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Flexible operation of CCS power plants to match variable renewable energies

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Abstract

The German Energiewende is resulting in high grid load changes caused by renewable energies. Therefore flexibility of power plants is getting more and more important. Future CCS power plants are usually equipped with more components than conventional power plants, resulting in a more complex and inert reaction on changes in power output. Additionally, due to the change in price structures and higher fixed and operational costs for CCS power plants, it is harder for them to be economically efficient. This study will show different options to increase the flexibility of CCS power plants and evaluate their benefits.

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Keywords: CCS; Flexibility; Post combustion capture; Oxyfuel; Solvent storage; Pipeline

1. Introduction

Growing shares of renewable energy in the German power grid urge fossil fuelled power plants to reduce load or to shut down completely with increasing frequency and amplitude. Shut down, load changes and the following restart or ramp-up procedures often have to be carried out as fast as possible.

To realize such fast transitions is already complicated and expensive for conventional power plants – if further measures for CO_2 reduction are applied, the task is even harder. Capture equipment and transport systems will add further process steps as well as additional masses of fluids and construction material.

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This will result in a generally slower system reaction on changes in parameters like load, temperature and pressure in the power plant components and capture units. On the other hand there is only limited time to earn money by selling electricity - if there is a chance to sell more electricity in a short term, efficiencies (and net power output) should be as high as possible. Any capture unit that would reduce the efficiency causes economic conflicts. Therefore measures are analysed to offset the power generation from the capture process in time or to reduce the capture load temporarily.

2. Flexibility measures for CCS power plants

Regarding CCS, there are some general measures that could be applied to increase the flexibility of CCS power plants (besides the measures that are applied at all types of power plants like improvements at turbines and furnaces) [1]. Two of these measures for post combustion power plants are:

- Bypassing of flue gas and venting without capturing (fig. 1a)
- Intermediate storage of CO_2-rich solvents and time shift of the capture process (fig. 1b).

Bypassing takes place just before the capture unit, this means, the energy used for capturing (mainly steam for the solvent regeneration process) the CO_2 can now be used for the generation of electricity. Disadvantage is the significantly higher CO_2 emission rate during bypassing.

Intermediate solvent storage takes place within the flue gas scrubbing process steps of post combustion or pre combustion power plants. CO_2 is captured selectively and absorbed into a solvent (for example monoethanolamine, MEA) in a first step. The second step usually would be the regeneration of the solvent by applying heat (from steam of the low pressure turbine). By storing the loaded solvent, the time and energy consumption of the regeneration process can be shifted away from the peak-load periods.

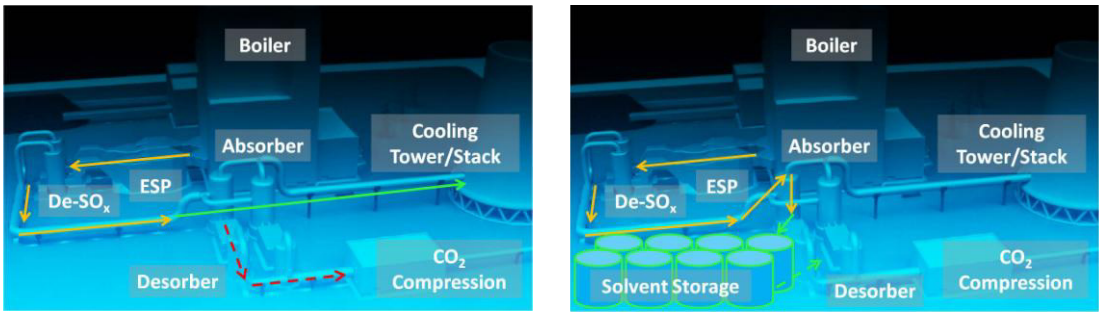

Figure 1: (a) CO2 bypass at a post combustion capture power plant (yellow line: conventional flue gas path, green line: bypass, red line: full CO2 capture); (b) Solvent storage at a post combustion capture power plant (yellow line: conventional flue gas path, green line: intermediate solvent storage)

Regarding oxyfuel power plants, due to the different process scheme, there are slightly different options:

- Bypassing of flue gas (fig. 2a) before the purification and compression processes
- Intermediate storage of liquid O_2 and time shift of the air separation process (fig. 2b).

