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TCCS–10

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Nils A. Røkke and Hanna Knuutila

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SINTEF Academic Press
Address: Børrestuveien 3
PO Box 124 Blindern
N-0314 OSLO
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CO_2 CAPTURE OPPORTUNITIES IN THE NORWEGIAN SILICON INDUSTRY

A. Mathisen[1*], **F. Normann**[2] , **M. Biermann** [2], **R. Skagestad**[1], **A.T. Haug**[3]
[1] SINTEF Industry, Porsgrunn, Norway
[2]Chalmers University of Technology, Division of Energy Technology, Gothenburg, Sweden
[3] Elkem, Oslo, Norway

* Corresponding author e-mail: anette.mathisen@sintef.no

Abstract

CO_2 capture opportunities for the Norwegian silicon industry have been assessed through a techno-economic investigation. Two silicon plants have been studied for integration with a split-flow MEA-based CO_2 capture plant. The two plants considered produce different silicon products, and while the base production process is similar, there are differences that affect implementation of CO_2 capture. Initially, the purpose of the investigation was to identify partial capture scenarios that could reduce the cost of capture and thereby the threshold for implementing CO_2 capture. The investigation showed that there was sufficient excess heat to achieve a capture rate of 90% for both plants. However, as there are silicon plants that do recover the energy today for power and heat production, a seasonal partial capture scenario was developed. Here, the energy is converted to district heating and sold during the winter months and assumed available for CO_2 capture during the summer months. Due to there being sufficient heat, a major part of the investigation was still centered around exploring 90% capture rate scenarios. The first plant is a small plant (~55 kt CO_2 annually) with a low CO_2 concertation in the furnace off-gas (1 vol%), which resulted in a high capture cost, ~ 120 €/t CO_2. The second plant is a larger plant (~250 kt CO_2 annually) with a higher CO_2 concentration in the furnace off-gas, but still quite low from a CO_2 capture perspective at ~4 vol%. For this plant, the effect of off-gas recycling to increase the CO_2 concertation was assessed. Three scenarios were studied, and the result gave a capture cost between 45 – 55 €/t CO_2 captured. Even though the plants both produce silicon products, they have a very different starting point and economic potential when it comes to implementation of carbon capture and storage (CCS). The investigation into seasonal partial capture gave some interesting results and warrants further investigation.

Keywords: *CO_2 capture, process industry, excess heat recovery*

1. Introduction

The most abundant element in the Earth's crust after oxygen is silicon (Si), more than 25%, in the form of silicates [1]. The Norwegian silicon industry is the 4th largest in the world with a reported annual production of 380 000 metric tons in Year 2018 [1]. The silicon industry is an energy-intensive industry, which consumes both electricity and carbon-based raw materials. Silicon produced in Norway has one of the lowest overall CO_2 emissions in the world, mainly because of high energy efficiency and the majority of Norway's electricity stemming from hydro power [2]. Still, the industry is a significant contributor to the industrial CO_2 emissions in Norway due to the carbon consumed in the process. The industry is pursuing several pathways to reduce emissions in addition to carbon capture and storage (CCS), such as development of the production process, excess heat recovery, and increased share of carbon from biomass.

The work presented is part of the CO_2stCap project [3]. CO_2stCap is a Norwegian-Swedish research initiative aiming to reduce the cost of carbon dioxide (CO_2) capture in the process industry by developing concepts for partial capture. The project started in 2015 and ends in June 2019. Four different industries were investigated; iron & steel, cement, pulp & paper, and silicon.

The aim of this paper is to assess the potential for CO_2 capture at two different silicon production plants located in Norway. The developed scenarios are investigated using techno-economic assessment.

