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Improving Energy Efficiency of Carbon Capture Processes with Heat Pumps

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Abstract. Carbon capture based on chemical absorption in amine-based solvents is the most relevant technology option to reduce CO_2 emissions from hard-to-abate industrial CO_2 sources and power plants. Because of the energy consumption of the carbon capture process, which is mainly attributed to heating the desorber, carbon capture has a negative impact on the efficiency of the process where CO_2 is removed. Heat pumps allow for heat recovery and provide high temperature process heat. Due to recent developments, heat pumps are now capable of supplying steam and providing high temperatures enabling new applications. This contribution investigates the integration of heat pumps into the carbon capture process of a furnace for steel processing to determine the most suitable heat sources and sinks and the achievable energy savings. The energy consumption of the carbon capture process can be lowered by 50% due to the integration of steam generating heat pumps. The cost analysis shows that the costs of steam have the highest influence on the costs of captured CO_2.

Keywords: Heat Integration, High Temperature Heat Pumps

1. Introduction

Carbon capture technologies are an important element of the future energy system to lower CO_2 emissions to the excepted levels to comply with the climate targets. In 2022, 40 Mt CO_2 were captured all over the world. According to IEA's World Energy Outlook 2023, continuous growth is expected for CCUS. In the Stated Policy Scenario STEPS, 115 Mt CO_2 have to be captured in 2030 and about 500 Mt CO_2 in 2050. In the most ambitious scenario, the Net Zero Emission NZE, the volumes of captured CO_2 increase considerably to 1 Gt CO_2 by 2030 and 6 Gt CO_2 by 2050. About half of the CO_2 emissions come from industry and from power generation. [1] Most commonly, chemical absorption of CO_2 is applied using amine-based solvents. The process is carried out in two columns, one for absorption and the other for desorption, where the CO_2 is released, and the solvent is regenerated [2]. The desorption step requires energy and is carried out at a higher temperature. Already in the IPCC report in 2005, optimization potential for future cost reductions was pointed out to reduce the energy requirements for capture. At that time, the cost for electricity production from natural gas combined cycle was increased by 35-70% by carbon capture [3]. Studies on process modifications focus on absorption enhancement, heat integration and heat pumps, which are mainly mechanical vapor recompression systems [4]. [5] and [6] analysed the integration of mechanical vapor recompression in the desorber lowering energy consumption by up to 25%, but also mentioned the risk of corrosion and degradation when integrating compressors directly into the process.

In the last decade, the operating range of heat pumps has been significantly expanded towards high temperatures. They are on the verge of commercialization and enable waste heat recovery and heat integration for new applications. In the range of 100-140°C, there are already first of their kind commercial applications in the paper, food and chemical industry. Up to 160°C, there are pre-commercial demonstrations, e.g. in drying processes and for steam production. Up to 200°C, special refrigerants and compressors are needed, which are still in prototype stage, except for the use of water vapor as a refrigerant, where suitable compressors are already available. These systems are mechanical vapor recompression systems. Furthermore, steam generation with heat pumps is an important development, as these heat pumps can be integrated easily in existing equipment and steam networks. [7]

In this contribution, a simulation analysis of heat pump integration into an amine-based carbon capture process is presented. In particular, the application of carbon capture in steel processing is investigated: currently reheating furnaces are operated on natural gas with corresponding CO_2 emissions, whereby the CO_2 content in the flue gas is approximately 8.5 vol.-% on average. Switching to hydrogen may not be possible due to detrimental influence on steel quality or lack of experience and availability of hydrogen burners for such complex high-capacity furnaces. Thus, a concept has been developed in which synthetic natural gas is produced by capturing CO_2 from the flue gas with an amine scrubber and subsequently methanized with green hydrogen. The generated synthetic natural gas can be combusted in the furnace again. Details on this concept are published in [8]. This contribution focuses on the amine scrubber of the system. To improve energy efficiency and thus reduce operating costs, heat pumps are integrated in the amine scrubber. Therefore, available heat sinks and heat sources in the amine scrubber, such as recovery of latent energy from the desorber and amine cooler as well as steam supply for the desorber are considered. The analysis is based on a stationary simulation model of the furnace and the industrial scale carbon capture system in IPSEpro, which is used to study different scenarios, such as heat recovery at different temperature levels. Heat pumps that are market-available or close to market introduction are included in the analysis. Results are evaluated in terms of energy savings, investment and operation costs and process complexity using Sankey diagrams.

2. Methodology

The carbon capture process and the integration of heat exchangers and heat pumps were investigated using the simulation software IPSEpro (Integrated Process Simulation Environment), which was developed for process simulations in the field of power plant and energy technology. It is an equation-oriented simulation program for stationary flow processes [9].

The process is represented as a flow diagram in IPSEpro in accordance with the actual layout of the process. The individual components (carbon capture unit, heat exchanger, heat pumps, etc.) are connected to each other by pipes transferring mass and energy. The process components are balanced according to the conservation laws for mass and energy and can either be taken from the model library of the simulation software or created by the user. Specific models were developed for the carbon capture unit and the heat pump. The component for the carbon capture unit represents a simplified model using typical key performance indicators, such as the specific heat demand, the specific electricity demand, and the separation rate, which are typically provided by manufacturers. Based on these, the total heat and electricity demand is calculated and the inlet stream is separated into two outlet streams considering the conservation of mass and the separation rate. More details about the model of the carbon capture unit can be found in chapter 3. A simplified heat pump model is used for the investigations based on the process temperatures, Carnot efficiency and second law efficiency to be defined. The simplified model does not contain any detailed information on the design of the heat pump (e.g. selection of the refrigerant or compressor), it can be used in any temperature range to estimate the potential and can be adapted to real conditions by selecting the second law efficiency.

Mass and energy balances of the initial process set up are calculated in IPSEpro. This is the basis to determine the heat recovery potential using heat exchangers and heat pumps. Therefore, pinch analysis is carried out to yield the hot and cold composite curve, that are visualized in a Q-T diagram. A total of four different heat integration measures are derived and compared in terms of energy efficiency, costs, and process complexity.

3. Carbon capture process

There are several routes to capture CO_2, which differ in terms of CO_2 generation and the method of capture. One of these is post combustion, where CO_2 is captured from the flue gas before it is emitted into the atmosphere [10]. In this study, the flue gas originates from the combustion of natural gas in an industrial furnace for steel processing. The flue gas is characterized by a CO_2 concentration of approximately 8.5 vol.-% and a temperature of ca. 140°C. Among the different capture technologies, the amine scrubbing is selected as a suitable carbon capture technology. Amine scrubbing is based on chemical absorption using absorbents of high selectivity for CO_2. [10]

Figure 1 illustrates the basic process flow diagram of an amine scrubber, which consists of two columns, the absorber and the desorber. First, the flue gas is cooled and impurities are removed in a pre-washing step. The flue gas then enters the absorber, where CO_2 is absorbed by the aqueous amine solution. The clean flue gas leaves the absorber at the top and the CO_2-rich amine is transferred into the desorber after being preheated in the heat exchanger. In the desorber, the amine is heated with steam and CO_2 is released from the amine. The regenerated CO_2-lean amine is transferred back into the absorber passing through the heat exchanger and providing the heat required to preheat the CO_2-rich amine. The CO_2-lean amine is further cooled by an amine cooler before entering the absorption column again. During the regeneration of the amine in the desorber, CO_2 dissolves from the amine and ascends together with steam (H_2O) to the top of the desorber. Here, a washing step is integrated to cool the CO_2-H_2O mixture and to separate the condensate. Finally, CO_2 leaves the top of the desorber.

