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Report

CO₂ capture potential in the Eyde cluster

Findings from pre-study based on five cases

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ABSTRACT

In this pre-study, five cases from the Eyde Cluster members were selected by the project steering group: Elkem Bremanger, Eramet Sauda, Alcoa Lista, REC Solar in Kristiansand and Saint-Gobain Ceramic Materials in Lillesand. SINTEF made a preliminary assessment of the CO₂ capture potential for the cases, based on information provided by the sites themselves, supplied by site visits. For REC Solar the assessment was based on data from another study (the CO₂stCap project). The assessment included a review of capture technologies with different Technology Readiness Levels (TRL) as well as a general overview of alternatives for CO₂ capture and utilization (CCU). Also, possibilities for transport of CO₂ from the different sites to a location at the West coast (Kollsnes, as suggested by the Norwegian full-scale CCS project) were considered. Amongst the five cases, Elkem Bremanger, Eramet in Sauda, and Alcoa Lista seem to be the better candidates for CO₂ capture in a shorter time perspective.

It is recommended that the work continues according to recommendations put forward in workshop 13.12.2018 and later determined by the project's steering group.

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APPENDICES

Overview of CO₂ emissions in Norway

1 Background and purpose of the project

A combination of a well-regulated industry and the sole use of renewable power ensures that Norway has one of the lowest industrial carbon footprints in the world. One implication of the low carbon economy is higher demand for products with low carbon footprints from both production and use. In the Process industry Roadmap [1] from 2016 CO₂ capture, (utilization) and storage – CC(U)S is identified as one of the low-carbon technologies that is possible to implement in a 2050 perspective. Carbon capture and storage (CCS) is fundamental for achieving the goals set in the process industry roadmap; expected to contribute to more than half of the CO₂ emission reduction. It is therefore crucial that a deep understanding of the potentials and pitfalls for capturing CO₂ sources is widely present in the industry. Each emission site is unique with individual combinations of CO₂ concentrations, temperatures, other emissions and process heat availability.

The Eyde Cluster has responded to the challenge regarding CC(U)S in the Roadmap by initiating a project to collect data and evaluate how capture technologies can be fitted to the energy-intensive industry plants within the cluster. Initiating additional data collection and discussions with potential plants may lead to ideas for innovations - both to the CO₂ capture technologies and for alternative technologies for utilization of off-gasses as well as utilization of excess heat in process industry plant.

The work includes a mapping of CO₂ emission sites in the study (> 20 000 t CO₂ annually). To put the CO₂ sources included in the Eyde cluster into context, an overview of CO₂-sources in Norway from Trøndelag and southwards has been prepared. Nordland is subject to a separate study, and the northernmost part of Norway will not be included in this overview, apart from being included in the general overview of CO₂ emission sources.

This report focuses on the following industry plants from the Eyde Cluster (NCE Eyde) members: Elkem Bremanger, Eramet Sauda, Alcoa Lista and Saint-Gobain in Lillesand. These plants have been visited by the SINTEF project team. In addition, the REC Solar plant in Kristiansand is included, based on data gathered in another ongoing project (the CO₂stCap project, in which Elkem is also a partner). Plant studies have identified possibilities for CO₂ capture and transport of the CO₂ from the site. Site-specific characteristics like available space, location (sea-front, in-land) in addition to flue gas composition etc. have been investigated.

2 CO₂ capture, transport and storage

CO₂ capture, transport and storage, abbreviated CCS, include in addition to the capture of CO₂ from flue gas, also necessary conditioning and intermediate storage of the CO₂ before transport either by pipeline or by ship, eventually a CO₂ terminal, injection and geological storage. This report focuses on capture and includes also a preliminary assessment of possibilities for shipment or other transport of CO₂. The rest of the CCS chain is not considered. Also, possibilities for utilization of CO₂ are included, at this stage in general terms.

2.1 Technologies for CO₂ capture

There are three main categories of CO₂ capture technologies, pre-combustion, post-combustion and oxy-combustion. The main concept of the three categories can be summarised as follows; in post-combustion the CO₂ is separated from the flue gas after combustion, in pre-combustion the CO₂ is separated before combustion, and oxy-combustion entails that combustion takes place in an oxygen atmosphere. Common for all CO₂ capture technologies is that they require an energy input, in the form of steam, electricity or both.

Of the three categories, post-combustion will be the focus and a simplified illustration is provided in Figure 1. The main benefit of post-combustion is that there is limited interaction between the base plant and the capture plant as the CO₂ separation takes place after combustion.

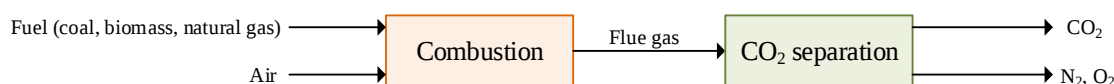


Figure 1. Simplified illustration of post-combustion CO₂ capture.

Of post-combustion processes, there are several different sub-technologies, but four main process categories for removing CO₂ from a flue gas stream, Eimer [2];

- **Absorption** A liquid absorbent with affinity for the unwanted gas components is used.
The sorbent is regenerated through changes in temperature or pressure.
- **Adsorption** A solid adsorbent with affinity for the unwanted gas components is used.
The sorbent is regenerated through changes in temperature or pressure.
- **Cryogenic** The definition of cryogenics is a process with operating temperature below 150 K. In gas separation, the temperature is not necessarily this low. The temperature is at the degree needed to liquefy (or freeze) the unwanted gas component for easier separation from the gas phase.
- **Membrane** The principle behind membrane separation is that different gases differ in permeability. However, this difference is normally too small for efficient separation. A driving force is needed, a difference in partial pressure between the two sides for the unwanted gas.

A schematic overview of the post-combustion sub-categories are provided in Figure 2, from Songolzhadhe et al. [3].

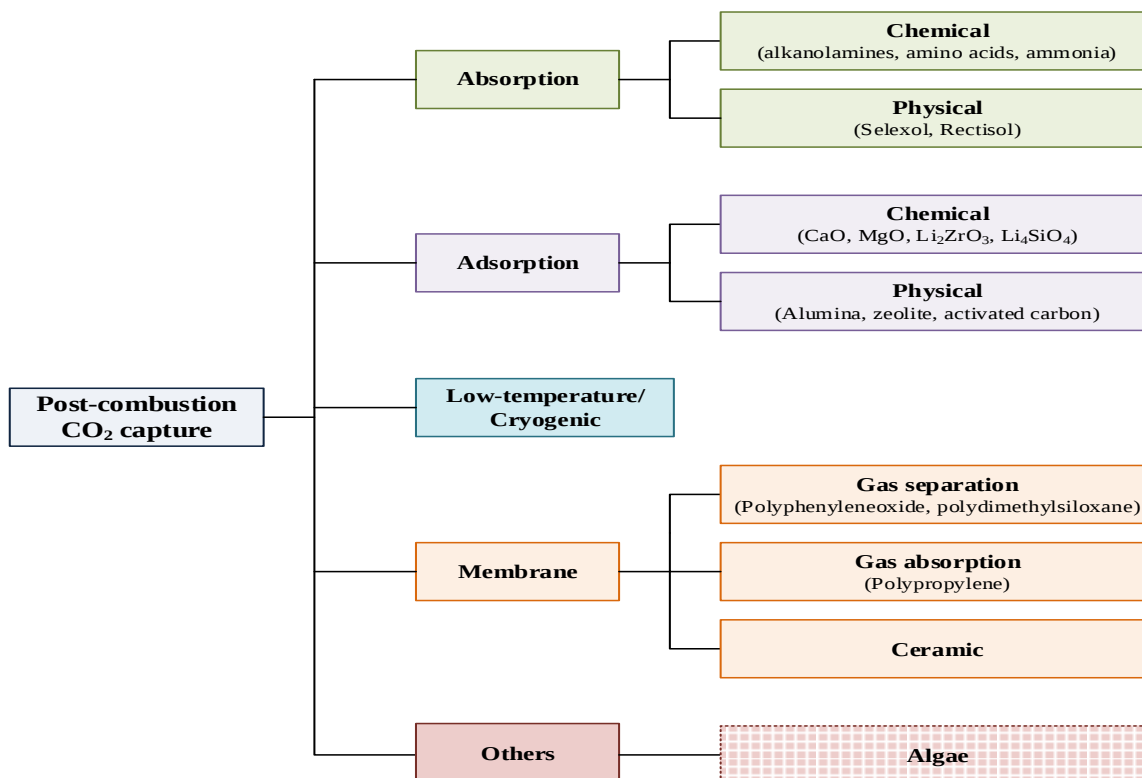


Figure 2. Overview of post-combustion sub-technologies.

2.1.1 Absorption processes

A sketch of a reactive absorption plant is shown in Figure 3. The most essential component in this process is the circulating solvent, most commonly consisting of an amine dissolved in water. Amines can react chemically with CO₂, but they can also release the bound CO₂ when heated. This forms the basis for circulating the solvent from an absorption to a desorption column.

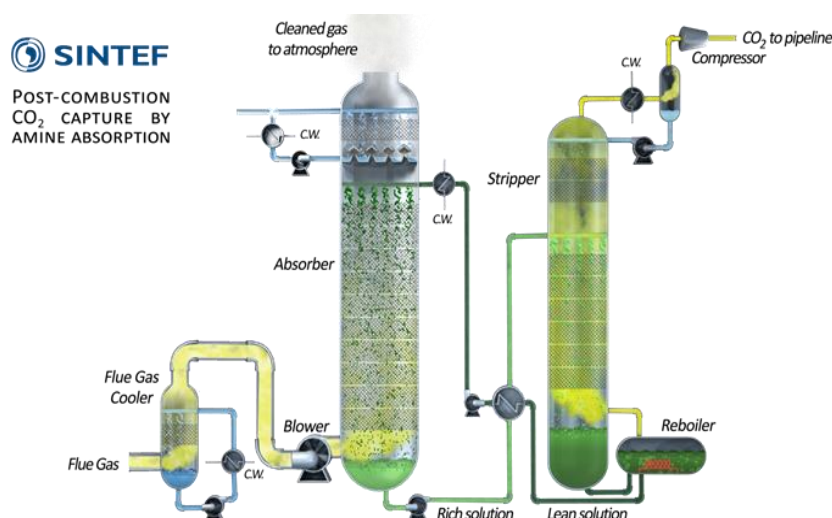


Figure 3. Reactive absorption is the most mature and commercially available technology for post combustion CO₂ capture

The treated gas is sent to the absorption column at 30-40°C where it flows upwards in contact with the solvent that flows down from the top of the column. The solvent efficiently washes CO₂ out of the gas and typically 90% of the CO₂ is captured before the gas is released. The solvent, rich in CO₂, is sent from the absorber to the desorber, where CO₂ is removed by steam stripping. The resulting steam/CO₂ blend is sent to a cooler and 99% pure CO₂ results after condensation of water. The process also partially compresses the CO₂ to about 1.5 bar which is a typical desorber outlet pressure.

