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Process evaluation of CO_2 capture in three industrial case studies

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Abstract

This work evaluates the technical performance of post-combustion CO_2 capture integrated with industrial processes through three plant level case studies; a kraft pulp mill, an oil refinery and an aluminum mill. As a reference, a comparison is made by applying the same capture process to a coal-fired power plant. Size and quality of the CO_2 streams as well as opportunities for waste heat utilization at each industrial plant are evaluated. The heat requirement for MEA and ammonia based capture are found to be in the ranges of 3610-4400 and 2760-3680 kJ/kg CO_2 for the different industrial processes, with the range strongly influenced by the CO_2 concentration in the treated flue gas. For comparison, the heat requirement of the two capture processes when applied to the power plant is 3850 kJ/kg CO_2 using MEA and 2850 kJ/kg CO_2 using ammonia. Waste heat utilization is also crucial to the implementation of CO_2 capture; one case, the aluminum mill, covered almost 60% of the heat requirement with waste heat. Industrial sources could therefore offer opportunities for efficient implementation of carbon capture

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Keywords: CO_2 capture; post-combustion; industrial sources; chemical absorption

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1. Introduction

Manufacturing industries, such as pulp and paper, (petro) chemicals, and ferrous- and non-ferrous metal plants, are large point sources of CO_2 emissions with a large potential for CO_2 capture. Compared with power generation, the industrial CO_2 emission sources represent a wide variety of exhaust composition and flow conditions; large differences are found between different sectors, but also within specific sectors as well as within specific plants. The most important qualities of the CO_2 source are the size of the source, CO_2 concentration, presence of difficult

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impurities, and possibilities for heat integration between the existing process and the capture process. Due to the large variation in process conditions, industrial processes may be either better or poorer options for cost efficient carbon capture compared to CO_2 removal from power plants. This, together with the fact that many fossil fuel dependent industries are not be able to meet their long term CO_2 emission reduction targets without carbon capture and storage (CCS) [1], has increased the focus of carbon capture research on manufacturing and process industry. Due to the heterogeneous nature of the industrial CO_2 emission sources, case specific investigations are of special importance.

Most studies on post-combustion applications have focused on state-of-the-art coal fired power plants. A number of techno-economic studies have been published, many of them using MEA as a solvent for a benchmarking case, e.g. Abu-Zahra et.al. [2], Abu-Zahra et.al. [3] and Schach et.al. [4]. Also, a few studies focusing on capture in power plants using aqueous ammonia have been published, e.g. Jilvero et al. [5]. The literature also includes a number of comparisons and evaluations of different industries, with respect to possibilities for carbon capture and heat integration. Carbon capture from different CO_2 sources within petroleum refineries has been investigated in several studies, see the review by Kuramochi et.al. [6]. In general, these studies emphasize that site specific conditions greatly influence the capture cost and choice of capture technology and due to the heterogeneity of a modern refinery, the capture cost can vary significantly between CO_2 sources at the refinery site. In this context, CO_2 capture from hydrogen production units, i.e. steam methane reformers (SMR), is generally in the low-end of the capture cost range. Several studies have investigated the possibility for carbon capture in the pulp and paper industry. The post-combustion technology applied to a pulp mill has been studied by e.g. Hektor [7] and Möllersten et.al. [8]. Based on these studies it may be concluded that the post-combustion technology has a significant CO_2 reduction potential when applied to a chemical pulp mill while it is not as feasible to apply on an integrated pulp and paper mill due to limited heat integration possibilities. Studies have also been published on application of CO_2 capture to less suitable sources such as primary aluminum plants. In a recent study, Lassagne et.al. [9] reviewed the existing literature and performed a techno-economic study of CO_2 capture from electrolytic cells. They concluded that a redesign of the electrolytic cells to increase the CO_2 concentration in the flue gas from 1 to 4% is required for a feasible process implementation, with respect to both technical and economic performance. In addition, it was concluded that waste heat recovery allowed for a significant reduction of the capture cost. In our previous work, [10] we showed that the quality of the emission source with respect to CO_2 content in the flue gas greatly influences the technical performance of both the MEA and ammonia based capture processes. It was concluded that it is important to consider the absorber temperature profile, especially at high flue gas CO_2 concentration and for solvents with high reactivity, high heat of reaction and high solvent concentration. The present work applies these conclusions to specific cases with the aim to investigate the practical consequences of the effects of CO_2 quality and to identify suitable process conditions for post-combustion CO_2 capture. The cases include three industrial plants; a kraft pulp mill, an oil refinery and an aluminum mill, as well as a coal fired power plant.

