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Analysis of retrofitting coal-fired power plants with carbon dioxide capture

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Abstract

The retrofitting of existing coal-fired power plants with a carbon dioxide capture offers a promising opportunity to achieve the global target reduction in CO_2 emissions. This paper deals with the integration of an amine-based flue gas scrubber with a coal-fired power plant including compression of CO_2 and the resulting effects of the integration on the power plant's operation.

Keywords: coal; power plant; CO_2 capture; CO_2 compression; retrofit

1. Introduction

Fossil fuel-fired power plants, especially coal-fired ones, will keep playing a major role in global power generation. In order to meet strict climate protection aims carbon dioxide capture and storage of such plants will gain more and more importance. The basis of the analysed coal-fired power plant is provided by the concept study "Reference power plant North Rhine-Westphalia" which currently presents the state-of-the-art of hard coal-fired power plants in Germany with a net efficiency of 45,9 % (LHV) without CO_2 capture. At first connection points between the flue gas scrubber and the power plant had been identified. The most important one is the heat supply from the power plant's water/steam cycle in order to be able to regenerate the amine in the reboiler. For this, corresponding steam properties in the extraction steam pipes have to be characterised in order to fulfill the requirements of the capture process in terms of mass flow, pressure and temperature. The reduced steam flow through the turbine resulting from the extraction can lead to considerable changes in thermodynamic steam parameters depending on the necessary specific heat demand of the gas scrubber considering that 90 % of the flue gas CO_2 is captured. To ensure a smooth power plant operation with and without CO_2 capture, changes at the power plant have to be undertaken, which will be shown in detail. In addition to heat supply the power plant has to provide electrical energy for the gas scrubber, flue gas blower and CO_2 compressor. Furthermore, the demand of cooling water increases, since additional cooling water is needed for the capture and liquefaction of CO_2. The needed modifications to retrofit the presented power plant with a CO_2 scrubbing process and their effect on power plant's operation will be discussed.

2. The coal-fired power plant

Figure 1 shows the process flow diagram of the coal-fired power plant. The basis of the analysed coal-fired power plant is provided by the concept study "Reference power plant North Rhine-Westphalia" [1] which currently presents the state-of-the-art of hard coal-fired power plants in Germany with a net efficiency of 45,9 % relating to the lower heating value and without CO_2 capture. The thermodynamic model of the coal-fired power plant process contains the water/steam cycle as well as the air/flue gas path.

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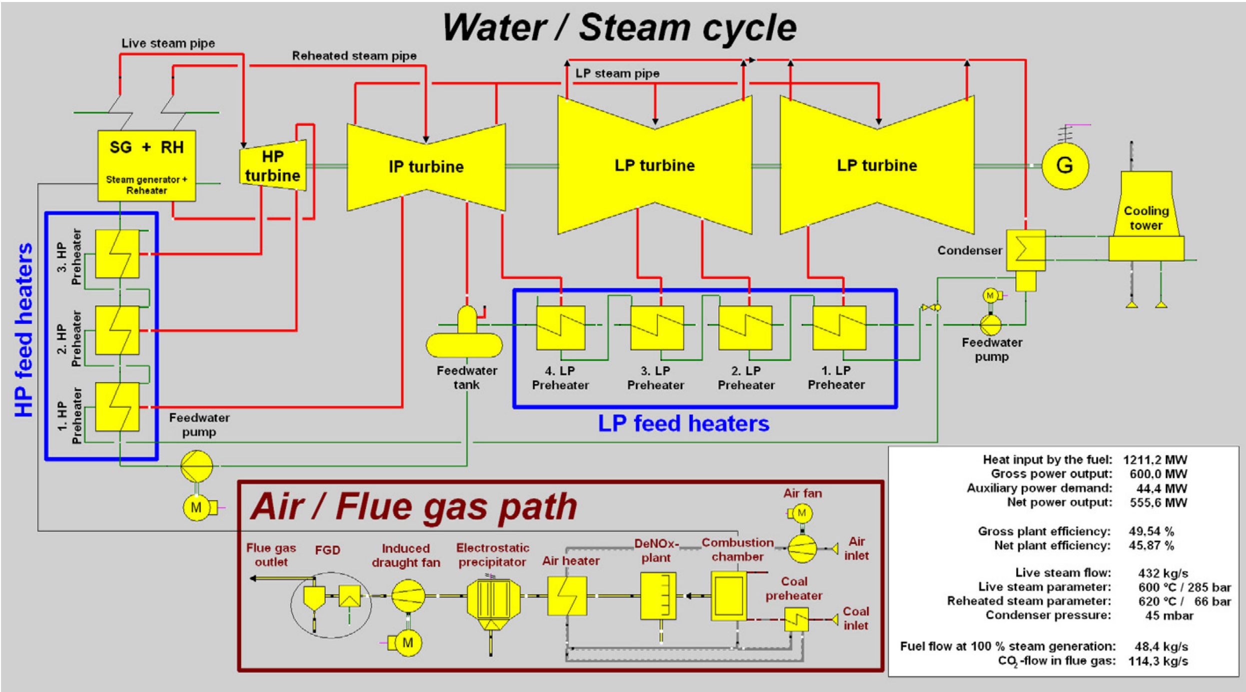

