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Comparison of natural gas combined cycle power plants with post combustion and oxyfuel technology at different CO_2 capture rates

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Abstract

Within this work a natural gas-fired combined cycle plant is investigated with post-combustion CO_2 capture (PCC) and as a semi-closed oxyfuel combustion combined cycle (SCOC-CC) using process simulation tools. In most studies the CO_2 capture rate of PCC units is set to 90 % while the SCOC-CC is often considered for zero emission plants. To allow a comparison between the processes the capture rate needs to be taken into account. If a certain CO_2 emission value is required a different capture rate may be economically attractive. The effect of the capture rate is investigated from 60 % to 97.5 % for PCC and from 75 % to 100 % for the SCOC-CC. For PCC the capture rate has a strong influence on the efficiency penalty. For a broad range of capture rates the specific heat duty is found to be approx. constant. However, for very high capture rates the heat duty strongly increases. The efficiency penalty of the SCOC-CC is much less affected by the chosen capture rate, because the duty of the air separation unit (ASU) is independent on the capture rate. However to achieve a sufficient CO_2 purity a reduced capture rate can be necessary.
The processes are compared regarding the loss of electrical energy per kg CO_2 captured. PCC has a significantly lower specific loss for low capture rates of approx. 0.38 $kWh_{el}/kg\ CO_2$ compared to the SCOC-CC with more than 0.48 $kWh_{el}/kg\ CO_2$. For capture rates of > 90 % the losses of both processes approach each other. With high purity oxygen the SCOC-CC can achieve a capture rate of 100% as well as a CO_2 purity of >96 vol.-% at a specific loss of 0.49 $kWh_{el}/kg\ CO_2$.

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Keywords: NGCC; post-combustion capture; oxyfuel; capture rate

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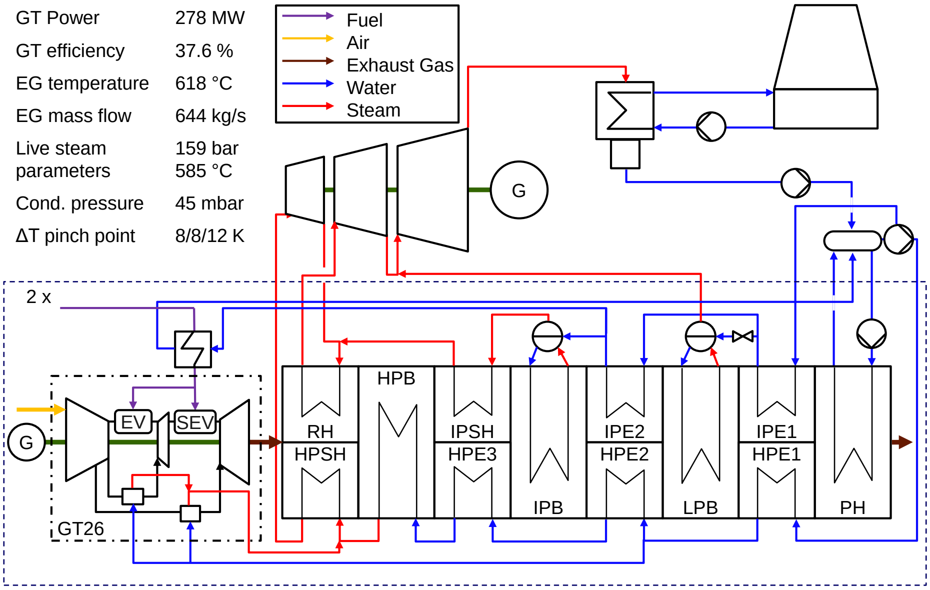
1. Introduction

Post combustion capture (PCC) and oxyfuel combustion are two of the most promising technologies to implement carbon capture and storage (CCS) in fossil-fuelled power plants. While most studies on CCS technologies focus on coal-fired steam power plants (SPP) both technologies are also considered to reduce the emission for natural gas-fired combined cycle (NGCC) power plants. With approx. 350 g CO_2/kWh_{el}, the fuel specific CO_2 emissions of natural gas in combined cycle plants are significantly lower compared to bituminous coal-fired steam power plants (approx. 750 g CO_2/kWh_{el}). The application of CCS technologies for NGCC plants allows a further reduction of the emissions far below 100 g CO_2/kWh_{el}. However, more energy is needed to separate a given amount of CO_2 from an NGCC plant than from a coal-fired SPP. For post-combustion capture this can be explained with the lower partial pressure of CO_2 in the flue gas resulting in lower rich loadings of the amine. For oxyfuel combustion more oxygen has to be supplied per generated CO_2 due to the lower C/H-ratio of natural gas. Despite the higher energy demand per kilogram CO_2 captured, the efficiency penalty for NGCC plants with CCS is generally equal or lower than for coal-fired SPP since less CO_2 is separated.