2. Methodology

2.1. Modeling of capture processes

The performance of the chemical CO_2 absorption process is evaluated for two solvents, MEA and ammonia, by means of process modelling. These two solvents have been chosen since they represent well-known solvents applied in post combustion capture. In addition, MEA-based absorption is widely used for benchmarking post combustion capture performance. Ammonia is of interest as it differs considerably to the amine based processes in characteristics e.g. with respect to process setup and solvent properties. Reaction kinetics and heat of reaction are examples of factors that significantly affect the process performance, and, which differ to a large extent between the two processes evaluated.

Both the absorption processes are based on a typical absorber-stripper setup, in which CO_2 is removed from the flue gas in an absorber using a liquid solvent. Prior to the absorber, the flue gas is cooled in a flue gas condenser, operating at 40 and 15°C for the MEA and ammonia based system, respectively. The CO_2-rich solvent is regenerated in the stripper by adding heat to release gaseous CO_2. The ammonia-based model uses a staged-absorption setup with intercooling between the two columns in order to reduce ammonia slip with the exhaust gas, such as the design suggested in Ref. [11], with the intercooling temperature being the same as in the flue gas condenser. A downstream ammonia abatement system was not included in the any of the case studies, however the ammonia emissions from the capture process are considered and their impact on a downstream abatement system discussed. A simple schematic of the model setups and the system boundaries are presented in Figure 1. The system delivers a CO_2-stream with over 95% purity, ready for compression and consequent transport and storage, thus the modelling of the compression section is omitted from all the case studies.

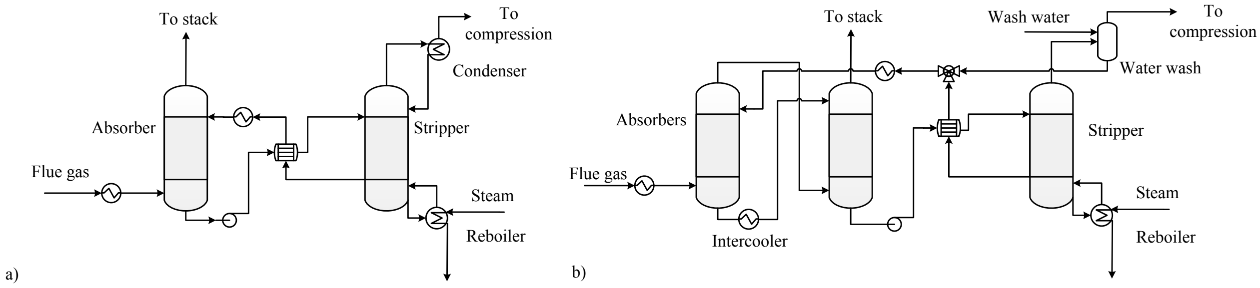


Figure 1: Overview of a) the MEA-based process and b) the staged-absorption setup in the ammonia-based process.

The models of the MEA and ammonia based absorption processes are built in the process modeling software Aspen Plus v8.2 and have been described in our previous work [10]. Both models are rate-based. The mass-transfer between the gas and liquid phase is modeled using the two-film theory and the reaction kinetics of the liquid phase has been described in our previous work as well [10]. Absorbers and strippers are modelled as multistage separation columns with the absorbers modelled as packed columns using Sulzer Melapak 250Y packing. The stripper is assumed to operate at equilibrium, which is justified by the higher operating temperatures that makes the effects of reaction kinetics negligible. Both models utilize the Aspen Plus built-in electrolyte NRTL method and Redlich-Kwong equation of state for computing properties in liquid and vapor phase, respectively. The default thermodynamic models describing the MEA [12] and ammonia [13] based systems in Aspen are used for the simulations. Intercooling in the MEA based process is modeled by implementing heat loss on a specific stage in the absorber so that the temperature of the liquid solvent reaches a specific set value. The temperature in the intercooler was varied between 40 and 50°C and its position was varied in the absorber until the optimal conditions was found, i.e. the location and temperature which required the lowest solvent rate to achieve the desired capture rate.

2.2. CO_2 capture applied to industrial processes

The investigation includes implementation of post-combustion CO_2 absorption to a kraft pulp mill SCA Östrand, located near Sundsvall, Sweden, the oil refinery operated by Preem, located on the west coast of Sweden, and the aluminum mill Hydro Sunndalsöra in Norway. In addition, a case of a state-of-the-art coal-fired power plant is investigated since the technical performance of the post-combustion process has been relatively well studied in this application compared to the industrial cases [14]. In this case, the modern power plant Nordjyllandsvaerket (NJV) in Denmark is used as a reference plant.