The main energy requirement for this process is in the form of heat input to the reboiler (Figure 3). Heat is typically supplied as steam at 130 °C. This is relatively low-grade heat and also explains a major advantage with reactive absorption, since the technology can efficiently and directly utilize waste heat to drive the CO₂ capture. If the same heat were to be used for electricity generation, the efficiency would be very low. This is also partially the reason why reactive absorption has been developed for CO₂ capture in the power industry, utilizing heat in the low end of the steam cycle.

Absorption technology is the only industrial technology being demonstrated for post-combustion CO₂ capture from large point sources at commercial scale. Post-combustion carbon capture (PCC) with amine has developed significantly during the last 15 years. The benchmark CO₂ technology used for comparison in the beginning of 2000s was 30 wt% standard MEA process, in which, the heat requirements (reboiler duty) for solvent regeneration were in the range of 3.8 and 4.2 GJ/ton CO₂ captured from coal and natural gas-based processes, respectively. Today, the commercial suppliers report heat requirements around 2.4-2.9 GJ/t CO₂ captured based on demonstration plants with proprietary solvent systems and process modifications.

Aker Solutions, Mitsubishi Heavy Industries, Shell, BASF and GE are examples of vendors with solvent based capture technology. Technology development have been, to a large extent, aimed at fossil fired power plants with regards to flue gas composition and integration aspects. However, many industrial flue gases have similar CO₂ concentrations as in the power industry and vendors will be prepared to deliver capture plant also for other industries. Aker Solutions already offers modular CO₂ capture systems with capacity up to 100 000 tons per year aimed at a wide range of industrial off-gases.

As a rule of thumb, the energy requirement for CO₂ capture by chemical absorption will be 70-100 GWh to capture 100 000 tons CO₂ per annum. This corresponds to a continuous thermal energy demand of 11 MW. The numbers will vary with CO₂-concentration in the gas, solvent type and process design that varies between different vendors.

The CO₂ which is produced at 1.5 bar should be compressed and liquefied for transport. This will require approximately 100 kWh electric energy per ton CO₂ from an absorption-based capture plant.

Installing new equipment is space demanding. An estimate of the area needed has been provided by Aker Solutions who claims that their compact carbon capture plant for capacities up to 100 kt CO₂ annually has a footprint of 18 x 25 m [4]. However, this does not include conditioning for transport and intermediate storage before transport.

2.1.2 Membranes

Membrane technology can be used to separate CO₂ from other components of a gas mixture. CO₂ can be either selectively removed by the membrane or other components be removed so to concentrated CO₂ in the retentate stream. The first option is more relevant for this study.

The basic principle of membrane separation requires a driving force (chemical potential) between the permeate and retentate side. To ensure a sufficient driving force, a large pressure gradient may need to be established. This is particularly relevant for application with medium to low CO₂ concentration of the gas mixture and for application at atmospheric pressure (these conditions are found in most of the case studies considered in this study). A possibility is to pressurize the feed gas stream. The pressurization would require large compressors and a rather high energy usage for the compression process. An alternative is to decrease the pressure of the permeate side by implementing vacuum.

Several types of membrane exist and are often characterized by the material ensuring the permeation process:

- Polymeric membranes (i.e., totally organic or organic/inorganic combinations such as in mixed matrix membranes)
- Inorganic membranes (i.e., ceramic materials, carbon, silica, zeolite, various oxides such as alumina, titania and zirconia, and metals such as palladium, silver and their alloys)

An advantage of using membranes is that there is no need for thermal regeneration and, thus, to generate steam. This is of importance for those applications that have no steam readily available from a steam network and that would, thus, need to design a steam generation unit adding to the cost of CO₂ capture.

2.1.3 Adsorption

In adsorption processes one or more components of a gas or liquid stream are adsorbed onto the surface of a solid adsorbent and separation is obtained. In commercial processes, the adsorbent is usually in the form of small particles in a fixed bed (even if there are applications with fluidized and moving beds). A fluid is passed through the bed and the solid particles selectively adsorb some components. When the bed is almost saturated, the flow is stopped, and the bed is regenerated through a pressure decrease (Pressure Swing Adsorption), a temperature increase (Temperature Swing Adsorption) or a combination of the two. The adsorbed components (adsorbate) are thus desorbed and recovered, and the solid adsorbent is ready for another cycle of adsorption.

Pressure Swing Adsorption (PSA)

In a Pressure Swing Adsorption (PSA) system, the saturated adsorbent material is regenerated by means of a pressure reduction. If the regeneration pressure is lower than atmospheric, the process is often called Vacuum Pressure Swing Adsorption (VPSA). For the type of application analysed in this study, the vacuum would be reasonably needed to achieve the necessary working capacity of the adsorbents while pursuing energy efficiency. A main issue associated with PSA is the large footprint of the CO₂ capture units.

Temperature Swing Adsorption (TSA)

In a Temperature Swing Adsorption (TSA) system, the regeneration is achieved through an increase of the temperature. The temperature swing has positive effects on the working capacity of the adsorbents, especially for rather low CO₂ concentrations. However, TSA processes come with significant challenges. A main issue is the long time needed for an efficient heating and cooling of the adsorbent. Standard cycle times could, thus, become rather long.

2.1.4 Low-temperature CO₂ capture

In a low-temperature (or cryogenic) CO₂ separation process, a gas mixture is conditioned to specific pressure-temperature levels to allow physical phase separation of CO₂ from the other components. The process could be either vapour-liquid separation (CO₂-rich liquid phase), vapour-solid separation (solid CO₂) or a combination such as CO₂ slurry separation. Low-temperature processes showed some limitations when atmospheric gas mixtures with relatively low CO₂ concentrations are considered, with difficulties to attain high capture ratios and energy efficiency at the same time [13]. The feed CO₂ concentration is, thus, a key parameter for the performance of such systems. An interesting opportunity can emerge to use the technology in an integrated system. The low temperature separation process, displaying very good performance to purify streams with relatively high feed CO₂ concentrations, could be used as the second stage of an integrated system. The initial bulk separation could be carried out by another technology, more effective in obtaining large capture ratios at low levels of requested purities (e.g., membranes, adsorption processes).

2.2 Summary of CO₂ capture technologies

In Table 1, advantages and disadvantages of the presented capture technologies are given.

Table 1. Advantages and disadvantages of CO₂ capture technologies.

Technology	Advantages	Disadvantages
Chemical absorbent – MEA	- Well documented technology - Several technology suppliers available with proprietary amine blends available today - Low degree of integration with base plant - Robust technology in regard to CO₂ concentration - Delivers a CO₂ stream of > 98% CO₂ - Up to 90% CO₂ captured	- Regeneration of absorbent is energy intensive - Potentially sensitive to components in the flue gas (O₂, NO_x, SO_x and dust) - Chemicals
Membrane	- Low degree of integration with base plant - No chemicals - Might be less sensitive to other components in the flue gas (O₂, NO_x, SO_x and dust) - Easy scale-up, modular design - Hollow fibre membranes have small footprint	- Achieving higher CO₂ capture efficiency (up to 90%) and sufficient CO₂ stream purity could be a challenge, additional membrane stages might be needed (cost and energy) - Efficiency increases with increased CO₂ concentration in the flue gas

	• Efficient start-up and shutdown, quick retaining of performance • Energy Efficient (integration of warm flue gas for el. power generation required by fan and vacuum pump)	
PSA	• Low degree of integration with base plant • No chemicals • Might be less sensitive to other components in the flue gas (O₂, NO_x, SO_x and dust), adsorbent dependent • Energy efficient (integration of warm flue gas for el. power generation required by fan and vacuum pump) • Easy scale-up, modular design	• Achieving higher CO₂ capture efficiency (up to 90%) and sufficient CO₂ stream purity could be a challenge, additional stages might be needed (cost and energy) • Efficiency increases with increased CO₂ concentration in the flue gas • Water removal might be necessary, adsorbent dependent • Efficiency dependent on flue gas temperature • Discontinuous process, parallels/trains needed
Low-temperature	• Should be considered if location at a CO₂ hub is possible. At the hub, refrigerated CO₂ is received, compressed and heated. The cold CO₂ could potentially be utilised for cryogenic CO₂ capture • High CO₂ capture rates (> 90%) and CO₂ purity possible • Easy scale-up, modular design • The CO₂ stream leaves the plant as a liquid	• Production of cold refrigerant is energy intensive • Compressor efficiency • Heat/cold transfer efficiency • Refrigeration mediums potentially hazardous

2.3 Transport and Storage

Transport of CO₂ can be done by pipelines or by ships and barges, eventually also by truck or rail. Figure 4 illustrates the CCS chain and the main transport options.

Ship transport; two alternatives

- ship only
- ship and pipeline combined

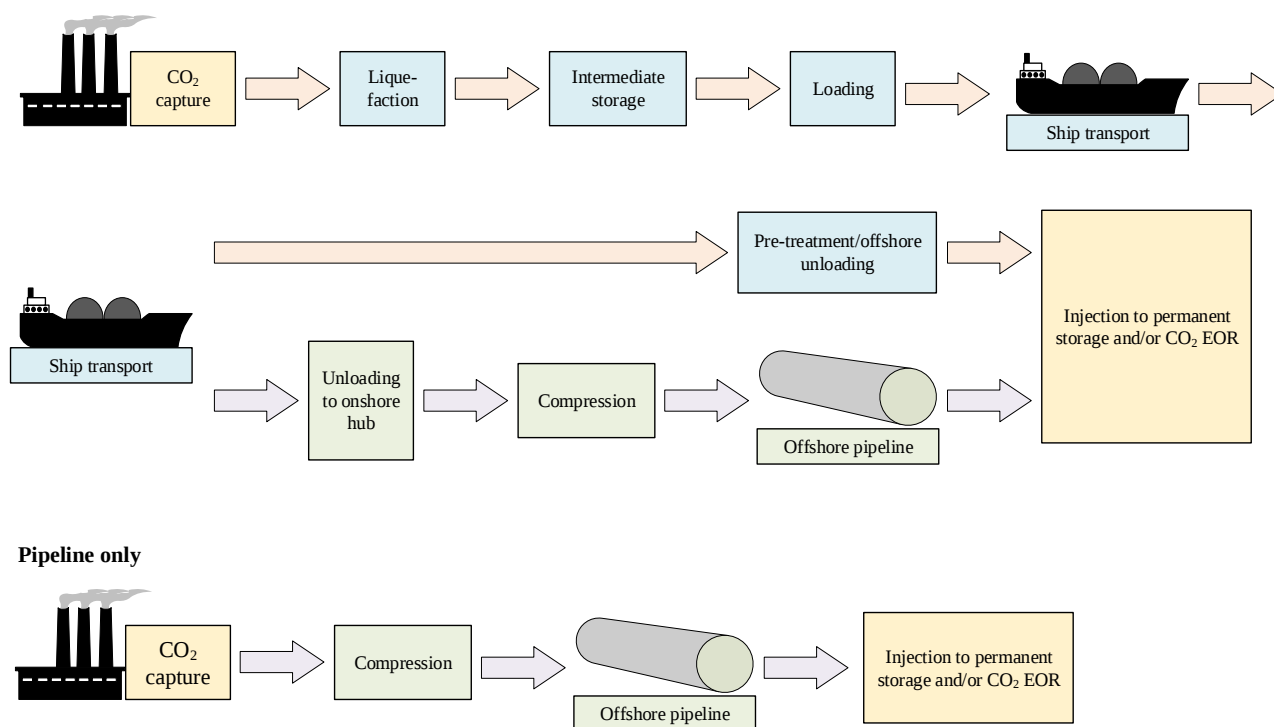


Figure 4. The CCS chain with transport either by pipeline or by ship.