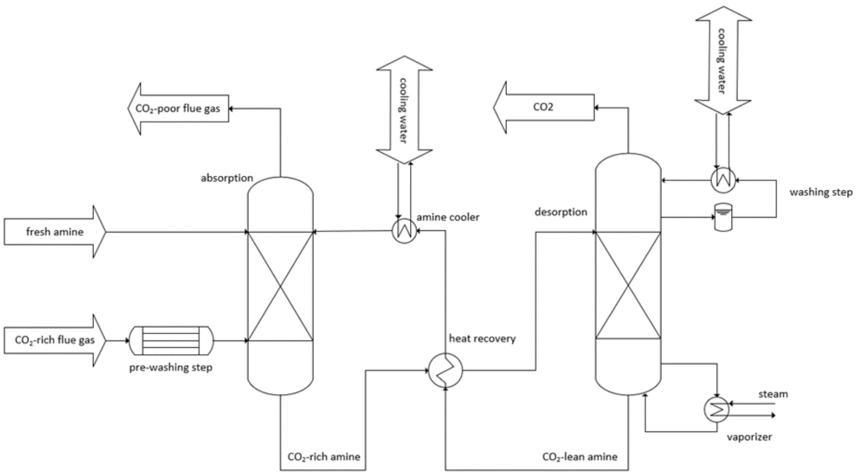


Figure 1. *Carbon capture unit.*

Based on this process, a simplified model of an amine scrubber is set up in IPSEpro, which consists of several steps. First, the flue gas is cooled down before entering the carbon capture model, representing the pre-washing step of the carbon capture unit. Then, the flue gas enters the carbon capture model, where the inlet stream is separated into two outlet streams, one being the CO_2 - H_2O stream and the other being the clean flue gas. The separation of the streams follows the conservation of mass of the respective gas components, considering separation rates for CO_2. The CO_2 poor flue gas stream is assumed to be fully saturated with water vapor. The remaining water is present in the CO_2 - H_2O stream, which leaves the carbon capture model with a temperature of approximately 100-120°C. The captured CO_2 is purified in the head of the desorber during washing steps, whereby the remaining H_2O is condensed. The top of the desorber is modelled separately by two heat exchangers, which are adapted to condense water in a gas flow. This ensures the appropriate simulation of the heat recovery in the head of the desorber. After the washing steps, CO_2 is delivered at 40°C with a concentration of approximately 97 vol.-% CO_2.

The total heat demand for desorption, the electrical power demand and the cooling demand for the amine cooler are calculated separately and are based on manufacturer specifications. These specifications can be found in Table 1.

$$P_{therm} = q_{desorb}\,\dot{m}_{CO2} \tag{1}$$

$$P_{el} = P_{spec,el}\,\dot{m}_{CO2} \tag{2}$$

$$\dot{Q}_{Amine\ cooler} = \dot{m}_{Amine}\,c_{p,Amine}\,(T_{Amine,Out} - T_{Amine,In}) \tag{3}$$

Table 1. *Input parameters for the carbon capture unit*

Description	**Value**	**Unit**
Operating hours	8000	h/y
CO_2 concentration in flue gas	8.6	vol.-%
Mass flow captured CO_2	2.3	t/h
Specific heat demand, q_{desorb}	3020	kJ/kg
Specific electricity demand, $P_{spec,el}$	176.6	kJ/kg
Separation rate	95	%
Inlet temperature amine cooler, $T_{Amine,In}$	51.7	°C
Outlet temperature amine cooler, $T_{Amine,Out}$	40.0	°C
Mass flow lean amine to amine cooler, $\dot{m}_{Amine}$	17.7	kg/s
Heat amine cooler, $\dot{Q}_{Amine\ cooler}$	725	kW

4. Heat integration measures

A pinch analysis was performed to identify the potential of heat recovery of the carbon capture process. Steam at 4.5 bara is used to heat the process, cooling water with 30°C is used in several heat exchangers to provide cooling. The cold composite curve (blue) in Figure 2 represents evaporation of water to produce steam to cover the heat demand of the carbon capture unit. The hot composite curve (red) represents the cooling demand of the amine cooler and the cooling demand of the washing step at the head of the desorber that is currently covered with cooling water. Other waste heat sources of the carbon capture unit such as the pre-washing step were not taken into consideration due to the low temperature levels. The overlap of the hot and cold composite curve indicates that internal heat recovery with heat exchangers is possible. Because of the minimal overlap, the potential for heat exchangers amounts to 0.3 MW. However, there is both heating and cooling demand, which raises the prospect of integrating heat pumps. Therefore, the heat pump should provide the required steam by using the unused waste heat originating from the cooling demand.

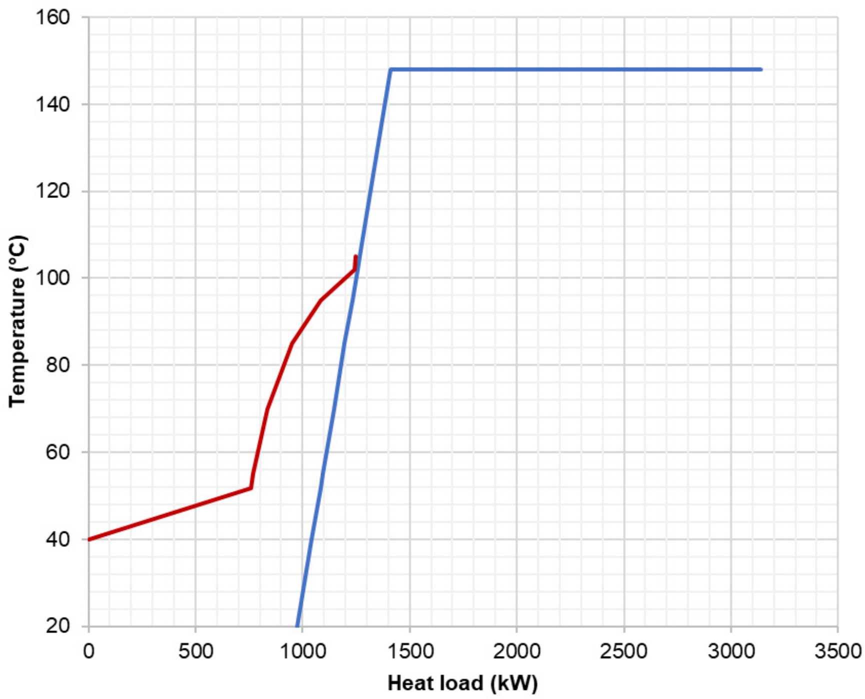


Figure 2. *Composite curve for amine scrubber.*

In the following, four different options for heat integration are discussed:

- Integration of a heat pump in the desorber
- Integration of a heat pump in the amine cooler
- Combination of the two heat pumps (desorber and amine cooler)
- Integration of a heat pump in the cooling water system

The options differ by their degree of process integration and by the temperature level of the heat sources. Integration of a heat pump on the utility level, e.g. the cooling water circuit, is typically less complex, but also less efficient. Integration of a heat pump into the process, e.g. for cooling the aqueous amine solution in the amine cooler or for cooling the washing water at the head of the desorber, requires adaptions of the process equipment, but allows to recover heat at higher temperatures. The selected options are discussed in terms of energy savings, economics, and complexity for plant engineering.