Bypassing takes place just before the compression unit, this means, all the energy used for compressing the CO_2 can now be used for the generation of electricity. Disadvantage is the higher CO_2 emission rate during bypassing.

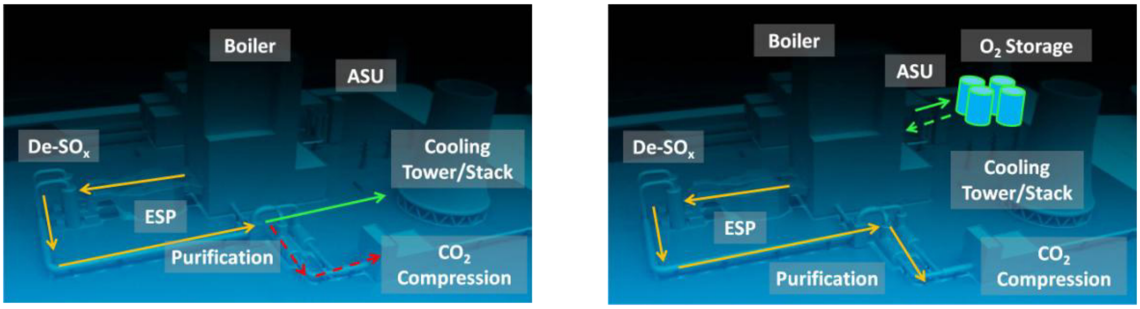

Figure 2: (a) CO2 bypass at an oxyfuel power plant (yellow line: conventional flue gas path, green line: bypass, red line: full CO2 capture); (b) Liquid Oxygen storage at an oxyfuel power plant (yellow line: conventional flue gas path, green line: intermediate oxygen storage)

Liquid oxygen storage will be used to shift the oxygen production by air separation into periods of lower electricity prices, allowing to switch of the ASU (mainly large air compressors) and generate a higher net load in high price periods.

All of these options both have advantages and disadvantages, most of them strongly bound to the cost of electricity and emission certificates [2].

The following sections will present some of the effects of these measures on the production of electricity and the emission of CO_2 at power plants.

3. Flexibility modelling and scenarios for flexible CCS operation

To evaluate effects of renewable energies and flexibility measures, simple models of different CCS power plants were developed and simulations for a predicted future load curve were performed.

Scenarios are named as follows:

- Post combustion and bypass: PC-B
- Post comb. and solvent storage: PC-S
- Oxyfuel and Bypass: Oxy-B
- Oxyfuel and O_2 storage: Oxy-S

Each scenario will be compared to the reference scenario in the most important parameters and most interesting points will be discussed.

Parameters and boundary conditions are described in the following sections.

3.1. Load curve

To model a load curve representing the effects of high grid load from renewable energies, load output of a power plant was combined with fluctuating energy production from a single wind park, resulting in high load changes and load ramps at the power plant.

A period of 2 months was chosen, effect of renewables was set so that an equivalent number of about 5650 full load hours per year was achieved. This equals the predicted number of full load hours for a lusatian lignite power plant in the years 2020 to 2030 [3].

As shown in fig. 3, there are some periods, where the power plant is not running at all, a lot of periods, where high load ramps have to be realized and periods, where the power plant is under full load operation. These different periods usually depend on grid load and electricity prices on the market.

The generation of the load curve included following boundary conditions:

- Minimum load of power plant: 40% (shut down if load is below)
- Minimum time for Shut-down/start up of the power plant: 2.5 h / 4 h
- Load rates max. 3.5%/minute

Data that did not fulfil these requirements were adjusted manually. All values are 30-minute-average data for a period of two months.

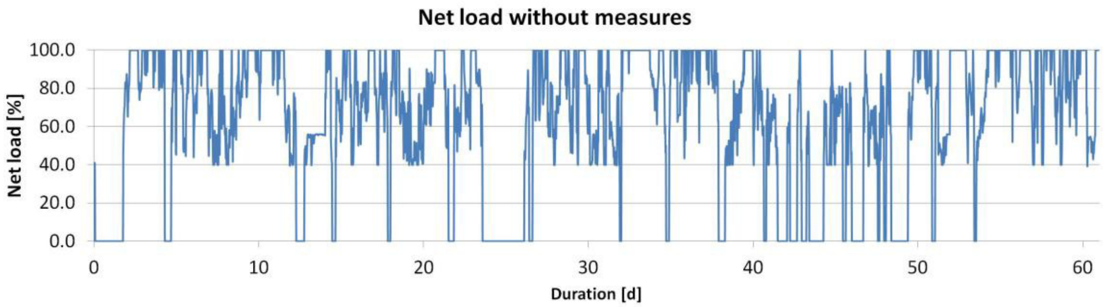

Figure 3: Net load power plant (without further measures)