2.2.1. Evaluation of industrial excess heat and heat integration

In each of the industrial case studies the available waste heat is estimated as the heat that can be extracted from flue gases. With this approach, interference with the production/industrial process is minimized. In the three industrial case studies, the amount of waste heat with respect to the heat requirement of the capture process itself is evaluated in two ways. Firstly, by estimating how much of the total heat requirement, at 85% capture rate, which can be supplied from waste heat, and, secondly in a similar way by estimating the total amount of CO_2 which can be captured by waste heat alone. For the second alternative, linear dependence is assumed between the capture rate and energy consumption in the reboiler. Thus, construction of new heat sources is not considered and neither was the possibility to use a heat pump with low quality waste heat. In the case of a coal-fired power plant low quality steam is extracted from an appropriate location in the steam cycle for supplying the heat required for 85% CO_2 capture, resulting in a loss in electricity production. In the case studies, the temperature difference of the system, i.e. between the solvent in the reboiler and the flue gas leaving the waste heat boiler, is assumed to be 20K. In the process models, the reboiler operates at 120°C and 160°C in the MEA and ammonia-base process, respectively.

3. Industrial case studies of CO_2 capture

Figure 2 shows the principal process arrangement of the capture unit as applied to the three industrial processes investigated; the chemical recovery system of the pulp mill (Figure 2a), the aluminum smelting cell (Figure 2b) and the hydrogen production unit of the oil refinery (Figure 2c). A brief description of each of the processes is presented in the following sections along with the results from process simulations and evaluation of waste heat utilization in the industrial processes.

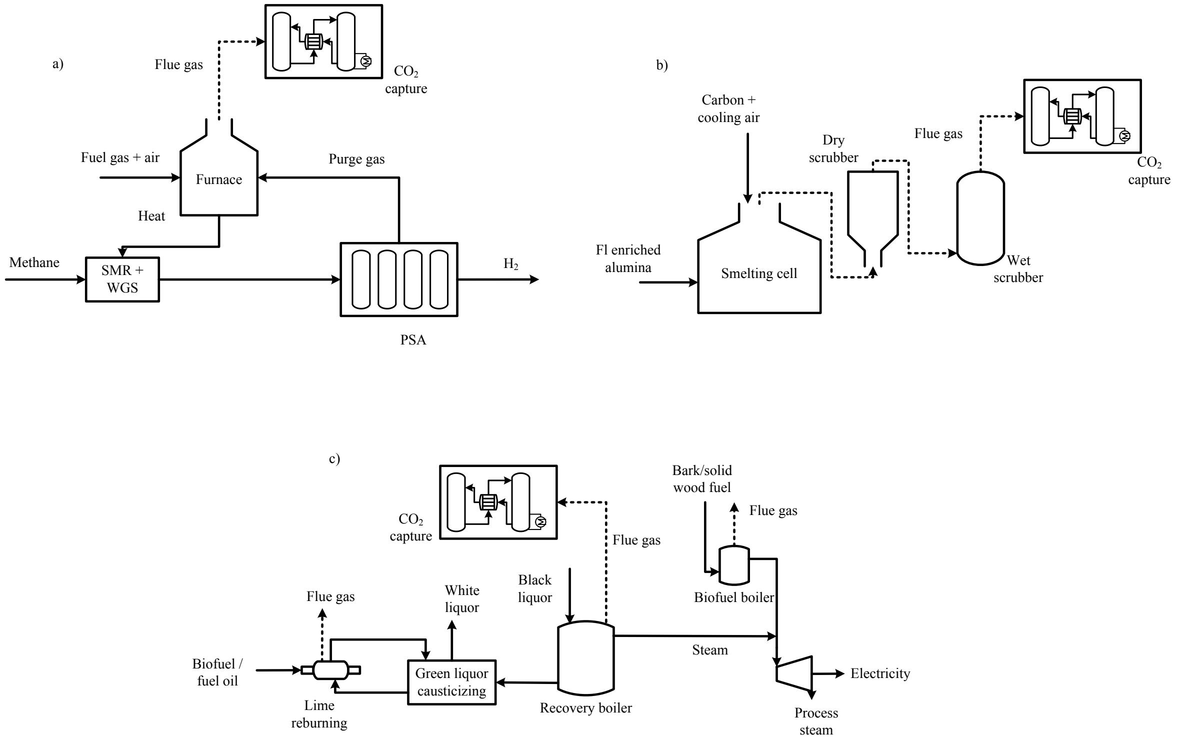


Figure 2: Overview of the industrial processes, a) the hydrogen production unit, b) aluminum smelting cell and c) the heat and chemical recovery system of the pulp mill, integrated with a CO_2 capture unit.

