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CO_2stCap - Cutting Cost of CO_2 Capture in Process Industry

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Abstract

This paper is a presentation of the CO_2stCap project to be undertaken in the four year project period (2015 – 2019). The project focuses on partial CO_2 capture in process industry and how this can be applied to reduce cost. By performing techno–economic analyses, the optimal capture rate, including optimal design, application and configuration for different industry sources can be obtained. Cost estimation methods are used as a basis to identify and verify potentials for cost reduction when applying different options for implementation of partial CO_2 capture. CO_2stCap. Industries studied in this project are pulp & paper, steel, cement and metallurgical production of silicon for solar cells.

Nomenclature

BFG	Blast furnace gas
BOFG	Basic oxygen furnace gas
CAPEX	Capital expenditure
CCS	Carbon capture, transport and storage
CHP	Combined heat and power
COG	Coke oven gas
OPEX	Operational expenditure

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Keywords: CO_2 capture; partial capture; cost reduction; process industry

1. Introduction

Ambitious goals for the reduction of carbon dioxide emissions have been established on national, regional and global level and the large efforts made on research has resulted in the development of technologies that could heavily reduce the emissions. It is, however, clear from the low level of implementation that the cost of avoiding CO_2 emissions is still too high both from an industry and a society perspective. Carbon capture and storage (CCS) is one of the technologies that has reached a level of maturity where it could be implemented on a large scale and heavily reduce the global emissions of CO_2 but suffers from a low level of implementation Therefore, a recent cooperation between industries and research organizations in Norway and Sweden initiated the project CO_2stCap aiming to reduce the cost of carbon capture by focusing on partial capture. The work is still in an early phase, but initial results can be found in the paper by Normann et al. [1].

It has been a standard goal for carbon capture schemes to aim for an as high CO_2 capture rate as possible. From a technical perspective, it is relatively straight forward in most cases to achieve capture rates above 90%. When applied to a conventional CO_2 source (typically a coal fired power plant) with access to heat from a steam cycle, a high capture rate will usually also lower the specific capture cost and be beneficial to the plant owner (given that the penalty for emitting CO_2 is higher than the capture cost). However, in many industries with less conventional CO_2 sources and heat supplies a high capture rate may imply excessive costs that actually increase even the specific capture cost. The reasons for the higher costs are often linked to the fact that in process industries, access to energy for CO_2 capture is a limiting factor and also that emissions often come from several stacks with potentially different emission rates and flue gas compositions. In addition, in many studies, the capture plant is assumed to have the same high operational time per year as the industry source itself. There might be good reasons to detach the operational time of the capture plant from that of the source, to get a cost optimal CO_2 capture rate. The focus of the CO_2stCap project is to investigate the concept of partial capture in industry and how this can be applied to reduce the cost for CO_2 capture in the industrial sector. This paper provides an introduction to the project.

2. About CO_2stCap

The full name of the project is "Cutting Cost of CO_2 Capture in Process Industry". The research partners are Tel-Tek, Chalmers University of Technology, The University College of Southeast Norway, Innventia and Swerea MEFOS. The industry partners are SSAB, Elkem AS, Norcem Brevik AS, AGA Gas AB. The partners involved in the project, represent large industries with considerable emissions of CO_2, including cement, steel, pulp and paper, and silicon production. In addition, the Global CCS Institute (GCCSI) and IEA Environmental Projects Ltd. (IEAEPL) represented by IEA Greenhouse Gas R&D Programme are involved. The project is funded by the Norwegian CLIMIT–Demo program via Gassnova, The Swedish Energy Agency, and the participating industries and research partners. The total project budget is approximately 2.7 million Euros. It was launched in 2015 and is planned to be completed in 2019.

2.1. Objective

The project will give an overview of partial capture possibilities for the four industries (cement, steel, pulp and paper, and silicon production), including an estimation of the CO_2 capture cost, both in capital expenditures (CAPEX) and operational expenditures (OPEX). The project will take into account that individual plants may have several scattered CO_2 sources of varying quality; that the possibilities for heat supply differ between plants, as well as the fact that some plants emit CO_2 originating from biogenic sources. The overall aim is, thus, to suggest a cost effective carbon capture strategy for future CCS systems considering utilization of waste heat and intermittent power supply, a more efficient use of biomass resources, different capture technologies and optimization, as well as changed market conditions. The project will investigate where and how CCS, particularly partial CO_2 capture, may be applied cost efficiently to emission intensive industry.

