INTEGRATION OF INDUSTRIAL CO_2 CAPTURE WITH DISTRICT HEATING NETWORKS: A REFINERY CASE STUDY

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Abstract

Industrial carbon capture and storage is recognized as an important technology to reach net zero emissions and mitigate global warming in accordance with the Paris agreement. Absorption-based carbon capture requires considerable amounts of low-grade heat, and a high degree of integration with the plant's energy system is thus of high importance in order to achieve low operating costs for the capture plant. In this context, it is important to redefine what is commonly referred to as process "excess heat". This work evaluates the impact of heat integration of a carbon capture plant with an existing refinery and two excess heat-powered district heating networks. The results show that a capture rate of ~60% of direct emissions at the refinery will consume all of the plant's available residual heat. However, the results also indicate that a significant amount of heat can be recovered from the capture plant and exported for district heating supply purposes. Subsequent to capture plant integration, the potential district heating supply is 87 MW, compared to 100 MW in the reference case.

Keywords: *Carbon capture and storage, heat integration, district heating, excess heat, process industry**,** partial capture*

1. Introduction

The industrial sector accounts for around 20% of global CO_2 emissions [1]. Mitigation of these emissions is therefore necessary in order to achieve current internationally agreed climate goals. Carbon capture and storage (CCS) and increased energy efficiency are viable options for reduction of direct plant emissions. Carbon capture is however an energy-intensive process, and approximately 3-4 MJ heat/kg CO_2 are required to regenerate the solvent in common absorption-based processes, which will decrease the plant's energy efficiency. The heat required is typically at a relatively low temperature (around 130°C) and residual heat (often referred to as "excess heat") at such temperature levels is often available at industrial plants. Therefore, several studies (see e.g. [2], [3]) have focused on identifying opportunities to collect and utilize excess heat to provide the heat necessary to regenerate the solvent in the capture process, with the aim of reducing both cost and emissions compared to using primary heat. However, in many cases the excess process heat may be reduced by energy efficiency measures, or is already utilized for other purposes, e.g. in steam cycles or for district heating (common in the Nordic countries). The utilization of industrial excess heat, which is usually considered as a waste stream and not burdened by emission allocations, together with the expansion of the district heating networks has provided a way to reduce direct emissions in the heating sector [4]. Furthermore, supplying heat to a district heating network provides an opportunity for industries to monetize their excess heat. CCS requires considerable amounts of heat and will have a major impact on the plant's energy system, and the relation between heat recovery for CCS and for delivery of district heating should be investigated. A methodology for exploring the trade-offs between recovering industrial excess heat for increased use on-site or export to a regional district heating network has been developed by Eriksson et al [5]. The competition between CCS and district heating has been discussed by Bartela et al. [6] in the context of a supercritical coal-fired CHP plant. They concluded that some of the heat released by the CO_2 capture plant could be recovered and supplied to the district heating system, which reduced the economic impact of the carbon capture process on the CHP plant operation significantly.

1.1. Aim and scope

This work evaluates the theoretical potential for heat integration of absorption-based carbon capture in a refinery heat recovery system. The work quantifies the reduction of direct emissions that is achievable by utilizing available heat in the plant energy system and the impact on the existing district heating network caused by the carbon capture integration, including an estimation of the amount of heat that can be recovered from the capture plant and delivered to the district heating network. Furthermore, in relation to the heat integration between an industrial plant, the district heating network and the capture plant, a suitable definition of excess heat is proposed, including a discussion of what consequences the excess heat definition has on the district heating supply from an industrial plant subsequent to the integration of carbon capture.