1.1 The silicon production plants

Two different silicon production plants form the basis of the investigation. They consist of one or more electric arc furnaces, in which quartz (SiO_2) is reduced by carbon;

$$SiO_2 + 2C = Si + 2CO$$

With the present production process, all CO from the process is oxidized above the charge level. The off-gas leaves the furnace at temperatures in the range of 400 - 700°C, it is then cooled before entering a filter (typically baghouse) where the valuable byproduct microsilica is recovered. The two plants considered produce different silicon products, and while the base production process is similar, there are differences that affect the implementation of CO_2 capture. A scheme of the production process is presented in Figure 1.

Plant one is a real plant, REC Solar, located in Kristiansand. It has one furnace with an annual production of ~10 kt silicon metals. The product is mainly used in solar panels. The corresponding CO_2 emissions are ~55 kt, of which ~20% are of biogenic origin. The main challenge for CO_2 capture for this plant is the rather small amount of CO_2 emitted in combination with a low concentration of CO_2 in the furnace off-gas of ~1 vol%.

The second, larger plant has two furnaces, and produces ferrosilicon (FeSi) primarily for use in the iron and steel industry. Here, the expected CO_2 concentration in the furnace off-gas is ~4 vol%, and the annual CO_2 emissions are ~250 kt. This is a generic plant, still it is representative of FeSi plants operating in Norway today. The industry is working on increasing the CO_2 concentration, and one of the focus areas is off-gas recycling. For a plant with multiple furnaces, this might entail off-gas recycling on one or several furnaces.

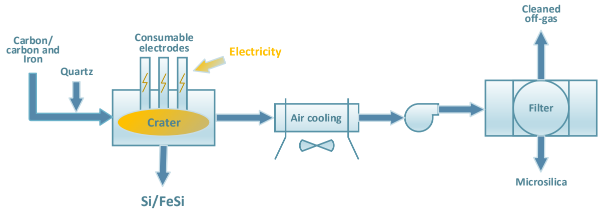

Figure 1: Scheme of the silicon production process.

2. Methodology

Figure 2 gives a schematic overview of the methodology applied in both the CO_2stCap project and the present study. The design of cost-efficient capture processes is determined in a techno-economic analysis in form of an iterative procedure between costing and process modelling. The technical investigation is based on detailed process simulations in Aspen Plus to design and dimension the MEA capture unit. In the work presented, the silicon production plants are coupled with a rich-solvent split-flow MEA-based CO_2 capture plant followed by compression of the CO_2 to 110 bar, see Figure 3. The process models used have been presented in, amongst others [4] and [5].

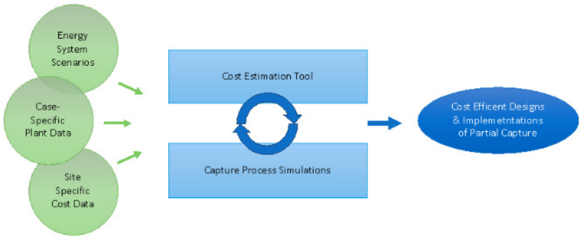

Figure 2: Methodology adopted in the project.

The cost estimation is performed with the Aspen In-plant Cost Estimator combined with a well- proven, in-house developed installation factor model, [6] - [8].

The investment cost (CAPEX) is estimated from equipment lists containing dimensions that are derived from the process simulations. The operational cost (OPEX) is based on mass and energy flows across the battery limits of the plant per hour and is obtained from these simulations. The annual OPEX are calculated based on a utility and personnel price list, and maintenance cost, see Table 1 for details.

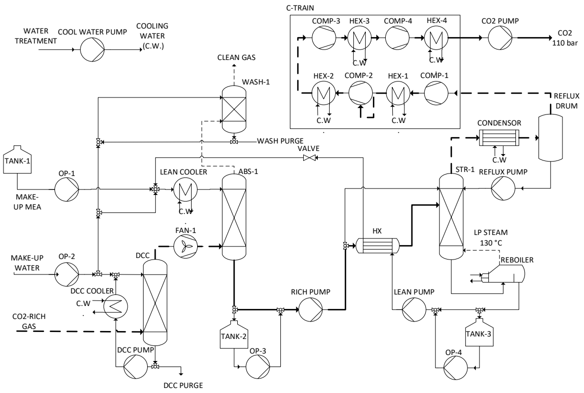

Figure 3: Illustration of the MEA capture process with rich-solvent split-flow configuration.