2.2. Motivation

The motivation for the CO_2stCap project is to significantly reduce the cost for carbon capture. CCS has shown to be a too expensive investment to motivate a broad implementation with current market condition.. The hypothesis is that the capture cost can be significantly reduced when applied to the most suitable CO_2 sources and the possibility of managing the energy requirements. Today, CCS is commonly evaluated on the total present fossil CO_2 emission without taking into account that a substantial part of the total emissions can be omitted by increased use of renewable energy or increased energy efficiency. The required energy needed for CO_2 capture is an important parameter, and this energy may have different value depending on season, the amount produced and energy demands. By including these factors in the design of the capture plant, it may reduce the capture cost and make CCS a cost-efficient CO_2 mitigation asset.

2.3. Partial capture

Partial capture is defined as a process that for economic reasons is deliberately designed to only capture parts of the CO_2 produced. It differs from the prevailing idea about CO_2 capture that a high capture ratio (>90%), which is environmentally beneficial, should be sought. The design conditions typically used for concluding on a 85-90% capture rate are a conventional flue gas stream with up-time as close to 8760 hrs/year as possible. Cases that could motivate partial capture include plants or facilities:

- with multiple stacks
- that must reach a certain level to meet emission regulations
- with access to low-cost energy to cover parts of the demand
- that can vary their product portfolio depending on market conditions

The concept of partial CO_2 capture has been advocated previously, primarily although with focus on power generation; see for example Hildebrand [2] and the IEA Greenhouse Gas Programme [3]. The IEA report points to the fact that multiple capture units will be needed on large power plants, and defines the concept of partial CO_2 capture as one of two options of capturing a relatively low fraction of CO_2 in each power generation unit, or capturing a high (e.g. $\geqslant$85%) fraction of CO_2 in one or more power generation units and not capturing CO_2 at the other units. A third option, not mentioned by IEA Greenhouse Gas Programme, may be to utilize partial capture through a time varying capture rate taking into account the spot price of energy, for example differences between night and day. More recently, applications in process industry have been investigated e.g. by Garðarsdóttir et al [4].

It is important to investigate and understand the operational philosophy of the individual industrial plants to be able to assess the potential of partial capture concepts. It is expected that there will be significant differences between the industries and even on a plant level regarding the applicability of the concepts. Below is the four partial capture concepts described.

2.3.1. Plants with multiple stacks

A typical example is a plant with multiple CO_2 sources that are collected and emitted through multiple stacks. The CO_2 concentration and the volume flow may differ considerably between the stacks, i.e. there are large differences in the suitability to apply capture to the different sources/stacks. It may also include capturing from CO_2-

rich process stream within processes. In this, case removal of CO_2 may actually favor the process performance. The size of the CO_2 source is obviously important to the economy-of-scale of the capture process. The CO_2 concentration has also been shown important to the cost and performance of CO_2 capture [5]

2.3.2. Plants seeking to comply with emission targets

It might be a solution for some industries to use less effective (but low-cost) technologies or absorbents and thereby a lower capture rate than the 90 % "standard" capture rate. This will also reduce the capture cost. Industries may also have several other options to reduce the CO_2 emission; e.g. change of electricity source, change of fuel, introduction of renewable energy carriers, energy efficiency. These options may be in combination with partial CO_2 capture enough to reduce the emission to the desired level.

This concept is illustrated in Fig 1. It shows an industry plant with several options for CO_2 reduction, and a target for 85 % reduction of CO_2 emission (2020 level) in 2040. Instead of installing CCS for a capacity of 85 % of the CO_2 emission, partial capture of 25 % in 2025 and 10 % in 2035 is installed. In combination with other CO_2 reduction methods, like energy efficiency, fuel change, etc. it gives the desired 85 % reduction of CO_2 in 2040.