2. Definition of excess heat

The definition of *excess heat* is important to process economics as it decides the allocation of emissions between energy products and is therefore discussed. It is common that industrial excess heat is simply defined as "*the heat discharged from an industrial process*". Bendig et al [7] discuss the important distinction between *avoidable* and *unavoidable* excess heat. Pettersson et al. [8] propose adopting a pragmatic techno-economic perspective whereby avoidable excess heat refers to heat that could be reused internally within the process through heat recovery measures that meet the plant owner's investment performance criteria. Olsson et al. [9], on the other hand, propose a definition whereby "*excess energy [is energy] that cannot be utilized internally and where the alternative is that the heat is released into the surroundings*", which does not consider heat (cooling) that may be avoided by internal heat integration. It is a common conclusion that utilization of excess heat (as in heat free of cost and emission allocation) may significantly reduce the specific cost of CO_2 capture. However, in accordance with the excess heat definition by [9], the claim that *excess heat* may be used for CCS implies that the capture plant is not an internal part of the industrial plant. Considering that all industrial processes must reach zero emissions to limit global warming [10], it is reasonable to consider CCS – or other CO_2 mitigation technologies - as an internal emission control technology required to meet stringent regulations, similar to e.g. desulphurization. Heat available at a temperature level suitable for recovery and use in the CO_2 capture plant should, thus, not be considered as excess heat. This work defines excess heat as: "*the energy that cannot be re-used within an industrial process, including processes for emission control and zero-carbon emissions, and where the alternative is that the heat is released into the surroundings*". Instead, the heat that can be made readily available for CCS within the existing plant energy system is designated as "available heat". "Excess heat" is heat at a quality not suitable for CCS integration.

3. Method

The studied system, illustrated in Figure 1, includes the industrial plant, the CO_2-capture plant and the district heating network. The capture plant specifications consist of both flue gas flow and composition and available heat from the industrial plant (i.e. the refinery). In the capture plant, CO_2 from the refinery flue gases is chemically absorbed into aqueous monoethanolamine (MEA), chosen for its status as benchmark solvent for CO_2 absorption. The available heat from the refinery is then utilized to regenerate the solvent and release the CO_2. Prior to capture plant integration, the input for the district heating network is available heat and excess heat from the refinery. As a result of the integration of the capture plant, potential energy flows to the district heating network consist instead of excess heat from the extended refinery heat recovery system, which includes the capture plant. Specifications regarding the refinery and the district heating network are based on previous studies ([11],[12],[13]), while the capture plant performance is based on simulations carried out in this work.

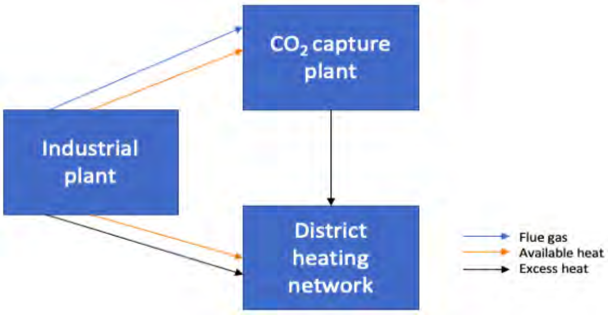

Figure 1: Overview of the studied system including the three parts and the material and energy flows between them.

3.1. Case study

The industrial plant used as a case study is a Swedish refinery with a crude oil capacity of 6 Mt/a, and direct CO_2 emissions of 0.5 Mt/a [11]. The heat needed for the internal refining processes is generated by combustion of refinery excess gas, i.e. gas that originates from the processes but cannot be utilized as a component in any of the products. CO_2 is assumed to be captured from two stacks where the flue gases from the heat generation are emitted. The CO_2 emitted from these stacks account for around 89% of direct plant CO_2 emissions [11]. It is assumed that these stacks are combined to form a single flue gas flow. The flue gas composition, presented in Table 1, was calculated assuming combustion of natural gas with 12% excess air. Furthermore, it is assumed that the refinery and the capture plant have the same operating hours, i.e. 95% availability or 8322 hr/a [12].

Table 1: Refinery flue gas characteristics.

