used for DH generation.

Two load profiles for district heating demand are used depending on the DH system's geographical location, Southern or Northern Sweden. The hourly heat demand profiles for Southern district heating systems are predicted based on a profile from the district heating system in Västerås, Sweden. The yearly distribution is assumed to be the same for all DH networks in Southern Sweden, but the profile is scaled to match the annual demand (Q_{tot}) in each network by adjusting the parameter Q_{peak} (peak demand) according to Equation 1. F_t is the fraction of the annual heat demand for hour t. An example heat demand profile is presented with the results, Section 3.2. For DH systems in Northern Sweden, the hourly heat demand profile is estimated based on a correlation describing the heat demand as a function of air temperature. A temperature profile for Storuman, Sweden is used to represent Northern Sweden.

$$Q_{tot} = Q_{peak} * \sum_{t=1}^{8760} F_t \qquad (1)$$

The plant merit order is presented in Table 1 and is applied to all DH systems. The selection of plant types and merit order are based on the current operational practices of Swedish DH networks. If a plant type is not applicable for a DH network, the next plant type in order is operated instead. If there are more than one plant in a category, the plant with the most recent commissioning date is selected first. “Other units” refer to heat production technologies such as: heat only boilers, heat pumps, electric boilers or reserve CHP plants. Industrial excess heat deliveries are assumed to be constant throughout the year and always used in full.

Table 1. Plant merit order and minimum load levels of heat production units in district heating networks. Industrial and peak capacity are considered as aggregates with continuous load spans; therefore a minimum load level is not used for these plant types.

Running order	Plant type	Minimum load level
1	Industrial excess heat	-
2	Waste-fired CHP plants	0.7
3	Biomass-fired CHP plants	0.4
4	Other units (peak plants)	-

A set of logical conditions determine the load level of each plant for each hour of the year. Firstly, if the hourly heat demand is lower than the maximum heat production of the first plant in the running order, the CHP plant load level is set to part load to match the heat demand. If the heat demand is higher than the CHP plant maximum heat production, the load level of the CHP plant is set to full load. If there are more CHP plants available in the DH system, the procedure is repeated until the heat demand is met. If the CHP plants’ heat production is not large enough to cover the demand, peak units are started. A sub-loop ensures that CHP plants do not operate below the minimum load level, by lowering the load of the previous unit. The plant operation is determined for each hour of the year separately, without consideration of dynamic effects; i.e. maintenance stops, ramp rates and minimum up/down times are neglected, and load changes are assumed to be instantaneous.

The output from the model are the hourly heat and electricity production from each CHP plant, as well as the associated CO_2 emissions.

2.3 Operational strategies for CHP plants with CCS in DH systems

When CCS is integrated, the CHP plant production of heat and electricity is affected, but the plant might be able to minimize the impact on one of the products. Thus, two steam cycle operational modes are compared: maximization of electricity or heat production. The maximum electricity-mode corresponds to conventional cogeneration operation but with steam being extracted from the turbine to power the reboiler. For maximum heat-production, the steam turbine bypass is used, directly condensing all live steam without any electricity generation (see Section 2.1). Given the potential competition between the CHP plant products and CO_2 capture, three strategies on how to operate CHP plants with CCS, and their impact on DH system operation, are compared:

- **All CHPs-max el**: All CHP plants present in each network are equipped with CCS units. The CHP steam cycles are operated for maximum electricity production.
- **All CHPs-max heat**: All CHP plants present in each network are equipped with CCS units, but the steam cycles are operated for maximum heat production.
- **Base load CHPs-max el**: For each of the 78 networks, only the first (base load) CHP plant in the running order is equipped with CCS and operated for maximum electricity production.

The carbon capture plants are assumed to be in operation at all hours when the respective CHP plants are running, with 90% capture of CO_2 in the flue gas flow. For each operational strategy, the total annual change in electricity and heat production from the CHP plants is compared to operation without CCS, as well as the change in CHP plant fuel use, i.e. plant utilization. The total annual CO_2 emissions captured for each strategy are calculated and aggregated on a national level.

3. Results and discussion

3.1. CHP steam cycles with CCS – Impact on plant performance

Figure 3 shows the percentage of nominal heat and power generation that is retained when CCS is installed, for different intervals of steam cycle power-to-heat ratios (alpha values) and operational modes; i.e. maximization of electricity or heat production. Each bar represents the average generation retained for CHP plants with power-to-heat ratios in the specific interval. The results pertain to operation at boiler full load, and the thermal load of the boiler is kept constant for operation with and without carbon capture. A general result is that maximizing heat production obviously maintains most of the nominal steam cycle production (since exergy loss is not valued) whereas electricity is more sensitive to the additional heat demand required for powering the capture unit.