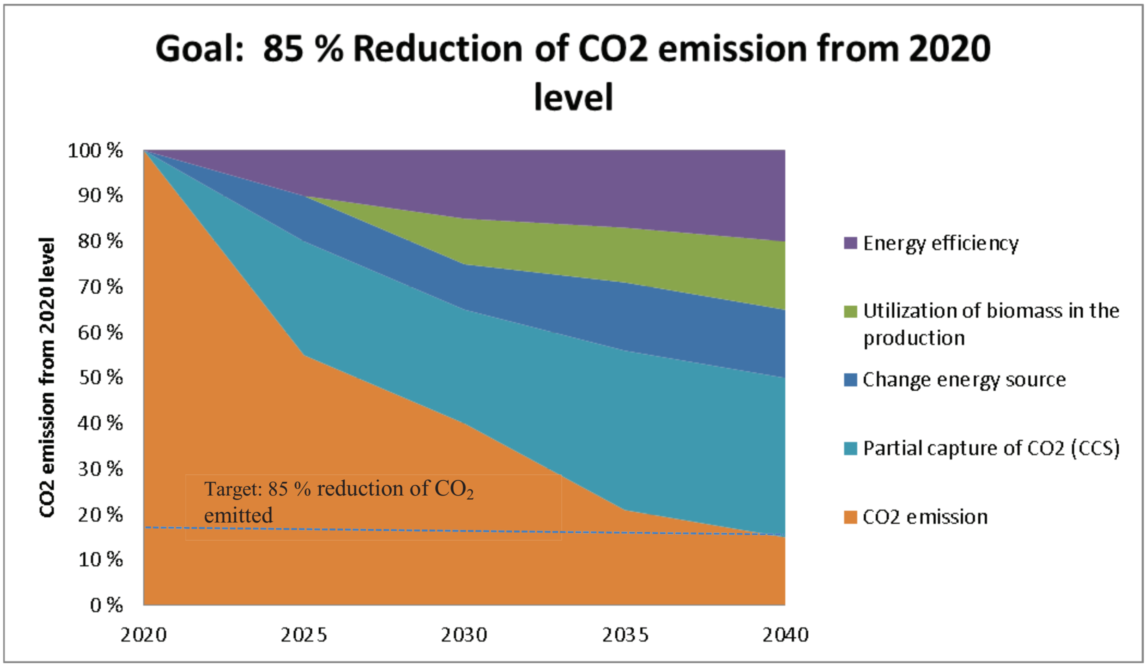

Fig. 1. Illustration of how partial capture can in combination with other methods give a total reduction of 85 % CO_2 emitted.

2.3.3. Plants with access to low-cost energy.

The options to power the capture process will differ between the industrial sites (e.g. excess heat, steam extraction, existing steam boiler, new steam infrastructure) and they will have different cost levels. The effect of the multiple options to power the capture process on the capture cost is illustrated by Fig. 2. which is a process with a fixed amount of excess heat that may be utilized for CO_2 capture. The specific capture cost is decreasing as the volume is increasing. However, the cost to capture beyond the capture rate achievable with low cost energy supply will be considerable. As Fig 2 illustrates; if new infrastructure for supplying heat will be required, the capture cost will rise.

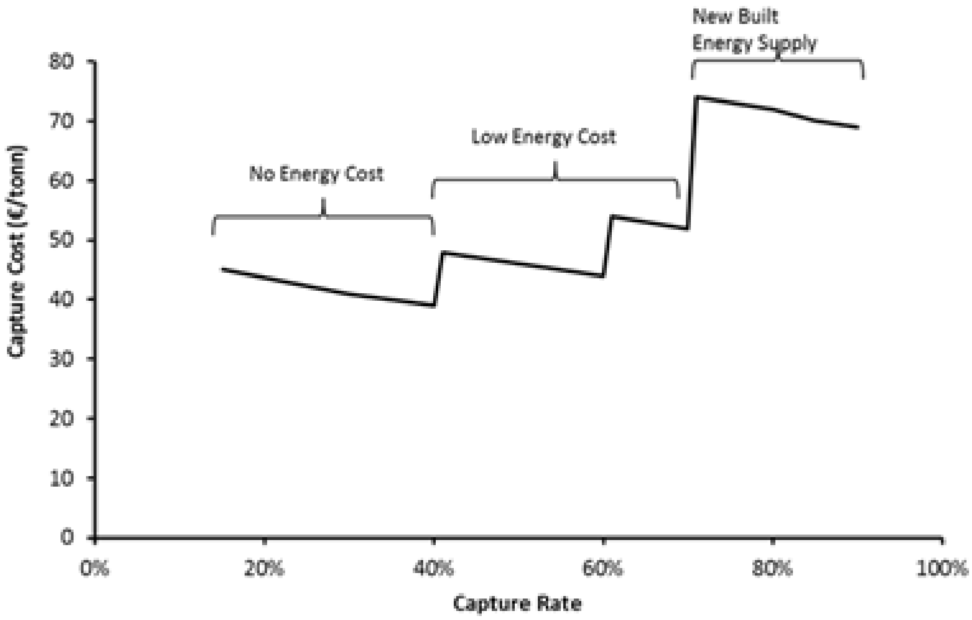

Fig. 2. Illustration of how capture cost may vary with capture rate for an industrial CO_2 source with available waste heat.

2.3.4. Plants with variable operating conditions

Power plants may run at variable load over time. Establishing a capture unit that captures an “average” CO_2 amount, and which is not dimensioned to take the peaks, would reduce both CAPEX and OPEX for the capture plant. In intensive periods some of the CO_2 may be released, while for normal operation the CO_2 capture unit will have sufficient capacity.

