The application of AI for CO_2 capture in waste CHP plants

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AI: artificial intelligence; **CHP**: Combined heat and power.

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AI: artificial intelligence; **CHP**: Combined heat and power.

Background

Swedish climate goal: net-zero GHG emissions by 2045

- Bioenergy with carbon capture and storage (BECCS)[1]
- Biomass/waste CHP plants[2]

A program from Swedish Energy Agency:

Contribute to the energy transition through research, innovation and business development in digitalization

Project title

- AI assisted CO_2 capture in biomass CHP plants

Funding

- Swedish Energy Agency

Project leader

- Hailong Li

Objectives

- The project aims to develop AI assisted solutions to optimize and control the dynamic operation of CO_2 capture and its integration in CHP plants. Such solutions are expected to increase CO_2 emission reduction and reduce the energy penalty and cost of CO_2 capture.

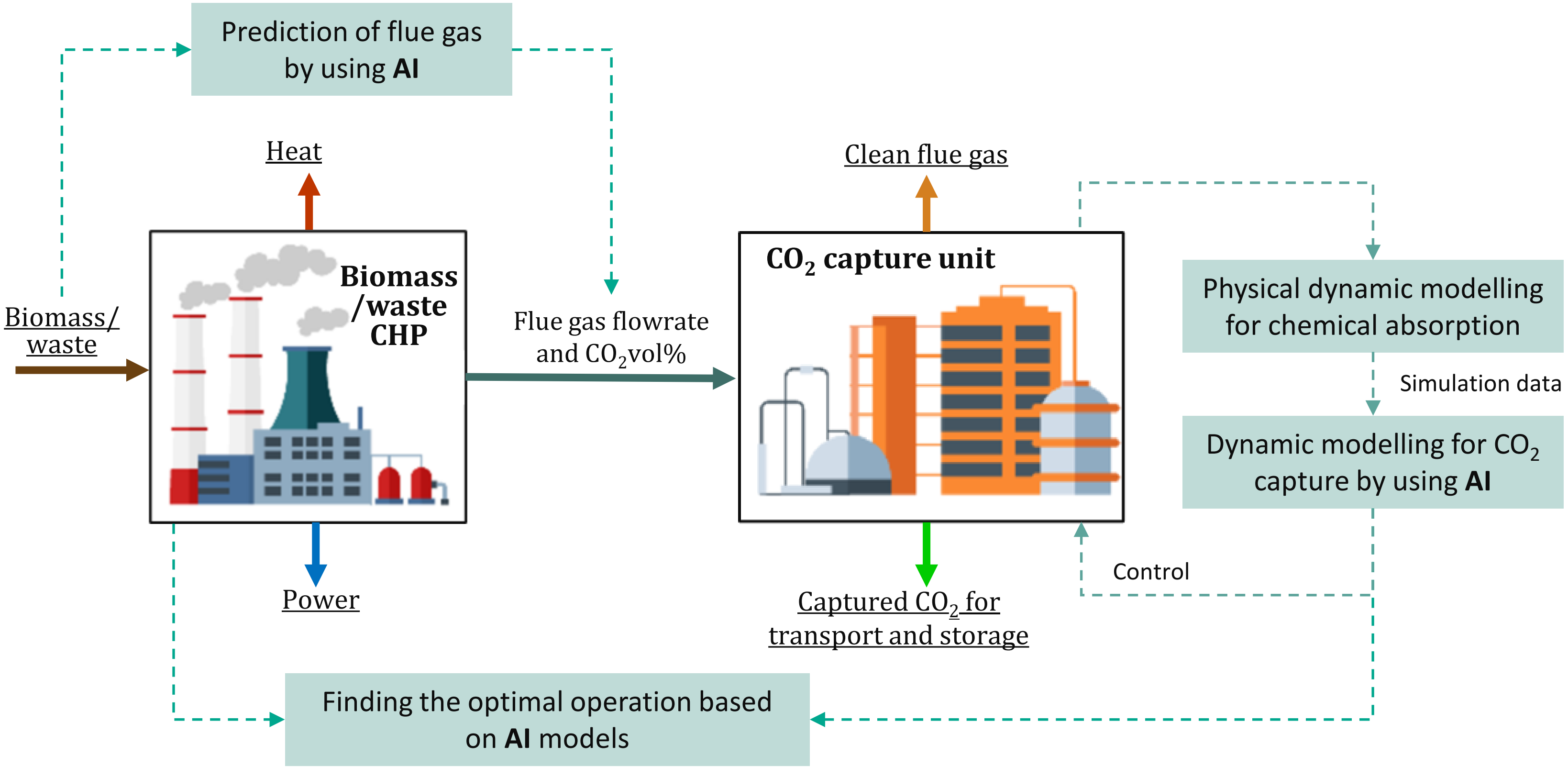
Collaboration partners

- Industry: Stockholm Exergi, Mälarenergi, Eskilstuna Strängnäs Energi och Miljö

1. Government Offices of Sweden. Ministry of the Environment, 2020. Sweden's long-term strategy for reducing greenhouse gas emissions.
2. Johnsson F., 2019. Avskiljning, transport och lagring av koldioxid i Sverige Behov av forskning och demonstration. Institutionen för Rymd-, geo-, och miljövetenskap, Avdelningen Energiteknik.

GHG: Greenhouse gas; **AI**: artificial intelligence; **CHP**: Combined heat and power.

Applications of AI



AI: artificial intelligence; **CHP**: Combined heat and power.

Prediction of flue gas

Challenges

- Larger fluctuations of flue gas
  - ➢ Versatile biomass/waste
  - ➢ Dynamic heat demand
- Slow response of CO_2 capture to fluctuations

It is important to predict the flue gas flowrates and compositions.