To examine the influence of carbon dioxide capture and measures to increase the flexibility of CCS power plants, two types of power plants and for each power plant two possible measures were examined:

3.2. Power plants, cost of electricity and CO_2 certificates

Two types of power plant are examined: a post combustion power plant, using MEA (data form [4]) and a oxyfuel power plant equipped with a cryogenic air separation unit (data from [5], scaled to match a net load of 666 MW).

Table 1. Data of power plants

	Post combustion	Oxyfuel (scaled to net load)
Thermal output [MW_{th}]	1913	1990
Net load [MW]	666	666
Capture efficiency [%]	87.5	90
CO_2 produced [t/h]	623.4	704

To estimate some costs and financial impact, a 25 €/MWh price difference between high price period (>95 % load) and low price period (regeneration of storage volumes) and a price of 10 € per ton CO_2 emitted is assumed. Any CAPEX and OPEX for bypass systems or storage tanks and related auxiliary equipment are not considered in this study.

3.3. Flexibility measures

Different measures to increase flexibility are applied to each type of power plant. These are:

- full bypass before CO_2 absorption (post combustion),
- rich solvent storage for 8 hour continuous full load operation (post combustion),
- full bypass before CO_2 compression (oxyfuel),
- liquid oxygen storage for 8 hour continuous full load operation (oxyfuel).

These measures are active if load is above 95% of reference net load (666 MW). Regeneration (performed with 150 % of normal load) will take place if load is lower than 95%. Storage tank sizes for intermediate storage (8 hours full load operation) in the post combustion and oxyfuel case are:

- solvent (MEA+H_2O) 8 tanks, 25 m diameter, 25 m height,
- liquid oxygen: 4 tanks, 10 m diameter, 17 m height.

4. Results and discussion

4.1. Reference scenario

The reference scenario, representing each CCS power plant without further measures (standard carbon dioxide capture operation), will be compared to the applied flexibility options and discussed in the following sections.

4.2. Scenario PC-B

By bypassing the flue gas to the stack and switching off all capture units, the net load of a post combustion power plant can be increased significantly. Figure 4 is showing the resulting load curve, with peak load due to bypass shown in red.

During times of bypassing, the net load can be increased by 11.5 %. This results in an increase of electricity produced of 5.6 % while the emissions increase by 387 % during the observed period of 2 months. During the observed period, bypassing would generate a loss of 1,964,795 € due to the price of the CO_2 emission certificates. Economically, it would be efficient to bypass the CO_2 if the price for a MWh electricity is 8.1 times the price for a ton CO_2 emitted (certificate price).

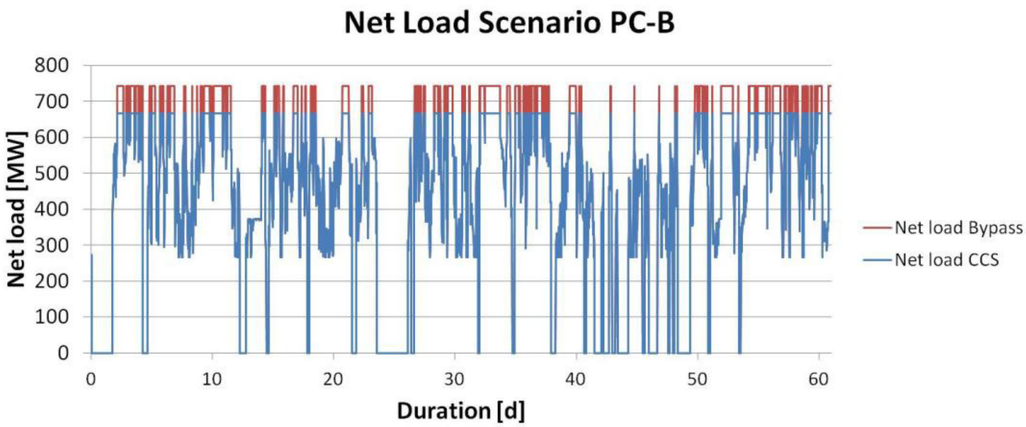

Figure 4: Net load post combustion with bypass

Detailed results of net load, CO_2 emissions and other effects due to bypassing are shown in table 2:

Table 2. Results scenario PC-B

Scenario PC-B			
Thermal output [MW_{th}]	1913	Electricity produced (reference) [MWh]	627800
Net load [MW]	666	Electricity produced (bypass) [MWh]	662912
Net efficiency [%]	34.81	CO_2 captured (reference) [t]	587621
Net load bypass [%]	743	CO_2 captured (bypass) [t]	303361
Net efficiency bypass [%]	38.84	CO_2 emissions (reference) [t]	73453
Capture efficiency [%]	87.5	CO_2 emissions (bypass) [t]	357712
Thermal input for regenerator [MW]	34.81	Relation of electricity price to emission certificate price for cost-effectiveness [(€/MWh)/(€/t)]	8.1
Loss resulting from bypassing [€]	-1964794.6		

4.3. Scenario PC-S

If the option of solvent storage is applied, the CO_2-rich solvent (aqueous MEA) is stored in tanks during high price periods and sent to the desorption/regeneration process in low price periods.

Figure 5 is showing the difference in net load that can be achieved. It can be seen, how the load increases in peak demand from the grid and decreases afterwards, when regeneration is active.

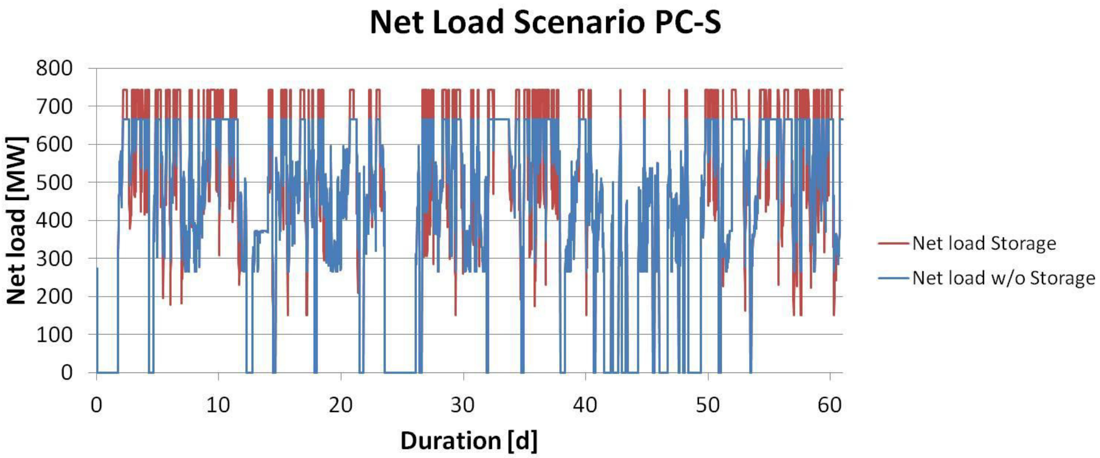

Figure 5: Net load post combustion with solvent storage

A more detailed part of the scenario is shown in figure 6. Until day 39.5 the power plant operates in partial load. When 100% load are reached, the difference in net load with (blue line) and without solvent storage (green line) is visible. CO_2 (absorbed by MEA) is stored (violet line) while the grid demand (and corresponding electricity prices) is high and captured when grid demand is lower (red line), resulting in a lower net load (blue line) compared to the reference scenario.