For the cases studied in this report, it seems shipping is the most likely option. Apart from one plant, all have access to sea and good quay facilities. This will be briefly described case by case. For Saint-Gobain, located a few kilometres inland and with no immediate access to sea, road transport may be the likely option.

Just like the capture plant itself, preparation and conditioning of the captured CO₂ for transport also need suitable areas. Such areas should preferably be located as close to the quay as possible. Liquefaction is dependent on energy supply, and the liquefied (cold and pressurized) CO₂ will need tanks for intermediate storage. Tanks have often been assumed to be designed for storing 1.5 times the ship load. The Norwegian full-scale CCS project has recommended ships carrying 7 500 m³ of liquid CO₂. Such a ship size would then imply intermediate storage capacity at each industrial site of 11 250 m³. However, the need for intermediate storage capacity is also dependent on factors like frequency of ship calls at the quay. The loading of CO₂ from onshore tanks to a vessel requires loading arms, flexible hoses and other equipment at the quay. Using the same conditions as in the Norwegian full-scale CCS project implies CO₂ to be carried at -28/30 °C and 15 bar. These conditions are well-known as they are identical to what has been normal practice by Yara and Praxair for several years, in their commercial CO₂ business. Figure 5 shows a CO₂-ship in operation at harbour.



Figure 5. M/T Yara Gas III alongside the quay near Yara's ammonia plant in Porsgrunn (Capacity: 1200 t of liquefied CO₂ in 2 tanks of 600 tons capacity each. Ship type: Converted container vessel).

As already stated, storage of CO₂ is not part of this project. Storage of CO₂ in saline aquifers has a more than 20-year history in the North Sea, starting in 1997 at the Sleipner field where about 1 million tons of CO₂ extracted from the produced natural gas has been safely stored each year. Storage is considered by the Norwegian full-scale CCS project in an offshore geological formation (an aquifer) called the Johansen formation. This formation is located to the South of the Troll field, about 80 km to the West of Kollsnes in Øygarden. Kollsnes is identified as the location to where CO₂ from sources in the Norwegian full-scale project will be carried by ships. There will be a pipeline going from the CO₂-hub at Kollsnes to the Johansen formation. Kollsnes is therefore also the likely destination for ships eventually carrying CO₂ from any of the five studied sites in this project.

2.4 CCU

CCU or CO₂ capture and Utilization may be regarded as an alternative to CCS or CO₂ capture and Storage. The main difference between the two alternatives is in how the CO₂, once captured, is treated further.

The whole idea behind CCS is to capture CO₂ from a flue gas and permanently store it, thereby preventing the CO₂ from entering the atmosphere. Safe storage is key in CCS. The objective of underground (often offshore) storage is to contain the CO₂ for a long enough period of time to mitigate climate change. Retention time should be in the order of a few thousand years or more [5], which underlines the importance of permanence.

It is an observation that CCU technologies only rarely will be able to fulfil the need for sufficient retention time. On the other hand, CCU may for some industries or plants, still be of interest as a local or limited CO₂ abatement technology if conditions are favourable. Also, since the capture part of the CCU chain often will be similar to capture in a CCS chain, CCU may contribute to the development and reduced cost of CO₂ capture technologies. It should be noted that utilization of CO₂ to make products

will need substantial high-quality energy input. Energy used for such purpose should also be "green" and not fossil. This brings up the question of what the more efficient use of limited energy resources will be, both from an environmental as well as an economic point of view. CCU projects therefore as a rule of thumb should always consider this question.

With CCU the focus is on utilization (or re-use) of CO₂ for production of different products. This can be done either by using CO₂ as any industrial bulk chemical as an input factor to a chemical conversion process, or by utilizing the CO₂ with no chemical conversion. In either case, the CO₂ must first be captured from the flue gas source in the same way as for CCS. Use of commercial CO₂ for mineral water is a well-known example of direct use of CO₂, though with a very short retention time. Another, indirect, CCU alternative is to utilize natural photosynthesis. Enhanced algal growth is one example, the produced biomass may then be used for different purposes from synthesis of chemicals to simple combustion. Growth of algae will not necessarily require capture before utilization. Direct use of CO₂ in greenhouses is another example to enhance biomass production. The different CCU options are briefly summarized in Figure 6.

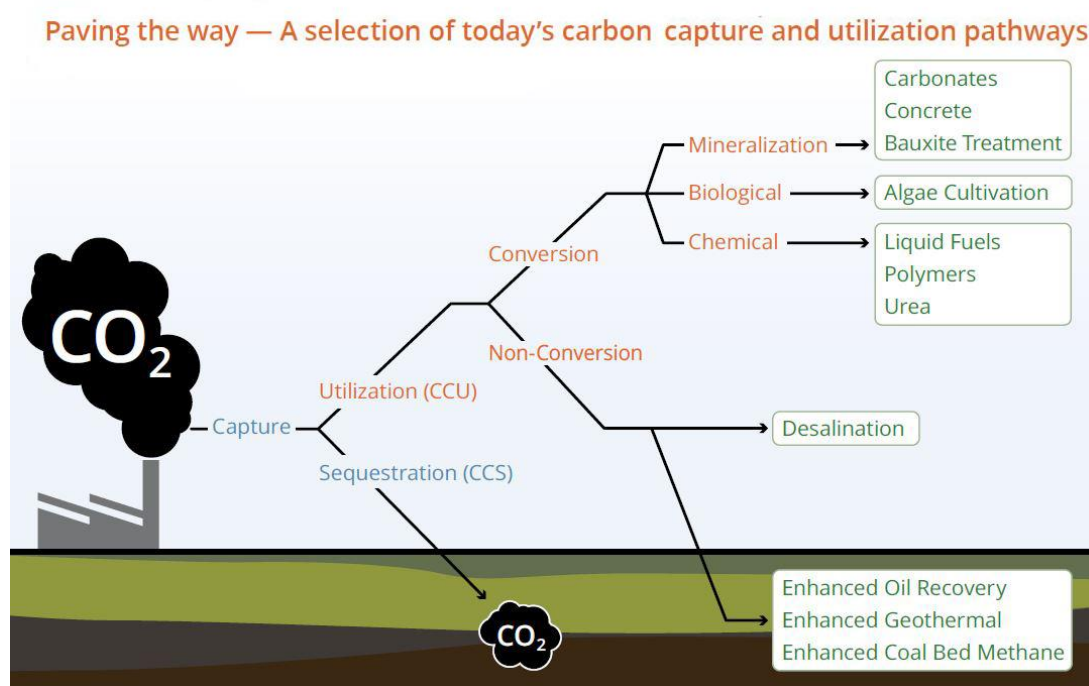


Figure 6. CCS and CCU(S). In addition to Permanent storage (called sequestration in the figure), there are pathways for utilization of CO₂ as shown in this figure from Pembina.org [12]

2.4.1 Enhanced oil recovery and other geological utilization technologies

Enhanced oil recovery by means of CO₂ (CO₂-EOR) is the most well-known alternative to geological storage of CO₂. It is probably also the only geological utilization technology that is suitable on the Norwegian Continental Shelf (NCS) in large scale and provides a possible economic incentive that other CCS or CCUS technologies cannot offer.

Injecting CO₂ in a producing oil field can increase oil production substantially, given favourable reservoir conditions. CO₂ can also be injected into abandoned oil fields, thereby resuming oil production.

According to the Norwegian Petroleum Directorate, [6], CO₂-EOR may increase oil production from certain fields by 3-7 percentage points and produce between 150 and 300 million Sm³ of extra oil. There are however, not only income but also cost issues associated with CO₂-EOR. One of the more important is corrosion in wells and process plant when CO₂ mixes with water. Also, other technologies for enhanced oil recovery have so far proved more cost efficient.

Often, it is claimed that using CO₂ to produce more oil will only add to the CO₂-problem. According to Størset et al. [7] however, CO₂-EOR on average will give a production increase of 4% and in addition 70-100 % of the injected CO₂ will be permanently stored.

For the industry in the Eyde cluster, CO₂-EOR is interesting mostly as an eventual source of income to the CC(U)S chain, by contributing to reducing the overall CO₂ mitigation cost. Any one industry source will of course only benefit from such an option if it becomes practice on NCS. CO₂-EOR is the utilization method with the highest potential for taking large volumes of CO₂, by far.

CO₂ may also be used to enhance production of natural gas (CO₂-EGR). This technology will eventually result in increased concentration of CO₂ in the produced natural gas, and introduce a need to remove the CO₂ before the natural gas can be exported and sold.

2.4.2 Chemical conversion of CO₂

If CO₂-EOR has a high volume/high income perspective, both these advantages are unlikely to be gained from any of the other CCU technologies. Also, retention time is a challenge for most alternatives.

Urea is a common fertilizer product with a yearly production volume of ca 160 million tons, which utilizes ca. 120 million tons of CO₂. Retention time is short, the CO₂ returns to the atmosphere after weeks or months.