In many studies the CO_2 capture rate of the PCC unit for NGCC plants is adapted from the coal-fired case. In general a capture rate of 90 % is considered. Depending on the legislative framework it could be favourable not to focus on a fixed capture rate but to achieve a fixed specific CO_2 emission value. For natural gas-fired oxyfuel plants, e.g. the semi-closed oxyfuel combustion combined cycle (SCOC-CC), full CO_2 capture is often assumed regardless of the CO_2 content in the flue gas. To compare the processes at different capture rates the loss of electrical energy due to the capture process has to be related to the amount of CO_2 captured.

2. Reference case

A conventional NGCC plant based on two ALSTOM® GT26 gas turbines as shown in Figure 1 is used as reference process. The GT26 uses sequential combustion with an EV (environmental) and an SEV (sequential environmental) combustor. Each gas turbine supplies a triple pressure reheat HRSG. The process is modelled using EBSILON®*Professional*. Further details on the reference process can be found in [1]. The fuel is natural gas with an LHV of 46.2 MJ/kg which contains by volume 90 % CH_4, 6.5 % higher hydrocarbons, 2 % N_2 and 1.5 % CO_2. The reference process reaches a gross efficiency of 59.8 % and net efficiency of 59.2 %.



GT Power	278 MW
GT efficiency	37.6 %
EG temperature	618 °C
EG mass flow	644 kg/s
Live steam parameters	159 bar 585 °C
Cond. pressure	45 mbar
ΔT pinch point	8/8/12 K

Fig. 1. Flow sheet of the reference NGCC

3. NGCC with post combustion capture

Applying the basic post combustion capture (PCC) process leaves the power plant almost unchanged. The flue gas coming from the heat recovery steam generator is led to a carbon capture unit (CCU) where part of the CO_2 is separated from the remaining flue gas. For this paper, an amine based washing plant is used with 30 wt-% MEA as solvent. The basic capture unit consists of an absorber and a stripper. In the absorber, flue gas and washing solution are flowing in counter current and 90 % of CO_2 is absorbed by the solution. The CO_2 rich solution is heated up in the rich-lean heat exchanger (RLHX) and enters the stripper at the top afterwards. In the stripper the CO_2 is removed from the solution using heat to produce a gaseous phase consisting of water and CO_2. This gas is cooled down in the overhead condenser, where most of the water is condensed and returned to the stripper, while the CO_2 is led to the compressor. The CO_2 is compressed to 110 bar to allow for easy transport. The CO_2 lean solution is cooled down in the RLHX and led back to the absorber.

There are different energy demands in the capture plant leading to a reduction of energy efficiency of the overall process consisting of the power plant, the capture plant and the CO_2 compressor by 7.12 %-pts. from 59.22 % to 52.10 %. The difference between the net efficiency of the reference plant and the overall efficiency of the plant with CO_2 capture is called overall efficiency penalty, which can be divided into different contributors. The different contributors are shown in Figure 2 for a base case without any process modifications.

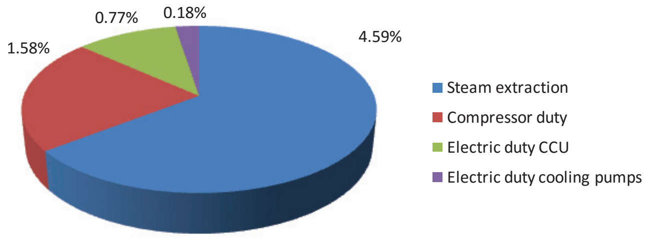


Fig. 2. Contributors to the overall efficiency penalty for base case

The largest contributor with 4.59 %-pts. loss of net efficiency is the penalty due to steam extraction. The heat required for solvent regeneration in the stripper is provided by steam which is extracted from the IP/LP-crossover between the intermediate pressure (IP) turbine and the low pressure (LP) turbine in the steam cycle of the power plant. Since this steam is not available for electricity production any longer, the net output of the plant decreases. The second largest contributor with 1.58 %-pts. is the penalty due to the electric duty of the CO_2 compressor. The electric duty of different consumers in the CCU (0.77 %-pts.) and the electric duty for additional cooling pumps to supply cooling duty for compressor and CCU (0.18 %-pts.) have only minor influence on the efficiency penalty.