Figure 1: Process flow diagram of the coal-fired power plant in EBSILON®Professional

2.1. Water/steam cycle

The main components in the water/steam cycle are the steam generator, the turbine set including the high, intermediate and low pressure (HP, IP, LP) turbine, the condenser, the pumps and the 8 feedwater heaters. The water is evaporated and superheated in the steam generator to 600 °C at 285 bar and led via the live steam pipe to the singleflow HP turbine. There the steam is expanded in the HP stages of the turbine and two partial flows are extracted to preheat the feedwater in the 2. and 3. HP preheater. The residual steam is reheated in the boiler to 620 °C at 60 bar and conducted through the reheated steam pipe to the double-flow IP turbine. The main IP steam flow is delivered to the two double-flow LP turbines while a small amount of the steam is extracted for the 1. HP preheater, the feedwater tank and the 4. LP preheater. In the LP turbines the steam is expanded to the condenser pressure of 45 mbar as partial steam flows are extracted for the first three LP preheaters. In the condenser the steam is converted into water and delivered by the feedwater pumps to the steam generator, where the cycle starts again. The heat-up of the feedwater is realised in 8 preheaters, whereas five of them are located in the LP path (before main feedwater pump) and three of them in the HP path (behind main feedwater pump). The temperature increase of the feedwater to 303,4 °C before entering the steam generator results from temperature steps of 34 K in each preheater.

2.2. Air/flue gas path

In the air/flue gas path coal and air is preheated and subsequently converted into hot flue gas in the furnace while a small part is carried out in form of ash at 300 °C. The ambient air is preheated to 350 °C and delivered to the furnace by a fan. For the combustion an air ratio of 1,15 is considered. The flue gas leaves the boiler at 360 °C and is conducted to the denitrification plant ($DeNO_x$). After denitrification the flue gas is cooled in air heater from nearly 360 °C to 115 °C and subsequently removed from dust in the electrostatic precipitator. By an induced draught fan the flue gas is delivered to the flue gas desulphurisation plant (FGD) and finally emitted at a temperature of approximately 50 °C into the atmosphere.

3. Retrofitting of a coal-fired power plant with carbon dioxide capture

The retrofitting of a coal-fired power plant with carbon dioxide capture presents one opportunity to reduce the CO_2 of the power plant flue gas. For this the carbon dioxide capture unit requires electrical and thermal energy (Table 1) which must be provided by the power plant [2].

Table 1: Required components for carbon dioxide capture with description of their intended use and their energy demand, which must be provided by the power plant process

energy form	component	intended use
electrical energy	• additional FGD • additional fan • CO_2 compressor • CO_2 scrubbing plant	• reduction of the SO_x < 10 ppm • compensation of the pressure drop in the absorber • liquefaction of the CO_2 • e.g. circulation of the detergent
thermal energy (heat input)	• reclaimer • reboiler	• reclaiming of the detergent • seperation CO_2 from the detergent
thermal energy (heat output)	• flue gas cooler • lean amine cooler • CO_2-cooler	• improvement of the absorption process + reduction of the energy demand for the additional fan • improvement of the absorption process • energetic optimization of the CO_2 compression + drying ot the CO_2

In the following subchapters the model of the carbon dioxide capture unit, which consists of the flue gas scrubber with subsequent CO_2 compressor is presented. Furthermore, the integration of the carbon dioxide capture unit in the power plant process is demonstrated in detail.