Chemicals containing one carbon atom (C1 chemicals): This group of bulk chemicals include methanol and formic acid. In the case of methanol assuming 15% mixing into fuel in Norway would require ca 2 million tons of CO₂ to produce 1.5 million tons of fuel. In addition, hydrogen is required. Producing fuel from CO₂ is generally a thermodynamically difficult route to pursue. Retention time is in the order of weeks. Methanol is also used as a base chemical for other products, in which case the retention time may be longer.

Higher C-chain (C2, C2+) products include other liquid fuels than methanol, and polymers. With polymers, market potential is limited for specialty plastics, although price may be attractive. Retention time is in the order of a few years.

2.4.3 Mineralization

Mineralization means making mineral products from the CO₂. The most likely pathway is to make carbonates (CO₃²⁻), that is precipitating CO₂ as carbonate to make a mineral salt, for instance CaCO₃, calcium carbonate or limestone.

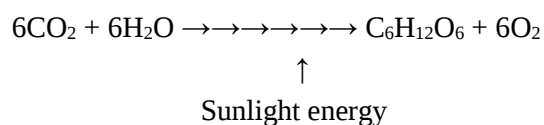
Another mineral that does have potential interest with regard to CCU, is anorthosite. This mineral is common in many places in Norway and may become a future source of raw material for aluminium production (and other products like calcium and silicon as well). Anorthosite can replace bauxite as starting point for making alumina (aluminium oxide, Al_2O_3) which is the compound that is electrolyzed when producing aluminium metal. In the process of producing alumina from anorthosite, CO_2 is utilized [8]. About 500 kt of CO_2 is needed to make 1 mill tons of alumina. CO_2 is precipitated as a carbonate (mineralized) in the process. So far, a change from bauxite to anorthosite in the aluminium industry does not seem to happen in the foreseeable future. It is worthwhile noting that such production relies on the

aluminium production to be of economic interest and not on the utilization of CO_2 , which instead should be regarded as a nice bi-effect of the aluminium production.

A general comment to mineralization as a CCU technology is that such processes do not create high-value products. Rather products are probably most likely to be deposited or as a best case, be used as fillers in tyres etc. Summing up: retention time for mineralized CO_2 is very long, but the value for the producer is generally limited or non-existent.

2.4.4 Biological utilization of CO_2

Photosynthesis in green plants converts CO_2 from the air and water (taken up by the roots) to carbohydrates (glucose) and oxygen by the means of energy from sunlight.



Apart from letting this process happen naturally, making use of the photosynthesis for production of microalgae in specially designed reactors, tanks etc. has attracted a lot of interest. Microalgae are (mostly) water-living photosynthesizing unicellular organisms between a few μm to a few hundred μm in size. Microalgae also need light (sunlight or artificial light), nutrients (nitrogen, phosphorus etc.), right temperature conditions and oxygen to grow. All these basic needs must be properly taken care of to make production of microalgae successful.

Microalgae are of limited interest unless finding a proper utilization. The most promising way of utilizing microalgae may be as feed for fish (in cultivation), as the microalgae is the key source of omega-3 fatty acids found in fish oils, and because aquaculture needs finding alternatives to other fish species for these sought-after nutrients for humans.

There are of course many other potential uses of microalgae, from fuels to fine chemicals. Value and volumes for such applications will vary a lot. Common to all, however, is that retention time for CO_2 is low, in the order of weeks to months only, unless it can be documented that the carbon is entering a cycle that is maintained over very long periods of time.

3 CCS in Norway

3.1 Ongoing CCS projects in Norway

3.1.1 The Norwegian full-scale CCS project

This Government initiative is now underway and has delivered or will deliver concept studies on capture, transport and storage during 2018. CO₂ capture is planned to take place at Norcem in Brevik and at Fortum's waste incineration plant at Klemetsrud, Oslo. Transport studies are finished, and the storage concept study is soon to come. Next phase is pre-engineering.

Investment decision is expected by Stortinget in 2020/2021, and the project can be in operation by 2024. Total amount of CO₂ to be captured, transported and stored as a result of this project will be about 700 kt/year. It is likely that additional volumes will be phased in because of other ongoing studies. Industrial plants of the Eyde Cluster may well be positioned to deliver CO₂ to the Norwegian full-scale project at a later stage.

Ships for transport of the CO₂ from sources to the Kollsnes hub will be of a type quite similar to LPG (Liquid Propane Gas) ships already in regular use, according to the Northern Lights project. (The Northern Lights project is set up by Equinor and partners Total and Shell to develop the necessary CO₂ infrastructure from ship to injection well).

The Norwegian full-scale project will have vital importance for all other ongoing CO₂ projects in Norway, and for European initiatives as well.

3.1.2 Other ongoing Norwegian CCS projects

Apart from the mentioned Sleipner and Snøhvit CO₂ injection projects, other ongoing CCS projects in Norway are in the R&D phase.

A similar project to the Eyde Cluster projects is the CO₂ hub Nordland project. This project has come a few steps further and is now looking more detailed into capture to come up with preliminary capture plant designs and recommendations for the demonstration phase. Also, the project is looking into new process solutions and CCU, intermediate storage and logistics and cost estimation. This project is scheduled to conclude by autumn 2020.

The CO₂ hub Nordland project is partly financed by the CLIMIT programme. The same is true for other relevant ongoing projects. Without mentioning any specific developments or projects, many initiatives focus on reducing the cost of CCS, in particular the cost of capture. A trend is to try and substantially reduce the size of the capture plant by the use of technologies that are modular in nature and therefore can be scaled up by adding modules instead of increasing plant size. Another interesting pathway to follow is partial capture. The idea is to capture a certain part of the total amount of CO₂ emitted, adjusted to local conditions like available waste heat.

3.2 Overview of CO₂ emissions

In Norway, most of the industrial CO₂ emission are from petroleum, metal, cement industries and waste incineration plants. This chapter provides an overview of the CO₂ emission sources in Norway and their

magnitude and location over the counties. Reported emission data from the European and Norwegian environmental agencies [14], [15] are used for the study. The latest data are from the 2017.

In 2017, greenhouse gas emissions only from petroleum activities corresponded to about 13.6 million tonnes (Mt) CO₂ eq (carbon dioxide equivalents). 13.2 Mt out of this was CO₂, and the rest was CH₄ (methane) [16]. The petroleum sector account for about one quarter of Norway's aggregate greenhouse gas emissions and they are expected to remain fairly stable over the next few years [16].

The global metals sector consists of metal production facilities that smelt, refine, and/or cast ferrous and nonferrous metals, including primary aluminum, ferroalloy, iron and steel, lead, magnesium, and zinc,

from ore, pig, or scrap using electrometallurgical and other methods [17]. In Norway, metal industry is dominated by metal alloy and additives (for alloys) manufacturing industries and the Aluminum production industry.

The locations and the magnitude of CO₂ emissions from the metal production plants in Norway are shown in Figure 7. Most of the metal production plants are located along the western coast of Norway. Quantitative summary of the all the emissions from the metal related plants in Norway are summaries in Table 1, for the year 2016 and 2017. The plants are categories in to three different groups based the products. There are 10 different plants which product metal alloys or the additives for the metal alloys. Three of them are owned by Eramet AS and produce silicone manganese and ferromanganese metal alloys in Porsgrunn, Kvinesdal and Sauda.

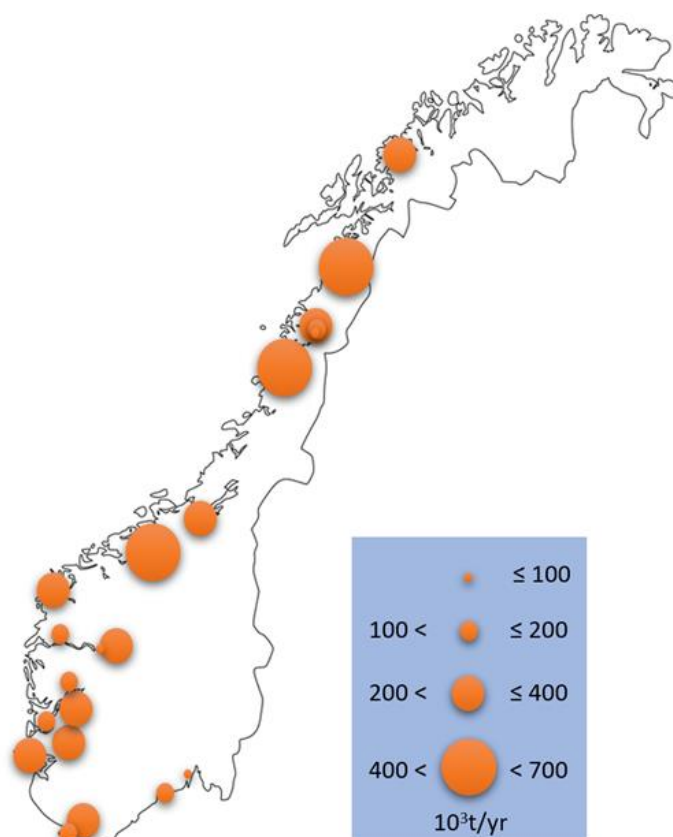


Figure 7. The location and the magnitude of CO₂ emissions from the metal production plants in Norway.

An overview of emissions from the metal industry in Norway is given in appendix A.

Total CO₂ emission from the three Eramet plants is about 0.7 Mt/yr while the Elkem produce 1.5 Mt/yr CO₂ from their five different metal and additives manufacturing plants. Total emissions from the metal alloy and additive plants are around 2.7 Mt/yr which is around 51% of the total emissions from the Norwegian metal industry. This includes the emissions from the metal alloy plants operated by the Ferrogløbe Mangan Norge AS and Finnfjord AS in Mo i Rana and Finnsnes.

The aluminum production plants are responsible for 42% (2.2 Mt/yr) of CO₂ emissions of the metal industry. There are seven different Hydro AS and two different Alcoa ANS, aluminum production plants are in business in Norway and emit 1.6 Mt/yr and 0.6 Mt/yr CO₂ respectively.

Saint Gobain Ceramic Materials in Lillesand has a yearly CO₂-emission of approximately 50 ktons.

Apart from the metal alloys and the aluminum plants, there is a pig Iron and Titanium production plant (Tizir Titanium & Iron AS) in Tyssedal and scrap iron and steel recycling plant (Celsa Armeringsstål AS) in Mo i Rana responsible for 261*10³t/yr and 99*10³t/yr of CO₂ emissions.

A summary of CO₂-emissions in Norway including maps are found in Appendix A.