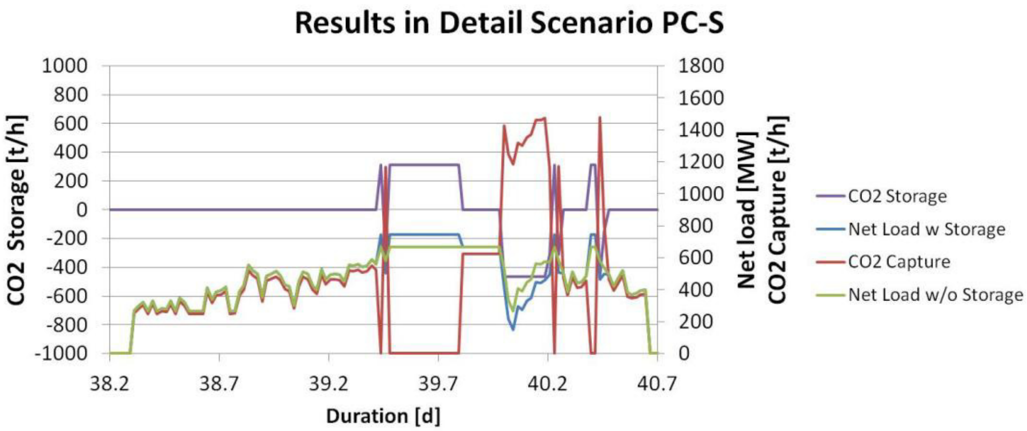

Figure 6: Detail of solvent storage

During times of storage, the net load can be increased by 11.5 %. Emissions and produced electricity do not change, they are only shifted in time. If assuming a price difference of 25 €/MWh between high and low price periods, an overall revenue of 618,888€ could be achieved by storing rich solvent during the 2 month period.

Detailed results of net load, CO_2 emissions and other effects due to bypassing are shown in table 2:

Table 3. Results scenario PC-S

Scenario PC-S			
Thermal output [MW_{th}]	1913	Electricity produced (reference) [MWh]	627800
Net load [MW]	666	Electricity produced (storage) [MWh]	628185
Net efficiency [%]	34.81	CO_2 captured (reference) [t]	587621
Net load storage [%]	743	CO_2 captured (storage) [t]	587621
Net efficiency storage [%]	38.84	CO_2 emissions (reference) [t]	73453
Capture efficiency [%]	87.5	CO_2 emissions (storage) [t]	73453
Maximum storage volume for loaded solvent [m^3]	95429	Revenues due to higher net load in high price periods (theor.) [€]	618888

4.4. Scenario Oxy-B

Like the PC-B scenario, bypassing leads to significantly higher CO_2 emissions (see fig. 7). Similar to the post combustion scenario, bypassing is only economically efficient if the relation between emission certificates and electricity prices is high (see details in table 4). This is only true for short periods, in this study, a conservative price difference of 25 €/MWh between low and high price periods is assumed.

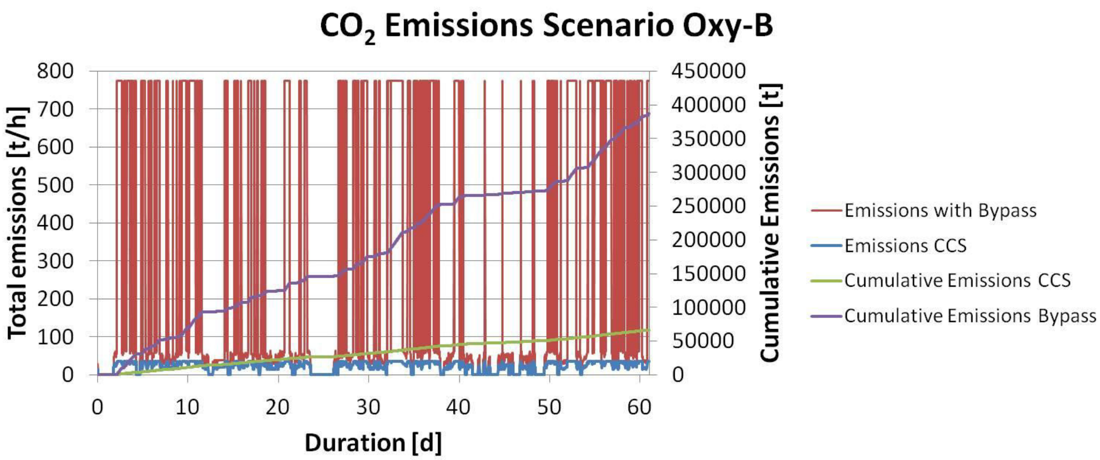

Figure 7: Detail of oxyfuel power plant bypass

Table 4. Results scenario Oxy-B

Scenario Oxy-B			
Thermal output [MW_{th}]	1990	Electricity produced (reference) [MWh]	627800
Net load [MW]	666	Electricity produced (bypass) [MWh]	661544
Net efficiency [%]	33.47	CO_2 captured (reference) [t]	663584
Net load bypass [%]	740	CO_2 captured (bypass) [t]	342578
Net efficiency bypass [%]	37.19	CO_2 emissions (reference) [t]	66358
Capture efficiency [%]	90	CO_2 emissions (bypass) [t]	387365
Air separation unit full load [MW]	139	Relation of electricity price to emission certificate price for cost-effectiveness [(€/MWh)/(€/t)]	9.51
Loss resulting from bypassing [€]	-2366466.76		