Composition	
CO_2 [mol%]	8.9
H_2O [mol%]	18.0
N_2 [mol%]	71.1
O_2 [mol%]	2.0
Flow [kNm^3/h]	317
Temperature [°C]	168
Pressure [barg]	0

3.2. Heat integration

The evaluation of the theoretical potential for heat integration between the industrial plant, the CO_2 capture plant and the district heating network was carried out in two steps. A global ΔT_{min} of 10°C between hot and cold streams was applied. The first step was an estimation of available heat based on the work by Berntsson et al. [13], who collected refinery energy system data and calculated the overall temperature profile of refinery process streams and flue gases in coolers connected to external heat sinks, which will hereinafter be referred to as "the refinery heat recovery system". The refinery currently delivers heat to two external heating networks, i.e. the heat recovery system has to separate parts. A low-temperature network (T_{supply} 90°C; T_{return} 50°C), which supplies district heat to the local municipality. A high-temperature network (T_{supply} 140°C; T_{return} 90°C), which supplies heat to a nearby industrial site where it is used for heating of buildings but also in the production, which is why it is delivered at higher temperatures than for ordinary district heating supply. To estimate the amount of refinery heat that could be utilized for operating the CO_2 capture plant, the reboiler temperature was assumed to be 121°C, which implies that heat at temperature levels at or above 131°C is available for CO_2 capture. The second step of the heat integration evaluation was to incorporate the heating and cooling duties of the capture plant into the existing refinery heat recovery system and thereby estimate the effect on the district heating supply. Figure 2 shows a schematic overview of the capture plant, with coolers and heaters included in the heat integration highlighted.

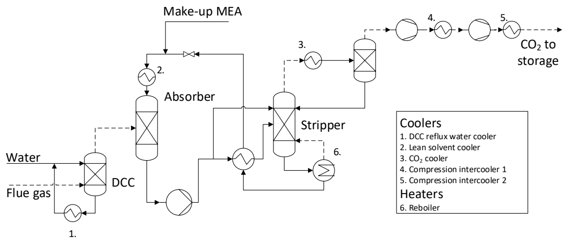

Figure 2: Process flow diagram of the capture process with rich solvent splitting. The process heaters and coolers are marked 1-6.

3.3. Capture process model

The capture process was modeled using Aspen PLUS V11 process simulation software. A standard set-up configuration with rich-solvent splitting was assumed. The set-up of the capture model was based on previous work by Garðarsdóttir et al. [14] and Biermann et al. [15]. The model was expanded to include a two-stage compression sequence with intermediate cooling. A transport pressure of 7 bar(a), suitable for ship transport, was assumed, with the CO_2 being compressed to 20 bar(a) before entering the liquefaction plant [16]. The electrolyte NRTL and RK property methods were used to estimate liquid and vapor properties, respectively, in the capture plant. In the compression sequence, the Peng-Robinson with Boston-Mathias extrapolation equation of state was used to estimate vapor properties. Table 2 lists the key specifications of the simulation set-up.

Table 2: Key specifications of the capture process simulations.

MEA concentration [wt%]	30
Lean CO_2 loading [molCO_2/molMEA]	0.3
Absorber/ stripper packing height [m]	20/15
Absorber CO_2 separation rate [%]	90
Absorber overhead pressure [bar(a)]	1.01
Lean solvent inlet temperature [°C]	40
Minimum temperature approach in cross heat exchanger [°C]	10
Stripper overhead pressure [bar(a)]	1.9
Stripper reboiler temperature [°C]	121
Discharge pressure compressor 1/2 [bar(a)]	6.3/20

4. Results and discussion

4.1. Analysis of available heat

Figure 3 and Figure 4 show the composite curves for the refinery heat recovery system connected to the low- and high-temperature networks prior to capture plant integration. There is a small process heating demand in each system (1.7 MW in the low-temperature network and 2.3 MW in the high-temperature network), however, the district heating water constitutes the main part of the cold composite curves. The curves are not balanced, indicating that trim coolers are needed to remove the remainder of the heat in both systems. The potential for district heating supply is 61 MW in the low-temperature network and 39 MW in the high temperature network. The grey dashed line in each figure represents the cold stream in the capture plant reboiler at 121°C. In the low-temperature network, 10 MW of heat currently delivered to the district heating network is available at temperatures of 131°C or higher, and can thus be supplied to the capture plant. The corresponding amount of available heat in the high-temperature network is 27 MW, thus, a total of 37 MW of heat in the current refinery heat recovery system is available for capture plant operation.