4 Process industry and CCS/CCU potentials in the Eyde cluster

Five of the industrial plants in the Eyde cluster was selected by the industrial partners for the detailed study. These are;

- Alcoa Lista
- Elkem Bremanger
- Eramet Sauda
- Saint-Gobain Lillesand
- REC Solar (previously Elkem)

4.1 Methodology for detailed study of selected plants

Relevant information about the plant was collected through communication with the plant responsible, with basis in site visits, with the exemption of REC (previously Elkem) Solar. The information needed from each site in order to provide/recommend tailor-made solutions is:

- Location and number of emission points (identify relevant and irrelevant emission points)
- Flue /process gas volume, composition, pressure, and temperature of relevant emission points
- Existing gas cleaning steps
- Excess energy (steam and hot water)
- Cooling water supply
- Possible area available for CO₂ capture and transport facilities
- Rerouting of flue/process gas channels to CO₂ capture site
- Quay facilities available for CO₂ transport
- Relevant future plans (that can be communicated and are relevant for the project)

4.2 Closed furnace

The following section is translated to English from a contribution from Ragnar Tronstad "Lukket ovn i Sauda – overførbare erfaringer til FeSi/Si drift".

The production of FeMn/SiMn og Si/FeSi follows two principally different reaction mechanisms. In order to get understanding of these, a short description is provided below where HC FeMn og Si represents the two routes.

HC FeMn: The raw materials in this process are manganese ore, flux materials, and reduction agents. The reactor is a furnace with three current carrying electrodes which supply the energy to a coke bed which acts as the resistance element of the furnace. Raw material is continuously added as the charge sags. The manganese minerals consist mainly of oxides and in some processes of carbonates. On the way through the standing charge layer the temperature increase and the reduction of MnO_2 begins. The reduced manganese ore reaches the coke bed in the form of MnO and has gone through the following reduction; $\text{MnO}_2 \rightarrow \text{Mn}_2\text{O}_3 \rightarrow \text{Mn}_3\text{O}_4 \rightarrow \text{MnO}$. The reduction agent CO , is formed in the coke bed; $\text{MnO} + \text{C} = \text{Mn} + \text{CO}$. At the right temperature range CO_2 , e.g. from $\text{Mn}_3\text{O}_4 + \text{CO} = 3\text{MnO} + \text{CO}_2$, react with C in the charge and again form CO following the Boudouard reaction: $\text{CO}_2 + \text{C} = 2\text{CO}$. From this it follows that the gas, when it reaches the top of the furnace, is rich in CO .

The temperature of the coke bed is higher than the melting point of slag and metal. Slag forming materials are added to keep the viscosity and melting point of the non-Mn/Fe bearing materials in the ore and coke. This is to keep the melting point of the slag at a sufficiently low level in order to maintain the good flow at the desired temperature. When the furnace is drained, the charge is moving, and as more charge is added at the top of the furnace, sag is achieved in the furnace without the need for mechanical aids. Because of the relatively high charge layer in the furnace, the gas is somewhat cooled when it reaches the top of the furnace. This combined with the lack of mechanical aids for ensuring bed sag and no combustion of furnace gas under the furnace cover (overpressure in the furnace) results in a moderate strain on the cover under normal furnace operation.

There are several reasons why coal is not used as reducing agent in HC FeMn, but the most important one is that it contains volatile, organic compounds. These compounds are released during heating and could disassociate, and in a closed furnace design, these components will not come in contact with oxygen and combust. Therefore, they would have to be separated from the furnace gas so not to deposit on gas channels and pipes. A wash tower is used to clean the gas of these unwanted components and takes place immediately after the gas exits the furnace. The use of coke leads to the same issue as it also contains volatile components, but to a lesser degree than when coal is used. Still, over time deposits will cause problems and separation is needed. In addition, the electrode paste, also contain volatile components. A sketch of the material flow of a FeMn furnace is shown in Figure 8 [18]. The figure also includes a mercury removal unit and a heat recovery facility.

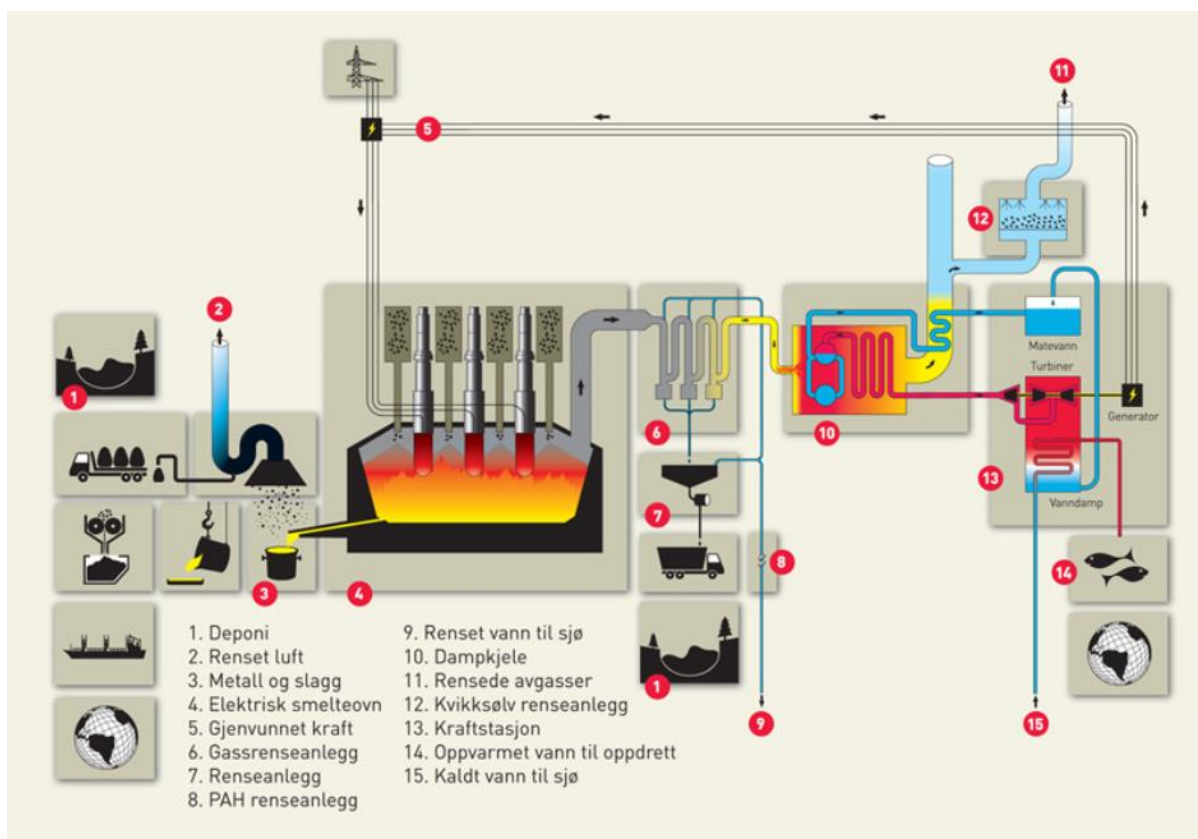


Figure 8. A sketch of a FeMn furnace [18]

Si/FeSi: The value chain for Si is largely similar to the one shown for manganese. The raw material is mixed, and added at the furnace top, while the product is drained from the bottom. In addition, the off-gas is hot and contain dust. The raw materials for Si production are quartz, coal, and charcoal. Pre-baked graphite electrodes are largely used in the Si production, while in the FeMn furnaces the Söderberg technology is commonly used, i.e. the electrodes are baked during operation. Graphite is produced at high temperatures and does not contain volatile components. Coal and charcoal on the other hand does, however this is not a major issue in today's furnaces as they are open, and oxygen is readily available.

It is important to understand what is happening in the furnace charge when evaluating cleaning steps and furnace design for Si furnaces, therefore a short introduction is given below.

At Elkem, several methods for charging is used; 1) use truck to transport the charge to the area on the charge top that needs refilling according to the operator, 2) charge is supplied through pipes at fixed points on the charge top, 3) charge is supplied through pipes with a rotating outlet enabling charge distribution to a larger area.

The carbonaceous materials are exposed to air and a part of the carbon is therefore lost as CO₂ without contributing to the process. The remaining material is transported from the furnace top and down the furnace, and this is the most critical part of the Si process. A crater is formed around the electrode point, and the resulting crater wall prevents supply of fresh material as Si is produced. Measures needs to be implemented to prevent the crater from forming, if not the crater will increase in size until it collapses. Such an occurrence results in a dangerous situation as cold, unreacted charge falls into the overheated crater and cause an explosion like reaction. A measure to prevent this is the furnace is manually (using

a rodding truck) rodded out. An alternative to this using a rotating ring as a part of the furnace side have been tested, and showed potential at small-scale and in FeSi, but reliable long-term solutions for Si furnaces are currently not available. This is the main reason why the furnaces are operated without cover – they must be rodded out using rodding trucks.

Another phenomenon that influences the charge sag is condensation of SiO. During normal production, SiO gas will flow from the crater zone and up through the charge and react with carbon to form SiC. This reaction does not return a 100% yield, as part of the gas reaches higher in the furnace before condensing (splitting into Si and SiO₂) when the temperature becomes low enough. This condensate acts as a glue and bind the raw materials together, reducing the charge sag. A sketch of the material flow of a Si furnace is shown in Figure 9. The figure also includes an energy recovery unit and silica filter.

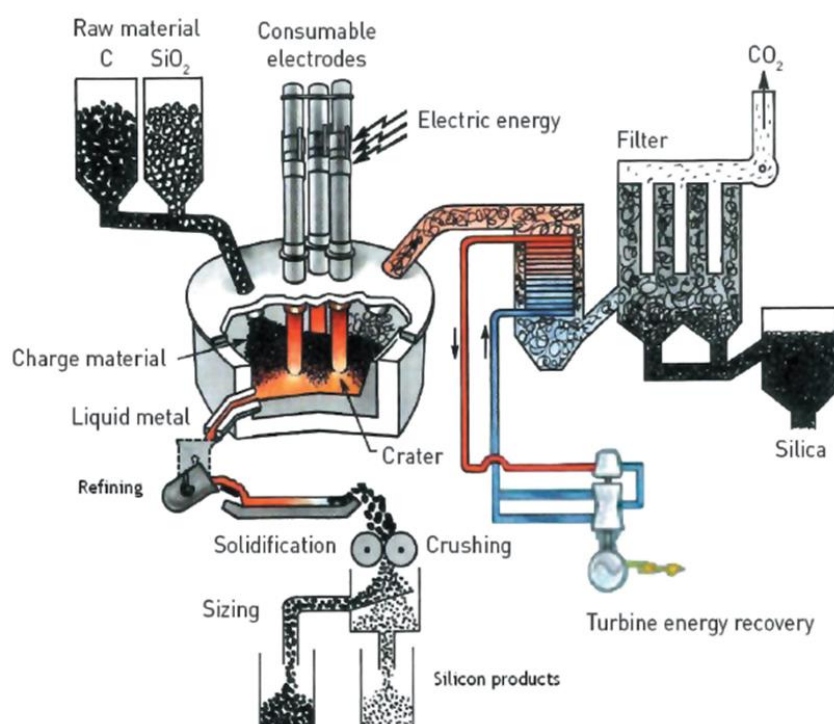


Figure 9. A sketch of a Si furnace.