4.1. Heat pump in the desorber

At the top of the desorber waste heat with the highest temperature in the process is available. The CO_2-H_2O mixture has a temperature of approximately 100-120°C and is cooled to condense the water to produce pure CO_2. After washing, the pure CO_2 has a temperature of 40°C. If condensation is carried out in two washing steps, the temperature after the first washing step can be optimized for heat recovery. In this study, four different temperature levels are analysed, which are listed in Table 2. Therefore, the design of the desorber head must be extended by a second washing step. A schematic representation of the heat pump integration at the top of the desorber and the adaptation of the design of the desorber head is shown in Figure 3.

Table 2. *Variation of first washing step on the top of the desorber*

Case	Mass flow washing water, t/h	Temperature washing water inlet cooler,,°C	Temperature washing water outlet cooler, °C	Heat, kW
1	16.94	77.7	55	447.2
2	14.98	88.6	65	411.8
3	12.53	99.9	75	364.2
4	9.94	105.2	85	234.8

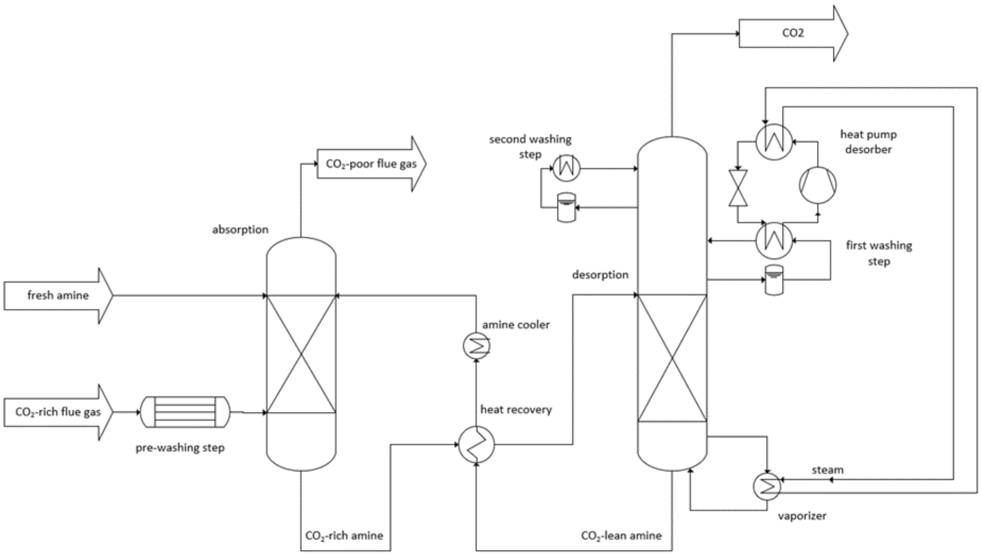


Figure 3. *Heat pump integration at the top of the desorber.*

To assess the heat recovery potential, a simplified heat pump model was used in IPSEpro. In Table 3, the process parameters are listed:

Table 3. *Parameters of the heat pump model*

Description	Value	Unit
Second law efficiency	50	%
Temperature difference between heat sink outlet temperature and condensation temperature	3	K
Temperature difference between heat source outlet temperature and evaporation temperature	3	K

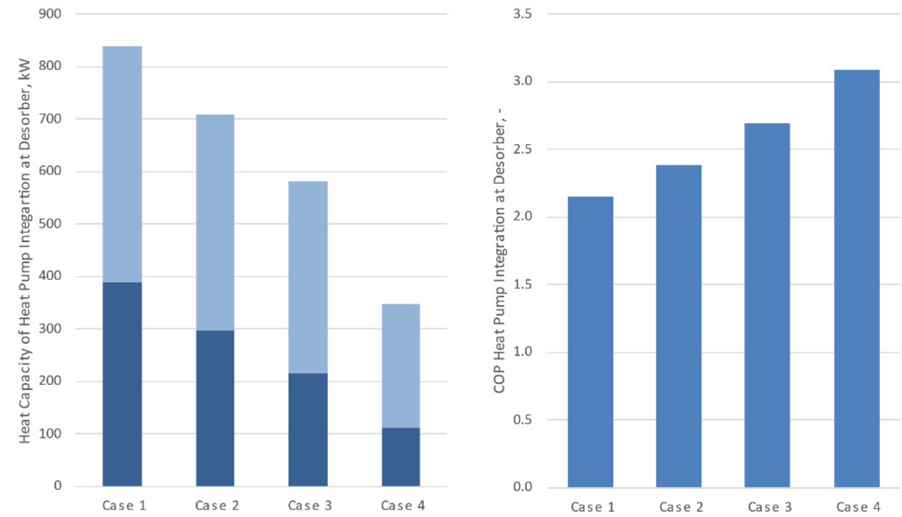
The second law efficiency describes the deviation of the real heat pump process to the ideal Carnot process. An efficiency of 50% was chosen based on manufacturer data on high temperature heat pumps [11],[12]. In this study, the heat pump is designed to provide steam at 4.5 bara, with the heating capacity being defined as:

$$P_{HP,Sink} = P_{HP,Source} + P_{HP,el} \quad (4)$$

The simplified heat pump model does not consider pressure losses nor heat losses to the environment. The coefficient of performance, COP, is the main parameter to describe the efficiency of a heat pump. It is defined as the ratio of the heating capacity provided by the heat pump and the electricity that is consumed. The COP depends on the heat source outlet temperature and the heat sink outlet temperature. The higher the temperature difference between heat source outlet and heat sink outlet, the more electricity is needed to operate the heat pump.

Figure 4 a) shows the heating capacity provided by the heat pump at the top of the desorber. Case 1 has the lowest heat source outlet temperature of 55°C, case 4 the highest with 85°C. The heating capacity decreases with increasing heat source outlet temperature. This is due to two effects: less heat is available as heat source for the heat pump if the temperature is higher shown by the decreasing cooling capacity (light blue) which in turn is due to smaller washing water mass flows at higher temperatures in the first washing stage. Simultaneously, this indicates that the cooling demand in the subsequent washing stage increases. This heat is neglected for heat recovery as the temperatures are much too lower. The second effect is that the COP increases with increasing heat source outlet temperature as illustrated in Figure 4 b). Thus, the electricity demand decreases.

If a heat pump is integrated in the top of the desorber, the steam demand of the carbon capture unit can be partly covered. It ranges from 18% of the steam demand (case 1, 85°C) to 43% (case 4, 55°C).



a) b)

Figure 4. *a) Heating capacity of heat pump integration at desorber consisting of cooling capacity of the heat pump (light blue) and the electrical power of the heat pump (dark blue) b) Resulting COP of the heat pump at the top of the desorber.*

4.2. Heat pump in the amine cooler

Another possibility to integrate a heat pump in the carbon capture unit is the amine cooler, whose operating parameters can be found in Table 1. The amount of waste heat ($\dot{Q}_{Amine\ cooler}$) that can be recovered is higher than from the desorber, but the temperature levels are much lower, leading to a lower COP of the heat pump of 1.86.