Table 1 gives the composition, temperature and mass flow of the flue gas at the stack from the industrial processes investigated as well as the coal-fired power plant. It can be seen that the CO_2 concentration in the flue gas stream from the steam methane reformer (SMR) at the oil refinery is relatively high, while the opposite is true for the aluminum plant. The composition of the flue gas stream in the pulp mill and the coal fired power plant is fairly similar and the concentration of NO_X and SO_X is highest in the power plant flue gas. The presence of NO_X, SO_X and other impurities is not included in the modeling of the absorption processes. All the plants are located near and have an access to cooling water sources, and thus cooling water availability and temperature is not considered a limiting factor. The power plant is the largest point source of CO_2 out of the four sources.

Table 1: Flue gas composition and properties prior to waste heat extraction in the investigated processes. The composition is specified as mol%, except for NOx and SOx which is specified in ppm.

Process	**CO_2**	**N_2**	**O_2**	**H_2O**	**NOx**	**SOx**	**Temperature [°C]**	**Mass flow [kg/s]**	**CO_2 emission [Mt/yr]**
Oil refinery – SMR	24	59	2	15	25	5	170	57	0.6
Aluminum smelting cell	4	74.6	20.5	0.9	-	>5	265	82	0.2
Pulp mill – recovery boiler	13.3	63.3	4.4	19	-	0	110	131*	0.9
Coal fired power plant	13.1	70.8	3.4	12.7	75	25	56	370	2.4

*** Biogenic emissions**

3.1. Results and discussion

3.1.1. Oil refinery – hydrogen production unit

The refinery investigated is relatively complex and includes crude and vacuum distillation, sulfur removal processes, a fluid catalytic cracker (FCC), and hydrogen production (SMR). The flue gases from the refinery are released through five stacks. The characteristics and origins of the flue gas at the stacks are shown in Table 2. The total CO_2 emission from the refinery is around 1.7 Mt per year.

Table 2: Characteristics of the flue gases at the different stacks of the refinery, the composition is specified as mol%.

Stack no./source	**CO_2**	**N_2**	**O_2**	**H_2O**	**Temperature [°C]**	**Mass flow [Mt/yr]**
Stack 1 – heaters	8	73	4	15	160	4.9
Stack 2 – heaters	9	72	4	15	180	3.0
Stack 3 – FCC	14	70	1	15	270	1.0
Stack 4 – SMR, heater	24	59	2	15	170	1.8
Stack 5 – heaters	8	74	3	15	130	0.5

The flue gas from stack 4, the SMR, is especially interesting from a CO_2 capture perspective, due to the high CO_2 concentration. The reason for the high CO_2 concentrations is that during production of hydrogen, methane is oxidized by water (steam reforming) according to reaction (1). The hydrogen and carbon dioxide concentration is further increased in a water-gas shift reactor (WGS). Hydrogen is finally separated through pressure swing adsorption (PSA) after which the CO_2 concentration may be as high as 55% on a dry basis in the off-gas. However, only around half of the CO_2 released from stack 4 is formed through reaction (2). The other half is formed through combustion of the PSA off-gas and fuel gas from the refinery for supplying heat to sustain the endothermic steam reforming reaction (1). The flue gas from the combustion is mixed with the PSA off-gas and the CO_2 concentration in the stack is around 24%. See Figure 2a for a schematic overview of the hydrogen production unit.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow H_2 + CO_2 \tag{2}$$

In addition, the emissions originating from the SMR is the largest point source of CO_2 at the refinery, accounting for roughly 0.6 Mt per year. The present case study investigates the possibility to solely capture CO_2 from the SMR, i.e. partial CO_2 capture. Even though the hydrogen production unit is the single largest point source at the refinery, it only accounts for roughly 30% of the total emission. CO_2 capture from this process does therefore not have as great net reduction potential at a plant level as the other two industrial cases.

In our previous work, we showed that increased CO_2 concentration in the flue gas generally decreased the heat needed for solvent regeneration [10]. The relatively high CO_2 content in the flue gas stream exiting the SMR thus affects the performance of the capture process. Primarily the specific heat requirement for CO_2 capture is lowered to 3610 and 2760 kJ/kg CO_2 using MEA and ammonia, respectively, which could be compared with the 3850 and 2850 kJ/kg required for the power plant. On the other hand, the temperature profile of the absorber is affected by the high CO_2 content, which may influence the absorption performance. However, in previous studies, see e.g. Ref [10], it was shown that by optimizing the absorber temperature profile, e.g. with intercooling, the process performance could be improved considerably at a relatively high flue gas CO_2 concentration (>20 mol%). In the present modelling work, intercooling to 50°C was applied in the MEA-based absorber. The optimum position was determined to be at 50% of the column height and the cooling is assumed to be achieved with on-site cooling water. The application of intercooling resulted in a decrease in the specific heat requirement by 7%, from 3880 to 3610 kJ/kg CO_2, which translates to a reduction in heat consumption of 5.5 MW in the stripper reboiler. Intercooling was however not applied in the ammonia-based absorber since the problem of too high absorber temperature was not present. If CO_2 should be captured from a different location in the SMR, which might have an even higher CO_2 concentration, e.g. in the PSA off-gas, it would be even more important with an appropriate lay-out of the absorber temperature profile in order to minimize the process heat requirement.