In summary, if a Si furnace is to be closed:

- The furnace off-gas that is not combusted will contain volatile organic components unless measures are taken
- There is need for an installation that can push the charge downwards without removing the cover
- An alternative is to develop new furnace design that provide sufficient retention time so that SiO react completely with C to SiC, i.e. 100% yield
- And at the same time develop carbonaceous materials that are highly reactive and free of volatile organic compounds

It is not given, even with these measures in place, that there won't periodically halts in the charge sag. Testing at small-scale have identified the need for symmetry, i.e. extensive rebuilding is necessary if one is to avoid rodding.

The most realistic development of the furnace technology is likely to include a mechanical rodding solution under the cover. There are many aspects to such a solution, but further discussion on this is not included here.

If implementation of the closed furnace is successful, i.e. the problems regarding charge sag and a high yield of SiO to SiC, the off-gas composition will be very different compared to today.

- The off-gas volume will be significantly reduced as dilution with air is avoided
- It would largely contain CO and H₂ (from the residual moisture in the charge), and also volatile organic compounds as it is not deemed feasible (at current cost level) to remove all volatiles from the raw material and at the same time keep the high reactivity
- The off-gas temperature will be low, this could result in condensing in the off-gas channel
- The quality of the microsilica (there is always some SiO that is not converted to SiC) is poor
- The cost of raw materials will increase

Positive aspects are;

- The off-gas can be used for high-grade energy recovery/use
- The size of off-gas channels and equipment can be reduced
- The concentration of CO/CO₂ in the off-gas is high

Knowledge transfer between HC FeMn and Si/FeSi could be related to;

- CCS/CCU
- Energy recovery from the off-gas
- Gas washing/separation of organic components in the off-gas
- Handling of tar-containing sludge
- Design of furnace cover
- ...

In what detail knowledge can be transferred is ultimately a discussion between Eramet and Elkem.

4.3 Alcoa Lista

Alcoa Lista produces 93 000 t aluminium per year and has been in operation since 1971. The production method is an improved Söderberg, called "Ny Söderberg", which was developed at the Lista plant, the implementation began in 1990. The current electricity consumption is 16.6 kWh/t aluminium. The CO₂ equivalent plant emissions are 175 kt per year, there are no CO₂ emissions from the electricity consumption as this is hydro based.

4.3.1 Site overview

The total number of emission points are 50, however only one is relevant in a CO₂ capture perspective. This main emission point represents the collected off-gases from the cells. Before exiting through the stack, the off-gasses go through and ESP (electrostatic precipitator), a dry scrubber for HF removal, energy recovery (to district heating), and a wet scrubber for SO₂ removal. The CO₂ concentration of the off-gas going into the stack is ~8 vol% CO₂. The other emissions sources are pot room emissions with a measured CO₂ concentration of 0.1 – 0.2 vol% [9].

An overview of the plant with emission source, quay facilities, and cooling water supply is given in Figure 10. Other relevant data is provided below.

- Excess energy: 2 GWh/year is recovered between dry and wet scrubber for district heating

- Cooling water: Current cooling water (freshwater) available from nearby lake, likely to be limited capacity for CO₂ capture. Seawater for scrubbing is taken from Lundevågen.
- Area: Should be sufficient area available as the area surrounding the plant is regulated for industrial use. The emission point is in-between buildings, the flue gas channel most likely needs to be routed over the top of buildings.
- Quay: There might be two options available, see **Error! Reference source not found..** The innermost one is owned by the municipality and land for intermediate storage of the CO₂ before transport should be possible here. The quay further out is likely to have limited space available for intermediate storage.



Figure 10. Overview of the Alcoa Lista plant and surroundings (© Google Maps).

4.4 Elkem Bremanger

Elkem Bremanger has an annual production of 70 000 t of ferrosilicon products from three furnaces. There are two 20 MW furnaces, furnace 2 and 4, that produces FeSi containing 75% silicon (inoculants). The third, furnace 5, is a 40 MW furnace that produce FeSi with a silicon content of 92%. This product is further refined to Silgrain® with a silicon content of 99%. The furnaces are electric arc, in which quartz is reduced by carbon ($\text{SiO}_2 + 2\text{C} = \text{Si} + 2\text{CO}$). The carbon source at the Bremanger plant is a combination of coke, char, and wood chips. The annual CO₂ emissions are 319 kt. The furnaces use ~750 GWh annually, of which 650 GWh are produced in an on-site hydro power station and the rest is from the grid.

4.4.1 Site overview

Fans are used to draw false air under the hood of the furnaces. The off-gases, including false air, from the furnaces are collected and transported from the furnaces to gas cleaning. The false air and the channel

transport cool the gases down. The first cleaning step is a cyclone where large particles are removed (mainly raw materials added to the furnaces and classified as waste). The second cleaning step is a baghouse filter, dust (valuable microsilica) is separated from the gas which is released to the atmosphere over the top of the filter. Part of the off-gases from furnace 5 is directed through a waste heat recovery unit. The flowsheet of furnace 5 is presented in Figure 11. The off-gases from all furnaces, 2, 4 and 5, is expected to be similar and after the bag house filter the CO₂ concentration is expected to be ~4 vol%.

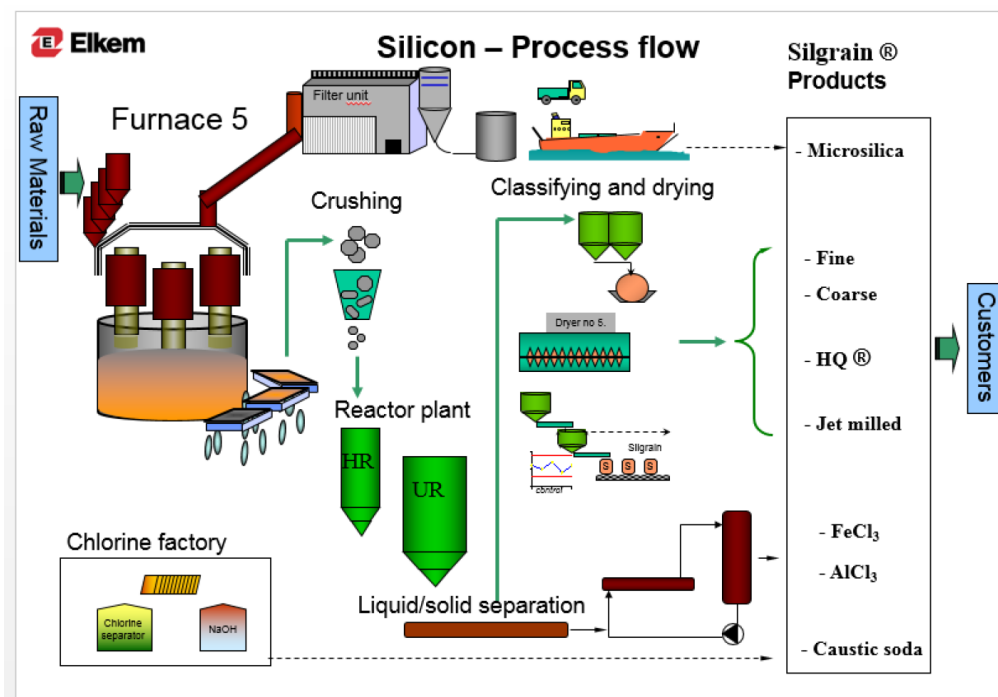


Figure 11. The flow-sheet of furnace 5 at Elkem Bremanger.

An overview of the plant with emission source, quay facilities, and waste heat recovery is given in Figure 14. Other relevant data are provided below.

- Excess energy: Energy recovery from part of furnace 5 off-gas before cyclone to district heating and for drying in the Silgrain® process
- Cooling water: Open system, no circulation. Cold water.
- Area: Limited space available, the existing production plant is located close to the hillside
- Quay: Needs to be considered further in future study



Figure 12. An overview of the Elkem Bremanger plant and surroundings (© Google Maps).

4.5 Eramet Sauda

Eramet has three plants in Norway producing manganese alloys. These are located in Sauda, Kvinesdal and Porsgrunn. The main raw material is Mn ore ($\sim 40\%$ Mn). This ore is mixed with metallurgical coke before it enters a closed electric furnace. The melt is tapped, sent to manganese oxygen refining (MOR) to reduce the carbon content, then it is casted, sized, and distributed to costumers. The final product is an FeMn alloy with $\sim 80\%$ Mn. In addition to the FeMn alloy, a FeMn slag is produced ($\sim 30\%$ Mn). This slag ($\sim 70\%$ Mn) is then utilised in the SiMn alloy production.

The Sauda plant produces FeMn, while the FeMn slag is transported to the SiMn furnace in Kvinesdal. The Sauda plant has two 40 MW closed electric furnaces and produces more than 250 kton FeMn alloy (liquid) and 180 kt FeMn slag per year. The plant consumes 730 GWh and emits ~ 325 kton CO_2 annually according to [10].

4.5.1 Site overview

Figure 13 gives an overview of the FeMn production plant in Sauda. The furnace gas is not a traditional flue gas that consist mainly of N_2 , O_2 , H_2O , and CO_2 . Here, the gas contains CO and H_2 , and therefore retains some value as fuel gas. Yet, most of the collected furnace gas is currently flared, with a smaller part being utilised. Before flaring the gas (collected from both furnaces) is sent through a venturi facility and a mercury removal unit (MRU). The furnace gas contains ~ 62 vol% CO and ~ 25 vol% CO_2 (dry basis), other components are N_2 , O_2 and H_2 .

There are additional emissions from site as shown in Figure 13, however these are disregarded in the current study as the CO₂ concentration is very low.

