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Integration of CCS in Combined Heat and Power Plants in a City Energy System

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Abstract

Carbon dioxide removal (CDR) is expected to play an important role in climate change mitigation. Bio-energy carbon capture and storage (BECCS) is a form of CDR discussed in the Swedish district heating sector where large-scale point sources of biogenic CO_2 emissions are found. This work investigates the retrofit of CO_2 capture processes to combined heat and power (CHP) plants in a city energy system context, to examine the impact on CHP plant energy output and city energy balances, and the cost-optimal way to integrate and operate the capture processes. An energy system optimization model is applied to a case study of the city Västerås, Sweden, with scenarios involving the retrofit to two existing CHP plants in the city of either a heat-driven (MEA) or electricity-driven (HPC) carbon capture process. The results show that it is possible to retrofit the CHP plants with either of these options without significantly impacting the district heating system operation or the marginal costs of electricity and district heating. The MEA process mainly causes a reduction in district heating output (up to 30% decrease on an annual basis), which can be partly offset with heat recovery from the capture unit, or increased utilization of the CHP plants (if possible). The electrified HPC process does not impact the CHP plant steam cycle, but implies increased import of electricity to the city (up to 44% increase) compared to a reference scenario.

Keywords: Carbon capture and storage; District heating; Combined heat and power; Heat integration; City energy system

Nomenclature

BECCS	Bio-energy carbon capture and storage	TES	Thermal energy storage
CCS	Carbon capture and storage		
CDR	Carbon dioxide removal	*C*	Cost
CHP	Combined heat and power	*D*	Demand
COP	Coefficient of performance	*E*	Annual CO_2 emissions
DH	District heating	*i*	Technology in the set of technologies, I
HP	Heat pump	*k*	CCS process in the set of processes, K
HPC	Hot potassium carbonate	*m*	Mass flow of CO_2 captured
MEA	Monoethanolamine	*p*	Electricity
PtH	Power-to-heat	*q*	Thermal energy (heat, fuel, cooling)

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s	Capacity of investment	*comp*	Compression
t	Timestep in the set of timesteps, T	*cool*	Cooling
TT	Length of timestep	*cycl*	Cycling
w	Imported electricity	*dch*	Discharge
W	Limit on electricity import	*el*	Electricity
z	Stored energy	*inv*	Investment
		recov	Recovered heat
Subscripts and superscripts		*run*	Running
bat	Battery	*SC*	Steam cycle
CC	Carbon capture	*store*	Storage
ch	Charge		

1. Introduction

Carbon dioxide removal (CDR) is expected to play an important role in reaching climate change mitigation targets to limit the amount of CO_2 in the atmosphere. The IPCC [1] include CDR in several of their scenarios to limit global warming to 1.5°C. Bio-energy carbon capture and storage (BECCS) is a technology with high maturity [2] that can be applied to biomass-combusting plants to achieve CDR. In Sweden, there is a proposed target [3] that BECCS should contribute with 3-10 MtCO_2 of CDR annually by year 2045 to achieve net-zero and thereafter net-negative emissions. Rapid deployment of BECCS is needed to be able to scale up CDR to the levels required to meet climate targets [4] and business models and/or policy support are needed to incentivize CDR installations [5]. In response to this, The Swedish Energy Agency [6] has announced that a reversed auctioning system will be put in place by year 2023 to help financing CCS projects in Sweden that contribute to CDR.

BECCS can be applied to large-scale point sources of biogenic CO_2 emissions, that are found in the Swedish district heating sector and pulp and paper industry. Several Swedish municipal district heating companies have expressed their interest in retrofitting some of their combined heat and power (CHP) plants with carbon capture systems [7] and a number of feasibility studies have been conducted to investigate site-specific conditions for BECCS and to estimate costs [8]. The utility company Stockholm Exergi has received EU funding to support the construction of a full-scale BECCS unit at a biomass-fired CHP plant to remove 800 ktCO_2 annually. If applied to all existing CHP plants in Sweden, the potential for BECCS amounts to at least 10 MtCO_2 removed per year that might be captured to a maximum cost of 100 €/tCO_2 [9], and an additional 15 Mt/year of biogenic CO_2 could be available for capture in the pulp and paper sector [10].

Although the interest for BECCS is large in the Swedish district heating sector, few studies have examined how BECCS could fit in with and impact the supply of district heating. It is established in the literature that absorption-based carbon capture applied to flue gases has an energy penalty that impacts the overall energy performance and heat delivery of CHP plants [9,11–13], although the magnitude of this impact will depend on (i) the type of capture process, and (ii) the heat integration of the capture process [9,14]. Levihn et al. [15] discuss the operation of the Stockholm district heating system with the implementation of BECCS, while other studies focus mainly on how BECCS technologies interact with the electricity system at large or the competitiveness of BECCS compared to direct air capture of CO_2 [16–20].