Advantages of AI models

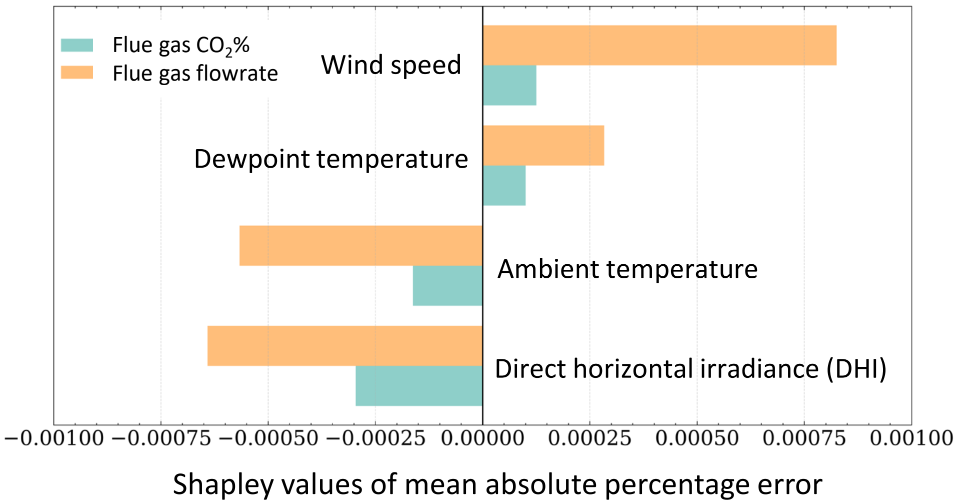
- Transformer: a new AI model, parallelization, larger datasets, multi-head self-attention mechanism
- Long short-term memory network (LSTM): sequence processing over long periods
- Artificial neural network (ANN): a traditional AI model for comparison

Feature selection -- meteorological parameters

Shapley values determine the contribution of input features to the prediction.

Input features

- Meteorological parameters
  - ➢ Wind speed
  - ➢ Dewpoint temperature
  - ➢ Ambient temperature
  - ➢ Direct horizontal irradiance (DHI)
- Near-infrared (NIR) spectral data



Prediction when NIR is not included as input

Mälardalen University

<u>When NIR is not included as an input:</u>

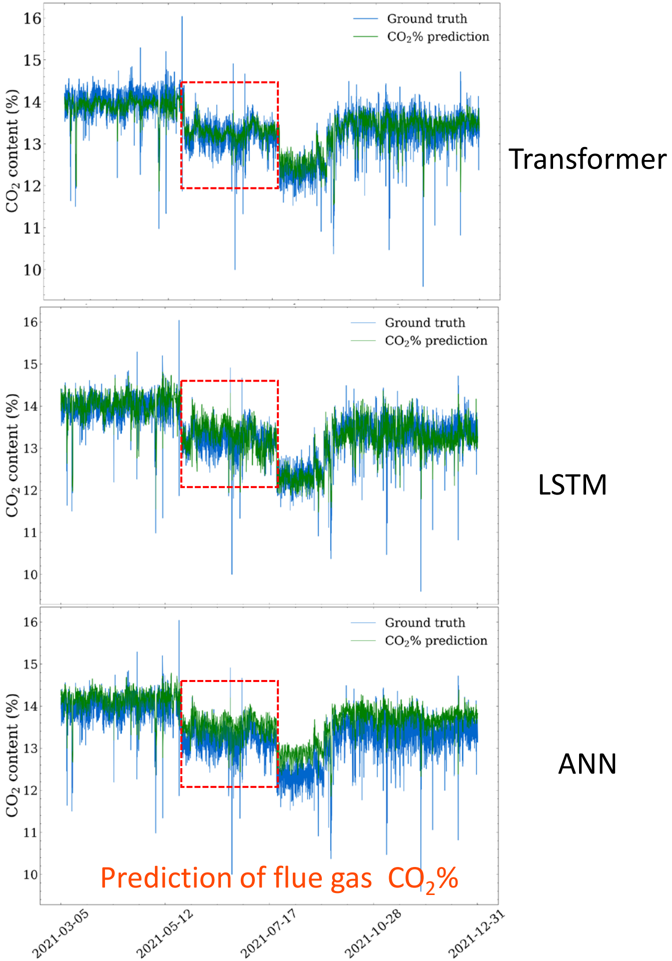
- Input: ambient temperature and DHI
- Output: flue gas flowrate and $CO_2\%$
- Time span: 2019.1.1-2021.12.31 (Time resolution: 1 hour)

Evaluation indicators

Mean absolute percentage error (MAPE):
$$MAPE = \frac{1}{q}\sum_{p=1}^{q}\left|\frac{y_p - \hat{y}_p}{y_p}\right| \quad (1)$$

Prediction performance of different AI models

Performance	AI models	Flue gas $CO_2\%$	Flue gas flowrate
MAPE	**Transformer**	**0.0189**	**0.0318**
	LSTM	0.0221	0.0368
	ANN	0.0289	0.0386

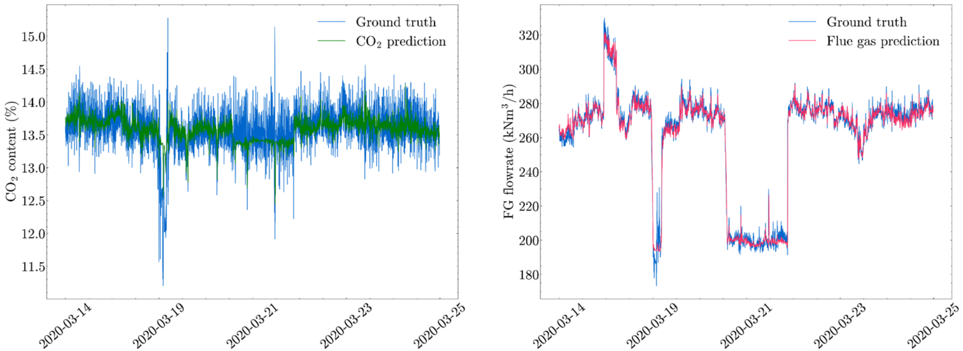


NIR: near-infrared; **DHI**: direct horizontal irradiance; **LSTM:** long short-term memory network; **ANN**: artificial neural network.