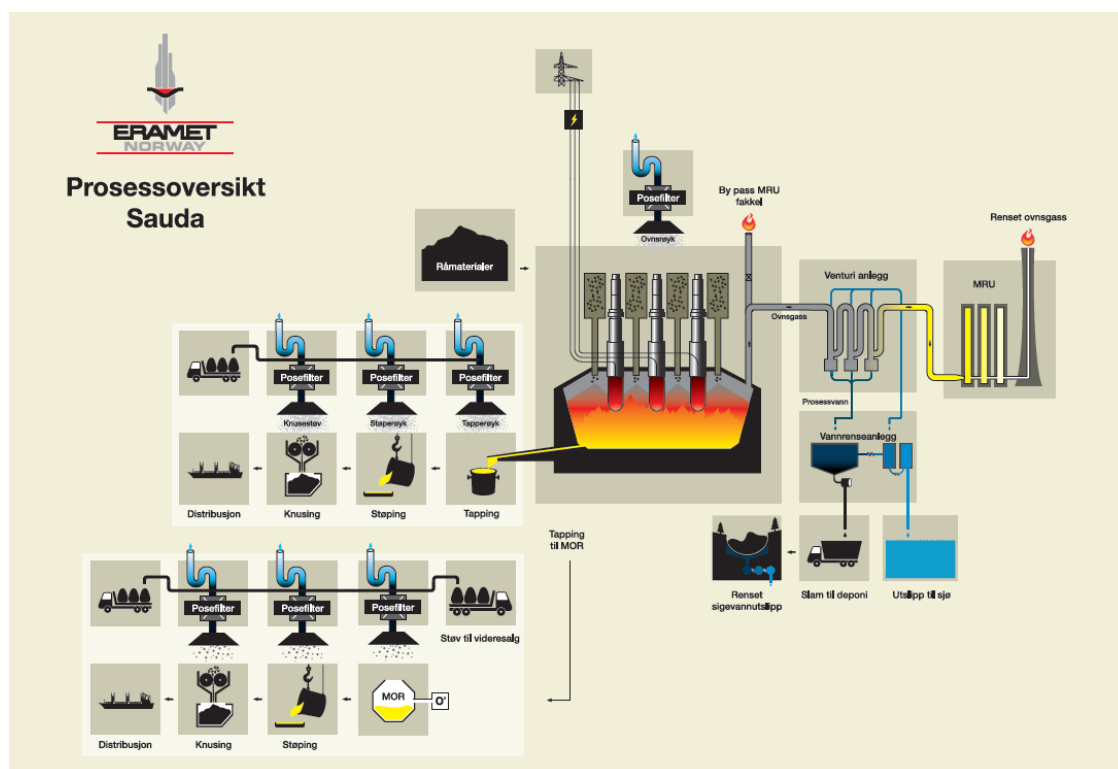


Figure 13. An overview of the Eramet Sauda plant.

An overview of the site is given in Figure 14. Other relevant information is provided below.

- Excess energy utilisation: Utilisation of furnace cooling water for district heating. Internal use of warm CO gas (20%) to preheat ladles/runners and provide energy for heating of buildings (3 MW boiler).
- Cooling water: Available, however verification on quantity is needed.
- Area: Area available for CO₂ handling facilities is identified.
- Quay: There are existing quay facilities.
- Future plans: Energy recovery based on gas engines, pilot to be installed in 2019.
- Other: The oxygen used in the MOR is produced on site in an ASU (air separation unit) operated by Praxair.



Figure 14. Overview of the Eramet Sauda plant and surroundings (© Google Maps).

4.6 Saint-Gobain Ceramic Materials, Lillesand

All information about the Saint-Gobain plant in Lillesand is prepared by Jaggi [11] as input to the project. CO₂ emission from the existing process at Saint-Gobain in Lillesand is from 28 emission points and is assumed to have a too low concentration in order to the existing technology for CO₂ capture. Saint-Gobain is currently working with a pilot plant for semi-closing of one of eight furnace groups. The project is based on tests carried out in 1982-84 with promising results, and an updated process design. Through this project, it is expected to achieve a CO₂ concentration that makes CO₂ capture possible. In the case that this project is successful, the concept may be developed further to include all the eight furnace groups.

The charge consists of petroleum coke and silica. Porosity is important for avoiding local pressure increases, leading to blowouts. The furnace bed is filled with a well-mixed charge, and a solid graphite electrode carries current from end to end, through the centre of the furnace.

The Acheson process is a batch process. Furnaces are filled with charge to a height roughly equal to its width. The furnace is then heated by resistive heating of the graphite electrode. The power is typically applied for 36-48 hours, although at a decreasing rate, as the increased core temperature increases the conductivity in the graphite and possibly some silicon carbide conduction. The furnace is then left to cool for a couple of days, before the bed is emptied.

In the furnace house, there are 8 furnace groups with 3-5 Acheson furnaces in each group, and one of the furnaces in each of the groups are in operation simultaneously.

Flue gas from the process contains several compounds such as carbon monoxide, carbon dioxide, water, sulphur compounds, dust and some PAH. At full operation, this constitutes the following approximate emissions. The annual emission is 47 000 metric tons per year of CO₂.

4.6.1 Site overview

Emission from the furnace has atmospheric pressure towards the furnace hall. In the furnace hall, the emission is diluted with significant amounts of air, and cleaned for dust in electrostatic filters before emission to air. From the electrostatic filters, there are altogether 28 emission points. The CO₂ concentration in the existing plant is significantly diluted and assumed to be too low for CO₂ capture, 0.1 – 0.3 vol%. Saint-Gobain is in progress with installation of a new pilot plant where the potential for CCS will be significantly higher, ~ 5 – 7 vol%.

An overview of the site is given in Figure 15. Other relevant information is provided below.

- Excess energy: Based on tests carried out in Acheson furnaces in 1982 - 84, average waste heat is evaluated to 1.9 MW per furnace on average during a furnace run. With one furnace in each furnace group in operation at all times and altogether 8 furnace groups, the total potential energy will be approximately 15 MW.
- Cooling water: Available, however verification on quantity is needed.
- Area: Area available for CO₂ handling facilities is identified.
- Quay: The plant is located 3 km from the coast line.
- Future plans: Pilot for closed furnace is being built.

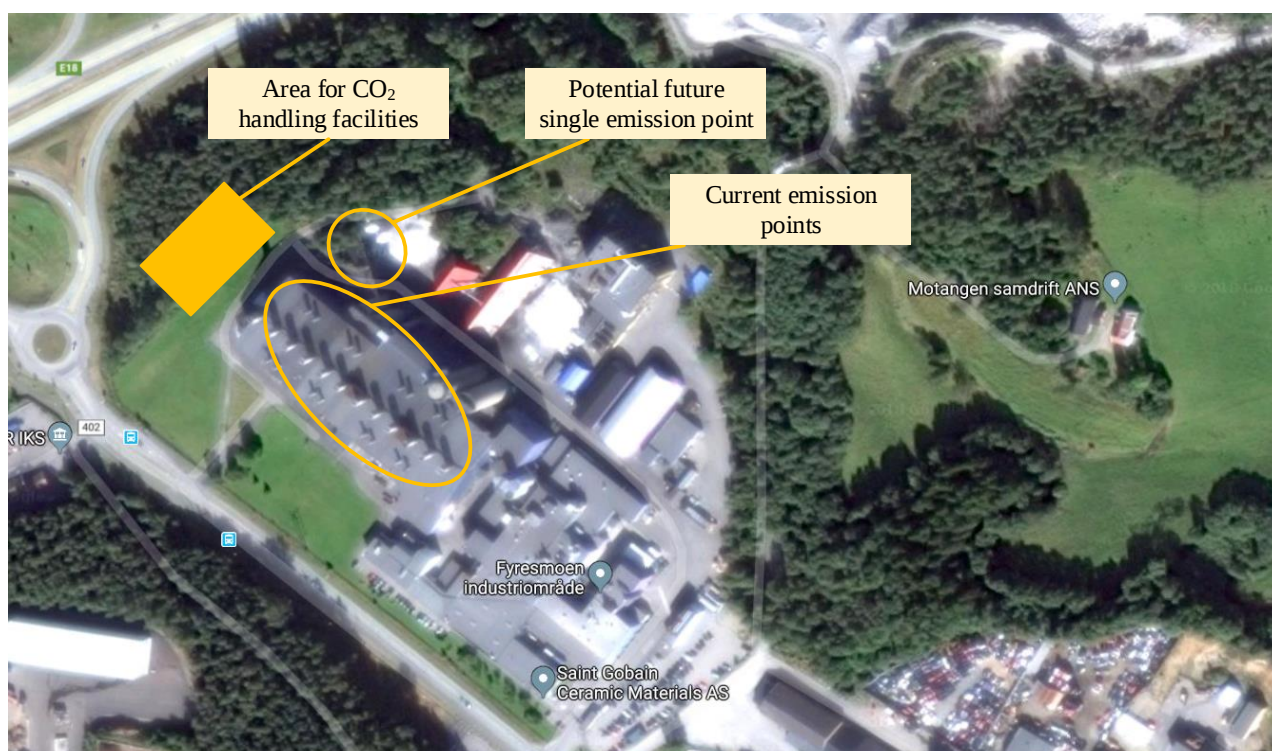


Figure 15. Overview of the Saint-Gobain Lillesand plant and surroundings (© Google Maps).

4.7 REC Solar Kristiansand

At the REC (previously Elkem) Solar plant in Kristiansand high purity silicon for use in solar cells is produced through reduction of quartz (SiO_2) with carbon, carbothermic reduction of quartz. Common carbon sources are coal, coke, wood chips and charcoal. 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 $2\,350^\circ\text{C}$, which then melts the quartz and carbon to form silicon and CO. With the present technology for Si production, all CO from the process is oxidized above the charge level.

The REC Solar plant produced close to 10 kt Si in 2015, and the corresponding CO_2 emission was 43 kt from fossil energy sources, and 12 kt from bio-based sources.

4.7.1 Site overview

An overview of the production process is given in Figure 16. The flue gas leaves the electric arc furnace at a temperature between $400 - 700^\circ\text{C}$, it is cooled down to below 230°C before entering a filter for removal of microsilica. Microsilica is a valuable product and recovery of this is a crucial part of the process.

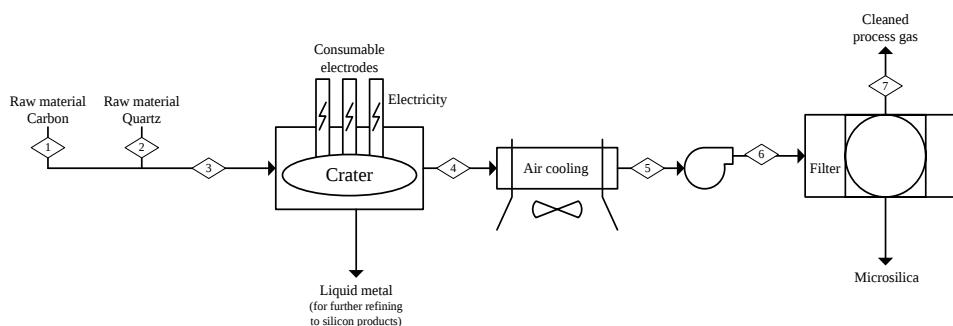


Figure 16. Illustration of production process at REC Solar.