This work compares the retrofit of two absorption-based carbon capture processes (one heat-driven, MEA, and one electricity-driven, HPC) to a waste-fired and a biomass (recycled wood) CHP plant in a city energy system context, considering the impact of the carbon capture process on CHP plant energy output and the city energy balance at large. Special attention is given to the possibility to recover low-grade heat from the capture process, and the heat integration of the capture process in the district heating system. An energy system optimization model is applied to study the optimal dispatch of the CHP plants with carbon capture, and the operation of the carbon capture process itself. To the best of our knowledge, this is the first energy system optimization model presented that considers in detail a city-level energy system with CDR applied to CHP plants, and the integration of these in the city energy system. Thus, the main novelty of the work lies in the modeling of carbon capture processes and heat recovery related constraints in a city energy system context.

2. Method

The work applies a cost-minimizing energy system optimization model to study the impact of retrofitting CHP plants with BECCS in a city-level energy system context, including the district heating and electricity sectors. Two absorption-based carbon capture processes are compared – the monoethanolamine (MEA) process that is commonly used for benchmarking, and the hot potassium carbonate (HPC) process that will be installed at a CHP plant in Stockholm. The capture processes differ in energy performances and impact on the CHP plant electricity and district heating generation, as detailed in Section 2.1. The optimization model is described in Section 2.2. Section 2.3 presents the case study and the scenarios examined.

2.1. Description of carbon capture processes

Both the MEA and HPC processes are based on absorption of CO_2 from flue gases. The CO_2 is absorbed by a solvent (MEA or HPC) in the absorber column, from which CO_2-lean flue gas exits. The solvent is regenerated (i.e., CO_2 is desorbed) in the stripper column. The desorbed CO_2 leaves the stripper column with high purity and is sent to compression and liquefaction processes prior to transport to a permanent storage site.

In the MEA process, the absorption/desorption is driven by temperature differences (temperature-swing), where the absorption is carried out at low temperature, and heat is added for the desorption step (heat requirement). Condensing steam at around 120°C is typically used to supply the heat for solvent regeneration. In contrast, the HPC process uses a pressure-swing to drive the absorption/desorption. The absorption is carried out at elevated pressure, and the desorption at a lower pressure level. Thus, the flue gas needs to be compressed for the absorption, which implies an electricity demand. Heat is also needed for solvent regeneration in the HPC process, but in slightly lower quantities than the MEA process. An internal heat recuperation system with flash boxes can be applied to supply the heat without using external steam [21].

The capture processes have cooling demands at temperature levels that could be recovered for district heating generation, i.e., above 60°C, as well as cooling demands at temperatures lower than 60°C, that could be recovered by heat pumps. If not used for district heating, the low-grade heat must be cooled from the process.

2.2. City energy system optimization model

The city energy system model was first presented by Heinisch et al. [22] and has been extended with equations that enable flexible operation of CHP plants [23]. In the present work, equations for the implementation of carbon capture processes at CHP plants are added. The objective of the model is to minimize the total system cost of supplying demands for electricity and district heating, including investment and operating costs (Eq. 1-3), while complying with targets on CO_2 capture from CHP plants (Eq. 4). Transmission between the regional electricity grid and the city is included, but with a limit on grid connection capacity, Eq. 5. For a description of terms, please refer to the nomenclature list. The available investment options and cost data can be found in [23]. The model is run for one year with a time resolution of three hours.

$$MIN: C^{tot} = \sum_{i\in I\setminus I_{store}}\left(C_i^{inv}s_i + TT\sum_{t\in T}\left(C_i^{run}p_{i,t} + C_i^{run}q_{i,t} + C_{i,t}^{cycl}\right)\right) + \sum_{i\in I_{store}} C_i^{inv}s_i + \sum_{t\in T}\left(C_t^{el}w_t + C^{cool}q_{cool,t}\right) + C_{CC}^{inv}s_{CC} \quad (1)$$

$$D_t^P + z_{bat,t}^{ch} + \sum_{i\in I_{PtH}} p_{i,t} + \omega\sum_{k\in K}\sum_{i\in I_{CHP}} m_{CO2,i,k,t} + p_{HPC,t} \le \sum_{i\in I_{El}} p_{i,t} + w_t + z_{bat,t}^{dch}\ ,\ \forall t\in T \quad (2)$$

$$D_t^{DH} + \sum_{i\in I_{TES}} z_{i,t}^{ch} \le \sum_{i\in I_{Heat}} q_{i,t} + \sum_{i\in I_{TES}} z_{i,t}^{dch} + q_{recov,t}\ ,\ \forall t\in T \quad (3)$$

$$\sum_{k\in K}\sum_{t\in T} m_{CO2,i,k,t} \le 0.9E_i\ ,\ \forall i\in I_{CHP} \quad (4)$$