For the maximum electricity-mode, the relative reduction in heat generation (middle bars) increases with alpha value, while the opposite trend is seen for electricity generation (left bars), where a low alpha value results in a larger reduction in power output. The variation in performance with alpha value indicates that the product that dominates the steam cycle output without carbon capture, i.e. heat in the case of low power-to-heat ratios; will be the product with the highest retention when integrating CCS. Close to 70% of heat production is retained for low alpha values in the interval 0.1-0.2, reaching as low as 45% for alpha values above 0.4. The average electricity generation that can be retained is in the range 55-80% depending on power-to-heat ratio.

When retention of heat production is prioritized, a linear trend between alpha value and heat retention is observed, where the average heat retention increases from 70% to 100% when alpha increases from 0.1 to 0.6. Thus, it might be possible for plants with a high steam cycle alpha value to retain most of the district heating delivery when CCS is installed, but obviously at the expense of zero electricity generation, as the steam turbine is completely bypassed. In other words, the CCS reboiler heat demand is about the same as the electric capacity for steam cycles with high alpha values. However, unless there is a very high economic (and societal) value of negative emissions and access to other renewable electricity at a corresponding cost, such a change in operation is hardly economically sustainable.

For steam cycles with alpha values in the range 0.1-0.2, the retention of heat production is approximately the same, regardless of whether heat or electricity generation is maximized, due to the already low reference power output.

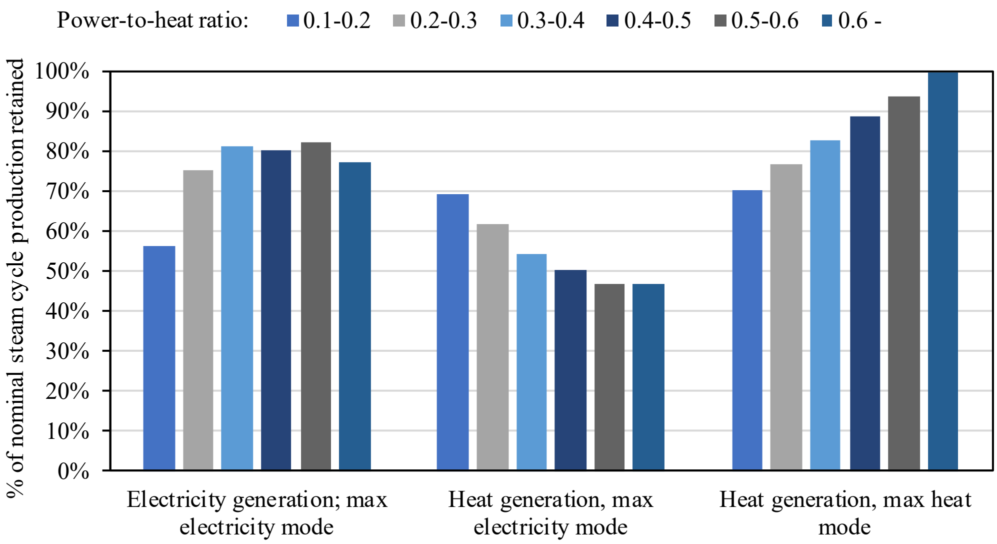

Figure 3. Impact on CHP steam cycle heat and electricity production of carbon capture integration for different intervals of steam cycle power-to-heat ratios, for 90% CO_2 capture at full load when the steam cycle is operated for maximum production of electricity (left and middle bars) or heat (right bars). The electricity generation is zero when heat production is maximized.

3.2. CHP plants with CCS – Impact on district heating system dispatch

Figure 4 exemplifies the impact on DH system operation of the City of Västerås when carbon capture units are installed at all CHP plants in the network and steam cycles are operated for maximum electricity production (All CHPs-max el case). Fig. 4a shows the modeled network operation for a reference case without carbon capture, and Fig. 4b presents the unit commitment with CCS integration.

With CCS and the All CHPs-max el strategy, the district heating production from the three CHP plants is reduced (see Fig. 3), which propagates to the DH system level: the total heat production capacity of CHP units in the system is reduced from around 400 MW to 250 MW, leading to an increased utilization of peak units or other heat generation technologies (denoted "Peak" in Fig. 4). On the other hand, the reduced CHP plant heat output also means that the utilization of the CHP plants increases, see for instance the increased use of CHP3 (yellow) in Fig 4b. This increases the fuel use of the CHP plants, but also has a positive feedback effect that presents opportunities to increase the amount of CO_2 captured in the system. Seasonal heat storages could be considered to let CHP units with CCS operate during periods with low heat demand and further increase the CO_2 capture at CHP plants; while reducing the need for peak heat generation at high-demand periods.