3.1. Capture process improvement

There are different means to reduce the efficiency penalty caused by the CCU, some of which are presented in the following. The main difference between PCC for coal fired power plants and gas fired power plants is the difference in flue gas composition. While flue gas from coal fired power plants contains around 13.5 vol.-% CO_2, flue gas from gas fired power plants contains around 4.3 vol.-%. Due to the lower CO_2 content, the specific heat duty is higher, since the partial pressure of CO_2 in the flue gas is lower resulting in slowed down absorption. This effect can be reduced by using flue gas recirculation to increase the CO_2 content of the flue gas. Part of the flue gas coming from the HRSG is cooled down and led back to the turbine compressor where it is mixed with fresh air. Depending on the recirculation ratio, the CO_2 content of the flue gas can be increased to around 9 vol.-%. The recirculation ratio is the ratio between flue gas flow being recycled to the compressor and flue gas flow coming from the HRSG. This results in a reduced energy demand of the capture plant, since a higher rich loading and thus a lower solution mass flow can be achieved. This positive effect is partly outweighed by a decreased efficiency of the power plant. The recirculated flue gas is cooled down to around 40 °C, still the temperature is higher compared to ambient temperature resulting in an increased compressor inlet temperature. This leads to an increased power demand for compression and thus lower power output of the gas turbine generator. Nevertheless, an increase of net efficiency by around 0.2 %-pts. is obtained with flue gas recirculation. In addition, the size of the capture plant is significantly reduced, since the flue gas mass flow is reduced by around 50 % for highest recirculation ratios. For high recirculation ratios, the gas turbine has to be modified, though, since the flue gas composition is changed.

Another way to reduce overall efficiency penalty is lean vapour compression. The lean solution coming from the stripper is throttled and steam is flashed off. The steam is compressed and led back to the stripper, while the remaining lean solution is led to the RLHX. The reboiler heat duty can be reduced significantly at the cost of increased electricity demand for compression of the vapour. In total, the net efficiency of the overall plant can be increased by 0.51 %-pts. for the base case.

3.2. Capture rate variation

Most studies on PCC use CO_2 capture rates of 90 % with the capture rate being the ratio between captured CO_2 mass flow and total CO_2 mass flow coming from the power plant. This value was first used for PCC at coal fired plants and was found to be adequate [2]. It was adapted for PCC at NGCC plants as well and only few studies have given attention to this topic. In the following, the energetic performance of the overall plant is evaluated for capture rate between 60 and 97.5 %. The capture rate can be varied by changing the solution flow rate or the exchange area in the absorber. All numbers shown in the following are for newly designed capture plants, with the diameter of the absorber resulting from a fractional approach to flooding point of 70 %. The height of the absorber is kept constant at 15 m leaving the solution mass flow as the only variable to affect the capture rate.

The effect of different capture rates on the specific heat duty and the overall efficiency penalty of the base case are shown in Figure 3. For each capture ratio, the solution flow rate, and thereby the lean loading, has been varied to find the operation point with the lowest specific heat duty. It can be seen that the specific heat duty increases with increasing capture rate. This results from the lower partial pressure of CO_2 that has to be achieved when more CO_2 is captured. The increase is moderate up to around 85 % and accelerates for higher capture ratios. This is reflected in the optimal lean loading as well, which increases slightly from 0.24 mol CO_2/mol MEA for 60 % capture rate to 0.23 mol CO_2/mol MEA for 85 % capture rate, but to 0.17 mol CO_2/mol MEA for 97.5 % capture rate. Simultaneously, the overall efficiency penalty increases almost linearly from around 4.8 %-pts. for 60 % capture rate to 6.6 %-pts. for 85 % capture rate, but to 9.4 %-pts. for 97.5 % capture rate.