$$w_t \le W\ ,\ \forall t\in T \quad (5)$$

The carbon capture processes are considered as possible retrofits to CHP plants. The HPC process is assumed to be fully driven by electricity ($p_{HPC,t}$) with an electricity consumption proportional to the amount of CO_2 captured ($m_{CO2,i,k,t}$), Eq. 6. The MEA process is assumed to be driven by heat, through the condensation of steam extracted from the CHP steam cycle. The MEA process is modeled as described in Equations 7 – 11. The steam extraction causes a reduction in CHP steam turbine electricity generation (Eq. 7) that also incurs a penalty on district heating delivery (Eq. 8). The electricity reduction is calculated assuming that 10% of the nominal electricity generation capacity is lost. A share of the energy used to drive the MEA and HPC capture and CO_2 conditioning processes can be recovered as low-grade heat of sufficient temperature to be used for district heating [13], as stated in Eq. 9. The share of low-grade heat that cannot be recovered for district heating directly through heat exchanging must either be cooled from the process (Eq. 10) or recovered for district heating generation with a heat pump (Eq. 11, coefficient of performance (COP) = 3). A cooling cost of 5 €/MWh [24] is included in Eq. 1. The mass flow of CO_2 captured is limited by the fuel load, the design capture rate of the CCS unit (assumed to be 90% of CO_2 emissions at full load) and the carbon content of the fuel, σ_C, Eq. 12. The actual capture rate during operation is optimized by the model and can vary between 0 – 90% of flue gas emissions. The parameters in Equations 6-12 are given in Table 1.

$$p_{HPC,t} = \lambda_{HPC} \sum_{i \in I_{CHP}} m_{CO2,i,HPC,t} \quad ,\forall t \in T \tag{6}$$

$$p_{i,t} = p_{SC,i,t} - \phi_i m_{CO2,i,MEA,t} \quad ,\forall t \in T, i \in I_{CHP} \tag{7}$$

$$q_{i,t} = q_{SC,i,t} - m_{CO2,i,MEA,t}(\lambda_{MEA} - \phi_i) \quad ,\forall t \in T, i \in I_{CHP} \tag{8}$$

$$q_{recov,t} \leq \sum_{i \in I_{CHP}} \sum_{k \in K} \lambda_k \gamma_k \theta_k m_{CO2,i,k,t} \quad ,\forall t \in T \tag{9}$$

$$q_{cool,t} = \sum_{i \in I_{CHP}} \sum_{k \in K} \lambda_k \gamma_k m_{CO2,i,k,t} - q_{recov,t} - q_{HP,CC,t} \frac{COP_{HP}-1}{COP_{HP}} \quad ,\forall t \in T \tag{10}$$

$$q_{HP,CC,t} \leq \sum_{i \in I_{CHP}} \sum_{k \in K} m_{CO2,i,k,t} \lambda_k (1 - \gamma_k \theta_k) \frac{COP_{HP}}{COP_{HP} - 1} \quad ,\forall t \in T \tag{11}$$

$$\sum_{k \in K} m_{CO2,i,k,t} \leq 0.9 q_{fuel,i,t} \sigma_{C,i} \quad ,\forall t \in T, i \in I_{CHP} \tag{12}$$

In addition to the energy demand for carbon capture, the electricity consumption associated with CO_2 compression and liquefaction (ω) is included in the modeling (Eq. 2). Costs for CO_2 transport and storage are not included since these are assumed to be the same for both capture options, and the analysis of these costs is outside the scope of this work. CO_2 capture and conditioning plant investment costs are included in the form of a linear term in Eq. 1. The biogenic share of waste is assumed to be 52% [25].

Table 1. Parameters describing the carbon capture processes.

Parameter	MEA	HPC	Unit	Reference
Steam turbine electricity reduction, ϕ	0.31-0.37	-	$MJ_{el}/kgCO_2$	
Electricity for compression and liquefaction, ω	0.1	0.1	MWh_{el}/t_{CO2}	[13]
CCS energy demand, λ	3.6 (heat)	0.85 (power)	$MJ/kgCO_2$	[26,27]
Cooling demand factor[a], γ	1.1	1.4	MW_{cool}/MW_{λ}	[28]
Heat recovery factor,	0.64	0.67	[-]	[13,28]
	Biomass	**Waste**		
CO_2 emissions, σ_C	0.405	0.33	tCO_2/MWh_{fuel}	

[a] Cooling demand from CO_2 capture, compression and liquefaction processes, relative to capture process energy demand.

2.3. Case study and scenarios

The model is applied to a case study of the city Västerås in Southern Sweden (NordPool electricity price area SE3). A brownfield approach is chosen, in which current capacities of district heating production units are included in the system, but it is possible to replace existing capacity with new investments. It is unlikely that Swedish district heating companies will invest in fossil-based capacity (the exception being waste fuels of partly fossil origin), therefore, fossil-fueled technologies are excluded from the investment options. Table 2 gives the current plant portfolio of the district heating system in Västerås, which is largely CHP-dominated. A long-term heat storage (up to 1 month storage capacity) is under construction in the city but is not included as existing capacity in the case study.

Hourly demand profiles for district heating and electricity are adapted from data from the city of Gothenburg, Sweden, and scaled to fit the annual demand data in Table 2. The shape of the demand profiles can be seen in Ref [23].

Table 2. District heating system plant portfolios of Västerås and annual electricity and district heating demand. Based on [29]. CHP heat generation capacity is exclusive of flue gas condenser heat.