For the All CHPs-max heat strategy, with maximum heat production from steam cycles, the impact on CHP heat deliveries to the system is obviously less pronounced given the high retention of heat production (Fig. 3), and in some networks barely affected at all (not shown). The Base load CHPs-max el strategy only affects the heat delivery of the first CHP plant in the running order; the subsequent impact on the dispatch of other CHP plants in the network will, thus, be dependent on the alpha value of the base load plant and the relative size of this plant compared to the system heat demand. For small base load plants, the impact on DH system dispatch in the Base load CHPs-max el case is low.

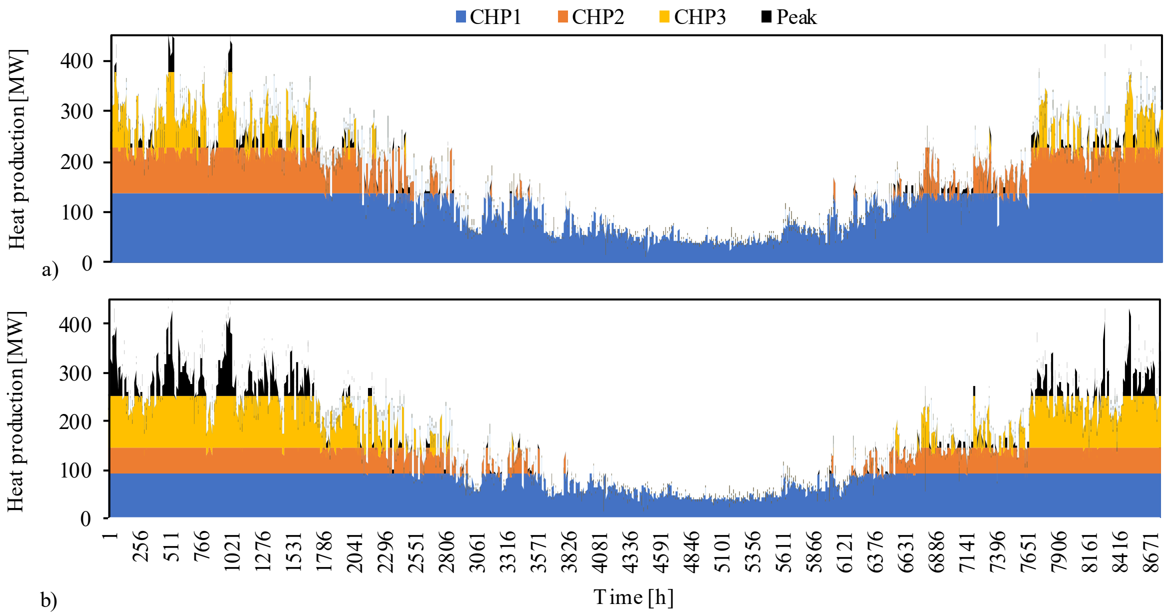

Figure 4. Modeled hourly unit commitment of CHP plants for one year in the DH system of Västerås. a) represents a reference case without carbon capture. b) shows the impact on CHP heat deliveries when installing CCS at the three CHP plants and operating the steam cycles for maximum electricity generation.

3.3. National potential for CO_2 capture at CHP plants

The impact of carbon capture implementation on DH system operation is summed for all the 78 local networks, for the three CCS operational strategies, and compared to a reference case without CCS. Table 2 presents the resulting total CO_2 captured and the corresponding impact on heat and power generation and CHP plant fuel use. The "Installed potential" represents the maximum theoretical potential for CO_2 capture when all existing Swedish CHP plants capture 90% of their CO_2 emissions for 8760 hours of full load operation, i.e. providing an upper limit but obviously hardly realistic; whereas the "Operational potential" refers to the total modeled DH system carbon capture potential for the three CCS operational strategies. The "CHPs > 150 kton/year" case is the total modeled CO_2 captured from CHP plants that capture 150 kton or more per year. Out of the 110 CHP plants studied, 45 plants have a modeled CO_2 capture of at least 150 kton/year.

In the theoretical "Installed potential" case, the CO_2 captured from all Swedish waste or biomass-fired CHP plants would add up to 25.2 Mton/year, including 21.7 Mton negative emissions. However, when considering the modeled DH system unit commitment of CHP plants, the carbon capture potential decreases. Out of the three CCS operational strategies, the All CHPs-max el case achieves the highest CO_2 capture (18.1 Mton/year) followed by the All CHPs-max heat case (15.0 Mton/year). The amount of CO_2 captured is higher in the All CHPs-max el case than the All CHPs-max heat case, due to the increased utilization of CHP plants (Δfuel use) in the All CHPs-max el case, which works in synergy with increased CO_2 capture. The Base load CHPs-max el CCS operational strategy results in 11.3 Mton/year of reduced CO_2 emissions.