Table 4. *Characteristics of the heat pump at the amine cooler.*

Description	Value	Unit
COP	1.86	
Cooling capacity Amine cooler, $\dot{Q}_{Amine\ cooler} = P_{HP,Source}$	724.8	kW
Electricity demand Amine cooler, $P_{HP,el}$	841.3	kW
Heating capacity Amine cooler, $P_{HP,Sink}$	1566.1	kW

Table 4 lists the characteristics of the heat pump at the amine cooler, while Figure 5 shows the design of the carbon capture unit with an integrated heat pump at the amine cooler. The heat pump in the amine cooler provides 81% of the steam demand of the carbon capture process.

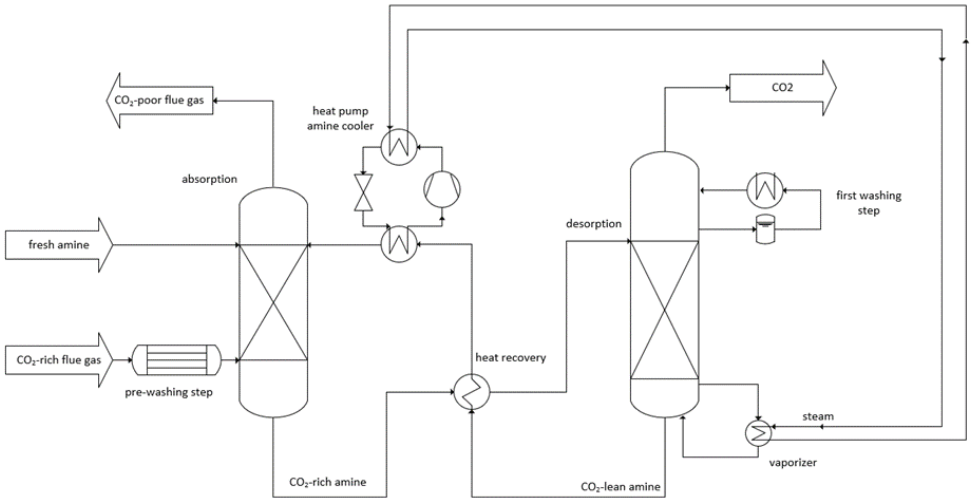


Figure 5. *Heat pump integration at amine cooler.*

4.3. Combination of the heat pumps

The previous analysis has shown that both sources, the top of the desorber and the amine cooler, cannot individually cover the heat demand of the carbon capture unit. Therefore, a combination of the heat pumps is considered, resulting in the schematic concept in Figure 6.

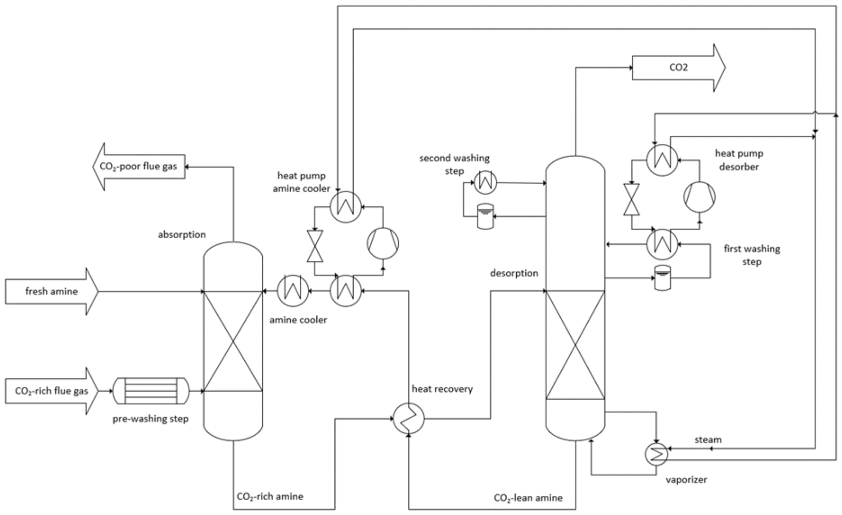
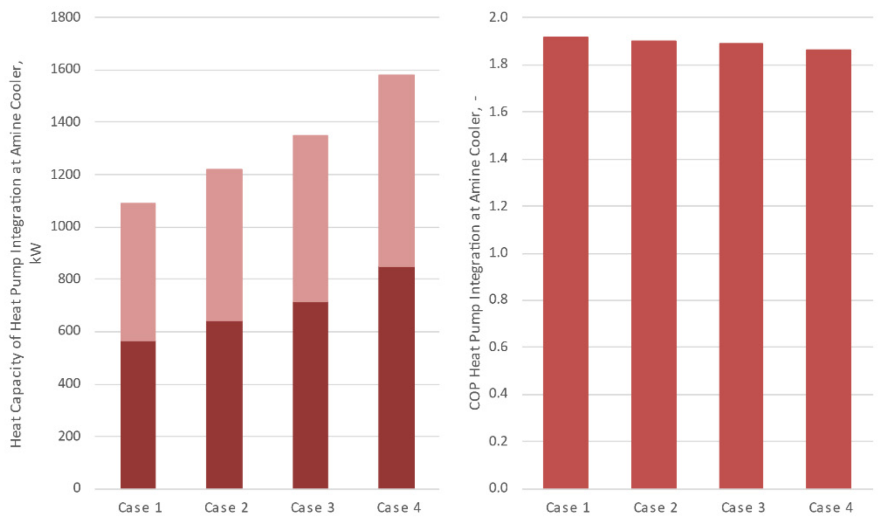


Figure 6. *Combination of heat pumps.*

This concept aims to cover the overall steam demand of the carbon capture unit. Thereby, the heat source at the first washing step of the top of the desorber is fully exploited, while the heat source at the amine cooler covers the remaining heat demand of the carbon capture unit. As shown in Figure 8 a), the heating capacity of the heat pump of the desorber decreases with increasing temperature levels whereby the heating capacity of the heat pump at the amine cooler increases. The increase in heating capacity of the heat pump at the amine cooler can be attributed to the increasing cooling capacity of the heat pump, as illustrated in Figure 7 a).

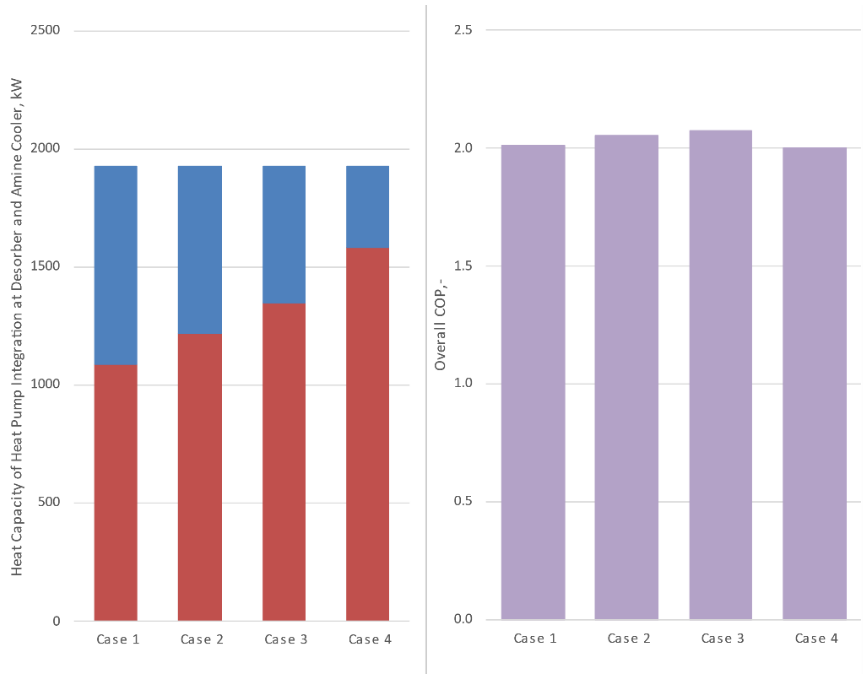
The electricity demand of the heat pump at the amine cooler increases accordingly, but remains similar in relative terms, as the COP of the heat pump at the amine cooler, shown in Figure 7 b) only decreases by 4 %. An additional amine cooler enables the variation of the cooling capacity of the heat pump at the amine cooler. This amine cooler ensures that the overall process is not changed and the remaining cooling demand at this point of the process is covered. So, as the cooling capacity of the heat pump increases, the cooling demand of the additional amine cooler decreases.