Similarly, some industries could choose to operate their CO_2 capture plant on a part-time basis. This can be determined by the energy cost or by operational conditions at the source. As an example the capture plant may only operate at nighttime or during summer. Fig 3.illustrates a capture facility that nearly runs only at summer when steam price is low, and not during winter when the steam is needed for district heating.. For such cases, the CAPEX and the fixed operational cost will be high, but the variable operational cost (steam, electricity etc.) will be lower. The total capture cost may be reduced compared to plants which are operating full time.

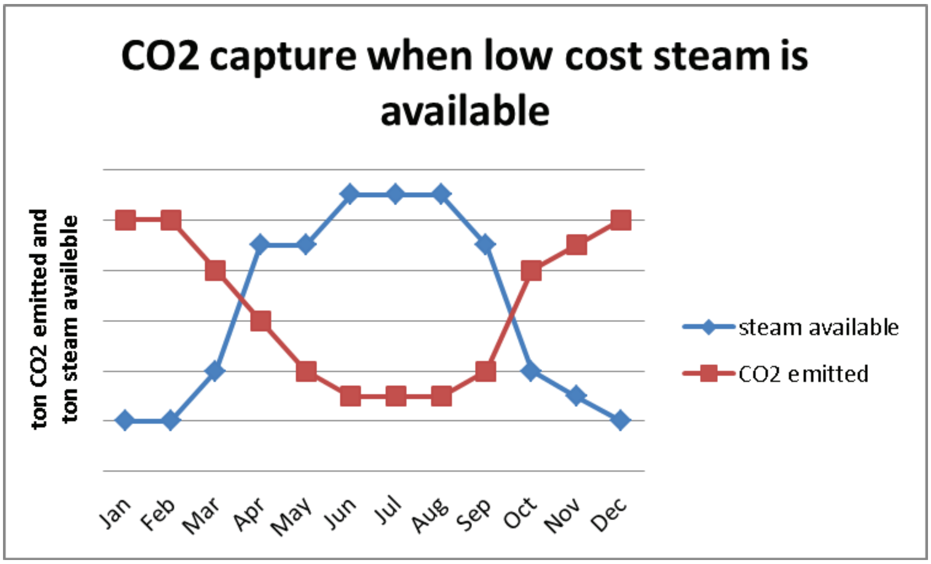

Fig. 3. Illustration of how partial capture when low cost steam is available.

2.4. Selected concepts

As a first step, two basic partial capture concepts have been selected for the study;

- Continuous capture – the capture plant follows the operational time of the base plant
  - The size of capture plant is adjusted to the available amount of waste heat
  - The size of capture plant is adjusted to a the base or average production scenario instead of peak production
- Discontinuous capture – the capture plant operates when the energy supply is favorable, day/night and summer/winter variations

From these, a number of variations can be developed. The next section will introduce the four industries, and give an overview of the selected partial capture technologies that will be investigated in the project.

3. Industrial cases

Four different industrial cases have been selected to investigate how the partial capture concepts may be introduced to the industries. These cases vary in size, type of production, emissions and available (excess) energy. The CO_2 sources studied are cement, pulp, steel, and silicon production for solar cells. This chapter introduces the industrial cases studied in the project. The partial CO_2 capture concepts are preliminary, and concepts will continuously be added and reassessed as the project proceeds.

Table 1 presents some examples of characteristics of the CO_2 sources as well as the possibilities to generate heat for the CO_2 separation to illustrate the broad span of conditions. The possibilities to separate CO_2 differ a lot between processes and will require different capture process designs for different processes.

Table 1. Examples of different industrial sites characteristics for their suitability for implementing CO2 capture.

Industry	Quantity kt CO_2 / year	Quality (vol.% CO_2)	Number of point sources (stacks)
Silicon	50	~1	1
Cement	1000	12-16	1
Iron and steel	2300	7-30	3 (~ 90%)
Pulp and paper	1600	20	3

There is available excess heat for recovery from hot flue gases, hot liquids and materials, energy rich gases, waste water, steam, etc.

3.1. Silicon production

The solar cell industry, which produces materials for renewable energy production, has a high environmental profile and high willingness to pay to get a CO_2-neutral product. Rootzén et al has previously discussed the value of creating CO_2-neutral products for the steel industry [6]. So far the industry has focused on energy efficiency, new furnace designs and fuel substitution. The need for carbon electrodes makes it difficult to be carbon neutral. The silicon/solar industry have not been involved in many CCS projects, mainly due to the relatively small amounts of CO_2 in the process gas. Even so, the willingness to pay may create a business case for CCS making the silicon/solar production carbon neutral.