The relatively low heat requirement for CO_2 capture from the SMR is primarily influenced by the high CO_2 concentration in the SMR flue gas. In addition to this, the refinery offers heat integration possibilities which could cover a significant share of the heat demand. In this study, only waste heat from the five stack streams, as presented in Table 1, was included. The waste heat was estimated to cover 24 and 8% of the heat demand in the MEA and ammonia based absorption processes, respectively, which translates to a capture rate of 21 and 7 % for a case when waste heat alone is used in the CO_2 capture process. For comparison, a detailed heat integration analysis performed on the same refinery by Andersson et al. [15] concluded that a replacement of 10 cold utility heat exchangers with a heat collecting system would result in roughly 31 MW of available waste heat for the MEA capture process. With the assumption of a linear dependence between the reboiler duty and the capture rate, this amount of waste heat would enable a CO_2 capture rate of 43% from the SMR flue gases.

3.1.2. Aluminum smelting

The investigated aluminum mill emits around 0.5 Mt CO_2 per year. The CO_2 emitted at a primary aluminum plant originates mainly from the aluminum smelting cells and for this investigation, carbon capture is implemented on one section of the plant. The Hall-Heroult process is by far the most used method in the smelting cells. A simplified overview of a smelting cell and its flue gas train is presented in Figure 2b. In short, the process involves dissolving alumina in cryolitic solution in a cell containing carbon cathodes. Carbon anodes are dipped into the molten pool of alumina and electric current is passed through the solution. As a result, the alumina is reduced to primary aluminum and CO_2 is released in the process according to the overall reaction:

$$2Al_2O_3 + 3C \xrightarrow{electricity} 4Al + 3CO_2 \tag{3}$$

The flue gases originating from the current process design contain nearly 1 vol% CO_2, due to the large airflows which are required to cool and ventilate the cells. A new design of the cells which enables to reduce the air ventilation and to increase the CO_2 concentration in the flue gas to 4 vol% has been proposed by Lorentsen et al. [16]. In this work, the new design with 4 vol% of CO_2 is used. The amount of SO_2 and HF in the process gas is reduced by dry and the wet scrubbers. One important issue with the flue gas from aluminum smelting is the degradation of amines in presence of high oxygen concentrations. MEA is known to be sensitive to oxygen degradation, which leads to equipment corrosion [17] and could thus have a strong influence on the cost of capture, e.g. with respect to maintenance and make-up-solvent costs. This issue was however not considered in this work.

The flue gases from aluminum smelting have a low concentration of CO_2 compared with the other processes investigated. This results in a relatively high heat requirement for both the absorption processes, 4400 and 3680 kJ/kg CO_2 for the MEA and ammonia absorption, respectively. A relatively large amount of ammonia leaves the system with the CO_2 lean flue gas, around 9000 ppm. Should a downstream ammonia abatement system based on steam stripping be used to reduce the ammonia slip to acceptable levels (<10ppm), this could add significantly to the total heat requirement of the system, over 1000 kJ/kg CO_2 [18]. However, due to the relatively high temperature of the flue gases from the smelting cells, a significant share of the heat needed for solvent regeneration can be provided with waste heat - 57 and 47% for the MEA and ammonia based processes, respectively, which allows for a capture rate of 48 and 40%.

3.1.3. Chemical pulp mill – recovery boiler

The investigated kraft pulp mill emits around 1.3 Mt CO_2 each year (biogenic emissions). The Kraft chemical process is based on cooking wood chips in a mixture of chemicals in order to extract cellulose and hemicellulose from the wood and further process the material to produce the desired pulp product. The spent cooking chemicals along with the rest of the wood, which is not used in the product, are combusted together in a so called recovery boiler in order to recover the cooking chemicals. The heat released is used to generate steam which is needed in various processes within the pulp mill and it may also be used to produce electricity in a steam turbine. The recovery boiler is responsible for the nearly 70% of CO_2 emission from the plant. The rest of the CO_2 emitted originates from combustion of bark and solid wood fuel in a boiler as well as combustion of biomass in the lime kiln including also a relatively small amount of fuel oil [19]. The heat and chemical recovery system of the pulp mill is illustrated in Figure 2c, including the main CO_2 emission sources at the plant; the recovery boiler, the biofuel boiler and the lime kiln.