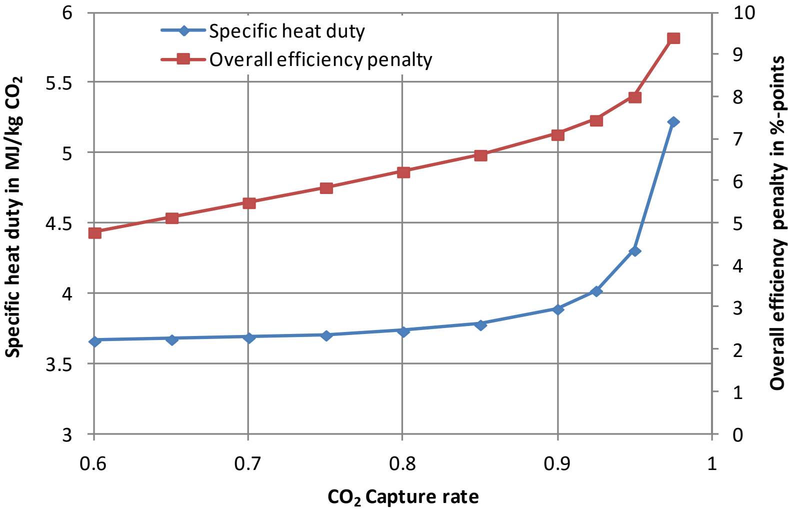


Fig. 3. Specific heat duty and overall efficiency penalty for different capture rates for base case

When the modified processes with lean vapour compression or flue gas recirculation are used to obtain different capture rates, the results show the same tendency. Higher capture rates result in higher specific heat duties and higher overall efficiency penalties. For the LVC case, a flash pressure of 1 bar was used. Again, the increase in specific heat duty is moderate for low capture rates: it increases from 3.03 MJ/kg CO_2 for 60 % capture rate to 3.15 MJ/kg CO_2 for 90 % capture rate. For 97.5 % capture rate the specific heat duty increases to 4.48 MJ/kg CO_2. The positive effect of LVC on the overall efficiency decreases for both very high and very low capture rates. While the net efficiency was increased by 0.51 %-pts. for 90 % capture rate, the increase is only 0.35 %-pts. and 0.33 %-pts. for 60 % capture rate and 97.5 % capture rate, respectively. This is due to the reduced influence of the specific heat duty when LVC is applied.

The case with flue gas recirculation was evaluated with a recirculation ratio of 50 %. The high recirculation ratio results in an increased CO_2 content in the flue gas, resulting in a reduction of the overall efficiency penalty by 0.17 %-pts. for 90 % capture rate. As for the LVC case, the trend for both specific heat duty and overall efficiency penalty are similar for different capture ratios. For low capture ratios, the curve ascends moderately. Towards higher capture ratios, the increase accelerates. The point where the slope of the curves ascends is shifted to higher capture rates (around 90 %), though. This is due to the higher CO_2 content in the flue gas, facilitating the absorption of CO_2 for high capture rates since the partial pressure of CO_2 is higher compared to the base case.

4. SCOC-CC

The SCOC-CC process is derived from the reference process shown in section 2 as shown in Figure 4. The original ALSTOM® GT26 gas turbine (Figure 1) is modified to an oxyfuel gas turbine by adding oxygen from the air separation unit (ASU) upstream of the first combustor, i.e. the original EV combustor. The turbine inlet temperatures and component efficiencies are kept constant. Downstream the HRSG the flue gas is further cooled to 40 °C and condensing water is removed. Approx. 90 % of the flue gas is then recycled to the compressor of the gas turbine to moderate the turbine inlet temperature of the reference gas turbine. As the gas turbine is strongly affected by the change of the working fluid a more detailed gas turbine model is used to evaluate the oxyfuel cycle. A more detailed description of the SCOC-CC model can be found in [1]. The oxygen is provided by a cryogenic ASU at atmospheric pressure and is compressed to combustor pressure. A compressor with two intercooling sections is used to keep the oxygen temperature at the compressor outlet below 200 °C for safety reasons [3]. Two oxygen purities will be considered in this study. The energy demand as well as composition and temperature of the supplied oxygen are given in Table 1. As a base case scenario 95 vol.-% oxygen is used. The ASU delivers 1.8 % more oxygen than what is needed for stoichiometric combustion (global oxygen excess). Due to the oxygen in the recycle, this results in an excess oxygen ratio of approx. 1.3 in the SEV combustor and a residual oxygen content in the flue gas of 3 vol.-% (dry).