a) b)

Figure 7. *a) Heating capacity of heat pump integration at amine cooler consisting of cooling capacity of the heat pump (light red) and the electrical power of the heat pump (dark red) b) Resulting COP of the heat pump at the amine cooler.*

To sum up, although the heat pump at the top of the desorber has a higher COP at higher temperatures, it has a lower heating capacity. So, the heat pump at the amine cooler having a lower COP, must provide more heat to cover the overall heat demand of the carbon capture unit.



a) b)

Figure 8. *a) Heating capacity of heat pump at the top of the desorber (blue) and the heat pump at the amine cooler (red) b) Overall COP of both heat pumps.*

This is also reflected in the overall COP of both heat pumps, which is the ratio of the sum of supplied heating capacity and the sum of electricity consumed in both heat pumps. It is shown in Figure 8 b) for the different temperature levels. For further analysis, case 3 with the highest overall COP is considered.

In Figure 9 the Sankey diagram of the carbon capture unit with heat pump integration at the desorber and the amine cooler is shown. It highlights that the total steam demand of the carbon capture unit can be covered by the two heat pumps. The energy saving potential is also visualized here. The two heat pumps only require 0.93 MW of electricity instead of 1.93 MW steam, which corresponds to an energy reduction of 52%. Furthermore, the cooling load of cooling equipment is reduced by 51% due to the recovery of waste heat. This results in a reduction of water and energy consumption for the operation of the cooling equipment.

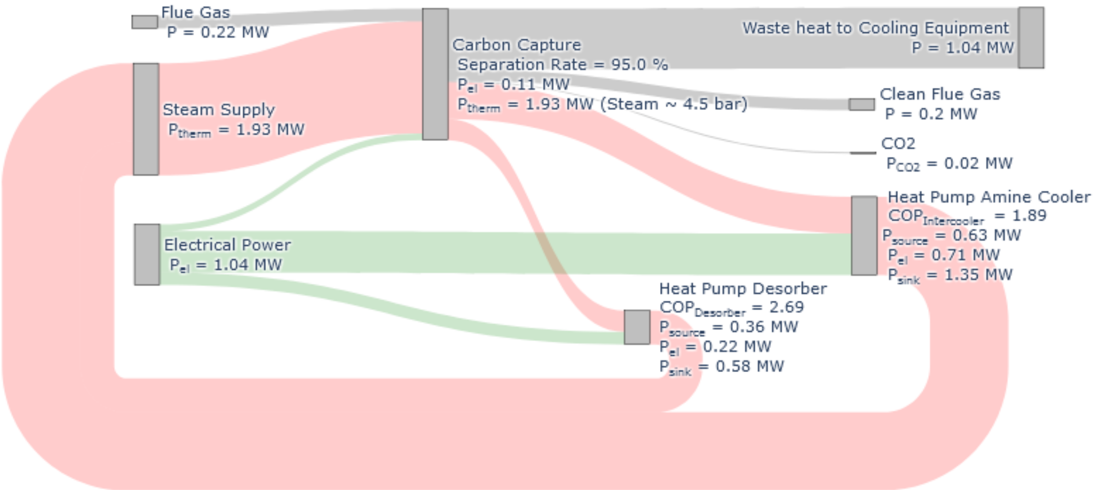


Figure 9. *Sankey diagram of heat pump integration at desorber and amine cooler for case 3.*

4.4. Heat pump in the cooling water system

Here, a central heat pump is integrated in the cooling water system. Thereby, the two heat sources, the first washing step at the top of the desorber and the amine cooler, are connected in the cooling circuit, as shown in Figure 10.

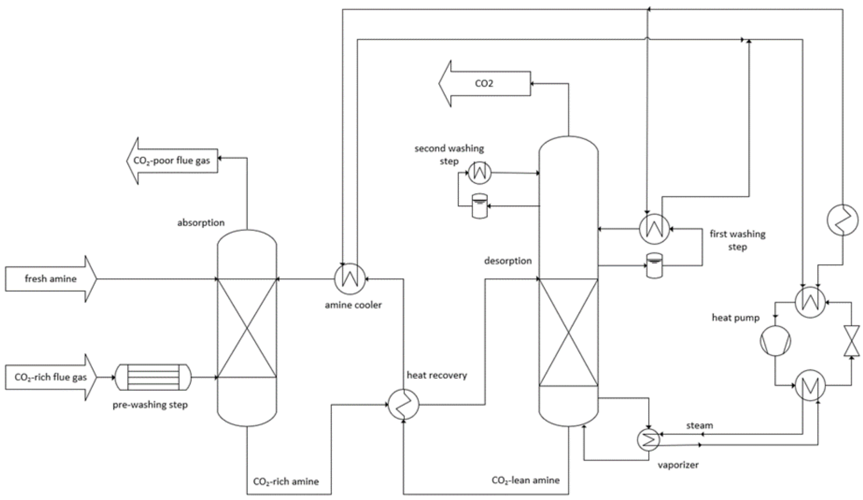


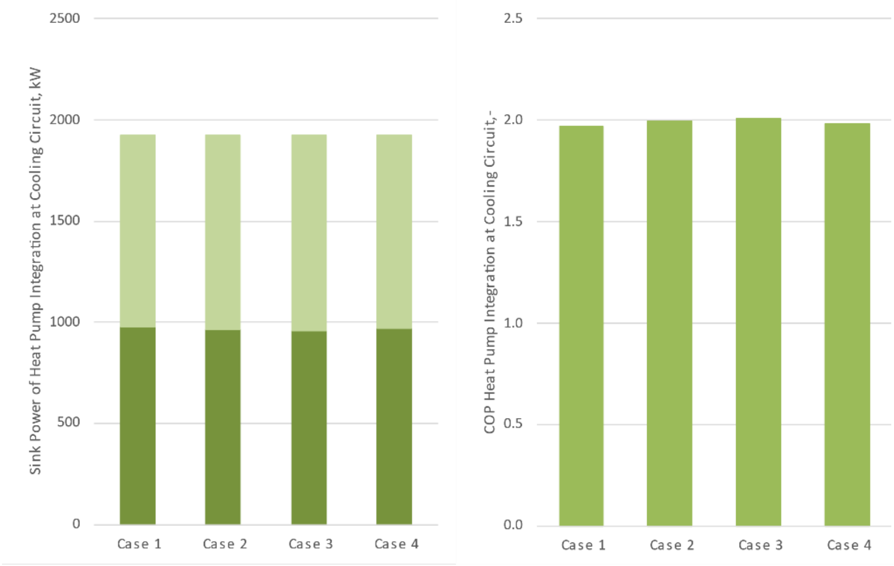
Figure 10. *Heat Pump integration at cooling circuit.*

This concept also aims to cover the total heat demand of the carbon capture unit and investigates four cases, where the temperature levels at the first washing step at the top of the desorber are varied according to Table 2, while the cooling water from the amine cooler has a constant temperature as listed in Table 1. This leads to the mixing temperature in Table 5.