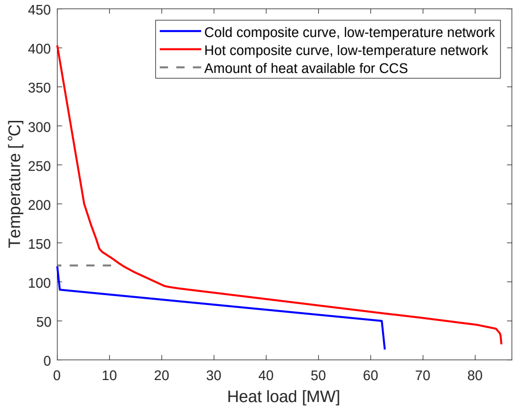

Figure 3: Low-temperature network composite curves. District heating potential (blue line between 50 and 90°C): 61 MW. The amount of heat suitable for CCS (indicated by the grey dashed line at 121°C) is about 10 MW.

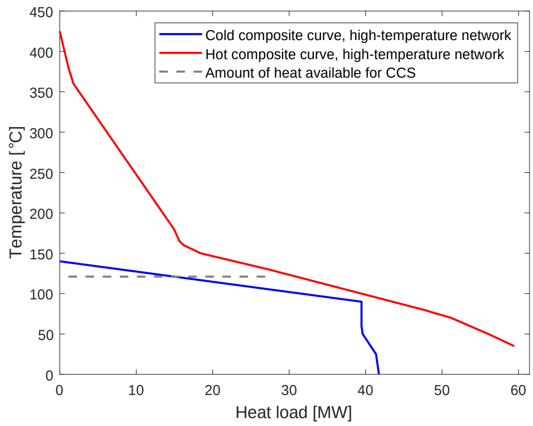

Figure 4: High-temperature network composite curves. District heating potential (blue line between 90 and 140°C): 39 MW. The amount of heat suitable for CCS (indicated by the grey dashed line at 121°C) is about 27 MW.

Table 3 presents key findings from the capture plant simulations. 37 MW of available heat is sufficient for capturing 60% of the direct plant emissions.

Table 3: Capture plant performance.

CO_2 capture rate [kton/a]	298
Direct plant emission reduction [%]	60
Specific reboiler duty [MJ/kg CO_2]	3.72

4.2. Evaluation of heat integration potential and effect on the district heating supply

Table 4 presents the demand for heating and cooling in the capture plant. Large amounts of heat, although at low temperatures (<56°C), are found in the DCC reflux water cooler (1) and the lean amine cooler (2). The excess heat with the highest temperature is found in the compressor intercoolers (coolers 4 and 5) as well as the stripper condenser (cooler 3). In the compressor intercoolers, the amount of heat is low, meaning that the possibility for heat recovery is limited despite relatively high temperatures. Cooler 3 has a highly curved cooling profile, due to the simultaneous water condensation and CO_2 cooling. This profile was represented by a two-segment (3a and 3b) piecewise linear approximation in the analysis. In total, 9.5 MW of excess heat may be recovered from the capture plant to supply heat to the low-temperature district heating network, which corresponds to about 26% of the amount of available heat that is supplied to the district heating networks in the reference case (i.e. prior to capture plant integration). The amount of recoverable heat from the CO_2 capture plant is however dependent on assumptions made, e.g. the chosen ΔT_{min}. It is also dependent on technical factors regarding the capture plant itself, such as e.g. the chosen solvent and the stripper pressure level, thus, the exact amount of recoverable heat will be case specific.

Table 4: Temperature and heat duty of the heaters and coolers in the capture plant and compression sequence. See Figure 2 for numbering.