The amount of fossil CO_2 captured is more or less independent of operational strategy: between 2.5 and 2.8 Mton/year in terms of "Operational potential". This can be explained by similarities in the operation of waste-fired CHP plants, that are modeled to operate as base load in DH systems; thus, yielding comparable capture of emissions from waste-incineration in all strategies.

As the estimated potential of carbon capture is narrowed down to only include CHP plants that capture more than 150 kton/year (the "CHPs > 150 kton/year" case), the total CO_2 capture is reduced by around 4.5 Mton/year compared to the "Operational potential", but a significant amount of negative emissions can still be achieved; the highest number being 11.5 Mton/year for the All CHPs-max el strategy. Thus, limiting the installation of CCS units to the 45 large-emitting CHP plants-only could still yield up to 75% of the total operational potential for carbon capture estimated when considering CCS implementation in all 110 existing CHP plants.

Table 2. National potential for annual CO_2 capture in Swedish CHP plants, comparing modeled installed and operational potentials; and the corresponding impact on aggregated annual heat and power generation and fuel use of CHP plants, compared to a reference case without carbon capture. Entries for the total, modeled, carbon capture from CHP plants that capture 150 kton/year of CO_2 or more are also given.

	Total CO_2 captured [Mton/year]	Fossil CO_2 captured [Mton/year]	Biogenic CO_2 captured (negative emissions) [Mton/year]	ΔPower generation [TWh]	ΔHeat generation [TWh]	ΔCHP fuel use [TWh]
Installed potential	25.2	3.6	21.7	-	-	-
Operational potential						
All CHPs-max el	18.1	2.8	15.3	0.1	-7.1	10.7
All CHPs-max heat	15.0	2.7	12.3	-12.3	-0.6	0.8
Base load CHPs-max el	11.3	2.5	8.8	0.5	-3.4	7.7
CHPs >150 kton/year						
All CHPs-max el	13.7	2.2	11.5	-	-	-
All CHPs-max heat	10.6	2.1	8.5	-	-	-
Base load CHPs-max el	7.2	1.9	5.3	-	-	-

3.4. Competition and synergies between carbon capture and CHP plant electricity and heat generation

Integrating carbon capture at CHP plants in DH systems impacts the energy system balances in terms of CHP plant electricity production, heat production and fuel use (Table 2), depending on the CCS operational strategy. Considering the "Operational potential", the All CHPs-max el and Base load CHPs-max el strategies lead to increased fuel use of 10.7 TWh and 7.7 TWh, respectively, but with a corresponding decrease in heat generation of 7.1 and 3.4 TWh, while the total electricity production is more or less unaffected. The All CHPs-max heat strategy does, on the other hand, result in a significantly reduced electricity output (12.3 TWh), while keeping the heat production and fuel use at largely unchanged levels. To put numbers in perspective, the estimated current total heat demand in the 78 networks studied is 39.4 TWh. Integrating CCS according to the three strategies would mean that the annual heat delivery from CHP plants is reduced by 2-18%, which would need to be covered by other units, although not necessarily CHP or thermal plants.

The total installed electric capacity of the 110 CHP plants is approximately 2.4 GW, which would be reduced by 0.5 GW if installing CCS at all CHP plants. An electric capacity of 0.5 GW corresponds to 2% of the peak electricity demand in Sweden (25.2 GW in 2019). At a national level, 2% of peak electricity generation might be feasible to replace, especially considering the strong expansion of wind power in Sweden. However, from a local (city) perspective, local electricity generation from CHP plants is an important contribution to the city electricity supply, and a reduced power output when installing CCS might be non-negligible. A number of Swedish cities are facing problems with limited electricity import capacity in transmission lines while the city electricity demand grows [17].

One synergy between carbon capture and CHP plant operation is identified. The reduced heat generation from plants retrofitted with CCS can lead to an increased number of full load hours for CHP plants that might otherwise be out of operation, or operated at part load in relation to the district heating demand (Fig. 4). If the CHP plants that get a higher utilization are equipped with CCS, the potential amount of carbon captured at the plants increases. Increased utilization of CCS-CHP units could also be positive in the sense that it provides an opportunity for plants to recover investment costs at a higher rate, and existing assets can be put to better use. In line with this, Mac Dowell and Fajardy [18] argue that, under a national-scale CO_2 removal target, it could be preferable to operate BECCS plants as baseload to maximize plant utilization and capture of negative emissions, and dispatching electricity on an as-needed basis.