Plant type	Capacity	Unit
Waste CHP	48 / 98	MW_{el} / MW_{heat}
Recycled wood CHP	53 / 92	MW_{el} / MW_{heat}
Wood chip CHP	56 / 118	MW_{el} / MW_{heat}
Heat pump	27[a]	MW_{heat}
Tank thermal energy storage	2,100	MWh_{heat}
Annual electricity demand	1,248	GWh_{el}
Annual district heating demand	1,695	GWh_{heat}

[a]COP = 3.5

The model is run for six scenarios, summarized in Table 3. Firstly, two electricity import price profiles are compared, based on historical price data in the SE3 area for year 2019 and the period July 2021 – June 2022. The electricity price profiles are plotted in Figure 1. Year 2019 had a relatively flat electricity price profile with an average value of 38 €/MWh, while the 2021/2022 profile is significantly more volatile and with higher price levels (on average 95 €/MWh). We study ambitious scenarios in which either the MEA or the HPC process is installed at both the waste-fired and the recycled wood CHP plants. For the plants that are retrofitted with BECCS, annual CO_2 capture targets for each plant are derived from reference runs without carbon capture, and set to 90% of plant CO_2 emissions in the reference run (i.e., corresponding to regular operation with a 90% carbon capture rate). The fuel costs in all scenarios are: waste: 1 €/MWh, recycled wood: 10 €/MWh, wood chips: 20 €/MWh. Biomass fuel costs are based on current price levels [30].

Table 3. Scenarios studied. CO_2 capture targets are based on the 2019-Ref scenario.

Scenario	Electricity price profile	Carbon capture process	CHPs with BECCS	Carbon capture target [ktCO_2/year]
2019-Ref	2019	None	None	0
2019-MEA	2019	MEA	Waste CHP + Recyc. wood CHP	518 + 282 (waste CHP + wood CHP)
2019-HPC	2019	HPC	Waste CHP + Recyc. wood CHP	518 + 282 (waste CHP + wood CHP)
2021/22-Ref	2021/22	None	None	0
2021/22-MEA	2021/22	MEA	Waste CHP + Recyc. wood CHP	518 + 282 (waste CHP + wood CHP)
2021/22-HPC	2021/22	HPC	Waste CHP + Recyc. wood CHP	518 + 282 (waste CHP + wood CHP)

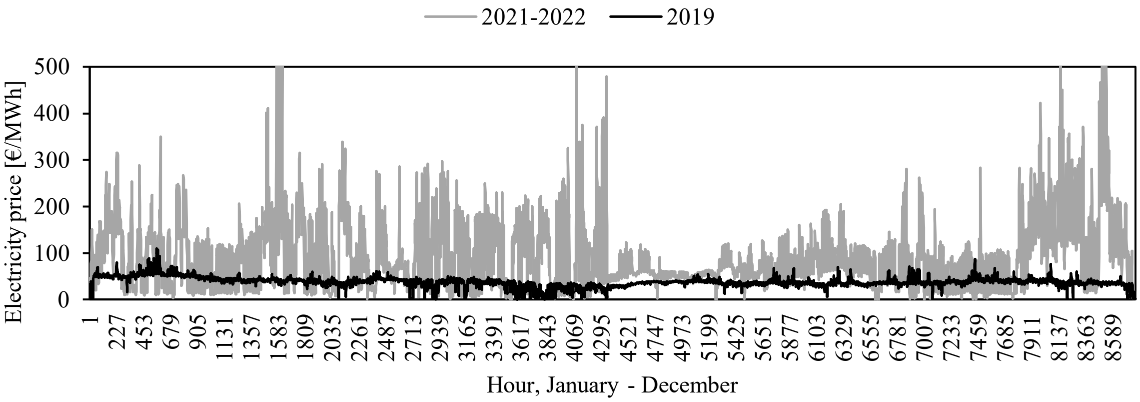

Figure 1. Import electricity price profiles, based on price data for the SE3 area, for year 2019 and the period July 2021 – June 2022.

3. Results and discussion

3.1. Impact of carbon capture on CHP energy use and output

The MEA and HPC carbon capture processes have different energy consumption requirements that impact the CHP energy balance. Figure 2 plots the modeled annual energy distributions of the waste-fired and recycled wood CHP plants in the scenarios studied. Compared to the reference scenario without carbon capture, retrofitting the MEA process causes a 30% reduction in district heating generation from the waste-fired steam cycle, while the electricity supplied is only slightly reduced (10% of reference electricity output). The electrified HPC process does not directly impact the steam cycle, but if the electricity consumption is provided by the steam turbine generator, the HPC process causes a 25% reduction in annual electricity supply for the waste-fired plant, compared to the reference scenario.