Prediction when NIR is included as input

When NIR is included as an input:

- Input: ambient temperature, DHI, and NIR data
- Output: flue gas flowrate and CO_2%
- Time span: 2019.11.1-11.3, 2020.1.16-3.25 (Time resolution: 1 minute)

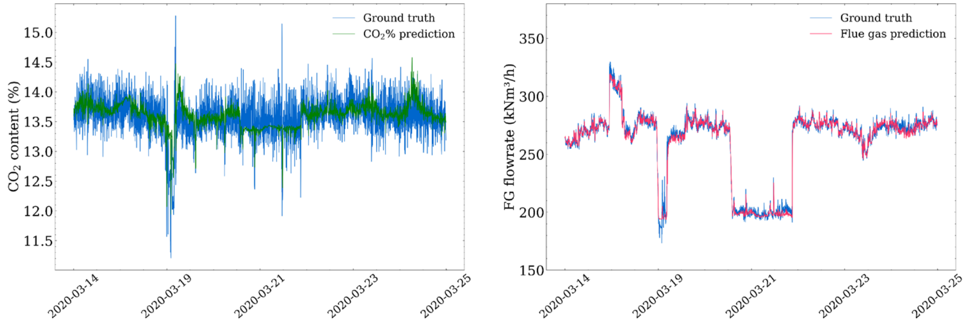


NIR is not included

Influence of NIR spectral data:

Prediction performance of Transformer

MAPE	Flue gas CO_2%	Flue gas flowrate
NIR is not included	0.0158	0.0141
NIR is included	0.0157	0.0121

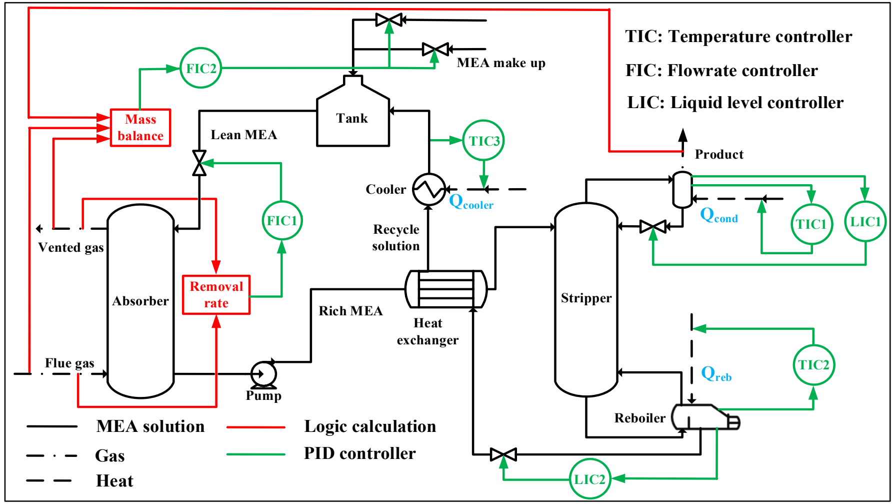


NIR is included

The influence of NIR may be restricted by the amount of available data.

NIR: near-infrared; **DHI**: direct horizontal irradiance.

Physical models of CO2 capture



Flowsheet of MEA-based chemical absorption CO_2 capture

Physical dynamic models of CO_2 capture

- Software: Aspen HYSYS Dynamics
- Model development and operation: time-consuming
- Difficulty in online control and optimization

Surrogate models (relate input data to output data)

- Simulation by physical models
- Simplified approximations by AI models

MEA: Monoethanolamine; **PID**: Proportional–integral–derivative.

Performance of AI models

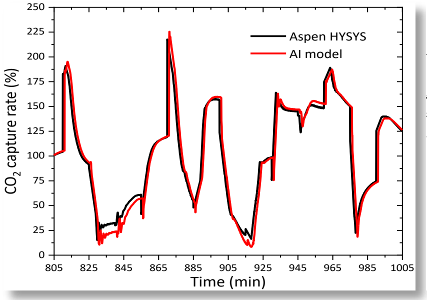
Depending on actual applications, different AI models can be developed with different inputs and outputs.

Application 1: to predict the response of CO_2 capture when facing multiple variations.

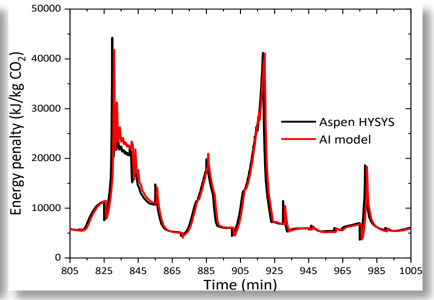
- Input: flue gas flowrate, CO_2vol%, solvent flowrate, available heat
- Output: CO_2 capture rate, energy penalty
- AI model: Informer

Application 2: to estimate CO_2 capture amount in CHP based on flue gas and available heat (by optimization).

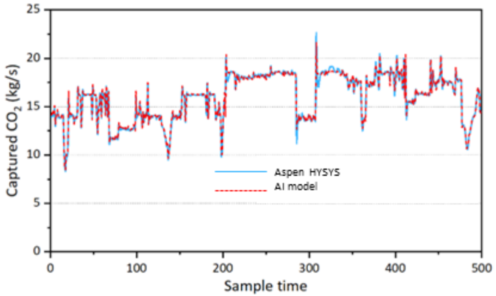
- Input: flue gas flowrate, available heat
- Output: CO_2 capture amount
- AI model: Back-propagation neural network



CO_2 capture rate, MAPE = 0.0625



Energy penalty, MAPE = 0.027



CO_2 capture amount, MAPE = 0.0085

Application 3: to control the operation of CO_2 capture in CHP at a given capture rate by adjusting flue gas and available heat from CHP.

……

MAPE: mean absolute percentage error; **CHP**: Combined heat and power.

Challenges about optimization

Optimization: to maximize economic benefit (it is assumed that heat generation is unchanged.)

Objective function = electricity revenue - carbon trading - fuel costs

$$= \max(\sum_{i=1}^{24}(Ele_i \times price_{ele,i} - m_{was,i} \times price_{was}) - m_{traded\ CO_2} \times price_{carbon\ trading})$$

Challenge:

- The trading of CO_2 is on a yearly basis.
- The heat demand and electricity prices vary hour by hour.
- It is impossible to do a yearly optimization.

Question: how should we decide when to capture CO_2 to reduce the yearly cost?