The base case does not include further purification of the CO_2. The non-recycled flue gas is completely compressed to pipeline pressure of 110 bar in a seven stage compressor ($\eta_{p,s}$ = 0.85, η_m = 0.99) with intercooling to 30 °C and water removal after each stage. This results in a capture rate of 100 %, neglecting some CO_2 dissolved in the condensed water. The steam cycle of the process remains almost unchanged but it is necessary to adjust the pinch point temperature differences to keep the HRSG in energy balance when the turbine outlet temperature changes.

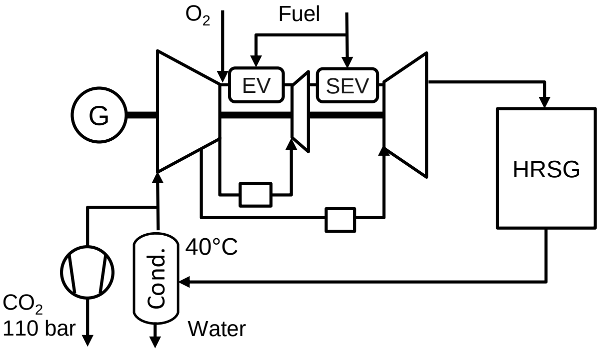


Fig. 4. Schematic view of the SCOC-CC

Table 1. Oxygen supply.

	95 vol.-% O_2	99.5 vol.-% O_2
Specific energy demand ASU in kWh_{el}/t_{O2}	202	241
Specific energy demand compression in kWh_{el}/t_{O2}	136	129
Oxygen temperature downstream compression in °C	183	181
Composition in vol.-%		
Oxygen	95	99.5
Argon	3.8	0.04
Nitrogen	1.2	0.01

As it is widely known for oxyfuel gas turbines, the high CO_2 content in the working fluid requires a significantly higher pressure ratio than in conventional gas turbines [4, 5, 6]. Due to the sequential combustion principle in the GT26, the pressure ratio of the reference gas turbine is already high at 32.8. The optimum efficiency of the modeled SCOC-CC process would require a pressure ratio of 90 which is considered as unreasonably high. In this study the process is considered at an assumed maximum pressure ratio of 60 which leads to a net efficiency of 50.3 % which is only 0.3 %-pts. below the optimum value. This results in an efficiency penalty compared to the reference process of 8.9 %-pts. The efficiency penalty can be divided into 5.9 %-pts. for oxygen production and 2.3 %-pts. for CO_2 compression. Furthermore, the auxiliary power of the basic plant increases by approx. 0.3 %-pts. The remaining difference is caused by the changed thermodynamics of the process. It should be noted that the gross efficiency of the SCOC-CC is several %-pts. higher than that of the conventional NGCC. This is due to the fact that the gas turbine compressor only accounts for the recycled flue gas while the oxygen compressor is considered as an additional consumer.

4.1. Zero emission case

As stated before, the capture rate of the base case process is 100 %. However, the purity of the CO_2 generated is only 86.5 vol.-%. This is well below common quality requirements of existing CO_2 pipelines and quality recommendations [7, 8]. Besides CO_2, the present study only considers water and non-condensable gases Ar, N_2 and O_2. It is assumed that complete combustion is achieved and no formation of NO_x and SO_x and other contaminants occurs. The sum of all non-condensable gases should not exceed 4 vol.-%. However, for EOR applications the oxygen content can be further restricted. Within this study, a CO_2 purity of 96 vol.-% (dry) is used as a guideline to evaluate the need for CO_2 purification. The removal of water is not investigated in detail. Due to the intercooled compression, the water content cannot be reduced below 1000 ppm. For a lower water content further measures have to be taken, e.g. the use of a molecular sieve.

The purity of the base case process is by far too low to achieve the desired value. The CO_2 purity can be increased by reducing the concentration of oxygen or the inert gases (Ar, N_2) in the flue gas. This can be achieved by reducing the oxygen excess or increasing the oxygen purity, respectively. Figure 5 shows the variation of the oxygen excess from the ASU for the two oxygen purities shown in Table 1. For 95 vol.-% oxygen purity the maximum achievable CO_2 purity is approximately 90 % for stoichiometric conditions. If a purity of 96 % is required a further purification step is necessary.