The waste-fired plant is operated as baseload in the district heating system, with a high number of full load hours. Thus, the carbon capture retrofit does not significantly impact the overall energy use of the waste-fired plant, considering that the capture target is set based on a high plant utilization, i.e., the plant operates close to its maximum capacity in the reference scenario. In contrast, the recycled wood CHP plant (Fig. 2b) is operated as intermediate load in the 2019-Ref scenario, setting the capture target at a moderate level (i.e., significantly lower than what can be captured if the plant is operated with maximum utilization). Thereby, the total energy use of the recycled wood CHP plant increases with the retrofit of a carbon capture process, which allows the carbon capture to be scheduled for periods with favorable energy market conditions (see Section 3.3). The annual energy output from the recycled wood plant is higher in the 2021/22 scenarios than in 2019, which is explained by the significantly higher import/export electricity prices in 2021/22 (Fig. 1) that incentivize increased electricity generation from the CHP plants.

With the increase in utilization for the recycled wood plant, the electricity supply in the MEA scenarios increases compared to the reference, and is in the HPC scenarios comparable to the reference. Thus, carbon capture retrofits do not necessarily decrease the electricity and district heating supply from intermediate load CHP plants, although the fuel use increases to cover the capture process energy demand. In absolute terms, the MEA process has a larger energy demand than the electrified HPC process, although the impact on electricity output is greater with the HPC process. However, there are alternative designs of the HPC process, involving use of steam rather than electricity, which would impact the CHP plant energy performance differently [11]. Research efforts are also made to reduce the energy consumption of the MEA process, with advanced solvents [31]. Such development of the carbon capture process would, of course, lead to a weaker impact on the CHP plant with higher retention of both electricity and district heating generation.

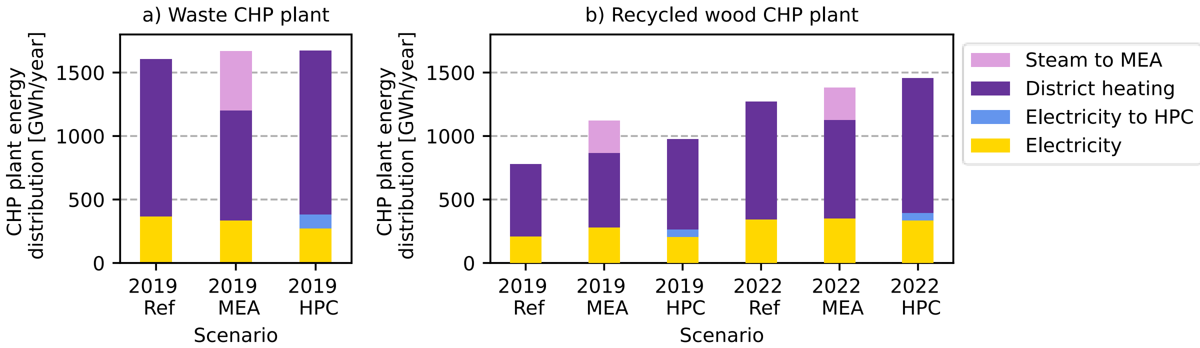

*Figure 2. Modeled annual energy distributions from **a)** the waste-fired CHP plant, and **b)** the recycled wood CHP plant, with respect to electricity and district heating generation, and the steam or electricity consumption of the carbon capture processes. For the waste-fired plant, the 2019 and 2021/22 results are similar, hence, the 2021/22 scenarios are omitted in a). The sum of the energy outputs corresponds to the total thermal energy input to the steam cycle.*

3.2. Heat integration of carbon capture processes

Figure 3 visualizes the cost-optimal share of heat recovered from the MEA and HPC processes in the modeled scenarios on an annual basis. Independent of electricity price levels, the share of heat recovered from the MEA and HPC processes equals the maximum recoverable share without applying heat pumps of 64% and 67%, respectively (Table 1). The recovered MEA process heat offsets a large share of the lost CHP district heating output (Fig. 1), which is also compensated by the increased utilization of the recovered wood CHP plant. Since the HPC process does not impact the district heating production from the steam cycle, the recovered heat from the HPC process does not compensate for any heat loss, as is the case for the MEA process, and represents a "new" heat production source in the district heating system. Depending on heat demand variations (mainly seasonal), the value of heat recovery changes over time. For instance, during summer when the heat demand is low, there is limited use for additional district heating supply from heat recovery, as the waste CHP plant can meet the heat demand on its own. Thereby, large-scale heat storage systems are needed to efficiently take advantage of larger shares of heat recovery, to be used at times with high heat demand.

Heat pumps are not applied to increase the share of recoverable heat in any scenarios. Again, increased heat output is not necessarily valuable in the studied district heating system, making a heat pump installation redundant. The cost