Cooler	Temperature [°C]	Heat [MW]
1.	50-20	25.6
2.	56-40	12.3
3a	99-60	8.3
3b	60-20	1.9
4	117-25	0.9
5	126-25	1.0
Heater		
6	121-121	37

Figure 5 shows the hot and cold composite curves of the new refinery heat recovery system subsequent to capture plant integration, i.e., where the heating and cooling demands of the capture plant have been included in the respective curves. Furthermore, it is assumed that the previous separate networks are combined in the new heat recovery system. The stripper reboiler duty of 37 MW corresponds to the horizontal part of the cold composite curve at 121°C, which is heated by hot streams at temperatures of 131°C or higher. Since all available heat is used in the stripper plant, it is no longer possible to deliver heat to the high-temperature network (140°C), corresponding to a heat delivery loss of 39 MW. However, even though the supply of available heat to the low-temperature network is removed, in the new heat recovery system, the potential supply to the network can actually be extended from 61 MW to 87 MW. This is partly due to the heat recovery potential arising from the capture plant, and partly due to that even though the supply to the high-temperature network is lost because of the temperature limitations, there are considerable amounts of excess heat (i.e. heat at temperature levels less than 131°C) in the high-temperature network that can be utilized for low-temperature district heating supply in the new heat recovery system.

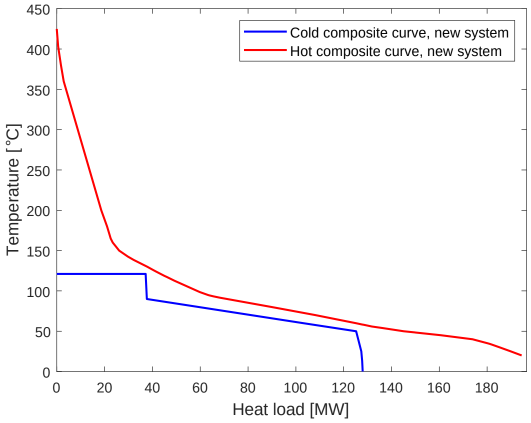

Figure 5: Composite curves of the new refinery heat recovery system, including the integrated CO_2 capture plant. The horizontal part of the cold composite curve, at 121°C, corresponds to the reboiler duty (~37 MW). The inclined part of the blue curve between 50 and 90°C indicates the potential district heating supply of 87 MW.

4.3. Excess heat: to be or not to be

The utilization of industrial excess heat for district heating has efficiently decreased the emissions from the Swedish district heating sector. Broad implementation of carbon capture for emission control will have a considerable impact on the plant energy system and thus, on the possibility to supply district heating. For example, the supply to the high-temperature network considered in this work is lost as a consequence of carbon capture plant integration. However, the heat to the high-temperature network will still have to be supplied somehow, implying that additional supply of primary energy might be needed. Thus, the implementation of CO_2 capture at the refinery might cause increased emissions elsewhere, even though the direct emissions of the industrial plant is significantly decreased. However, it is acknowledged in this work that the definition of excess heat will need to be revised in the future assuming that CO_2 capture is very likely to become a necessary feature of industrial plants, and thus is considered as an internal part of the industrial plant rather than an external application. The availability of low-cost and low-emission heat in the existing industrial energy system is important to make operation of the capture plant economically feasible. Thus, what is often denoted industrial excess heat may rather be available heat suitable for CCS. We therefore assert that the term excess heat should only be used to refer to such heat that is at temperature levels that are too low to be utilized for CCS. Other utilization areas, such as district heating, might still be possible, and might still provide a way to valorize the excess heat, although with more stringent restrictions on the quality of the industrial heat supplied. To provide industrial heat for high-temperature district heating or process heat networks similar to the one in this work will, per definition, not be possible, since the heat provided in the reference case is at temperature levels suitable for CCS utilization. Excess heat supply for low-temperature networks, e.g. for district heating in municipalities, will however still be possible, particularly if heat pumps are used. Considering the studied system in this work, the amount of district heat delivered to the local municipality might even be increased. Furthermore, since the available heat is only sufficient for reduction of 60% of direct plant emissions, in order to reach net-zero emissions, the current refinery energy system needs to be extended, and thus, some new excess heat will most likely arise from the extension. It should however be kept in mind that the study performed in this work only considers the theoretical potential for heat integration between the refinery, the capture plant and the district heating networks. To evaluate the actual feasibility of such integration, an economic evaluation including the capture plant and the additional heat transfer equipment needed would have to be performed, as well as a study considering the practical implementation according to the refinery site conditions. Furthermore, only the current refinery heat recovery system connected to external heat sinks was investigated in this work. For a more detailed analysis, the full refinery energy system should be considered in the heat integration.