There will obviously be a limit on the CCS-driven utilization of CHP plants, which will be determined by the level of incentive for negative emissions. It is, however, not obvious where the limit for such incentive is. Afterall, renewable (biomass-derived) heat, and even more so electricity, are valuable products and are likely to be prioritized, while in the longer run there should be no CO_2 emissions to the atmosphere; i.e. beyond 2050 it is likely that all stacks must be equipped with CO_2 capture if complying with the Paris Agreement (no fossil fuel emissions as well as net-negative emissions).

Two main CCS operational strategies are compared in this study, that prioritize electricity and heat generation, respectively. However, the most favorable strategy might be a flexible combination of these options, depending on, e.g., electricity price, heat demand, fuel prices and to what extent economic compensation is granted for negative emissions; and how price levels and demands vary over time. The value of the competing outputs (electricity/heat/negative emissions) must be compared to decide what the main purpose of the CHP plant should be, and to guide decisions regarding investments and plant operation.

4. Further work

Reduced district heating deliveries might be a factor that speaks against installation of CCS in CHP plants. Therefore, possible ways to increase the heat retention should be assessed. Potential options include heat recovery from the carbon capture plant [19], or partial capture of CO_2 [20]. Heat recovery from the CCS unit was discussed by Tsupari et al. [7], who found that for CHP plants that do not already have a flue gas condenser installed, the heat recovery potential from the CCS installment is large. However, approximately 80% of the existing Swedish CHP plants are already equipped with flue gas condensers and might therefore have a smaller potential for heat recovery. Another way to reduce the energy penalty of carbon capture could be to consider other CCS technologies than post-combustion absorption-based capture. For example, chemical-looping combustion with CCS has comparatively small energy penalties [21], but has a lower technology readiness level than absorption-based CCS and requires that the boiler is of circulating fluidized bed-type, which will imply more extensive repowering of the plant than a post-combustion installation, or a new plant to be implemented.

Although this study has found a significant potential for negative emissions from BECCS applied to CHP plants, the economic incentives and cost-effectiveness of such installations need to be investigated and compared to other alternatives on how to obtain negative emissions. In addition to biomass and waste-fired CHP plants, biogenic CO_2 emissions are abundant in the Swedish pulp and paper industry [22], which could also be considered for BECCS installations. Industries might have favorable site conditions for BECCS, in terms of large CO_2 flows that have economy-of-scale benefits, potential availability of excess heat to drive the capture process, and often coastal locations that facilitate CO_2 transport by ship. Combined heat and power plants are obviously geographically dispersed and might therefore have less favorable infrastructure conditions for CO_2 transportation, but if such infrastructure can be shared with industrial facilities, installations could become more cost-effective. It could therefore be of interest to expand the boundaries of the study to also include industrial facilities, to get a holistic perspective on pathways to achieve negative emissions through BECCS in Sweden.

5. Conclusion

This work estimates the potential for negative CO_2 emissions from absorption-based carbon capture applied to 110 existing Swedish biomass or waste-fired combined heat and power (CHP) plants, operating in 78 local district heating systems. Based on a unit commitment model of DH system operation in which CHP plants are equipped with CCS, the results show that the total potential for negative emissions could be up to 15.3 Mton annually, depending on CHP plant operating strategies; which can be compared to the recently proposed national targets of BECCS of 1.8 Mt/year by Year 2030 and 3-10 Mt/year by Year 2045, and a total target of 10.7 Mton/year of negative emissions by Year 2045. Furthermore, even if CCS is retrofitted only to plants that might capture at least 150 kton/year of CO_2, the potential for negative emissions is still high; up to 11.5 Mton/year.

Process simulation results indicate that CCS integration at CHP plants will reduce the steam cycle electricity and heat generation. Depending on the steam cycle power-to-heat ratio, 45-70% of district heat generation is retained when operating the CCS plant, but the reduction can be moderated at the expense of lowered electricity generation. Operating the steam cycle without electricity generation obviously defeats the purpose of having a steam turbine, but could be viable at times when the electricity price is low. In the district heating system context, the potential reduction of heat delivery from CHP plants with carbon capture means that the utilization of CHP plants might increase, with potentially increased CO_2 capture from plants equipped with CCS as a positive feedback effect. However, district heating system impacts of CCS integration, such as reduced local electric capacity of CHP plants and increased use of peak heat generation technologies must be evaluated, as well as the cost-effectiveness of CCS installations in CHP plants compared to other sources of negative emissions.

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