Table 1: Parameters used for OPEX calculation.

Parameter	Unit	Value
Electricity price	EUR/kWh	0.055
Cooling water	EUR/m^3	0.02
MEA make-up*	EUR/m^3	1 867
Personnel – operators (1 person per shift)	kEUR/an	663
Personnel – engineers (1 person)	kEUR/an	158
Maintenance (% of installed cost)	%	4
Uptime	H	8 760
Rate of return	%	7.5
Number of years		25

* MEA make-up is based on IEAGHG [9] assumed 1 wt% of lean MEA stream to continuous reclaimer and 5% MEA loss during thermal reclaiming.

2.1 Assumptions

The main assumptions are;

- 30 wt% MEA, split flow configuration
- Steam to reboiler, 2.7 bara and 133°C
- CO_2 compression to 110 bar
- Onsite steam generation for the stripper reboiler is included, electric boiler (EB) and excess heat steam generation (WHSG)
- Brownfield site
- Only direct plant emissions considered
- CAPEX
- Project contingency (20%) is included
- The detailed factor estimation method normally has an uncertainty of ± 40% (80% confidence interval)
- Cost year 2015
- n^{th} of a kind (NOAK)
- Start-up cost is not included

2.2 Partial capture

A rule of thumb in carbon capture and storage (CCS) from power plants has been to achieve a capture rate of

90% or higher. From a technical perspective, it is relatively straight forward in many cases to achieve such high rates, for instance when applied to power generation. However, in many process industries such high capture rates could imply excessive cost and a different CO_2 capture strategy, i.e. partial capture should be adopted. The partial capture concept is defined as capture of only a fraction of the available CO_2 emissions on site. The following examples illustrates plants where partial capture could be favorable to full capture, i.e. yields lower absolute and specific cost (€/t CO_2) – further aspects are discussed in;

- Plants that have excess energy or an energy system that constantly or depending on market conditions may produce a part of the heat needed for carbon capture at low-cost.
- For plants with multiple stacks, targeting the most suitable stack(s) instead of total site emission.
- Plants where carbon capture is cost-efficient in combination with other mitigation measures, such as biomass, electrification, energy efficiency measures, etc.

This work assesses also, whether applying partial capture is a relevant strategy for the Si/FeSi plants investigated here.

3. CO_2 capture scenarios

The scenarios investigated for the two silicon production plants are presented in the sections below. Because of the difference in the plants, different scenarios have been developed.

One of the most important aspects in CO_2 capture is energy supply to the stripper reboiler. In the scenarios studied, the steam is either supplied from an electric boiler or from excess energy from the furnace off-gas recovered in a WHSG.

A general observation from both plants is that there is sufficient heat available from the furnace off-gas (~ 600°C) to cover the energy (steam) needed in the stripper reboiler. This excess energy is to varying degree utilised today in Norwegian Si/FeSi plants. The most likely CO_2 capture scenario for both plants is that excess heat is utilised in the capture plant to reduce the capture cost. However, to increase the flexibility of the results (adaption to other plants where excess heat is not available) and to provide a reference, a scenario with an electric boiler is included.

Developing partial capture scenarios within this premise is limited as scenarios that are governed by how much CO_2 can be captured utilsing the excess heat is not applicable. However, if the alternatives for utilising the excess heat is either for CO_2 capture or for sale of district heating, one could consider seasonal capture, i.e. CO_2 capture during the seasons of the year where the district heating demand is low. Seasonal (partial) capture was only explored for plant 1.