The simulations of the two capture processes resulted in a heat requirement of 3760 and 2800 kJ/kg CO_2 for the MEA and ammonia absorption, respectively. The waste heat from the flue gas stream in the pulp mill cannot be directly utilized in the stripper reboiler due to its low quality, and there are in principal no sources of sufficiently high quality waste heat sources available at this specific plant. The pulp mill offsets a part of its low quality waste heat to a local district heating system, this heat is however still of too low quality to be used in the stripper reboiler.

As mentioned, the CO_2 emissions from the process originate almost entirely from biogenic raw material. The concept of combining bioenergy with carbon capture and storage (BECCS) to remove CO_2 from the atmosphere has been previously discussed in literature and in their studies, Möllersten et.al. [8], [20] concluded that the pulp and paper industry has the potential to become a net-exporter of biomass based energy while removing CO_2 from the atmosphere. In a more recent study, Azar et al.[21] discussed the possibility and economic feasibility to use BECCS for reaching stringent temperature targets by developing a global climate and energy system model. They concluded that under certain political and energy market conditions, stringent temperature targets could be reached with lower costs by implementation of BECCS, especially if an overshoot of the targets would be allowed. At present, a considerable share of the pulp mill's steam demand is covered by combustion of bark and solid wood fuels at the pulp mill. Should a part of, or all heat needed for CO_2 capture be supplied from increased combustion of these biofuels at the pulp mill, the mill has the possibility to become a negative net contributor to the global CO_2 emissions and could be a suitable candidate to which BECCS can be applied.

3.1.4. Coal fired power plant

The Danish pulverized coal power plant Nordjyllandsvaerket is used as a basis for the power plant case. Figure 3 gives a schematic overview of the power plant steam cycle and the integration with a post combustion CO_2 capture unit. The NO_X and SO_X in the flue gas from the power plant is reduced to a large extent before the stack and the capture unit. The steam used for solvent regeneration is extracted between two intermediate pressure turbines and the condensate from the reboiler heat exchanger is returned to the feedwater heating system, as shown in Figure 3. The simulations of the two capture processes resulted in a heat requirement of 3850 and 2850 kJ/kg CO_2 to regenerate the MEA and ammonia, respectively, which will seriously affect the electricity generation; the power plant electric efficiency is reduced from 46% to 38% with MEA and to 40% with ammonia as solvent. The electric efficiency is reduced even further, by a few percentage points, should the electricity needed for CO_2 compression be accounted for.

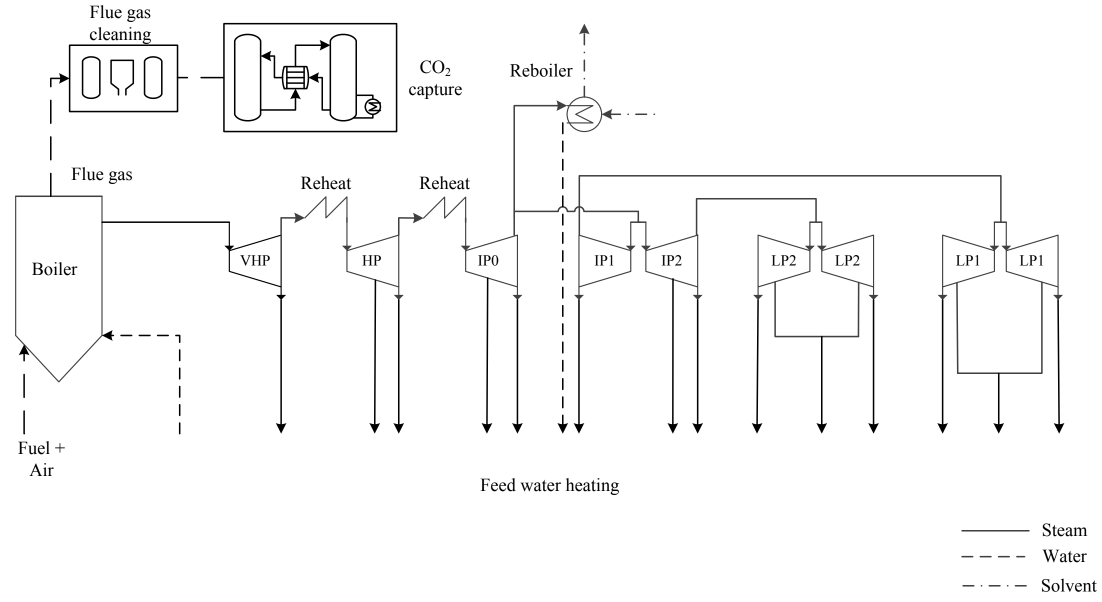
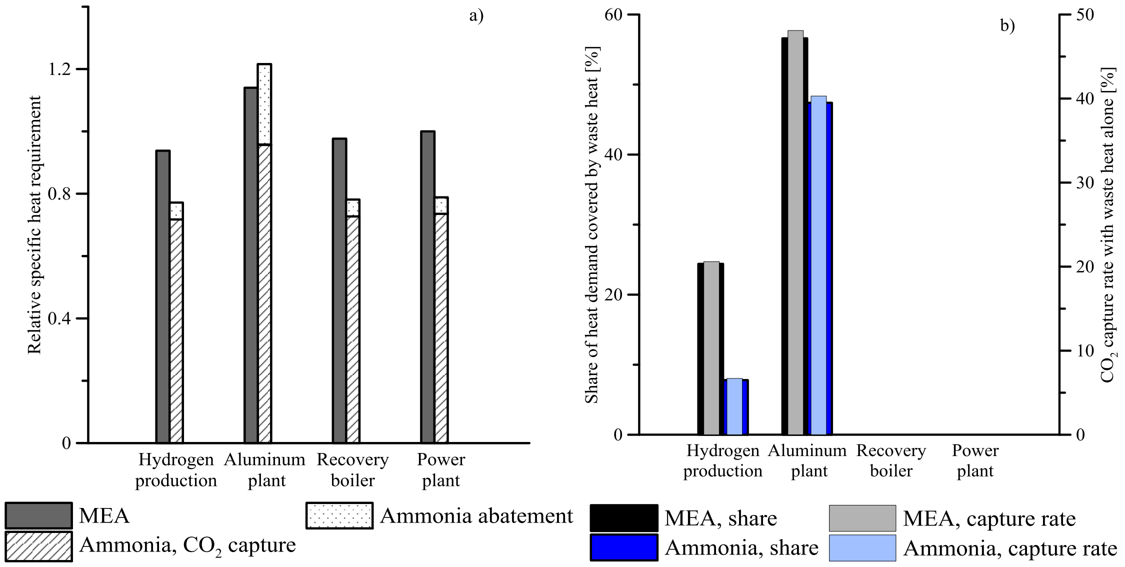