Table 5. *Mixing temperature of the two heat sources.*

	Case 1	**Case 2**	**Case 3**	**Case 4**
Mixing Temperature, °C	58.0	59.8	60.9	60.2

The mixing temperature ranges from 58 to 60°C, this is reason why the heat to be recovered from the cooling circuit is similar for all cases as shown in Figure 11 a). Mixture of the two heat streams leads to a lower temperature. In Figure 11 b) the COP for the heat pump in the cooling circuit is shown. The COP is approximately 2 and does not differ much from the overall COP of the heat pump integration at the amine cooler and desorber in Figure 8 b).



a) b)

Figure 11. *a) Heating capacity of heat pump integration at cooling circuit consisting of cooling capacity of the heat pump (light green) and the electrical power of the heat pump (dark green) b) Resulting COP of the heat pump at the cooling circuit.*

Figure 12 shows the Sankey diagram for case 3 of the heat pump integration at the cooling circuit. The heat pump at the cooling circuit provides the full amount of steam required. The heat pump consumes 0.96 MW electricity. Thus, energy savings of 50% are achieved compared to the carbon capture process without heat recovery. Furthermore, the cooling demand is reduced to 48%.

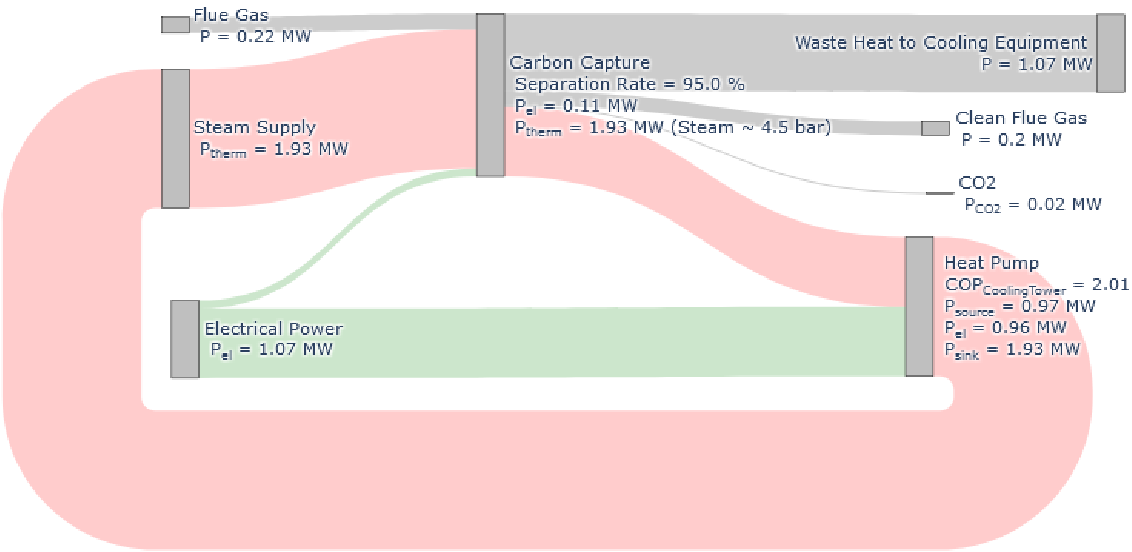


Figure 12. *Sankey diagram of heat pump integration at the cooling circuit for case 3.*

5. Techno-economic assessment

5.1. Energy consumption

Figure 13 compares the energy demand of the carbon capture unit without heat pumps to the energy demand of the carbon capture unit with heat pump integration. The comparison highlights the energy saving potential of heat pump integration, which is approximately 50% for both versions. As shown before, the heat pump integration at the desorber and the amine cooler has a slightly lower energy demand than the heat pump integration at the cooling circuit.

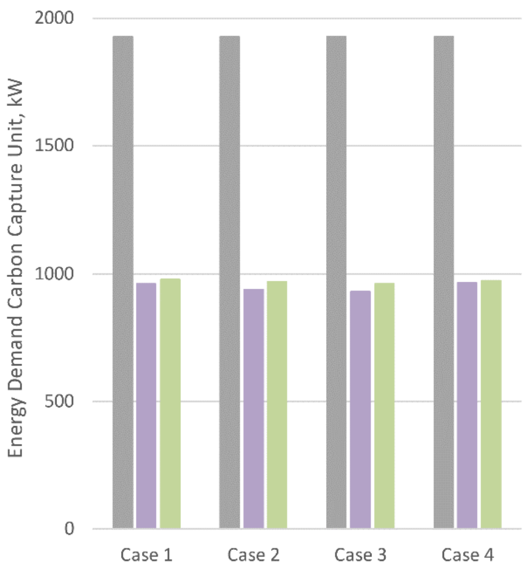


Figure 13. *Comparison of energy demand of the carbon capture unit without heat pumps (gray), with heat pump integration at the top of the desorber and the amine cooler (violet) and heat pump integration in the cooling circuit (green).*

5.2. Costs of CO_2 capture

The costs of CO_2 are estimated in the following using the assumptions in Table 6. The listed OPEX costs for the carbon capture unit only include operating and maintenance, costs for steam and electricity are included separately and are varied within the analysis.

Table 6. *Costs.*

Description	Value	Unit
CAPEX Amine Scrubber	300 000	€/t CO_2/h
OPEX Amine Scrubber [13]	8	€/t CO_2
CAPEX Heat Pump	1400	€/kW_{Sink}

Figure 14 illustrates the total costs of CO_2 depending on the steam and electricity costs. Hereby, the costs of CO_2 captured by a commercial carbon capture unit without heat pumps (grey) is compared to the costs of CO_2 captured by carbon capture unit with the heat pump integration at the desorber and amine cooler (blue) and the heat pump integration at the cooling circuit (green). With heat pump integration, the costs of CO_2 are constant for different steam costs but are sensitive to electricity costs. This can be attributed to the heat pumps generating the required steam by electricity and waste heat from the process which is free of charge. Conversely, the costs of CO_2 captured by the carbon capture unit without heat pump integration highly depend on the steam costs, whereas the electricity costs do not influence the CO_2 costs significantly. Furthermore, Figure 14 shows the break-even-points. With an electricity price of e.g. 80 €/MWh, the break-even-point is at a steam price of approximately 50 €/MWh. This means that with an electricity price of 80 €/MWh, the integration of heat pumps into a carbon capture unit is economically feasible at a steam price of approximately 50 €/MWh or higher.