For high purity oxygen a CO_2 purity of 96 % can be achieved if the global oxygen excess is below 0.7 %. Due to the recycled oxygen this leads to an oxygen excess ratio of 1.1 in the SEV combustor or 1.3 vol.-% residual oxygen in the dry flue gas. The higher energy demand of the high purity ASU leads to an increased energy penalty of 7 %-pts. although less excess oxygen is supplied. Furthermore, the process efficiency is slightly reduced at a constant pressure ratio due to the higher CO_2 content in the working fluid. In contrast to this the compression duty for the O_2 and CO_2 stream is slightly reduced because of the lower inert content. The resulting net efficiency of the process is 49.5 %.

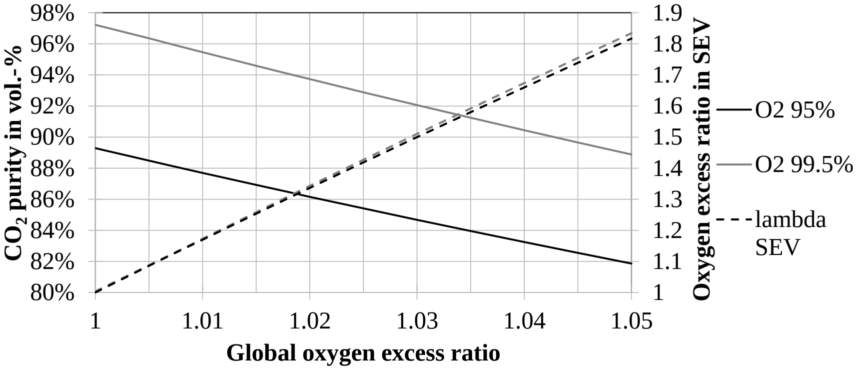


Fig. 5. CO_2 content in the flue gas (dry) and oxygen excess ratio in the second combustor in relation to the global oxygen excess ratio.

4.2. Additional CO_2 purification

The second option to achieve the recommended purity is the application of a partial condensation gas processing unit (GPU) in combination with a low purity oxygen ASU. Within this unit a CO_2 rich liquid phase is condensed from the flue gas, which can be pumped to pipeline pressure. However, the remaining vent gas still contains some CO_2 reducing the capture rate of the process. The purity of the CO_2 and the capture rate of the process depend on the pressure and temperature conditions within the GPU.

The GPU is modelled in AspenPlus® as shown in Figure 6 [9]. The flue gas is compressed by a six stage compressor with intercooling after each stage. Water is removed by a molecular sieve. The flue gas is then cooled to -25 °C for a first condensation step. At this temperature the CO_2 purity is high but at a low capture rate. The remaining gas can be further cooled to a minimum temperature of -50 °C. At this temperature more CO_2 can be captured but at a lower purity. Two cooling cycles with NH_4 and CO_2 as coolant are used for refrigeration. The vent gas is expanded through a turbine for energy recovery. Before expansion, the vent gas is heated by the compressed NH_4 coolant to avoid dry ice formation. The condensed CO_2 streams are mixed and pumped to pipeline pressure. After pumping, the cold stream is used to cool the compressed and dried flue gas. If a high share of CO_2 is separated on the low temperature level, the compressed flue gas can be pre-cooled below -25 °C. In this case, the NH_4 cooler is set to zero duty.

