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Aggregated Negative Emission from Biomass Fired CHP Plants in Sweden#

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ABSTRACT

To achieve net-zero emissions by 2045 in Sweden, bioenergy with carbon capture and storage (BECCS) has been identified as a key technology. Biomass fired combined heat and power plants (bioCHPs) constitute the second largest CO_2 emission source after paper and pulp plants. Therefore, integrating BECCS in bioCHPs will contribute significantly to achieve Sweden's climate goal. In the prerequisite of maintained heat generation for district heating (DH) sectors, this paper aims to estimate the aggregated negative emissions when integrating CO_2 capture into existing 110 bioCHPs, in which the boiler load can be increased to the maximum capacity. A physical model was developed for bioCHP, and the operation of an example bioCHP can be determined by the objective function of maximizing the heat for CO_2 capture. Based on results of example plant, the artificial neural network models were further established to predict the capture performance from other plants. Not only the amount of captured CO_2, but also the amount of avoided CO_2 was examined for a better understanding of the contribution of negative emissions. It is estimated that the heat generation used for DH is 33925.83 GWh/year. The aggregated amount of captured CO_2 is estimated of 23.11 Mton/year; the aggregated amount of avoided CO_2 is estimated of 20.22 Mton/year. The electricity generation is found to be decreased by 8810.82 GWh/year (63.6%) when BECCS is included.

Keywords: bioenergy with carbon capture and storage, biomass fired combined heat and power plant, CO_2 capture, district heating

NONMENCLATURE

Abbreviations	
BECCS	Bioenergy with carbon capture and storage
bioCHP	Biomass fired combined heat and power
DH	District heating
Symbols	
Q_{CC}	The heat that can be used for CO_2 capture
m_{CO2}	Amount of captured CO_2 from each plant hourly
m_{max}	Amount of total generated CO_2 from each plant hourly
M_{CO2}	Amount of captured CO_2 from each plant annually
q_{av}	The average energy penalty of CO_2 capture
j	The j^{th} hour
n	Sample size
y_i	The i^{th} predicted value
$\hat{y}_i$	The i^{th} actual value
$Em_{without\ CC}$	The emitted CO_2 of bioCHP without CO_2 capture
$Em_{with\ CC}$	The emitted CO_2 of bioCHP with CO_2 capture

1. INTRODUCTION

Sweden has set the climate goal that is to achieve net-zero emissions by 2045 [1], and bioenergy with CO_2 capture and storage (BECCS) has been identified by the Swedish Energy Agency as a key solution.

Based on the data from Swedish Environmental Protection Agency [2], CHP plants are the second largest CO_2 emission source after paper and pulp plants in

Sweden. Since biomass is the most common fuel used in CHPs, there is a great potential to integrate BECCS with CHPs to achieve negative emission in the district heating sector. Even though there have been some studies assessing the amount of negative emission from a specific CHP [3-4], the possible contribution from the entire district heating sector still remains unknown. Therefore, this paper aims to estimate the aggregated negative emission from all CHPs in Sweden. The result will provide insights to policy makers regarding the implementation of BECCS.

2. CAPTURING CO2 FROM A BIOCHP PLANT

There are 110 CHPs in Sweden, which spread over in 78 DH networks in most large towns of Sweden [3]. When integrating BECCS with CHPs, the production of heat and electricity will be affected as capturing CO_2 consumes energy. Since the core business of CHP is to provide heat to consumers, in this work, it is assumed that the heat generation remains unchanged, and electricity production can be sacrificed to enable CO_2 capture. Meanwhile, it is assumed that the boiler load can also be increased to provide more heat for CO_2 capture if it is not running at the full load. In addition, MEA based chemical absorption is adopted as CO_2 capture technology. To simplify the calculation, the energy penalty caused by CO_2 capture is assumed to be a constant, which is 3.8MJ/kg [5].