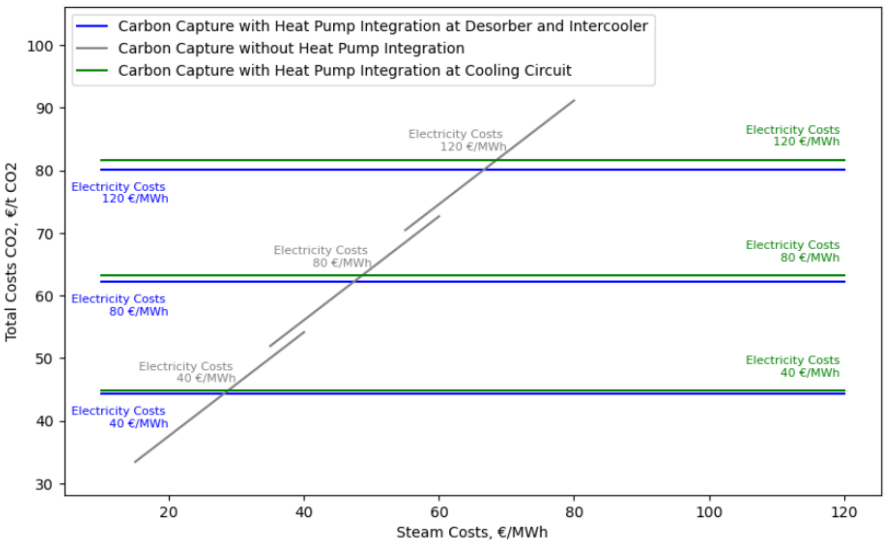


Figure 14. *CO2 capturing costs depending on steam and electricity costs.*

Next, a more detailed insight into the cost distribution of the carbon capture unit without and with heat pump integration is provided. Thereby, a fully decarbonized scenario is assumed, in which steam is produced electrically in an electrode boiler. According to [14] the electrode boiler is operated for 8000 h/a and has a depreciation period of 10 years. The analysis of [14] also shows, that there is no change in the levelized cost of heat varying the depreciation period from 10 to 15 years. Therefore, in this study it is assumed that the levelized costs of heat are still valid for a depreciation period of 20 years. This results in levelized costs of heat of approximately 60 €/MWh, assuming electricity costs of ca. 54 €/MWh. These assumptions result in the cost distribution in Figure 15 for the heat pump integration at the desorber and the amine cooler and the cost distribution in Figure 16 for the heat pump integration at the cooling circuit.

The costs for the carbon capture unit without heat pump integration are labeled as Total Costs CO_2 and are determined by the steam costs, while the CAPEX and the electricity costs have a minor impact on the overall costs. To estimate the total costs of CO_2 for the carbon capture unit with heat pump integration, the CAPEX costs of the heat pumps as well as the electricity costs for the heat pumps is added to the total costs of CO_2, while the steam generated by the heat pumps is considered a revenue. According to this analysis, the total cost of CO_2 reduced from 71 €/t to 51 €/t for both versions, which is a cost reduction of 30%.

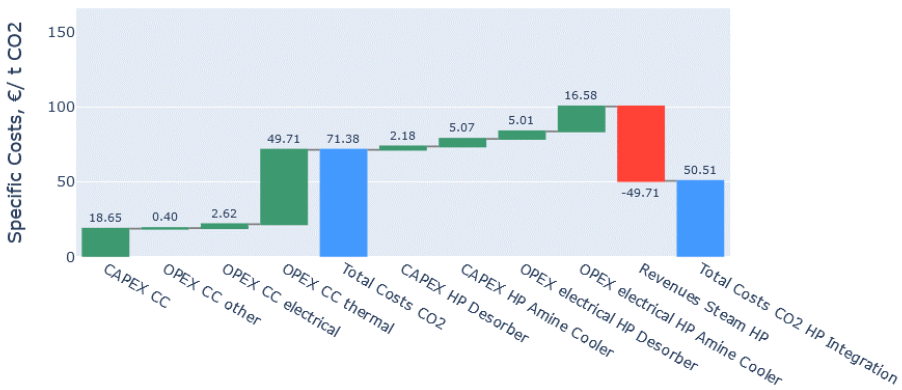


Figure 15. *Cost distribution of carbon capture unit without and with heat pump integration at desorber and amine cooler for case 3 assuming 8000 operating hours per year for 20 years, steam costs of 60 €/MWh and electricity costs of 54 €/MWh.*

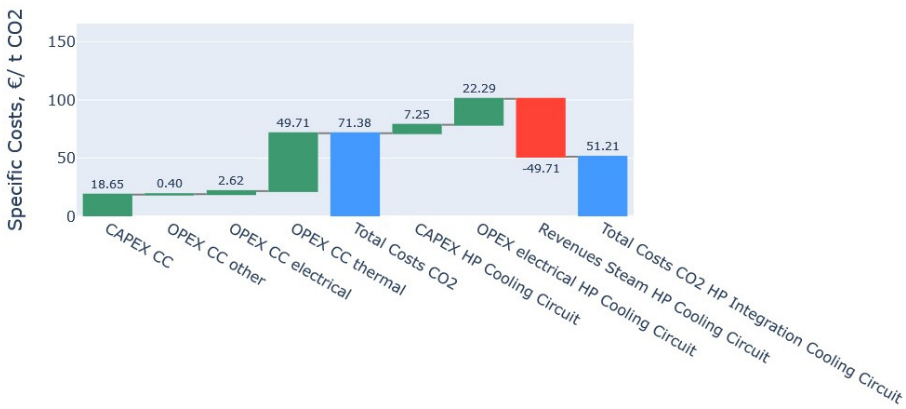


Figure 16. *Cost distribution of carbon capture unit without and with heat pump integration at the cooling circuit for case 3 assuming 8000 operating hours per year for 20 years, steam costs of 60 €/MWh and electricity costs of 54 €/MWh.*

5.3. Process complexity

The integration of heat pumps into existing processes is often complex, as the heat source and the heat sink may not be located close to each other and the space availability for construction of new equipment is limited. In the carbon capture unit, the heat sources at the top of the desorber and at the amine cooler are not located closely to the reboiler at the bottom of the desorber, where the steam is needed. If heat pumps are integrated in the desorber and the amine cooler, they are located close to the heat source. A steam piping connection is needed to provide steam at the bottom of the reboiler. If the heat pump is integrated in the cooling water circuit, the heat pump can be located close to the steam inlet of the reboiler. In this case, only water pipes are required. As the difference in COP of the two versions is negligible, using the cooling water as heat source is more beneficial. In this case, no alterations on the carbon capture process are necessary, only water pipes are required. The heat pump can be located next to carbon capture unit close to the reboiler, where the steam is needed.

6. Discussion and outlook

The analysis has shown that there is relevant energy savings potential in the carbon capture process by integration of heat pumps for steam generation. Both heat pump integration concepts lead to a reduction of energy consumption by ca. 50%. The use of the cooling water as the heat source has advantages in terms of process complexity, as it does not require alterations of the process equipment nor long steam piping. The cooling demand of the carbon capture process is reduced by ca. 50% resulting in reductions in water and energy consumption for the operation of the cooling facility.