Marginal cost of CO2 capture

- Instead of optimizing the operation, rule-based methods are proposed.
- The marginal cost of CO_2 capture (MC) is proposed, and it is estimated as the economic loss due to the operation of CO_2 capture.

$$MC = \frac{dC_{cc}}{dm_{CO2,cap}}$$

C_{cc} *is the total cost of* CO_2 *capture*; $m_{CO2,cap}$ *is the amount of captured* CO_2.

  - The cost due to reduced electricity generation and increased fuel consumption is included;
  - It varies dynamically with the heat demand and electricity price.

- The principle for formulating rules is CO_2 capture system operates at a lower MC.
  - When MC is lower than MC threshold, CO_2 capture system operates.
  - When MC is higher than MC threshold, CO_2 capture system doesn't operate.
- There are two ways to determine the MC.
  - Hourly MC
  - Monthly average MC

EU Emissions Trading System (EU ETS)

- The trading of CO_2 is on a yearly basis -- Annual compliance cycle.
  - Receive free allowances
  - Submit an annual emissions report
  - Surrender an amount of allowances corresponding to the emissions before the deadline, otherwise, a heavy fine
    - If CO_2 emissions < free allowances, excess allowances can be sold;
    - If CO_2 emissions > free allowances, additional allowances must be purchased.
- CO_2 trading for waste-CHP plants
  - It only includes fossil CO_2 (CO_2 captured from the fossil fuel), and negative emission hasn't been included in EU ETS.
  - Waste-CHP generate both fossil and biogenic emissions.
    - If generated fossil CO_2 - captured CO_2 > free allowances,
      allowance purchase = generated fossil CO_2 – captured CO_2 – free allowances;
    - If 0 < generated fossil CO_2 - captured CO_2 < free allowances,
      allowance sell = free allowances + captured CO_2 – generated fossil CO_2;
    - If generated fossil CO_2 - captured CO_2 < 0, ***allowance sell = free allowances***;
    - If generated fossil CO_2 - captured CO_2 = 0, ***MC threshold = MC (generated fossil CO_2 = captured CO_2)***.

For a case study of a waste-CHP plant,

- the fossil share of waste fuel is assumed as 45%.
- the free allowances received is 71.40 ktonCO_2 in 2022.

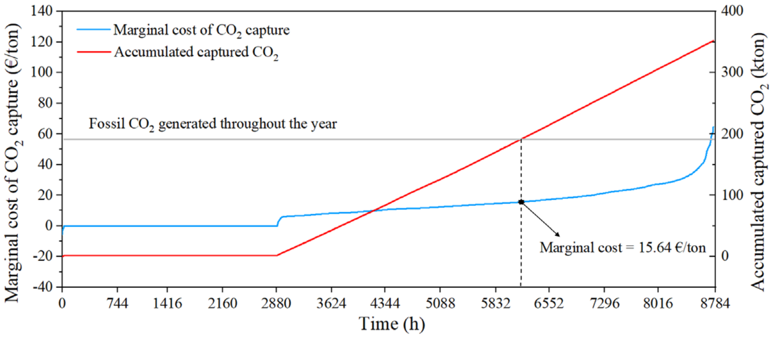
CHP: Combined heat and power; **MC**: marginal cost of CO_2 capture.

Operating rules

Rule 1: based on hourly marginal cost

1. Calculate marginal cost and plot its duration curve;
2. Plot the accumulated captured CO_2;
3. Determine the break-even point that all fossil CO_2 is captured (MC_{fos}), which is the threshold of marginal cost;
4. Rules: if real-time marginal cost is below MC_{fos}, CO_2 is captured; otherwise, not.

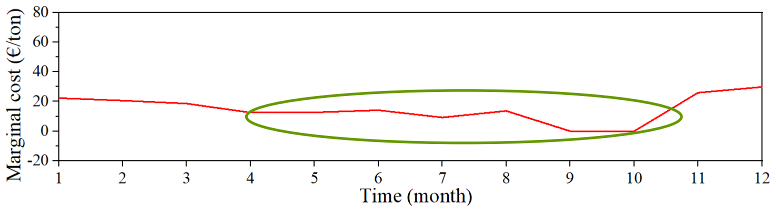
Example: MC_{fos} = 15.64 €/ton CO_2



Rule 2: based on monthly average marginal cost

1. Calculate average marginal cost for each month;
2. Calculate the accumulated captured CO_2 amount for each month;
3. Find those months with lower *MC*, in which accumulated captured CO_2 is equal to all fossil CO_2;
4. Rules: CO_2 capture system only operates in the identified months.