3.1 Plant 1 – Si production

An overview of the scenarios studied for plant 1 is provided in Table 2. The CO_2 concentration after the filter is ~1 vol%, however it was calculated to be 3.7 vol% before the filter, see Figure 1. Therefore, scenarios with both CO_2 concentration were included. However, the pre-filter capture scenario will entail changes in the existing Si production process as CO_2 capture from an off-gas containing particles is not recommended. In addition, the particles in this case is a valuable bi-product (microsilica) and must be recovered. The most obvious change would be a different filter design with less air dilution. The technical feasibility of such changes and associated costs has not been considered. Further, a study into increased plant size was also performed to investigate the effect of size. The sizes chosen, in addition to 1x55 kt CO_2 plant (original plant), were, 3x55 kt CO_2 and 5x55 kt CO_2.

Table 2**:** Scenario overview, plant 1.

Scenario	**CO_2 capture details**
1a	1 vol% CO_2 in off-gas, 90% capture rate, energy supplied thorough an electric boiler
1b	1 vol% CO_2 in off-gas, 90% capture rate, energy supplied thorough a WHSG
1c	3.7 vol% CO_2 in off-gas, 90% capture rate, energy supplied thorough a WHSG

3.2 Plant 1 – seasonal (partial) capture

Commonly for Si and FeSi plants in Norway is that they seek to recover the excess heat when there is a market for it. For plants with a favorable location, e.g. if there is a market for the heat as district heating in the surrounding area. However, if the heat recovered is sold, it could limit its availability for use in the CO_2 capture plant (steam to the stripper reboiler). To assess the consequences of such a scenario, the investigation into plant 1 was extended to assess seasonal capture. The main assumptions adopted for seasonal capture are;

- Excess heat for district heating is only sold during the winter months (six months of the year)
- Excess heat can be used "free of charge" for CO_2 capture during the summer months. CAPEX for WHSG is included.
- A full-sized capture plant is built (capacity to capture 90% of the CO_2 produced at the given time)
- The value of the steam as district heating was set equal to the value of 16.67 €/t
- All year capture includes a loss of revenue from sales of district heating during winter

The scenarios included in the investigation into seasonal capture are presented in Table 3.

Table 3**:** Scenario overview of seasonal capture for plant 1.

Scenario	CO_2 capture details
2a	1 vol% CO_2 in off-gas, 90% capture rate all year, steam from WHSG
2b	1 vol% CO_2 in off-gas, summer only capture, steam from WHSG
2c	3.7 vol% CO_2 in off-gas, 90% capture rate all year, steam from WHSG
2d	3.7 vol% CO_2 in off-gas, summer only capture, steam from WHSG

3.2 Plant 2 – FeSi production

In Table 4, the scenarios studied for the second plant are presented. The focus of this investigation was the effect of applying off-gas recycling for increased CO_2 concentration. The scenarios are, one where both furnaces were operated as normal (3a), one where both furnaces have off-gas recycling (3b), and one where the one furnace operates as normal and one has off-gas recycling (3c). The furnace off-gases in these scenarios enter the same CO_2 capture plant. A modified version of Figure 1 is presented in Figure 4 that illustrate the off-gas recycling. The energy needed in the stripper reboiler is supplied through a WHSG.

Table 4**:** Scenario overview, plant 2.

Scenario	CO_2 capture details
3a	Two furnaces, no recycling, 4.4 vol% CO_2 in off-gas, 90% capture rate
3b	Two furnaces, recycle in both, 15.1 vol% CO_2 in off-gas, 90% capture rate
3c	Two furnaces, recycle in one, off-gases combined, 6.8 vol% CO_2 in off-gas, 90% capture rate

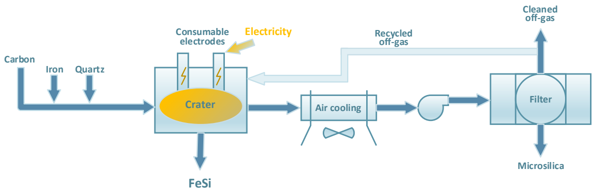

Figure 4**:** Plant 2 with off-gas recycling.

4. Results and discussion

The scenarios presented in the previous section were simulated and cost estimated. In this section the results are presented and discussed.