Depending on the application of silicon (i.e. the purity needed), there are several methods for extraction. A typical process is described below. The process consists of five well-known metallurgical operations, such as reduction smelting, slag treatment, hydrometallurgical leaching and directional solidification. The reduction process is illustrated in Fig. 4.

The raw materials, quartz and carbon, are fed into an electric arc furnace. Consumable carbon electrodes are lowered into the quartz and carbon mixture. The electrodes form an arc, with a temperature of 2350˚C, which then melts the quartz and carbon to form silicon and CO.

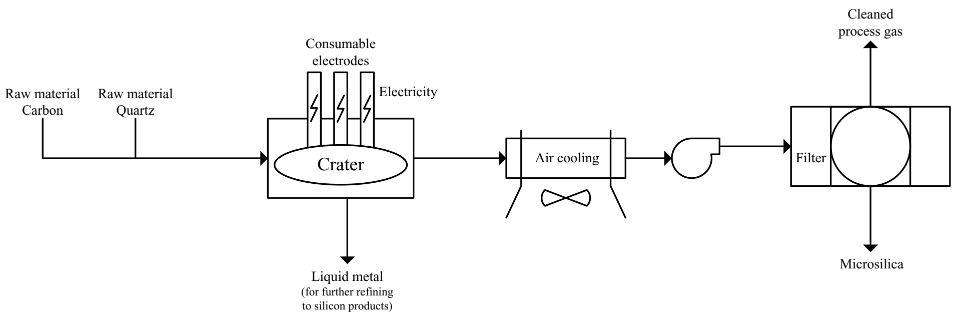

Fig. 4. Overview of silicon production (reduction smelting) at Elkem Solar in Kristiansand

This case is based on the Elkem Solar production site in Kristiansand, Norway. The industry plant produces approximately 10 kt silicon each year, corresponding to 43 kt CO_2 from fossil energy sources and 12 kt CO_2 from bio energy sources. The main challenge for CO_2 capture is the low emission volume of CO_2 in combination with low concentration of CO_2 in the flue gas. The flue gas goes through large filters that remove micro silica particles (dust) before the flue gas is emitted to air. The concentration is reported to be 3 vol% before the filters and 1 vol% after. The plant in Kristiansand does not utilize the waste heat today, and this energy could potentially be recovered for use in a CO_2 capture plant. The low CO_2 concentration limits the number of applicable CO_2 capture technologies, therefore only amine scrubbing will be considered initially. The CO_2 capture process is likely to be implemented after the dust filters, as the dust, micro silica; is a valuable product.

The following partial capture concepts will be investigated:

- Amine scrubbing using waste heat only
  - 90% capture from part of the flue gas
  - Less than 90% capture from the whole flue gas
- Amine scrubbing with electric boiler during periods with low(er) electricity price
  - Yearly variation
  - Day and night variation
- Combinations of concept 1 and 2

3.2. Cement production

The main ingredient of making cement is limestone ($CaCO_3$). Limestone in powder form is mixed with different correction materials in order to achieve the right quality for the cement. This powder mix is pre-heated to 1 000°C, at this temperature the limestone is reduced to calcium oxide (CaO) and CO_2. This process step is called calcination. The mixture then enters a rotating furnace where further heating to 1 450°C takes place. In this process, the powder mixture is sintered to form clinker. After cooling the clinker is ground to cement in a mill. The process steps in cement production are illustrated in Fig. 5.