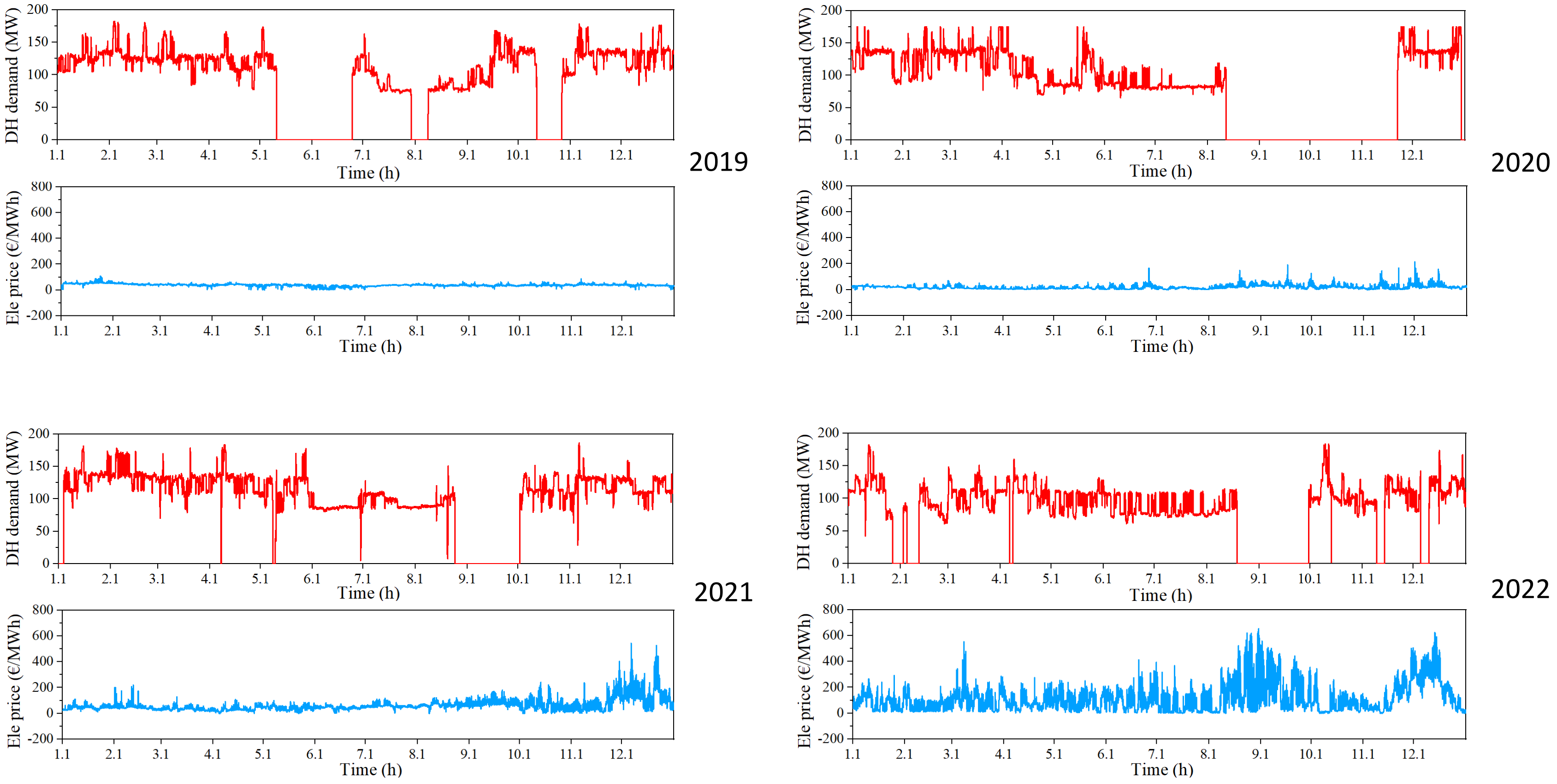
Operate CO_2 capture system in these months



AI models are to estimate CO_2 capture amount (output) in CHP based on flue gas and available heat (input).

MC: marginal cost of CO_2 capture; **CHP**: Combined heat and power.

Heat demand and electricity price

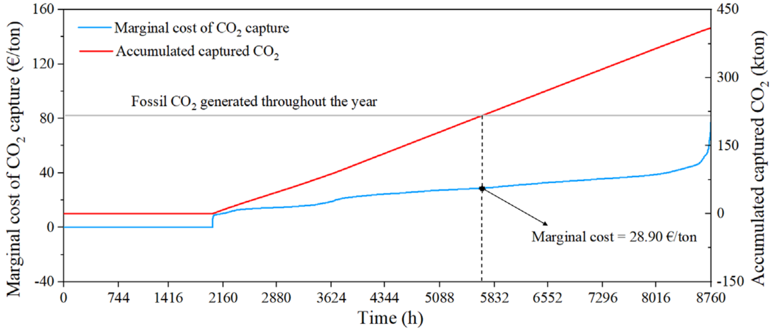


Rule 1

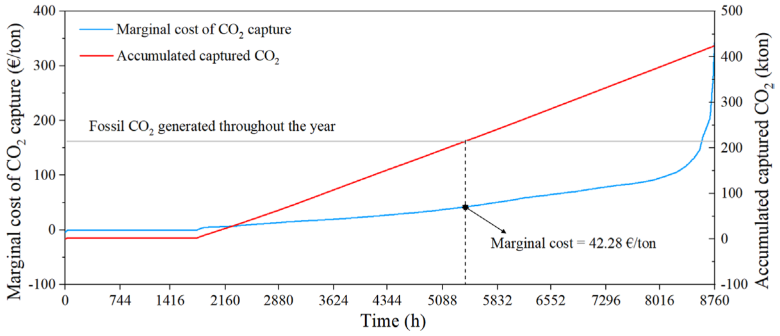
Using the average marginal cost of 2019-2022

$MC_{fos,\ average}$ = 29.43 €/ton CO_2

Capture limit: Fossil CO_2 emission (average): 214 kton/year



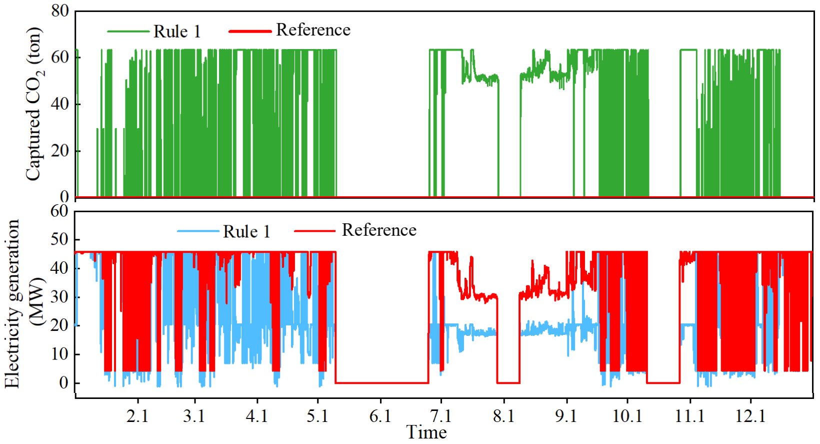
2019

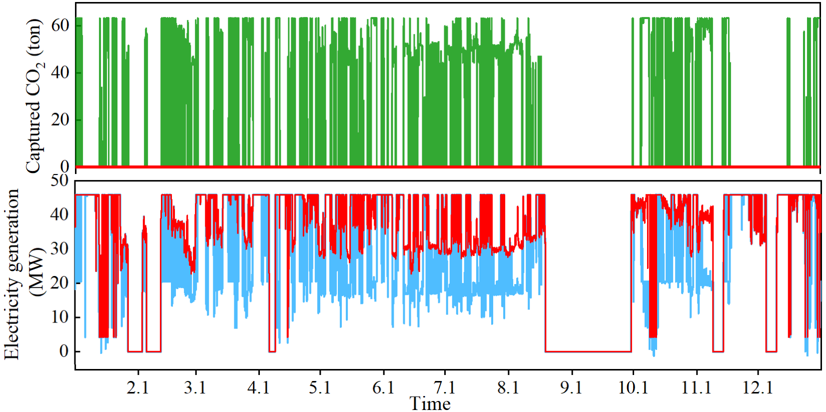


2022

Advantage: Always capture CO_2 at low marginal cost

Challenges: Could result in intermittent operation





MC: marginal cost of CO_2 capture.