4.1 Plant 1 – Si production

The results from the tecno-economic investigation of plant 1 is presented in Table 5 and Figure 5. For plant 1, two CO_2 concentrations are considered, in addition the effect of plant size is also studied. The results of the process evaluation showed that there is sufficient excess heat available from the furnace off-gas to fully cover the need of the stripper reboiler duty at 90% capture rate.

Table 5**:** The main technical results for plant 1.

Scenario	Specific reboiler duty, SRD	Steam supply
1a	3.53 MJ/kg CO_2 captured	All steam from electric boiler
1b	3.53 MJ/kg CO_2 captured	All steam from WHSG boiler
1c	3.34 MJ/kg CO_2 captured	All steam from WHSG

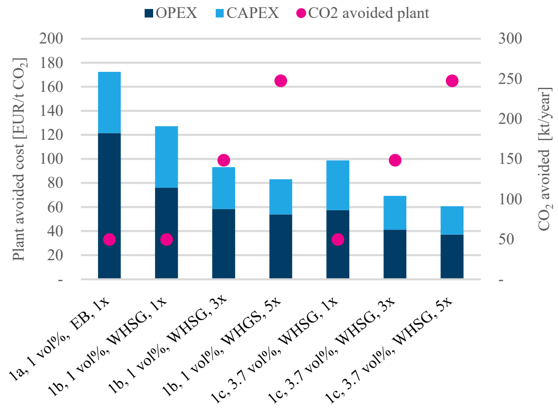

Figure 5**:** Results of the investigation into plant 1.

The results in Figure 5 show that the combination of low CO_2 concentration and small CO_2 amounts makes CO_2 capture costly with prices in the range of 125 – 175 €/t CO_2 for the current plant size (1x), depending on whether excess heat is utilised or not. A relatively small increase in CO_2 concentration, ~ 4 vol%, reduces cost significantly by ~30 €/t CO_2. The feasibility of increasing the concentration has not been assessed, the current process configuration needs to be reassessed, primarily the type of filter used, as CO_2 capture needs to take place after the filter to avoid operational issues in the capture plant and to ensure recovery of microsilica. Increasing the plant size is also beneficial in regard to capture cost. The specific CAPEX decreases due to economy of size. The breakdown of the OPEX is given in Figure 6.

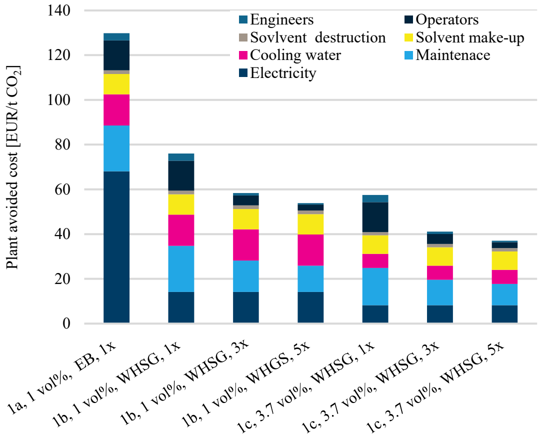

Figure 6**:** Breakdown of OPEX for plant 1.

The figure shows that the maintenance and personnel cost contribute disproportionally for the small plants (1x55 kt CO_2 annually). Finally, the utilisation of excess heat is highly beneficial as expected, clearly observed when comparing steam from an electric boiler (EB) versus a

WHSG. Note that for the EB case, the energy supply to the stripper reboiler (steam) is in the form of electricity as the boiler is electrically driven.

4.2 Plant 1 – seasonal (partial) capture

The results form the seasonal capture investigation are presented in Figure 7. The results show that for the summer-only capture, the CAPEX contribution to the cost increases and becomes the dominant one, compared to OPEX being the dominating element for all year capture.