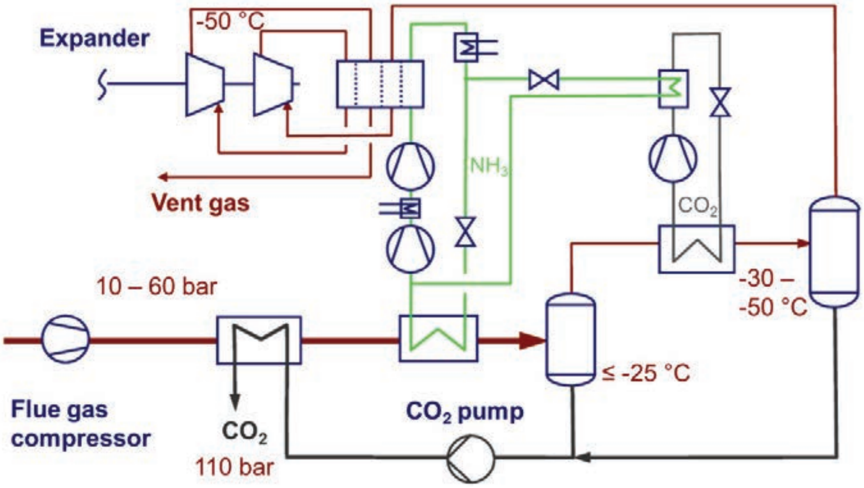


Fig. 6. Simplified schematic flow sheet of the partial condensation GPU according to [9]

For a fixed condensation temperature the CO_2 capture rate of the process can be adjusted by varying the pressure. Figure 7 shows the resulting CO_2 purity (a) and the change of the efficiency penalty associated with the GPU in relation to the base case (b) for a broad range of CO_2 capture rates. Generally, the purity of the CO_2 decreases as the capture rate rises. However, at -40 °C and -50 °C the curves show cusp points above capture rates of 0.84 and 0.92, respectively. This occurs when the required pressure for the respective capture rate reaches approx. 20 bar. Above this pressure, higher purity CO_2 is condensed at -25 °C and the energy demand of the GPU drops significantly. The lower the second condensation temperature the higher the capture rate at which the drop occurs.

For a condensation temperature of -50 °C a maximum capture rate of 95.8 % is possible while keeping the CO_2 purity above 96 vol.-% as well. At this capture rate, no significant change of the efficiency penalty is observed thus the net efficiency is 50.3 % as in the base case. If the capture rate is reduced to 90 %, it is energetically favourable to use -40 °C as condensation temperature. In this case the efficiency increases by 0.1 %-pts. compared to the base case. For the lowest considered capture rate of 60 %, the efficiency is increased by 0.65 %-pts.

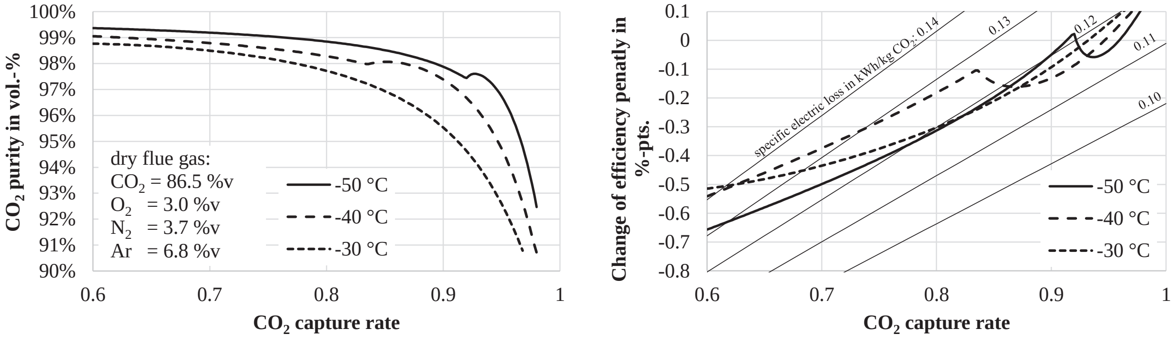


Fig. 7. (a) CO_2 purity and (b) change of efficiency penalty of the GPU at varying CO_2 capture rates and condensation temperatures.

5. Comparison of the processes

To compare the CCS technologies PCC and oxyfuel at different capture rates, the net efficiency is not a useful parameter. To relate the loss of electrical energy for CCS to the amount of CO_2 captured in the process a specific electric loss L in $kWh_{el}/kg\ CO_2$ is calculated using Eq. 1.

$$L = \frac{\frac{\Delta \eta}{\eta_{net,ref}}}{\varepsilon_{captured}} \tag{1}$$

Δη denotes the overall efficiency penalty between the net efficiency of the process with CCS and the reference process $\eta_{net,ref}$. $\varepsilon_{captured}$ is the specific amount of CO_2 captured per kWh of generated electricity (net).