Rule 2

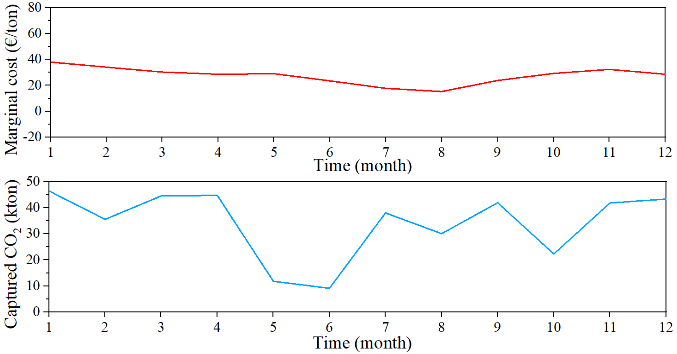
Advantage: continuous operation for months

Challenges: Could capture CO_2 at high marginal cost

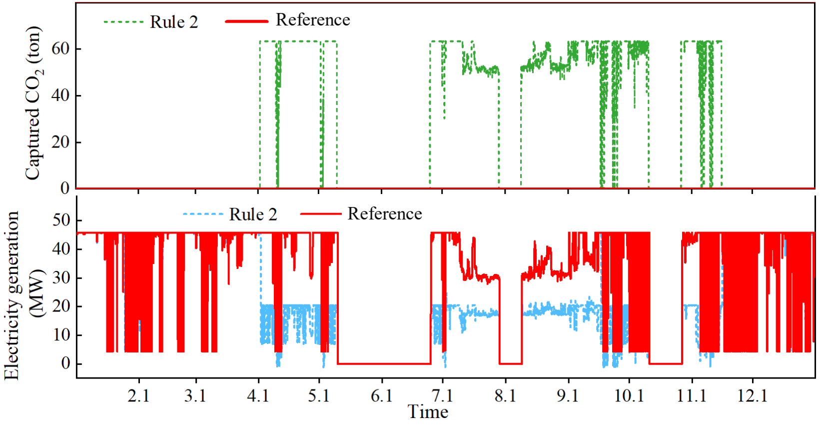
<u>Determining months based on 2019-2022</u>

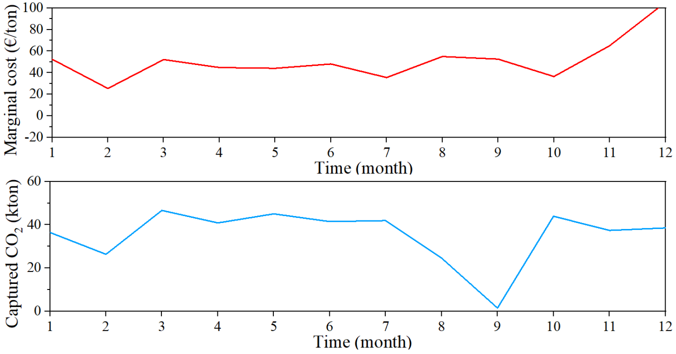
Capture limit: Fossil CO_2 emission (average): 214 kton/year