Figure 3. Overview of the NJV power plant and the CO_2 capture process integrated with the power plant.

Results for the three industrial case studies as well as those for the coal fired power plant case are summarized in Figure 4. The figure shows the heat requirement for capture in each of the cases, relative to the case of a coal-fired power plant with MEA based CO_2 capture. In addition, the share of heat demand covered with waste heat and how much CO_2 can be captured with waste heat alone is presented for all cases, as well as the amount of CO_2 captured and the net CO_2 capture rate at the industrial plants and the power plant.



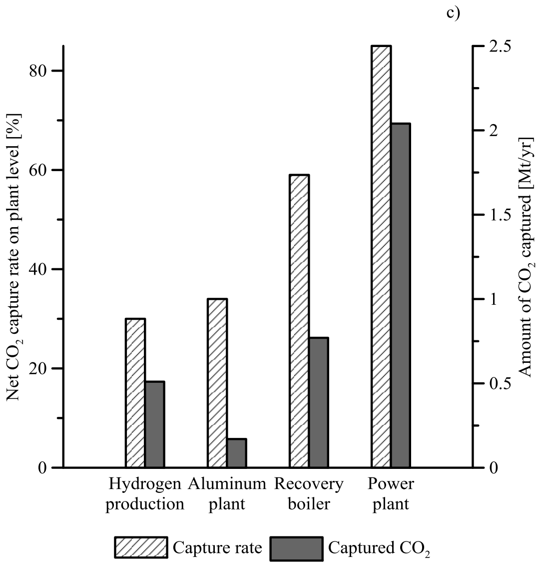


Figure 4. a) The heat requirement of CO_2 capture with MEA and ammonia for the three industrial cases relative to corresponding heat requirement for the coal fired power plant with 85% CO_2 capture rate. The values are relative to the case of MEA-based CO_2 capture at the coal fired power plant. The additional heat requirement for an ammonia abatement system is estimated from Ref [18]. b) Available waste heat as a share of the heat demand for capture and CO_2 capture rate with waste heat alone. c) The amount of CO_2 captured at each plant as well as the net CO_2 capture rate on a plant level.