3.1. Amine-based flue gas scrubber

The power plant flue gas must be pre-treated before entering the absorber to reduce undesired flue gas components, particularly the SO_x concentration (which mostly consists of SO_2 and just a low amount of SO_3). The main reason for lowering the power plant-sided SO_x limit value from 200 mg/m^3 to a limit value below 10 mg/m^3 is to prevent an irreversible degradation of the amine with the SO_x by forming heat stable salts. The reduction of the SO_x limit value below 10 mg/m^3 is achievable by implementing a second FGD [3], which is considered in the analysis. After leaving the additional FGD and passing through a cooler, the flue gas is conducted to the absorber by a blower, which compensates the pressure drop occurring in the absorber. Then the flue gas enters the absorber at the bottom and is led in reverse direction to the scrubbing agent to the top of the absorber, where it is emitted with reduced CO_2 content into the atmosphere. Meanwhile the rich amine solvent is accumulated in the bottom of the absorber and delivered to the stripper after preheating in the lean/rich heat exchangers, where the desorption reaction take place. The required heat to run the desorption reaction is taken out of the power plant process in form of steam and provided for the reboiler and reclaimer. At the top of the stripper a gas flow containing CO_2 and steam at nearly 120 °C is led to the CO_2 cooler, where the gas flow is cooled down to 40 °C. Saturated CO_2 gas is delivered to the compressor and separated water is returned back to the stripper. The lean amine solvent is accumulated at the bottom of the stripper and flows through the lean/rich heat exchangers and an additional lean amine cooler back to the absorber.

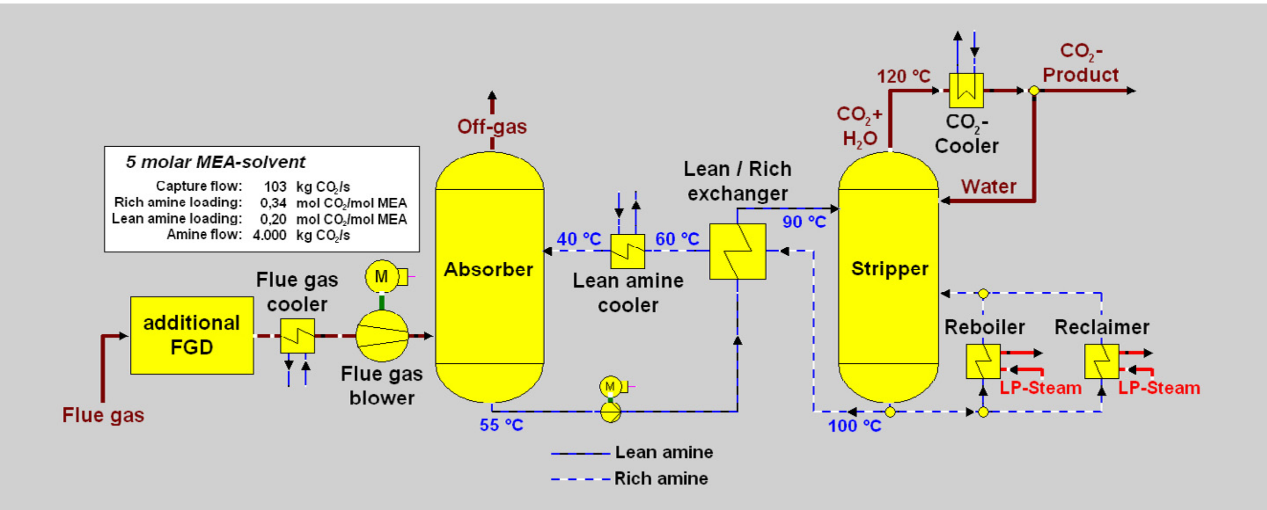

Figure 2: Model of the amine-based flue gas scrubber

3.2. CO_2 compression

For transport and storage purposes the saturated CO_2 gas coming from the amine-based flue gas scrubber must be compressed. Figure 3 shows a compression path with five stages.