The operation of bioCHP is primarily determined by the heat demand that varies from time to time with ambient temperature. Figure 1 shows the system scheme of a bioCHP integrated with CO_2 capture. The heat demand of CO_2 capture is covered by condensing the steam extracted from the intermediate stages of steam turbines due to the requirement of high temperature. Since it will reduce the amount of exhaust steam in the downstream steam turbines, less electricity will be produced. In the meantime, less exhaust steam also leads to less heat recovered from the exhaust steam condenser (ESC) for DH. To meet the heat demand of DH, some heat can be recovered from the flue gas condenser (FGC). With the increase of heat demand, when there is not enough heat from the ESC and FGC, steam can bypass the steam turbine. Once the minimum load the steam turbine is reached, all steam will be bypassed, and electricity generation will be stopped. If the heat demand further rises, the steam extracted for CO_2 capture will also be reduced and less CO_2 will be captured.

To determine the heat needed by CO_2 capture, a model was developed in Aspen Plus to simulate the operation of the bioCHP plant integrated with CO_2 capture. The detailed model description can be found in our previous work [4]. It is validated by using the real data from a bioCHP plant in Sweden, which can produce 110 MW heat and 48.5 MW electricity at full capacity. In order to obtain an accurate estimate about the yearly CO_2 capture potential, based on the real hourly heat demand, the heat that can be used for CO_2 capture is first maximized for each hour by using the model. When the hourly heat available for CO_2 capture is determined, the hourly and yearly captured CO_2 can be reckoned by using Eqn.1 and 2. There is a constraint about the hourly captured CO_2, which cannot exceed the total amount of CO_2 generated, as shown in Eqn.3.

$$m_{CO2,j} = Q_{CC,j}/q_{av} \tag{1}$$

$$M_{CO2} = \sum_{1}^{8760} m_{CO2,j} \tag{2}$$

$$m_{CO2,j} \leq m_{max,j} \tag{3}$$

where $m_{CO2,j}$ is the amount of captured CO_2 at the j^{th} hour, $Q_{CC,j}$ is the heat that can be used for CO_2 capture at the j^{th} hour, q_{av} is the energy penalty of CO_2 capture, M_{CO2} is the amount of captured CO_2 annually, and $m_{max,j}$ is the amount of total generated CO_2 at the j^{th} hour.

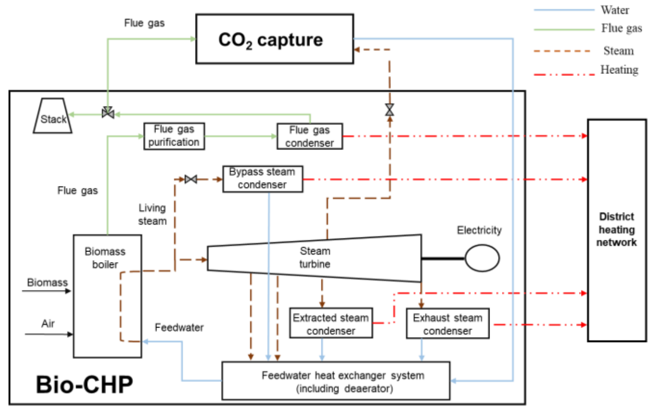

Fig.1 The schematic of a bioCHP integrated with CO_2 capture

3. AGGREGATED CO2 CAPTURE

Due to the lack of detailed operational data about other bioCHPs, it is assumed the same technologies are used in all bioCHPs. It implies that the other bioCHPs have similar performance, e.g. energy efficiency of devices, fuel, operating temperature and pressure, and energy penalty of regenerating CO_2, to the reference bioCHP studied in Section 2, but with different installed capacities and hourly heat demands. Therefore, the results from the example plant can be further extended to other plants. The procedure is shown in the flowchart (Figure 2).