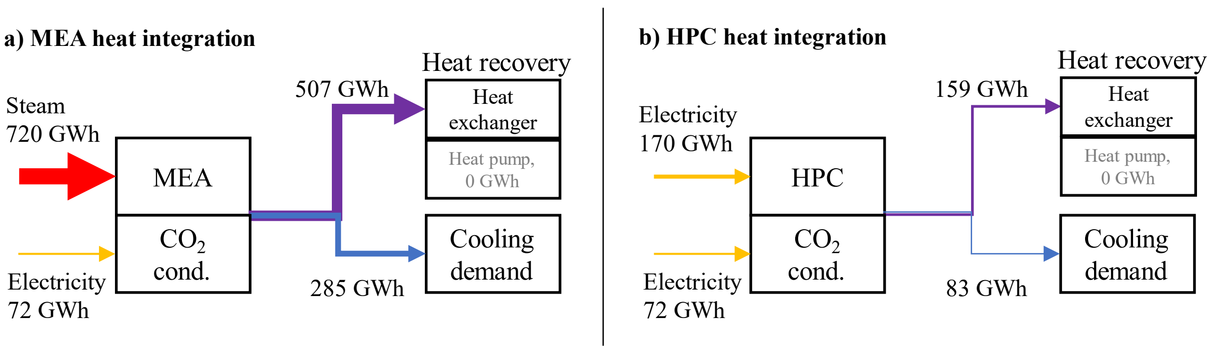

*Figure 3. Carbon capture process heat integration, with heat recovery to district heating and cooling demand. **a)** MEA process. **b)** HPC process. The numbers apply to both 2019 and 2021/22 scenarios. The same amount of CO_2 is captured from both processes (800 ktCO_2/year). The box "CO_2 cond." represents the CO_2 compression and liquefaction process.*

of cooling utility is set to 5 €/MWh in this work, which is relatively low-cost compared to the heat pump investment cost and the, occasionally high, electricity price that would be paid to operate a heat pump. However, in district heating systems with a need for increased heat production (increased demand or replacement of production units), heat pumps might be incentivized.

3.3. Operation of carbon capture processes

The operation of the capture plant is, of course, dependent on the CHP plant operation and the generation of CO_2 emissions. Figure 4 plots the load duration curves of the capture units retrofitted to the waste-fired and recycled wood CHP plants, as well as the duration of CO_2 emissions generated by the recycled wood plant. The waste-fired plant operates at full load for most of the year. Thereby, the capture plant retrofitted to the waste CHP plant (Fig. 4a) is operated at maximum capacity (55 tCO_2/h) for most of the year. The capture plant retrofitted to the recycled wood plant (Fig. 4b) has a lower utilization and operates at full capacity (58 tCO_2/h) for slightly less than half the year.

However, Figure 4c indicates that the optimal CHP-CCS plant dispatch captures significantly less CO_2 than is being generated, in particular in the 2021/22 scenarios, due to the method applied to set CO_2 capture targets (target based on 2019-Ref scenario). The high availability of generated CO_2 relative to the capture target implies that the recycled wood capture plant can be dispatched flexibly, and the carbon capture is scheduled to hours with favorable market conditions. Figure 5 shows the marginal cost of electricity and the MEA and HPC loads when retrofitted to the recycled wood CHP plant, during four weeks in February/March in the 2021/22 scenarios. It is evident that variability in the marginal cost of electricity influences the dispatch of the carbon capture units. High electricity costs cause reduced energy supply (steam or electricity) to the capture processes, and vice versa. This also means that the electricity consumption of the CO_2 compression and liquefaction processes is decreased. The same trends are visible also in the 2019 scenarios, even though the variability in marginal cost of electricity is significantly lower (Fig. 1).

A second trend relating to the capture plant load is also found in the results (not shown in Fig. 5), in that when the district heating demand peaks, the capture plant load is reduced to avoid the loss of CHP plant heat output. District heating demand peaks might also coincide with electricity price peaks, resulting in double benefits of reduced capture plant load (increased supply of electricity and district heating).

Flexible operation of the MEA carbon capture process, involving solvent storage in buffer tanks to decouple capture from solvent regeneration and CO_2 compression, was studied by Castilla et al. [32] using dynamic process simulation, who concluded that such operation of the capture plant is feasible. Using solvent buffer tanks as a strategy to increase the flexibility of coal-fired CHP plant with CCS was shown to increase plant revenue [33], and could be an interesting aspect to further develop in the city energy system model. However, the CO_2 emission market set-up might impact the incentives to operate CCS flexibly. With a market price on CO_2 emissions (fossil and/or biogenic), it might be relevant to consider flexible operation of the carbon capture unit to match temporal price variations, while a reversed auctioning system, as is underway in Sweden, might inhibit flexible operation strategies and rather benefit

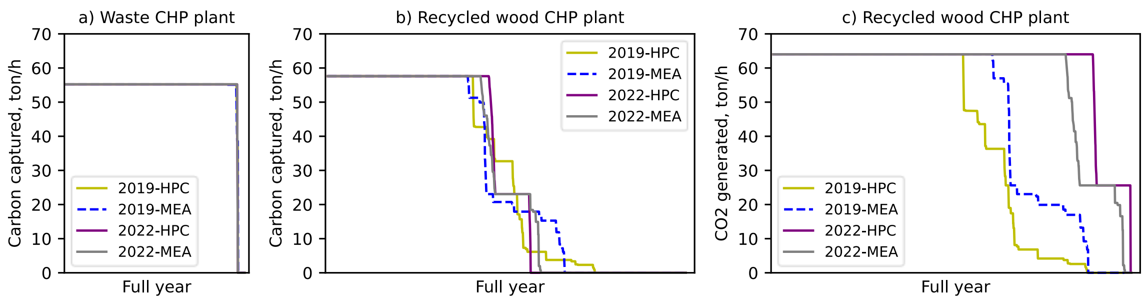

Figure 4. Carbon capture plant load duration curves for the capture processes when applied to the ***a)*** *waste-fired CHP plant, and* ***b)*** *the recycled wood CHP plant. Panel* ***c)*** *shows the duration curve of CO_2 generated by the recycled wood CHP plant. The data are arranged from highest to lowest load, i.e., not in chronological order.*