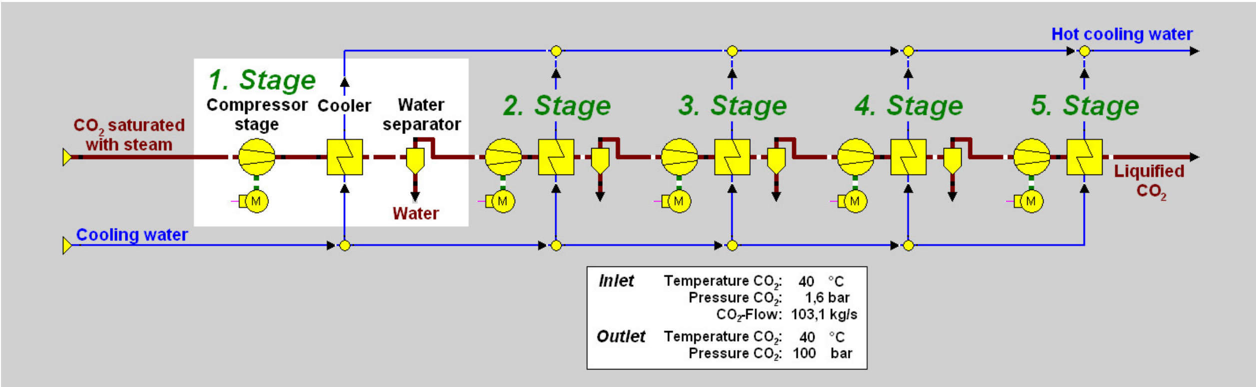

Figure 3: Supercritical liquefaction of the saturated CO_2 for a compressor with five stages

The saturated CO_2 gas enters the first stage of the compression path at 40 °C and 1,6 bar. Each stage of the compression path consists of a compressor stage where the pressure increase is realised and a cooler with following water separator where the CO_2 gas is separated from water which occurs in the cooler. Only the last stage doesn't have a water separator due to the supercritical pressure increase of the CO_2 gas in the last compressor stage. The cooling of the CO_2 gas in each stage is realised with cooling water of the power plant process. The inlet conditions of the cooling water in each cooler are the same because of parallel feeding. After heating-up the cooling water in every stage the water is accumulated and conducted back to the cooling water cycle of the power plant.

3.3. Integration of carbon dioxide capture in the power plant process

The power plant process has to provide a huge amount of heat in form of steam for the desorption reaction in the stripper besides supplying cooling water and electricity (Table 1). The steam of the power plant process has to fulfill certain criteria because the scrubbing agent has to be heated up to 130 °C [4]. One important criterion of the power plant steam is a minimum steam temperature of 140 °C and a minimum steam pressure of 3,6 bar respectively under consideration of a pinch point in the reboiler of 10 K. Basically steam can be taken out of the steam pipes which flows to or off the HP, IP and LP turbine as well as extraction steam, which is used to preheat the feedwater. A considerable amount of heat in form of steam can't be taken out of the extraction steam pipes due to the given cross section of the extraction steam nozzles. Because the extension of these nozzles seems to be not feasible, the use of extraction steam for carbon dioxide capture purposes is no longer considered in this paper. Also not considered are the steam extractions out of the live steam pipe and the cold reheat pipe, because both lead to an imbalance of thermal load in the boiler. For this reason the following investigations focus on the extraction of steam out of the LP steam pipe.

4. Analysis of the power plant behaviour with carbon dioxide capture by use of LP steam

The steam extraction out of the LP steam pipe for carbon dioxide capture causes a pressure drop in the LP steam pipe in any case. This pressure drop can lead to a fall of steam pressure below the minimum steam pressure of 3,6 bar ($t_{saturated}$ = 140 °C) which is required from the reboiler. A capture rate of 90 % (respresents a mass flow of 103 kg CO_2/s for the Reference power plant NRW) and a specific heat demand of the flue gas scrubber between 3 GJ/tCO_2 and 4 GJ/tCO_2 causes such a considerable pressure drop in the LP steam pipe that the steam pressure in the LP steam pipe falls below the required limit for the flue gas scrubber of 3,6 bar. The installation of a throttle in the LP steam pipe provides one opportunity to limit the pressure drop in the LP steam pipe in order to ensure a minimum steam pressure of 3,6 bar. Although the throttle limits the pressure drop in the LP steam pipe and guarantees the minimum steam pressure of 3,6 bar, it also leads to throttle losses which accompanies with losses in electricity generation [5].