4.5. Scenario Oxy-S

If liquid oxygen is produced and stored in partial load periods, the air separation unit that is consuming a lot of electricity can be switched off during high price periods leading to a higher net load of the power plant. After the high price period, the storage tank is filled up again, lowering the net load.

Figure 8 is showing the storage level for the tanks containing liquid oxygen. O_2 losses due to boiling are not considered in the storage level calculations yet.

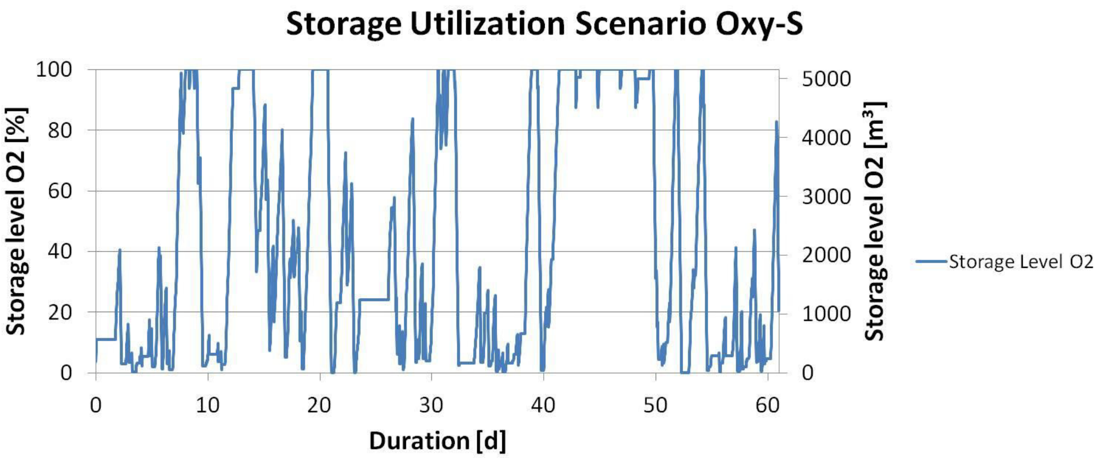

Figure 8: Storage level for liquid oxygen storage

If liquid oxygen storage is applied, a revenue of 575,772€ could be achieved in the 2 month period (see table 5). As mentioned, CAPEX for storage tanks and equipment are not considered in this number, only price differences of electricity and the higher net load of the power plant after switching off the ASU.

Table 5. Results scenario Oxy-S

Scenario Oxy-S			
Thermal output [MW_{th}]	1990	Electricity produced (reference) [MWh]	627800
Net load [MW]	666	Electricity produced (storage) [MWh]	628027
Net efficiency [%]	34.81	CO_2 captured (reference) [t]	663584
Net load storage [%]	805	CO_2 captured (storage) [t]	663757
Net efficiency storage [%]	40.45	CO_2 emissions (reference) [t]	66358
Capture efficiency [%]	90	CO_2 emissions (storage) [t]	66376
Maximum storage volume for liquid oxygen [m³]	5158	Revenues due to higher net load in high price periods (theor.) [€]	575772

5. Conclusions

Two options to increase the flexibility of two types of CCS power plants were examined. Simulations for a predicted future load curve were performed. Results show that due to the higher emissions and the related costs for CO_2 emission certificates, bypassing is only an economically efficient option if the relation between electricity prices per MWh and prices for emission certificates per ton CO_2 is high (8 to 10). The scenarios applying storage technologies for rich solvents or liquid oxygen performed better, but these involve numerous new components like storage tanks, pumps and other auxiliary equipment leading to higher CAPEX for the power plant. The influence of higher CAPEX was neglected in this study, however, results were showing a tendency of the performance of such flexibility measures.

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