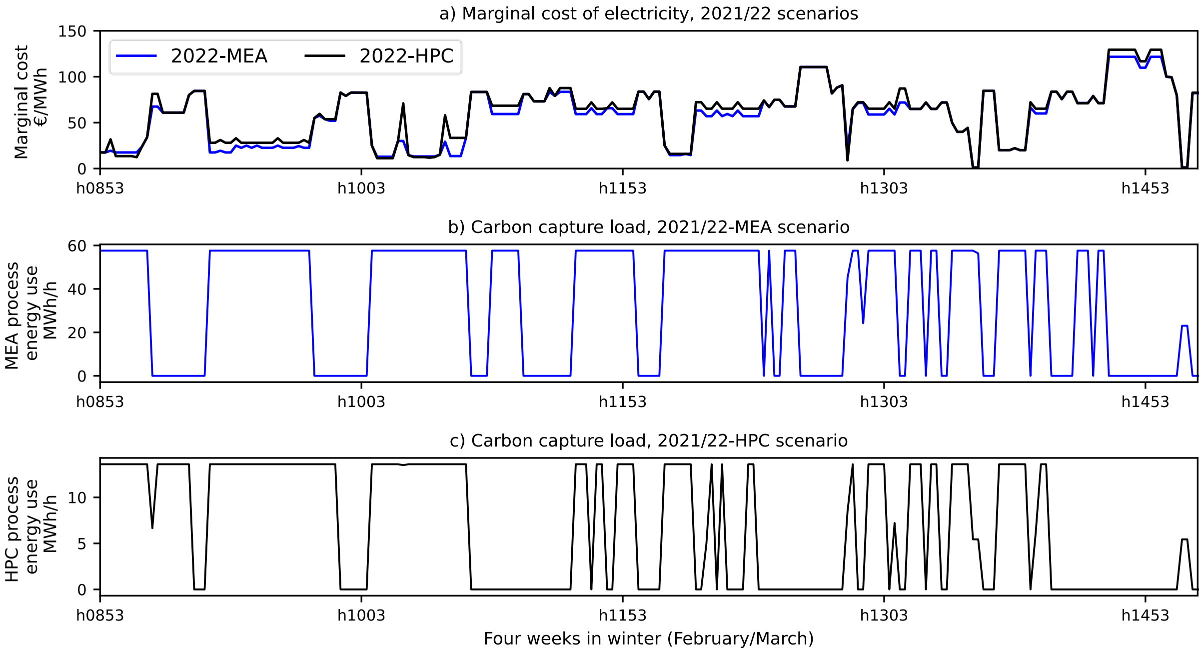

Figure 5. ***a)*** *Marginal cost of electricity in the 2021/22 scenarios with MEA and HPC.* ***b)*** *MEA process energy consumption in the 2021/22-MEA scenario, when retrofitted to the recycled wood CHP plant.* ***c)*** *HPC process energy consumption in the 2021/22-HPC scenario, when retrofitted to the recycled wood CHP plant. The figure shows four weeks in winter (February/March).*

maximization of carbon capture. Additionally, to keep the specific cost of carbon capture [€/tCO_2] as low as possible, it is beneficial to capture as much CO_2 as possible to make the capture plant investments worthwhile [9]. Thereby, the design of carbon capture targets might be adapted to suit either flexible carbon capture (target set lower than maximum capture rate) or cost-effective maximization of carbon capture.

3.4. Energy system impact of carbon capture

As shown in Figure 5, electricity price variability can impact the operation of the carbon capture plant. The retrofit of CO_2 capture to CHP plants can also affect the electricity balance in the city. In particular, the HPC process causes reduced electricity generation (Section 3.1) that, together with the electricity consumption of the CO_2 compression unit, must be compensated for. CHP plants can potentially increase their operation to supply more electricity (Fig. 2), but electricity import to the city also increases significantly. In the 2019-HPC scenario, electricity imports increase with 44% compared to the 2019-Ref scenario.

With the current electricity demand and assumed grid connection capacity (83% of peak demand), the increased import is feasible (with new investments in solar PV being cost-effective in the modeling). However, electricity demand is expected to increase as the industry and transport sectors are electrified and can cause congestion in the city if transmission capacity is not also expanded. In the case of Västerås, the grid capacity situation is strained already; industries that request grid connections above 10-15 MW might need to be turned down due to grid limitations [34]. In this context, it is important to ensure that sufficient grid connection or local electricity generation capacity is available to power carbon capture installments while also meeting the city electricity demand.