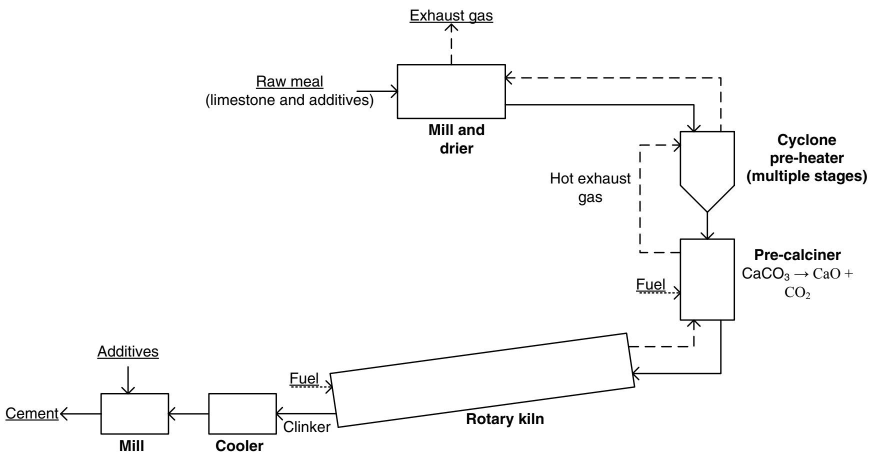

Fig. 5. Illustration of cement production

In this study, a cement plant in Brevik, Norway is chosen. In a Nordic perspective Norcem Brevik is a medium sized cement plant, with a reported production of 1 056 kton clinker and 1 265 kton cement in 2013 [7]. Calculations based on the CO_2 emission and the clinker and cement production from 2013, the associated CO_2 emissions are between 630 – 700 kg CO_2/ton cement produced. Norcem is continuously working on reducing the CO_2 footprint of the cement [8]. Several measures have been implemented: energy efficiency, increased share of biomass and alternative fuels, development of new cement products, and utilization of the carbonation effect. (Carbonation is the result of the dissolution of CO_2 in the concrete and this reacts to form calcite ($CaCO_3$). In addition, Norcem is also looking into the possibility of CCS. The Norcem CO_2 capture project was launched in 2013 and will continue until 2017 [7]. The aim of the project is to test several CO_2 capture technologies on actual cement flue gas and a small-scale test centre was established. Norcem has taken part in the Norwegian CCS study led by Gassnova [9]. The goal of this project is to identify at least one potential full-scale CCS project for Norwegian industry that can be realized by 2020.

Generally, about 60% of the CO_2 emitted from cement plants are due to the calcination process (limestone $CaCO_3$ is the main raw material), and the remaining 40% comes from the fuel consumption. Coal is the main fuel, but the process is highly flexible in types of fuels that can be used and different sorts of biomass and waste is increasingly used. The CO_2 concentration of the flue gas from cement production can be as high as 30 vol% depending on the technology used. At the Brevik plant the concentration is between 12 and 16 vol% and several post-combustion technologies are possible to use. Also oxy-combustion could be considered for retrofit even though it is more likely for new-build. The following partial capture concepts have so far been identified;

- Amine scrubbing using excess heat only
    - 90% capture from part of the flue gas
    - Less than 90% capture from the whole flue gas
- Amine scrubbing with electric boiler during periods with low(er) electricity price
- Variation in operation time
    - Yearly variation
    - Day and night variation
- Combinations of concept 1 and 2
- Other post-combustion capture technologies that use electricity during periods with low(er) electricity price
    - Yearly variation
    - Day and night variation
- Other post-combustion capture technologies that utilize waste heat
- Partial oxy-combustion, in calciner only
    - Partial oxy-combustion only
    - Combined with Selexol

3.3. Pulp and paper production

The forest industry is one of the most important industry sectors in the Nordic countries. The forest industry includes industries related to pulp- and paper industry and the wood mechanical industry (saw mills etc.). The forest is important from a climate perspective. The growing forest stores carbon dioxide and wood-based products continue to store carbon dioxide until their end of life. Products and materials based on forest raw material can replace fossil based products and materials and thereby contribute to a transit to a society based on renewable raw materials and reduced emissions of fossil CO_2. The forest industry is already today a large supplier of renewable electricity and district heating and is in addition one of the largest suppliers of biofuels to other sectors. The on-gong conversion of the pulp- and paper industry to so-called bio refineries producing multiple of bio-based products will increase the number of products based on forest raw material. Examples of new products include transportation fuels, bulk chemicals, textiles, carbon fibres and other bio-based products and materials.

The Nordic pulp and paper industry has put large focus on reducing their fossil CO_2-footprint over the last years. In Sweden, the CO_2 footprint has been more than halved since 1990 and is reported to about 1 Mton/y in Sweden in the national inventory report 2015 [10]. This number is to be compared to the total CO_2 emissions in Sweden of 45 Mton (as CO_2) [10]. It can also be compared with the biogenic CO_2 emissions from the pulp and paper sector which is about 22 Mton/year (information from year 2007 [11]), with about 10 individual installations with biogenic emissions between 1-2 Mton/year. Similar numbers can be found for the Finnish pulp and paper industry. Accordingly, in the current project the focus will be on BioCCS or BECCS, i.e. capture and permanent storage of emissions of biogenic CO_2 from the pulp mill's emission sources, resulting in negative emissions of CO_2,

First and foremost it is the pulp mill that is main source of the biogenic CO_2 emissions. There are emissions in the paper mill, but these are significantly lower compared with the pulp mill. In this case study, a stand-alone pulp mill has been chosen, mainly since there are limited amounts of steam available in an integrated pulp and paper mill to use in a CO_2 capture process. An overview of a general kraft pulp process is given in Fig 6..