Figure 8 shows the specific electric loss for the NGCC with PCC and the SCOC-CC for the range of capture rates investigated in Section 3 and 4. It shows clearly that the PCC captures far more efficiently than an SCOC-CC plant up to CO_2 capture rates of 95 %. Between 60 % and 90 % the capture rate of the PCC has only minor influence on the specific electric loss although a minimum value of 0.378 $kWh_{el}/kg\ CO_2$ can be observed at approx. 80 %. In this range the process can be adjusted to the boundary conditions, e.g. if a certain CO_2 emission limit has to be achieved. The SCOC-CC is not effective for operation at lower capture rates because the major loss of the process, i.e. the production of oxygen, remains constant and the specific loss increases quickly. In fact, more oxygen is vented to the atmosphere as part of the not captured CO_2. If very high capture rates are required, the SCOC-CC becomes more efficient than a PCC because of the sharp increase in specific heat duty. However, if the CO_2 purity is restricted to a minimum value 96 vol.-%. the capture rate has to be limited to a maximum of 95.8 % for the SCOC-CC base case scenario. In this case a specific loss of 0.467 $kWh_{el}/kg\ O_2$ is observed. Full CO_2 capture along with high purity CO_2 can be achieved if high purity oxygen is used at reduced oxygen excess. While the energy demand of the ASU for high purity oxygen is increased by approx. 20 %, the specific electric loss is increased only by 5 %.

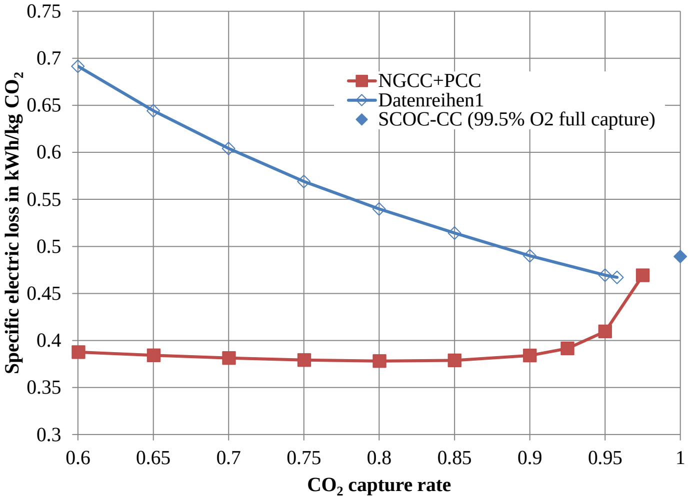


Fig. 8. Specific electric loss for the NGCC with PCC and the SCOC-CC.

For comparison, the specific electric loss for a modern pulverised coal fired power plants with CCS is determined for a capture rate of 90 %. For an assumed net efficiency of 45.6 % of the reference plant and an efficiency penalty of 8 – 11 %-pts. [10] the resulting range according to Eq. 1 is between 0.26 and 0.36 $kWh_{el}/kg\ CO_2$. At this capture rate the coal-fired plants emit approx. 100 g CO_2 per kWh_{el}. For natural gas fired plants the same specific CO_2 emissions would require a capture rate of only approx. 75 %.

6. Summary

The aim of this work is to compare carbon capture options for NGCC plants at various CO_2 capture rates. The specific electric loss in $kWh_{el}/kg\ CO_2$ of the respective plant is used to compare processes at different capture rates.

The net efficiency of a post combustion capture plant is strongly dependent on the chosen capture rate. Between capture rates of 60 % to 90 % the specific loss of the PCC is almost constant at approx. 0.38 $kWh_{el}/kg\ CO_2$. Due to a significant increase of the specific heat duty of the CCU at higher capture rates this value increases to approx. 0.48 $kWh_{el}/kg\ CO_2$ at a capture rate of 97.5 %. For the SCOC-CC, an oxyfuel process derived from the NGCC, high CO_2 purity (>96 %) directly suitable for transport and storage can only be achieved with high purity oxygen. In this case 100 % CO_2 capture is achieved at a specific loss of 0.49 $kWh_{el}/kg\ CO_2$. Oxygen with lower purity reduces the energy demand of the ASU but further purification of the flue gas is required reducing the capture rate of the process. To achieve a CO_2 purity of 96 %, a maximum CO_2 capture rate of 95.8 % is possible. In this case, the specific electricity loss is 0.47 $kWh_{el}/kg\ CO_2$. For the SCOC-CC, a reduction of the capture rate leads to a strong increase of the specific electricity loss.

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