Figure 6 plots the duration curves of the marginal cost of electricity and district heating in the city for one year. The electricity cost does not differ significantly between the reference, MEA and HPC scenarios. That is, carbon capture can be expected to have a low impact on the marginal cost of electricity in the city. Figure 6b and 6c show that the marginal cost of heat is zero for many hours of the year in all scenarios, indicating that CCS does not significantly increase the marginal cost of heat supply compared to the reference scenarios for the case study in this

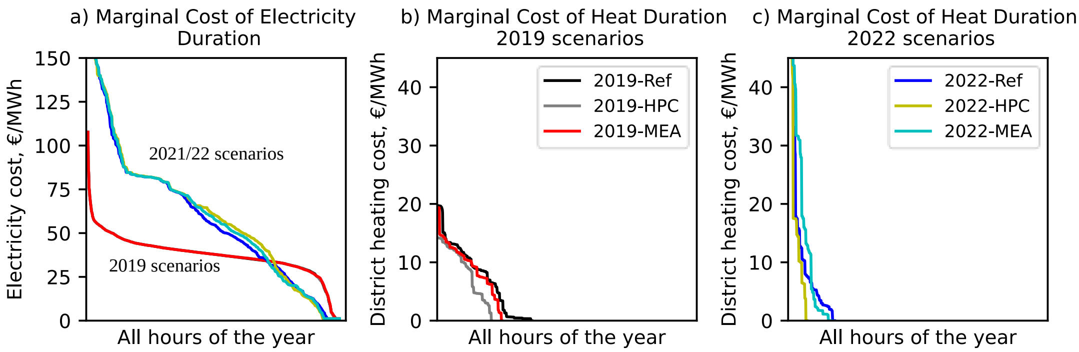

*Figure 6. Marginal cost duration curves for **a)** electricity, and **b-c)** district heating, for the scenarios studied. The x-axis covers all hours of the year, i.e., the data is not plotted in chronological order. Note that the marginal cost of electricity is essentially the same in all 2019 scenarios (only the red curve is visible).*

work. The average marginal cost of electricity differs with less than 0.1 €/MWh in the 2019 scenarios and up to 2 €/MWh in the 2021/22 scenarios.

The use of the two other heat production units in the studied district heating system (i.e., the wood chip CHP plant and the heat pump, Table 2) is affected by the retrofit of carbon capture to CHP plants. However, the wood chip CHP plant and heat pump are used sparingly in the reference scenarios (140 and 10 GWh of annual heat production, respectively, compared to the total demand of 1,695 GWh). Therefore, changes in the operation of these units have a small impact in the system as a whole. In the 2019-MEA scenario, heat supply from CHP plants with CCS decreases, and leads to larger heat production from the wood chip CHP plant and heat pump. In the HPC scenarios, wood chip CHP and heat pump operation decreases as extra heat is available to recover from the capture unit, reducing the need for additional heat production.

3.5. Considerations for carbon capture applied to waste and biofuels

In this work, the carbon in the municipal solid waste that is combusted in the waste CHP plant is assumed to be of 52% biogenic origin. Thus, only half of the CO_2 captured from the waste-fired plant can be credited as CDR, compared to the recycled wood CHP plant that only generates biogenic CO_2. However, considering the larger utilization of the waste-fired plant, over a year, the waste-fired plant captures approximately the same amount of biogenic CO_2 (242 ktCO_2/year) as the recycled wood plant capture target (254 ktCO_2/year, although the capture could be increased, see Section 3.3). Considering that the specific cost of carbon capture decreases with increased utilization of the capture plant [9], the waste-fired plant should, thereby, be able to provide a similar amount of BECCS as the recycled wood plant, but to a lower cost. However, economic incentives must be in place for both the reduction of fossil CO_2 emissions and CDR for CCS to be competitive for a waste-fired CHP plant. Business models for CDR from waste-fired plants are discussed in Ref [35].

4. Conclusion

This work investigates the cost-optimal operation of CHP plants retrofitted with a carbon capture process (heat-driven, MEA, or electricity-driven, HPC) in a city energy system, considering the electricity and district heating sectors. A novel optimization model formulation, with a detailed representation of the carbon capture processes and their heat integration possibilities, is presented and applied to a case study of the city Västerås, Sweden. Based on the results, it is concluded that both the MEA and HPC processes can be integrated in the city energy system without significant impact on the dispatch of district heating production units or the marginal costs of electricity and heat. For the MEA process, there is a loss of CHP heat production when retrofitting the capture process, which can be partly offset by heat recovery from the capture plant. The electrified HPC process does not necessarily interfere with the CHP energy output, as grid electricity can power the process. While substantial heat recovery opportunities are considered a benefit of the HPC process, this possibility is only partially utilized in the studied system. The optimal choice of capture process might, thereby, be a result of other factors than the energy performance itself. For instance, local conditions, such as grid connection capacity or the existing portfolio of production units, might be important to consider. While the present work investigates the retrofit of carbon capture to both a baseload (waste-fired) and an intermediate load (recycle wood) CHP plant, further research might examine the financial viability of carbon capture installations at both plants, and how CO_2 market designs (for fossil and biogenic CO_2) impact the setting of carbon capture targets and capture plant operation.

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