Operation: Apr - Nov

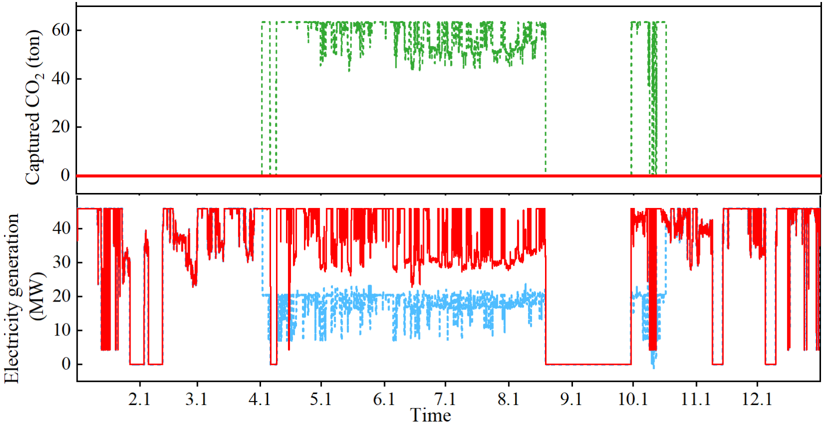


2019





2022



Comparison of total revenue

Breakdown of total revenue

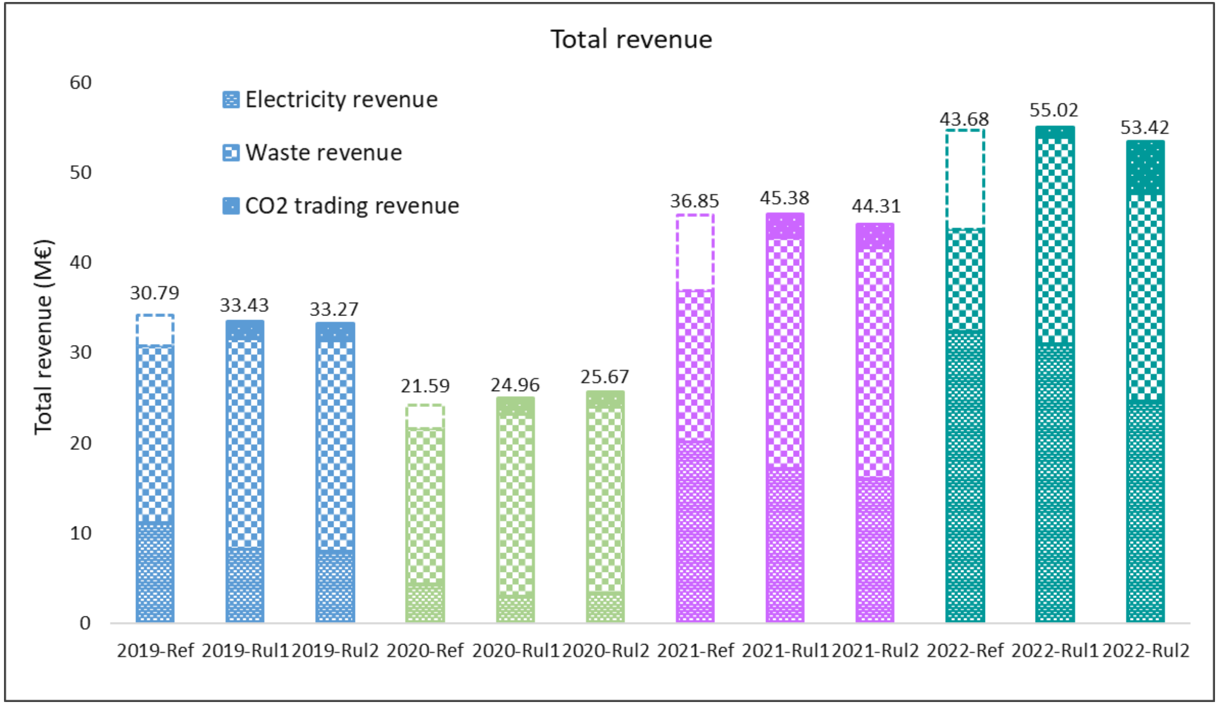
Revenue of trading is calculated based on real price:

Carbon trading price (2019): 25.05 €/ton

Carbon trading price (2020): 24.06 €/ton

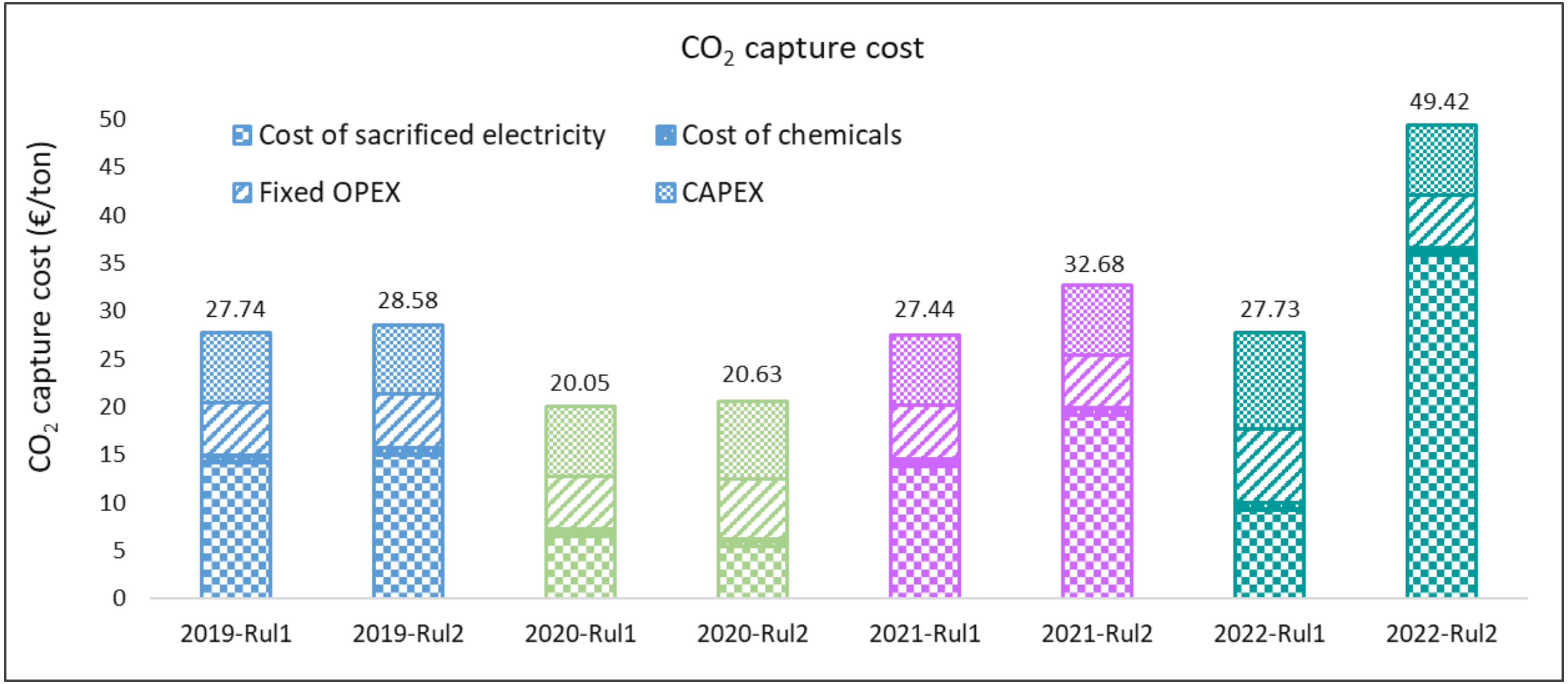
Carbon trading price (2021): 52.70 €/ton