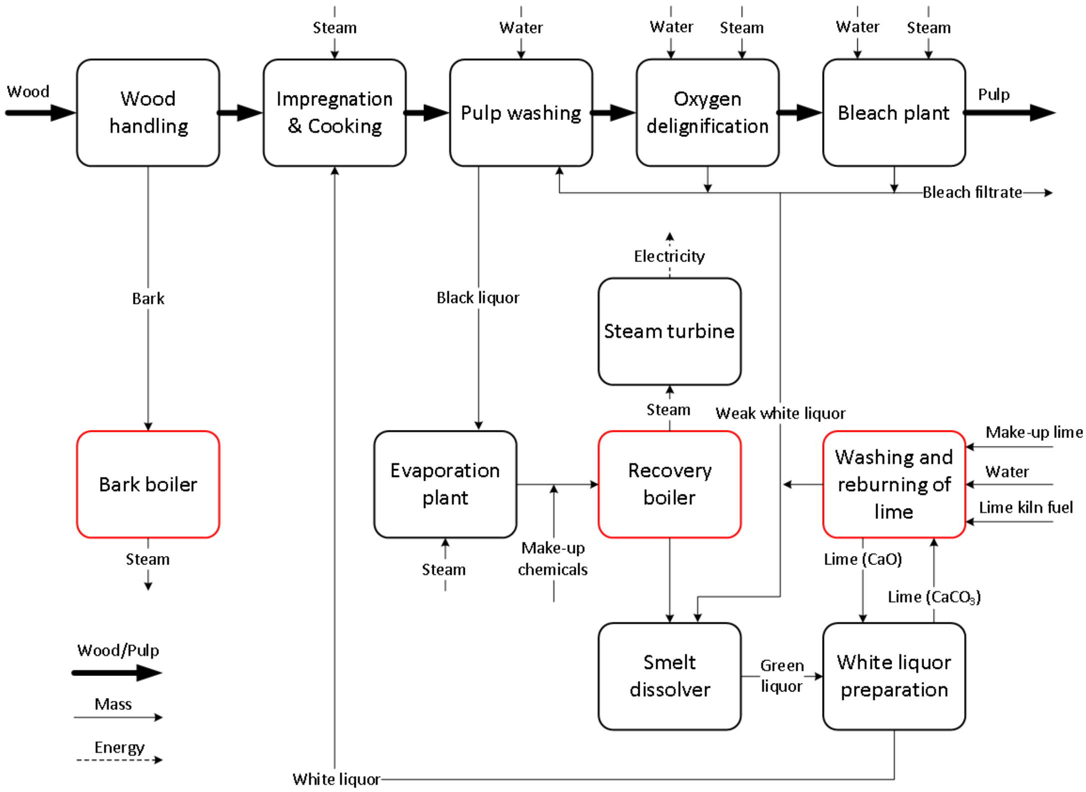

Fig. 6. Simplified illustration of the pulp process and mass and energy flows [12]

The CO_2 emissions are biogenic, and only a very small share is fossil CO_2 emissions related to use of start-up and support fuels, CO_2 from make-up lime and in some cases from use of fossil fuels in the lime kiln. Looking at the pulp mill, the recovery boiler is by far the largest source of CO_2, 70 - 80% of the pulp mill's emissions, followed by the lime kiln, and lastly the bark boiler. Based on the assumption that post-combustion CO_2 capture seems to be the lowest risk option for implementation and that it can be applied to all three of the CO_2 sources it has been decided to focus the investigations in the CO_2stCap project on post combustion capture of CO_2 from the recovery boiler and lime kiln. The investigation will look into the impact of full and partial capture utilizing residual energy and energy from low-cost wood by-products such as bark to fulfill the steam demand from the capture unit. Special focus will be put on the competition between using energy for CO_2 capture or for generation of green electricity.

3.4. Steel production

The majority of today's steel production uses a blast furnace, followed by an oxygen furnace with iron ore as the main iron source and coal/coke as reduction agent and energy carrier. This process route emits on average 1.8 ton CO_2 per ton steel [13]. Fig. 7 shows the typical process route for steel production.