Figure 4a shows how the heat requirement of the absorption processes is influenced by the CO_2 content of the treated flue gas. The CO_2 concentration is important, especially at very low concentrations such as found in the aluminum plant. Strictly from this perspective, capture from the aluminum plant is the least feasible option while capture from the oil refinery´s SMR is the most favorable. In addition, the ammonia abatement system, which recovers the ammonia leaving the absorber with the CO_2 lean flue gas, might add significantly to the total heat requirement of the capture plant, especially in the case of the aluminum plant for which the ammonia slip measured around 9000 ppm while in the other cases the slip is in the range of 2000-3000 ppm. The added heat requirement due to the ammonia abatement system can be estimated based on the work of Jilvero [18], and is indicated in Figure 4a. Besides CO_2 concentration, the possibility for heat integration is an important factor. Some of the industrial cases present favorable heat integration possibilities, and a significant portion of the CO_2 emitted could be captured using waste heat alone. A considerable amount of waste heat can be recovered at the oil refinery and the aluminum plant, *cf.* Figure 4b. The lower temperature requirement of the MEA process is favorable since a considerable amount of waste heat at temperatures lower than what is needed in the ammonia-based process is available at these industrial plants. The size of the CO_2 sources targeted at each plant varies considerably and thus the amount of CO_2 captured does as well, cf. Figure 4c. The coal-fired power plant dominates in amount of CO_2 captured and in addition, the net CO_2 capture rate on a plant level is highest for the power plant. A relatively small amount of CO_2 is captured at the aluminum plant compared with the other sources. Since only one section of the aluminum mill was included in the study, it might be possible to capture a larger amount of CO_2 at similar conditions if other sections of the mill would be included as well. However, if this would be the case, the amount of captured CO_2 would still be relatively low since the aluminum mill is such a small point source compared to the other plants.

The net relative heat requirement, i.e. the heat required in the capture process after the available waste heat has been utilized, is presented for all cases in Figure 5 (the coal-fired power plant with MEA capture is the reference with net heat requirement = 1). It should be pointed out that the steam consumption in the power plant is not regarded as waste heat in this context since it results in a drastic change in the power plant performance and therefore the net heat requirement of the power plant is not affected. Due to the high degree of heat integration in the case of the aluminum plant, a relatively low amount of heat needs to be supplied additionally to the process compared to the other industries. This is especially interesting since the capture process has the highest heat requirement out of all the cases, *cf.* Figure 4a. However, the large amount of waste heat balances this drawback. It could also be noted that in the case of the aluminum plant, the net heat requirement using MEA is slightly reduced compared with ammonia as a solvent while the opposite is observed for the oil refinery´s SMR and the pulp mill´s recovery boiler. Another interesting result is that CO_2 capture from the power plant has the highest net relative heat requirement while it has the highest CO_2 reduction potential as shown in Figure 4c, almost 10 times higher than for the aluminum mill.

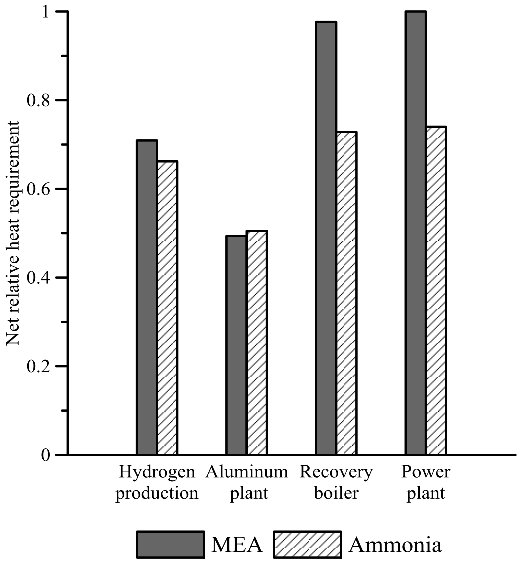


Figure 5: Net relative heat requirement of CO_2 capture, i.e. the heat required after the available waste heat has been utilized, for the three industrial cases relative to the MEA-based capture at the coal fired power plant, with 85% capture rate. The heat required for an ammonia abatement system has been excluded from the figure.

4. Conclusions

This work includes three case studies of the implementation of post-combustion CO_2 capture to different industrial plants with a focus on variations in CO_2 quality and heat integration possibilities. The CO_2 emission sources in the industrial processes include a wide range of CO_2 concentrations, 4-30 vol%. Relative to the power plant case using MEA-based absorption, the heat requirement of the capture process differs with -6 to +14 percentage points and -28 to -4 percentage points, for the MEA and ammonia based absorption, respectively. The general trend is that the heat requirement of the absorption processes increases with decreasing CO_2 concentration in the inlet gas stream. The level of heat integration varies considerably between the investigated cases. Almost 60% of the total heat requirement could be covered by waste heat alone in the case of the aluminum plant, while no waste heat of sufficient quality is available at the pulp mill. The hydrogen production unit has both high CO_2 concentrations and access to waste heat which covers around 25% of the total heat requirement. CO_2 capture at the coal-fired power plants shows by far the largest net emission reduction compared with the industrial cases and also has the highest net capture rate on a plant level. Since the CO_2 emissions from the pulp mill originate primarily from biomass, the pulp mill has the possibility to become a negative net contributor to global CO_2 emissions.

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