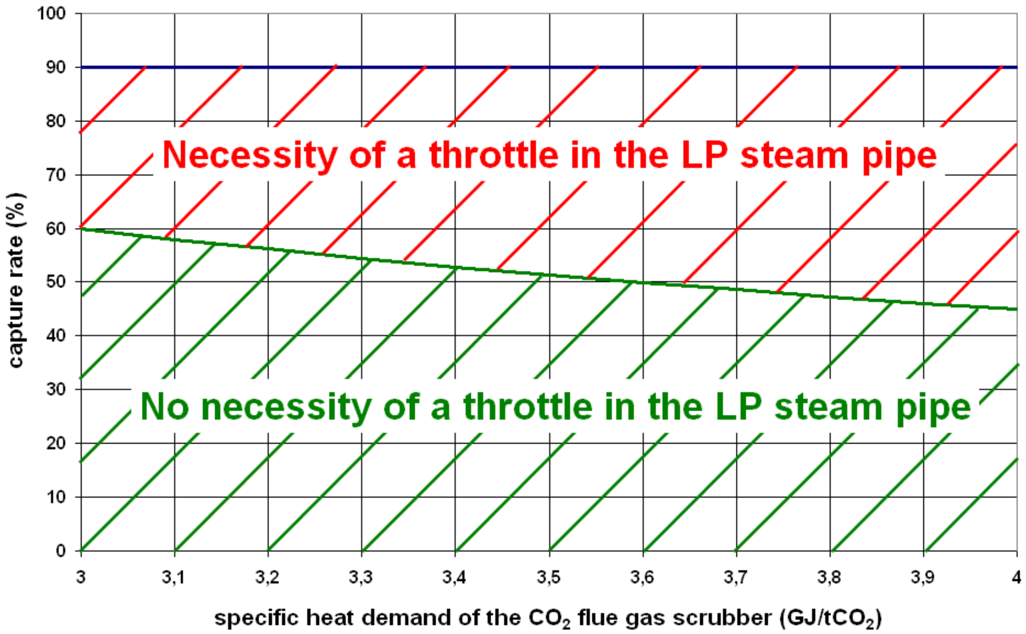

Figure 4: Capture rate of the power plant without and with installation of a throttle in the LP steam pipe depending on the specific heat demand of the flue gas scrubber by keeping a minimum pressure of 3,6 bar in the LP steam pipe

Figure 4 shows the influence of a throttle in the LP steam pipe on the capture rate of the power plant by varying the specific heat demand of the flue gas scrubber. As an example, there is no need to install a throttle for a capture rate up to 60 % if the specific heat demand of the flue gas scrubber is 3 GJ/tCO_2. Higher specific heat demands starting from 3 GJ/tCO_2 up to 4 GJ/tCO_2 lead to a reduction of the capture rate for the power plant without throttle from 60 % to 45 %. To achieve a capture rate of 90 %, the installation of a throttle in the LP steam pipe is necessary in any case.

4.1. Comparison of the power plant process without and with carbon dioxide capture

The comparison of the power plant process without and with carbon dioxide capture is presented in Table 2 for a specific heat demand of 3,5 GJ/tCO_2.

Table 2: Comparison of the power plant process without and with carbon dioxide capture (90 % capture rate, with installation of a throttle in the LP steam pipe) for a specific heat demand of 3,5 GJ/tCO_2 for the flue gas scrubber

		Power plant without carbon dioxide capture	Power plant with carbon dioxide capture (90 % capture rate)
Heat input by the fuel	MW_{th}	1211,2	1211,6
Gross power output	MW_{el}	600	500,6
Auxiliary power demand	MW_{el}	44,4	44,3
Power demand additional FGD	MW_{el}	-	7,2
Power demand additional fan	MW_{el}	-	5,5
Power demand of pumps and aggregates in the CO_2 scrubbing agent unit	MW_{el}	-	10,3
Power demand of the CO_2 compressors (5 stages)	MW_{el}	-	29,1
Net power output	MW_{el}	555,6	404,2
Net plant efficiency	%	45,87	33,36

Table 2 shows, that the gross power output of the power plant with carbon dioxide capture (500,6 MW_{el}) is nearly 100 MW_{el} lower in comparison to the power plant without carbon dioxide capture (600 MW_{el}) by nearly the same heat input by the coal. The main reason for the decrease results basically from the reduced steam flow through the LP turbine due to steam extraction for the flue gas scrubber. On the one hand the reduced steam flow leads to a drop of the LP steam flow through the turbine. On the other hand the reduction of the steam flow causes an operating in part load mode which accompanies with a reduction in efficiency of the LP turbine. Additionally the installation of a throttle in the LP steam pipe effects throttle losses which leads to losses in electricity generation.
All in all the retrofitting of a coal-fired power plant with carbon dioxide capture and a specific heat demand of 3,5 GJ/tCO_2 causes a significant decrease of 151 MW_{el} for the net power output and at the same time a drop in net plant efficiency of 12,51 percentage points.