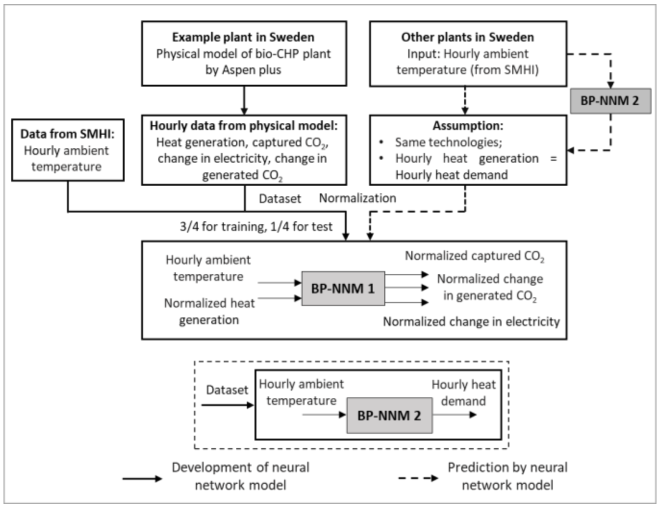

Fig.2 Neural network models for nationwide estimation

In order to minimize the influence resulted from the difference of capacity of bioCHPs, normalized values are employed, such as normalized heat generation, normalized captured CO_2, and normalized change in electricity. Based on the results of the reference bioCHP, the back-propagation neural network model (BP-NNM 1) is established to predict normalized captured CO_2, normalized change in electricity and normalized change in generated CO_2, which uses ambient temperature and normalized heat generation as input features. The ambient temperature is taken from the Swedish Meteorological and Hydrological Institute (SMHI) [6]. 75% of results are used for model training and the rest 25% are used for model validation.

As a key input feature, the hourly heat demand is needed. When such data are not available, another BP-NNM model (BP-NNM 2) is employed to predict it, which correlates the heat demand with the ambient temperature. The mean absolute percentage error (MAPE), defined by Eqn. 4, is used to evaluate the performances of BP-NNM-1 and BP-NNM-2.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}|(y_i - \hat{y}_i)/\hat{y}_i| \times 100\% \qquad (4)$$

where n is the sample size; y_i is the i^{th} predicted value; $\hat{y}_i$ is the i^{th} actual value.

As shown in Figure 3, using BP-NNM 1, it is clear that the average absolute deviation is 2.1% and the maximum deviation is 11.4% for the prediction of normalized captured CO_2. The MAPE of BP-NNM 1 are 4.6% for the prediction of change in generated CO_2, and 11.0% for the prediction of change in electricity production. For the prediction of the heat demand, it is found that the MAPE of BP-NNM 2 is 8.4%.

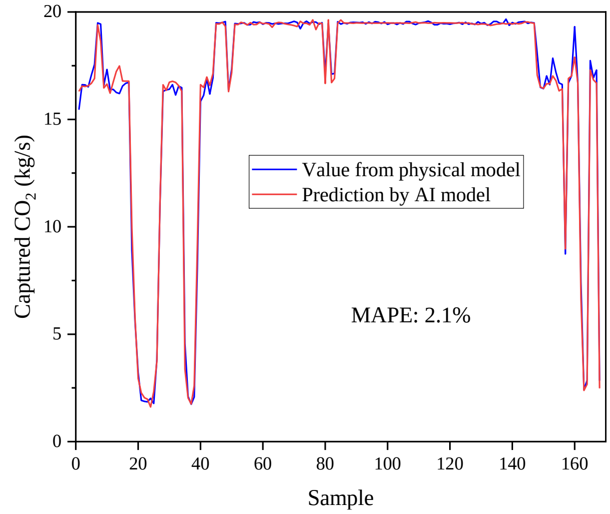

Fig.3 Prediction performance for captured CO_2 by BP-NNM 1

When the models were used for prediction, the hourly ambient temperature profiles of other plants are also obtained from SMHI. Based on BP-NNM-1 and BP-NNM-2, the normalized captured CO_2, normalized change in generated CO_2 and electricity can be estimated. Based on the change in generated CO_2, the amount of avoided CO_2 can be calculated to estimate the negative emission, which is defined based on the difference of CO_2 emissions of bioCHP without CO_2 capture and that with CO_2 capture, as shown in Eqn.5. When the amount of captured CO_2 and avoided CO_2 and the change in electricity are obtained for each plant, they are aggregated for the analysis at the national level.

$$Avoided\ CO_2 = Em_{without\ CC} - Em_{with\ CC} \qquad (5)$$

where $Em_{without\ CC}$ and $Em_{with\ CC}$ are the emitted CO_2 of bioCHP without CO_2 capture and with CO_2 capture, respectively.