5. Conclusions

In this work, CO_2 capture powered by available industrial heat was shown to be sufficient for a reduction of around 60% of direct emissions of the studied refinery. Furthermore, by assuming a ΔT_{min} of 10°C between the capture plant coolers and the district heating network, it can be concluded that 26% of the heat input to the capture plant can be recovered for district heating supply. In the analysis of recoverable heat, it is seen that the most important heat source in the capture plant is the stripper condenser, since it provides large amounts of heat at temperatures suitable for district heating supply. Furthermore, it can be concluded that all heat to the high-temperature network is lost as a consequence of CCS integration, since its supply temperature exceeds the temperature of the capture plant reboiler. For the low-temperature network, the potential supply can be extended by about 26 MW in the new refinery heat recovery system compared to the situation prior to capture plant integration.

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References

[1] Global CO_2 emissions by sector, 2018 [Internet]. IEA. 2020. Available from: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018.

[2] Andersson V, Franck P-Å, Berntsson T. Techno-economic analysis of excess heat driven post-combustion CCS at an oil refinery. *Int. J. Greenh. Gas Control*. 2016;45:130-8.

[3] Biermann M, Ali H, Sundqvist M, Larsson M, Normann F, Johnsson F. Excess heat-driven carbon capture at an integrated steel mill – Considerations for capture cost optimization. *Int. J. Greenh. Gas Control*. 2019;91.

[4] Werner S. District heating and cooling in Sweden. *Energy*. 2017;126(1):419-429.

[5] Eriksson L, Morandin M, Harvey S. (2018). A feasibility study of improved heat recovery and excess heat export at a Swedish chemical complex site. *Int J Energy Res*. 2018;42:1580–1593

[6] Bartela Ł, Skorek-Osikowska A, Kotowicz J. Economic analysis of a supercritical coal-fired CHP plant integrated with an absorption carbon capture installation. *Energy*. 2014;64:513-23.

[7] Bendig M, Maréchal F, Favrat D. Defining waste heat for industrial processes. *Appl. Therm. Eng*. 2013;61(1):134-142.

[8] Pettersson K, Axelsson E, Eriksson L, Svensson E, Berntsson T, Harvey S. Holistic methodological framework for assessing the benefits of delivering industrial excess heat to a district heating network. *Int. J. Energy Res*. 2020;44(4):2634-51.

[9] Olsson L, Wetterlund E, Söderström M. Assessing the climate impact of district heating systems with combined heat and power production and industrial excess heat. *Resources, Conservation and Recycling*. 2015;96:31-9.

[10] Global Warming of 1.5°C [Internet]. IPCC. 2018. Available from: https://www.ipcc.ch/sr15/.

[11] Johansson D, Franck P-Å, Berntsson T. CO_2 capture in oil refineries: Assessment of the capture avoidance costs associated with different heat supply options in a future energy market. *Energy Convers. Manag*. 2013;66:127-42.

[12] Garðarsdóttir SÓ, Normann F, Skagestad R, Johnsson F. Investment costs and CO_2 reduction potential of carbon capture from industrial plants – A Swedish case study. *Int. J. Greenh. Gas Control.* 2018;76:111-24.

[13] Berntsson T, Persson Elmeroth L, Algehed J, Hektor E, Franck P-Å, Åsblad A, et al. Towards a Sustainable Oil Refinery: Pre-study for larger co-operation projects. Chalmers University of Technology; 2008.

[14] Garðarsdóttir SÓ, Normann F, Andersson K, Johnsson F. Postcombustion CO_2 Capture Using Monoethanolamine and Ammonia Solvents: The Influence of CO_2 Concentration on Technical Performance. *Ind. Eng. Chem. Res*. 2015;54(2):681-90.

[15] Biermann M, Normann F, Johnsson F, Skagestad R. Partial Carbon Capture by Absorption Cycle for Reduced Specific Capture Cost. *Ind. Eng. Chem. Res.* 2018, 57, 45, 15411–15422

[16] Deng H, Roussanaly S, Skaugen G. Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities. *Int J Refrig*. 2019;103:301-15.