4.2. Sensitivity analysis of the power plant process with carbon dioxide capture

Figure 5 demonstrates the net power output and the net plant efficiency of the power plant process with carbon dioxide capture depending on the specific heat demand of the flue gas scrubber between 3 GJ/tCO_2 and 4 GJ/tCO_2. The increase in specific heat demand of 3 GJ/tCO_2 to 4 GJ/tCO_2 leads to a reduction of the net power output of 30 MW_{el} from 420 MW_{el} to 390 MW_{el}. Simultaneously the drop in net plant efficiency is 2,5 percentage points from 34,62 % to 32,15 %.

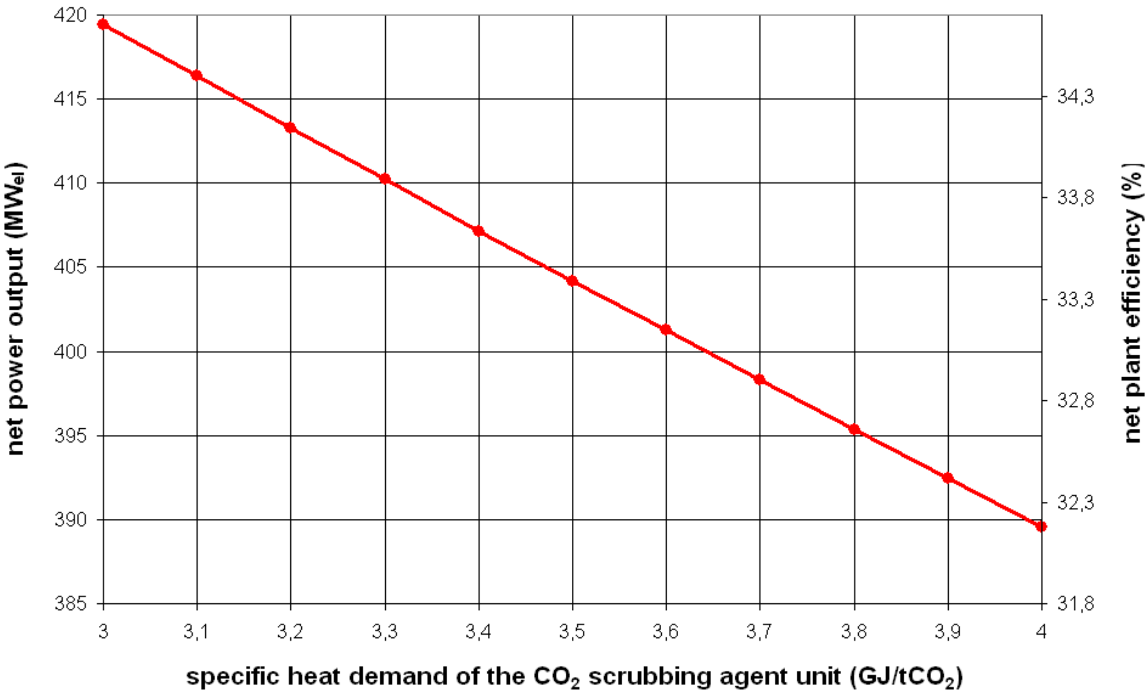

Figure 5: Net power output and net plant efficiency depending on the specific heat demand for the flue gas scrubber

5. Conclusions

The retrofitting of coal-fired power plants with carbon dioxide capture offers an opportunity to reduce CO_2 emissions. The presented paper focuses on the integration of an amine-based flue gas scrubber including CO_2 compression in the coal-fired power plant process and the resulting effects of the integration on power plant's operation.
Beside electricity and cooling water the operation of the carbon dioxide capture unit requires a huge amount of heat which must be provided by the power plant process. In order to cover the heat demand for the carbon dioxide capture, steam out of the LP steam pipe had to be extracted which causes a pressure drop in the LP steam pipe. The installation of a throttle in the LP steam pipe is necessary in any case to capture 90 % of the CO_2 out of the flue gas and at the same time ensuring a minimum steam pressure of 3,6 bar ($t_{saturated}$ = 140 °C) in the LP steam pipe required for the flue gas scrubber.
Based on the power plant without carbon dioxide capture (555,6 $MW_{el,net}$ / 45,87 $\%_{net}$) the retrofitting with carbon dioxide capture leads to a significant drop in electricity and plant efficiency. Both net power output and net plant efficiency fall between 420 MW_{el} and 34,62 % (3 GJ/tCO_2) and 390 MW_{el} and 32,15 % (4 GJ/tCO_2).

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