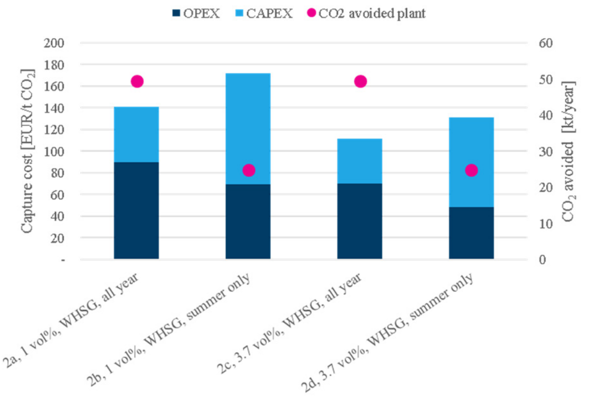

Figure 7**:** Results of the investigation into seasonal (partial) capture for plant 1.

4.3 Plant 2 – FeSi production

The focus of this investigation into plant 2, was the effect of applying off-gas recycling for increased CO_2 concentration, which yields a lower specific reboiler duty (SRD) for off-gas recycling, as illustrated in Table 6.

Table 6**:** The specific stripper reboiler duty for plant 2.

Scenario	Specific reboiler duty, SRD	Steam supply
3a	3.34 MJ/kg CO_2 captured	All steam from WHSG, 23.6 MW
3b	3.15 MJ/kg CO_2 captured	All steam from WHSG, 22.3 MW
3c	3.26 MJ/kg CO_2 captured	All steam from WHSG, 23.0 MW

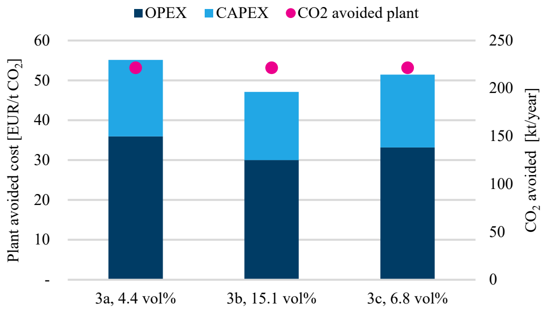

Figure 8**:** Results of the investigation into plant 2.

A comparison between the estimated cost for scenario 1a (50 kt CO_2 captured) and 3a (220 kt CO_2 captured), which represents todays situation for plant 1 and plant 2, illustrates again the benefit of size on the cost of capture. Figure 8 shows that the increase to ~7 vol% and further to 15 vol%, reduces the specific capture cost as expected, with 4 and 8 €/t CO_2, respectively. The CAPEX is reduced as the flue gas volume is reduced, while the reduction in OPEX is due to the reduced SRD with increased concentration. In addition. It should be pointed out that higher concentrations (> 10 vol%) make other post-combustion capture technologies more attractive, e.g. pressure swing adsorption (PSA), membrane, and low temperature/ cryogenic.

5. Concluding remarks

For plant 1, the capture cost was estimated to between 125 – 175 €/t CO_2, where the lowest cost represents the scenario for which the excess heat is utilized for capture. The combination of a low CO_2 concentration and small amounts of CO_2 makes CO_2 capture costly. A relatively small increase in CO_2 concentration, to ~4 vol%, is beneficial regarding cost. If such a scenario is possible the cost of capture is reduced with ~30 €/t CO_2. Increasing the plant size, and taking advantage of economy of size, gave further reduction in capture cost.

Seasonal capture could under the right circumstances be considered, still utilising the excess heat for CO_2 capture seems to be preferable. The results are highly dependent on the value of district heating A further investigation into the possibility of combining steam to stripper reboiler and district heating is recommended.

For plant 2 the current CO_2 concentration is ~4 vol% CO_2 with an associated cost of 55 €/t CO_2. With flue gas recycling there is a potential of reaching 6.8 vol% CO_2 with partial recycling and 15 vol% CO_2 with full recycling, resulting in a cost reduction of 4 and 8 €/t CO_2, respectively. In addition, higher concentrations may make other capture technologies attractive.

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