Carbon trading price (2022): 81.41 €/ton



Comparison of CO2 capture cost

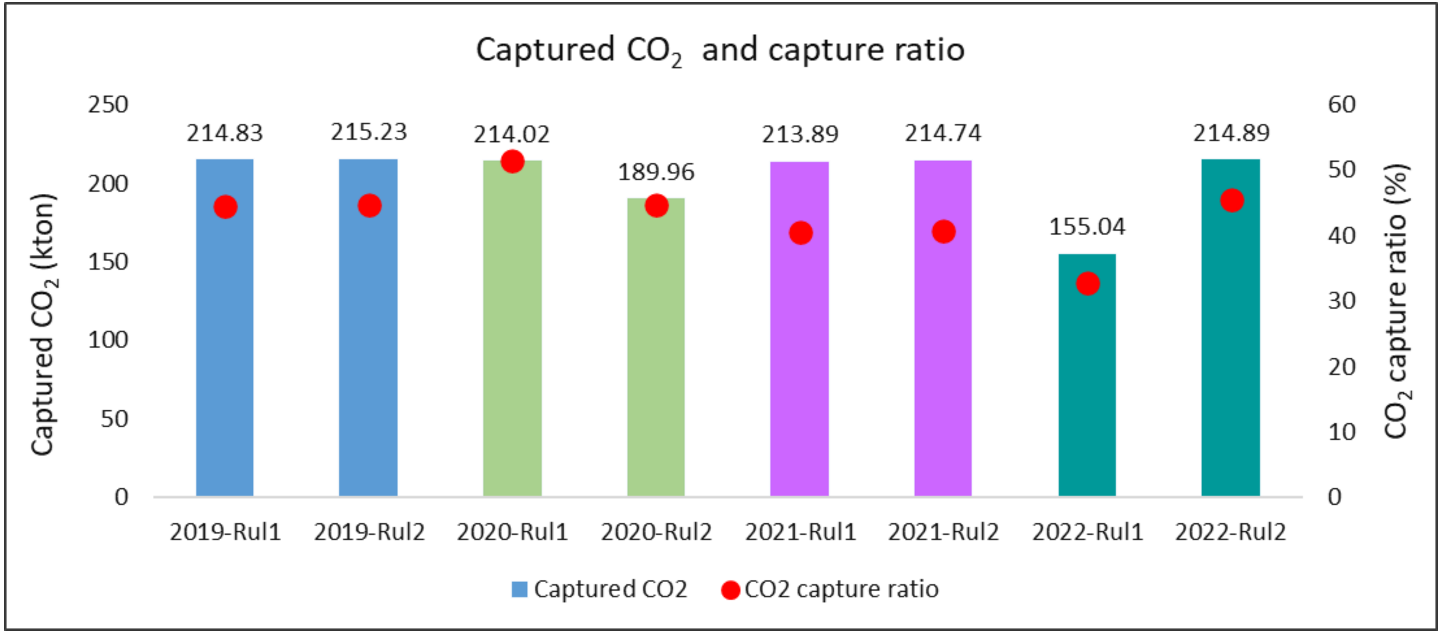
Breakdown of capture cost streams



CAPEX: capital expenditures; **OPEX**: operating expenses.

Comparison of CO2 capture ratio

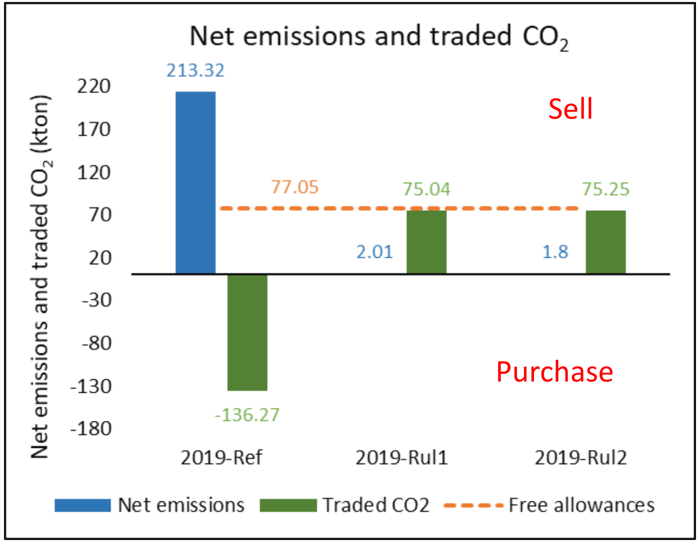
Captured CO_2 and CO_2 capture ratio

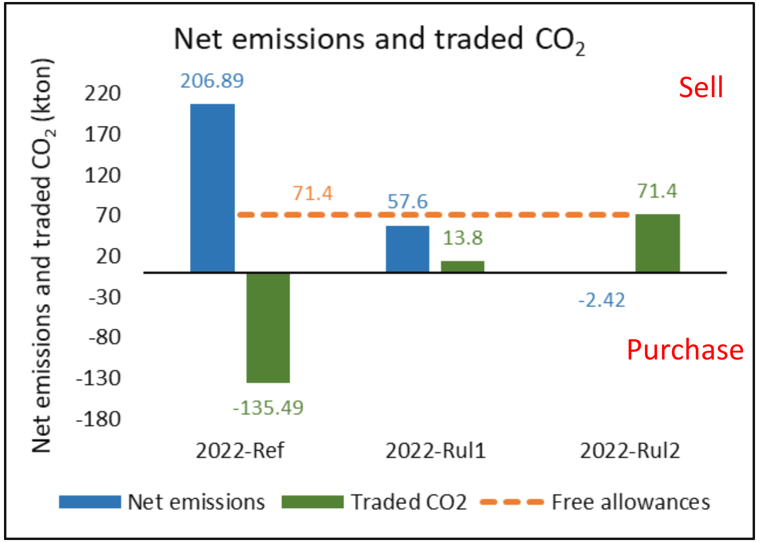


Comparison of CO2 trading

Net emissions and traded CO_2

Net emissions = generated fossil CO_2 - captured CO_2





<u>Mass balance approach to estimate the fossil CO_2 emission</u>

- The waste fuel comprises an average of 45% fossil carbon by mass. So, for each unit CO_2 emission, 55% is biogenic CO_2 and 45% is fossil CO_2.
- To improve accuracy, a more detailed analysis of fossil carbon content may be required.

Summary

An efficient and flexible CO_2 capture integrated in biomass/waste CHP plants contributes to the Swedish climate goals and the development of renewable energy system.

Current applications of AI

- By employing ambient temperature, direct horizontal irradiance, and NIR data as inputs, it was found that the MAPE of Transformer is 1.57% and 1.21% for the prediction of flue gas CO_2% and flue gas flowrates.
- For dynamic CO_2 capture, depending on actual applications, different surrogate models can be developed with different inputs and outputs (such as prediction and control) by using AI.
- The marginal cost of CO_2 capture is used to find the optimal operation of CO_2 capture in CHP based on AI models.

Potential applications of AI

- Prediction of carbon price
- Model predictive control of CO_2 capture
- Non-linear modelling of CHP

CHP: Combined heat and power.

Thank you!

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