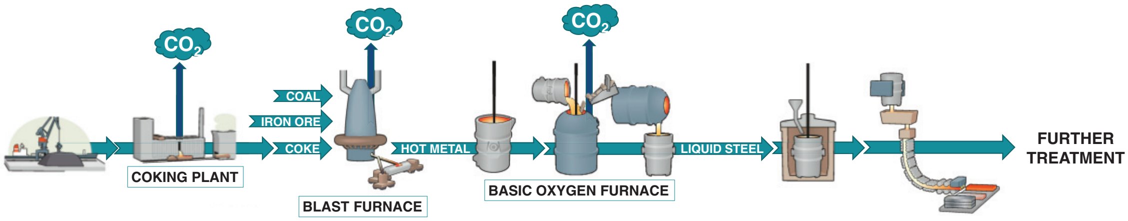

Fig. 7. Simplified illustration of the steel process and its CO_2 intensive processes

The steel industry is continuously searching for ways to decrease their CO_2 emissions, either by optimizing existing processes, developing new process schemes or introducing renewable materials into their processes. One of the largest European initiatives for CO_2 mitigation in the steel industry is the Ultra-Low Carbon dioxide Steelmaking (ULCOS) program [14] which had the objective to find ways to reduce the CO_2 emission by 5% compared to the best available techniques. ULCOS emphasized four breakthrough mitigation technologies, three of which have carbon capture as a prerequisite. Alternatives to CCS include introducing other reductants (e.g., renewable, hydrogen rich or electricity).

The integrated steel plant in Luleå has one of the most effective blast furnace operations in the world and will in this project be used as the basis for the development of partial capture concepts for iron and steel. Most CO_2 emissions in a steel plant are from the gases produced in the coking plant, blast furnace and basic oxygen furnace. The gases are then used as primary fuel at different locations inside, and outside, the plant to produce heat for the different processes.

In today's situation there is a low demand to recover and utilize excess heat in the steel mill. The surplus of fuel gases, which is not used for internal use, is often utilized for e.g., production of electricity and hot water production for district heating, which for Luleå is crucial during the cold winters. However, as the combined heat and power (CHP) plant will experience seasonal variation in demand of hot water, due to lower output to the district heating grid during summers, there are opportunities to utilize this to run e.g., a capture unit. Energy could also be recovered from cooling of e.g., slags, coke and flue gases but will require more investments to access.

This study has decided on four partial capture cases, two of which focus on post-combustions capture, A and B in Fig. 8, and two on pre-combustion, C and D. Case A is a typical post-combustion scenario on one of the CO_2 richest (~30 %) and largest streams out of the system. Meanwhile, case B handles an almost as rich (~25 %) process off-gas as A, but less flow in comparison. For the pre-combustion case C, capture is done on the mixed fuel gas out from the gas holder (BFG,BOFG and COG) before going to the CHP-plant and for case D, capture is done on blast furnace gas (BFG) going into the gas holder. The CO_2 content in the mix gas is around ~23 %, and has a higher flow rate than B, and BFG is around ~25 %. There is only a small difference in flow rate between C and D. Capturing before combustion has the advantage of increasing the heating value of the gas, increasing its value as fuel gas.

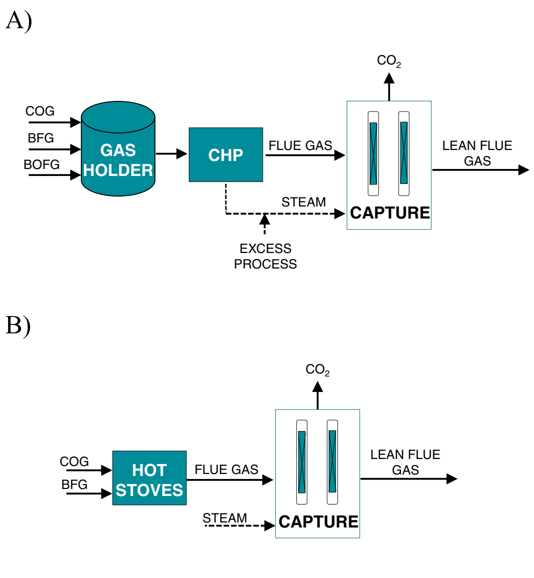

Fig. 8. Potential partial capture cases at the iron and steel plant: (A) post-combustion capture from CHP plant, (B) post-combustion capture form hot stoves, (C) pre-combustion capture gas mixture, and (D) pre-combustion capture BFG

4. Summary and expected results

The most promising partial capture concepts will be validated against a base case, a full-scale (90% capture rate) split-flow amine (MEA) scrubbing capture plant. Different partial capture concepts will be evaluated technically, and cost optimized to find the lowest total cost for the capture plant. Reducing the CAPEX will in addition to reduce the cost, reduce investment risk. When it comes to capture cost, it is generally the OPEX that is the major contributor. Reducing the yearly cost will have huge impact on the total cost picture, and may be the push needed for large-scale deployment of CCS.

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