The results for the integration of BECCS with all Swedish bioCHPs are summarized in Table 1. Based on the assumption of no change in heat generation and adjustable boiler load, the aggregated amount of captured CO_2 is estimated of 23.11 Mton/year; the aggregated amount of avoided CO_2 is estimated of 20.22 Mton/year, which correspond to a CO_2 capture rate of 93.54% and 92.69%. The avoided CO_2 emissions is estimated as 596 kg per MWh of heat. Compared with the scenario without CO_2 capture, the electricity production is decreased by 8810.82 GWh/year when BECCS is included, which corresponds to a drop of 63.6%. Figure 4 presented the avoided CO_2 and heat generation from each bioCHP.

Tab. 1 Results of integrating BECCS in Swedish bioCHPs

Parameters	Without CO_2 capture	With CO_2 capture
Heat generation (GWh/year)	33925.83	33925.83
Generated CO_2 (kton/year)	21815.27	24702.54
Electricity generation (GWh/year)	13850.66	5039.84
Captured CO_2 (kton/year)	/	23107.38
Avoided CO_2 (kton/year)	/	20220.03
Capture rate based on captured CO_2 (%)	/	93.54%
Capture rate based on avoided CO_2 (%)	/	92.69%

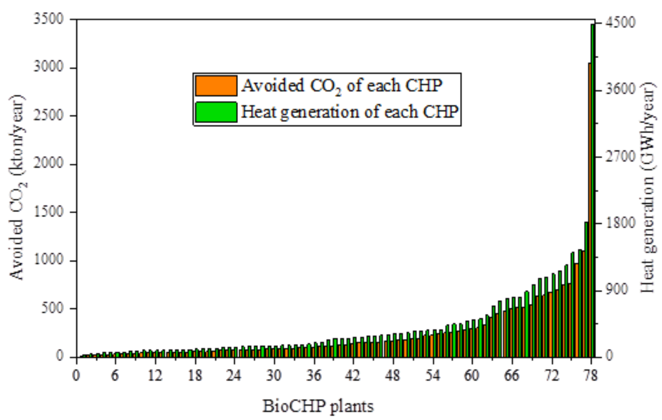

Fig.4 Avoided CO_2 and heat generation from each bioCHP

4. DISCUSSION

Due to the lack of operational data about other bioCHPs, it is simplified to use the reference plant to represent all bioCHPs. However, different bioCHPs may use different configurations, technologies and fuels, and operate in different temperatures and pressures. The influences on the estimated amount of captured CO_2 needs to be further investigated.

Since the cost of BECCS has been identified as a major barrier to its wider implementation, the potential costs on capturing CO_2 from bioCHP plants are crucial to decision makers, which will be investigated in the future work. The most favorable operation strategy might depend on electricity price, heat demand, fuel prices and carbon trading prices. Therefore, the optimization is needed for BECCS to be economically and environmentally sustainable.

5. CONCLUSIONS

In the prerequisite of maintaining heat generation, this work estimated the potential of negative CO_2 emissions from all existing BioCHP plants in Sweden. Based on the results, the following conclusions were drawn:

- It is estimated that the potential of total captured CO_2 from Swedish bioCHP plants is 23.11 Mton/year; the potential of total avoided CO_2 is 20.22 Mton/year.
- It is estimated that the electricity production is decreased by 8810.82 GWh/year (63.6%) when BECCS is included.

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