6.1 Heat pump design

The analysis provides the parameters for a more detailed design of the heat pump. The source inlet temperature of the heat pumps is ca. 60°C, the required steam temperature is 148°C. The carbon capture process requires 1.93 MW of steam to remove 2.3 t/h CO_2. As the required temperature lift of the heat pump is high, there are two main options to design a heat pump system according to these parameters:

- Two stage closed loop heat pump
- Combination of steam generating heat pump with steam compressor

The two-stage closed loop heat pump consists of two refrigeration cycles, a bottom and a top cycle that are connected by a condenser / evaporator heat exchanger. The bottom cycle is the heat source for the top cycle. In the condenser of the top cycle steam is produced. Suitable combinations of refrigerants for the two-stage closed loop heat pump are e.g. NH_3 and butane or propane and butane. In the heating capacity range of 2 MW, piston and screw compressors are used. The second option is the combination of a closed loop heat pump and a steam compressor. Here, steam is produced in the condenser of the bottom cycle. It is further compressed to 4.5 bara with a steam compressor. Heat pump systems in this temperature and capacity range are already offered on the market [11]. However, there is still a lack of references of installed heat pumps in industry.

6.2. Application of carbon capture in heating furnaces

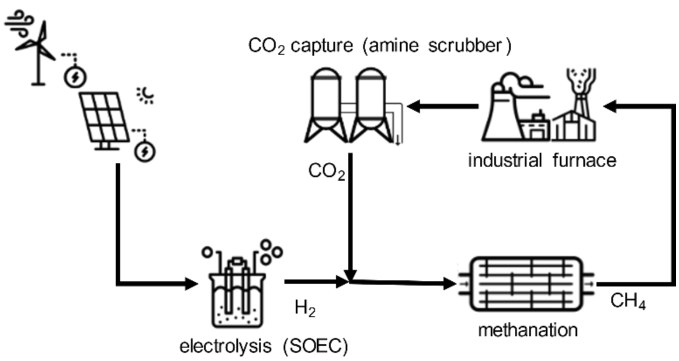


Figure 17. *Decarbonized reheating furnace, [8]*

The carbon capture process that was analyzed in this contribution is an integral part of a decarbonization concept for steel processing that is published in detail in [8] and illustrated in

Figure 17. Synthetic natural gas is used as fuel in a reheating furnace. CO_2 is captured from the flue gas of the furnace and is methanized with green hydrogen from electrolysis to be used again in the furnace. Figure 18 provides an overview on the heating and cooling needs in the decarbonized reheating furnace. The cold composite curve (blue) consists of the steam for the carbon capture process and the steam for the SOEC high temperature electrolysis process. The hot composite curve (red) summarizes the following heat sources:

- waste heat from the furnace with 90 – 235°C,
- the amine cooler and the desorber of the carbon capture process
- waste heat from exothermal reaction in the methanation reactor with up to 600°C

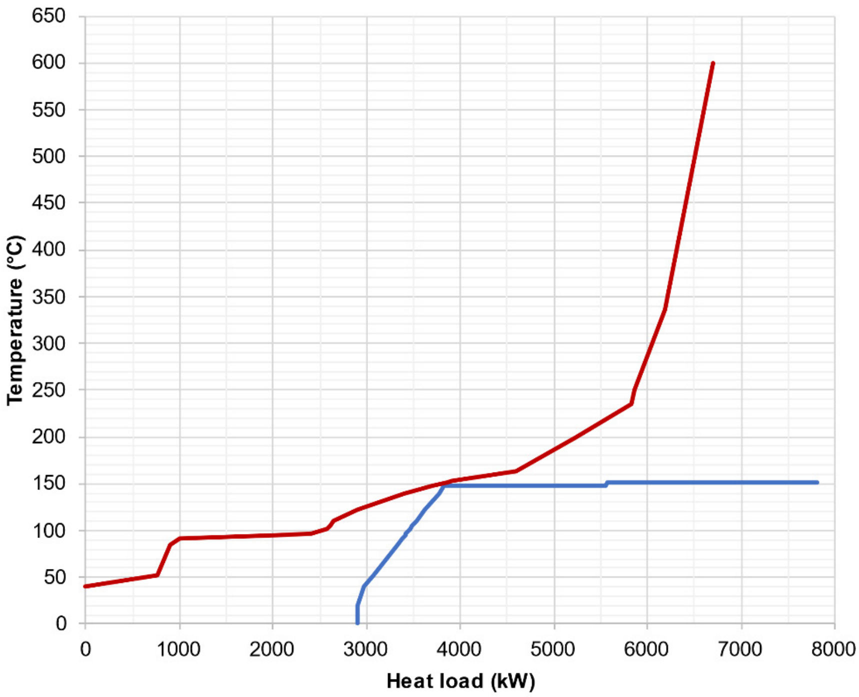


Figure 18. *Composite curve for decarbonized reheating furnace with carbon capture unit, methanization and electrolysis*

Due to the exothermal reaction in the methanation reactor a significant amount of high temperature waste heat is available, that can be directly used for steam generation. The heat recovery potential amounts to 3.8 MW. However, 1.1 MW steam cannot be supplied with internal heat recovery. As is sufficient waste heat available, a steam generation heat pump can for example use waste heat from the furnace at about 95°C or the heat sources of the carbon capture process as discussed before.

6.3 Conclusions

Heat pumps can improve the energy efficiency of the carbon capture process significantly. The washing step at the top of desorber as well as the amine cooler are suitable heat sources. Currently, the waste heat is released to the environment via cooling water. A favorable integration of a heat pump is to use the cooling water stream from the amine cooler and the desorber and to place the heat pump close to the reboiler, where the steam is consumed. The carbon capture process can be fully supplied with steam from the heat pump resulting in energy savings of 50%. Furthermore, the cooling demand of the process is reduced by half.

Using heat pumps instead of external steam supply for the carbon capture process has economic benefits. The costs analysis shows a strong influence of the steam costs on the total costs of captured CO_2. With steam costs of 60 €/MWh and electricity costs of 54 €/MWh, heat pump integration lowers the costs of captured CO_2 from 71 €/t to 51 €/t, this is a cost reduction of 30%.

Carbon capture units are integrated in industrial processes reduce CO_2 emissions from hard-to-abate industrial CO_2 sources and power plants. Therefore, it is important to consider the full process in terms of heat sinks and heat sources to determine the most efficient layout. The decarbonized reheating furnace for steel processing is operated with synthetic methane produced by carbon capture, green hydrogen from electrolysis and methanation. There is high heat recovery potential with heat exchangers due to the exothermal methanation reaction. However, for the remaining steam demand, a heat pump is suitable recovering waste heat from the furnace at ca. 95°C or from the carbon capture process at ca. 60%. Heat pump systems in the temperature and capacity range investigated in this contribution are already available on the market. It is expected that the number of installed steam generating heat pumps will increase considerably in the coming years.

Data availability

All relevant parameters are stated in the paper, further data will be made available upon request.

Author contributions

Conceptualization, VW, CZ; Methodology, VW, DL, CZ, AR, MS; Software, VW, DL; Investigation, VW, DL, CZ, AR, MS; Validation, VW, DL, CZ; Formal Analysis, DL; Data curation, DL, Visualization, DL; Writing – original draft, VW, DL; Writing -review & editing, VW, DL, CZ, AR, MS; Resources, VW, AR, MS; Project administration, CZ; Funding acquisition, CZ; Supervision, VW.

Competing interests

The authors declare that they have no competing interests.

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