The most relevant streams in Figure 16, are Streams 4 and 7. Detailed information about these is given in **Error! Reference source not found..** There are some uncertainties regarding the exact stream data. The basis is that 55.3 kt CO_2 is emitted annually, that the flow rate of Stream 4 is $97\,000\text{ Nm}^3/\text{h}$, and that the CO_2 concentration in Stream 7 is $\sim 1\text{ vol}\%$.

An overview of the site is given in Figure 17. Other relevant information is provided below.

- Excess energy: There is potential for energy recovery as no energy is recovered today.
- Cooling water: Unknown
- Area: Unknown
- Quay: Unknown

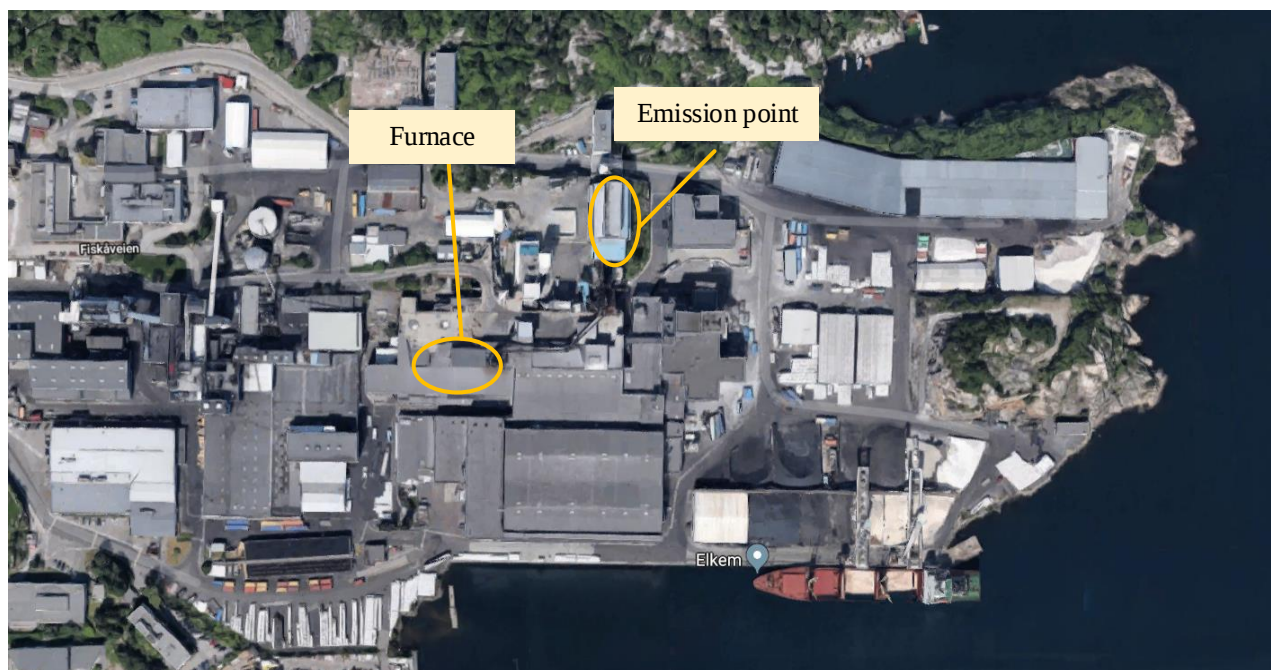


Figure 17. Overview of the REC Solar Plant (© Google Maps).

5 Overall summary and recommendations

5.1.1 Assessment of CO₂ capture readiness

The five industrial plants in the study are assessed for CO₂ capture readiness based on a set of key parameters:

- Number of emission sources – the fewer emission points the better as it generally means that less infrastructure is needed.
- CO₂ concentration – generally it is said that a CO₂ concentration of ≥ 4 vol% is needed for efficient CO₂ capture, still the higher the concentration is the better. Commonly only amine absorption is considered applicable at concentrations below 10 vol%, however hybrid technologies are merging and challenging this perception.
- Excess heat – CO₂ capture technologies need energy input in the form of heat, electricity or both. Amine absorption needs energy input in the form of steam at 130°C and 2.7 bar. If all or parts of this energy input could be recovered from the industrial plant, significant savings in the operational cost of the capture plant could be achieved.
- Area available – area for CO₂ capture plant including conditioning for transport and intermediate storage is needed.
- Quay facilities – it is likely that the captured CO₂ is to be shipped to permanent storage.
- Cooling water – a CO₂ capture plant needs cooling water, primarily for cooling of the flue gas before it enters the capture plant.

The key points of the assessment are provided in Table 2.

Table 2. CO₂ capture readiness for the selected plants.

Industrial plant	No. of emission sources	CO ₂ concentration	Excess energy	Area available	Quay facilities	Cooling water	Comments
Alcoa Lista	1	~ 8 vol%	Limited	Yes	Yes	Yes	Only one main emission source and a CO ₂ concentration of ~ 8 vol% makes Alcoa Lista a good candidate for CO ₂ capture. A challenge could be the lack of excess heat, however not all CO ₂ capture technologies uses heat as input, electrically driven processes could be a better option.
Elkem Bremanger	1	3 – 4 vol%	Yes	Limited	Yes	Yes	There is only one emission source, and while the CO ₂ concentration is relatively low it is still a good candidate for CO ₂ capture. A challenge might be available area for new installations.
Eramet Sauda	1	Furnace gas containing CO and CO ₂	Likely	Yes	Yes	Yes	The furnace gas has residual value as burn gas. Today, the furnace gas is flared, future plans include the installation of gas engines. It should be possible to install post-combustion CO ₂ capture on the flue gas from these engines. Alternatively, oxy-combustion could be considered. This might be worth pursuing as there is an air separation unit (ASU) production (operated by Praxair), next to the Eramet site. Still, it is likely that a capacity increase is needed.
Saint-Gobain (today)	28	0.1 – 0.3 vol%	No	Yes	No	Yes	The large number of emission sources coupled with a very low CO ₂ concentration makes CCS an unattractive option.
Saint-Gobain (future)	1 – 8	5 – 7 vol%	Likely	Yes	No	Yes	An increased CO ₂ concentration and reduced number of emission sources compared to today's plant making CCS a much more attractive option. The plant is located some km inland, however the small CO ₂ volume 47 kt annually makes road transport an option. It might also be possible to configure the flue gas system for energy recovery, optimized for use in the CO ₂ capture plant.
REC Solar	1	~ 1 vol%	Yes	Unknown	Unknown	Unknown	There is excess energy available to provide steam to amine absorption CO ₂ capture, however the small volume 55 kt CO ₂ annually and the low concentration makes CCS a less attractive option at least in a short to medium time perspective.

5.2 CO₂ capture technology

The most mature group of technologies for CO₂ capture is amine absorption. To be implemented at any plant, certain criteria should be met: the CO₂ concentration in the flue gas should be 3-4 vol % or higher, contaminants (in particular SO_x, NO_x, dust) should be removed before CO₂ capture, and there should preferably be energy available at the site. In addition, other utilities should be available or possible to install without excessive cost, and a capture plant must also have a suitable area for construction.

An amine absorption capture technology could in principle be implemented at all the five plants studied. However, the CO₂ concentration is too low for implementation at both REC Solar and Saint-Gobain, given today's plant conditions. It is technically possible to capture CO₂ from such low CO₂ concentrations, however the cost of doing so becomes disproportionally high, especially when the annual CO₂ volumes are low as it is for both plants. Plans to change production processes may increase the likelihood for CO₂ capture later on, which is the case for Saint-Gobain. Eramet Sauda, Alcoa Lista and Elkem Bremanger have flue gases with high enough CO₂ concentration. For Elkem Bremanger, the concentration is high enough for CO₂ capture as of today, but the current information needs to be verified. The opportunities for CO₂ capture are however regarded as good, but area may be a limiting factor. Alcoa Lista, as opposed to other aluminium plants in Norway, because their Ny-Søderberg technology has a CO₂ concentration of ~8 vol%, and this makes the possibilities for CO₂ capture good. Eramet Sauda has a very high CO₂ concentration (24.7%, dry basis), but there is also CO in the oven gas and therefore has residual value. The CO can be utilized in different ways, which will influence the final CO₂ concentrations. The resulting CO₂ concentration will in turn influence the effectiveness of the different CO₂ capture technologies.

All the CO₂ capture technologies considered would necessitate to cool down the gas stream before entering the CO₂ separation process. A cooling unit has, thus, to be envisaged and the amount of cooling water available evaluated accordingly.

More details on the possibilities for each individual plant are provided below. Here, the focus is on each plant's alternatives to amine absorption, i.e. CO₂ capture technologies with a lower TRL.

Alcoa Lista

The medium CO₂ concentration in the gas mixture together with the atmospheric pressure level makes the utilization of an alternative technology (to amine absorption) possible but challenging. Both membranes and PSA could meet the gas separation targets but would likely need to be developed in a two-stage process in order to achieve the desired CO₂ stream purity level. Vacuum conditions would be necessary, leading to concerns regarding the resulting footprint of the unit and the efficiency of vacuum systems in industrial applications. However, space availability does not seem to be a critical factor in this case. Systems based on CO₂ membranes showed the potential to achieve good energy and economic performance when a CO₂ recirculation scheme is included so to increase the CO₂ content in the feed gas stream. This would further increase the complexity of the system. On the other hand, the direct utilization of a gas mixture with medium CO₂ concentration (~8 vol%) would likely lead to a lower performance in comparison to an amine absorption-based system. PSA demonstrated competitive energy performance at higher CO₂ concentrations (~15%) than that evaluated here. It is uncertain if good energy performance could be obtained for lower CO₂ feed concentrations. Moreover, concerns about the footprint of a PSA-based CO₂ capture unit exist.

An additional issue connected to the use of PSA could be the presence of water in the gas mixture which would hinder the utilization of common adsorbents (i.e. zeolites). Water would need to be removed either through an upstream process or a pre-layer in the adsorption reactor, increasing the energy penalty

of the process. Alternatively, innovative adsorbent materials could be considered, e.g. metal organic frameworks (MOF), but the lower maturity level of those would entail a longer time frame for an actual implementation. An advantage related to both membranes and PSA is that they do not need thermal regeneration, for instance with steam. Thus, it would not be necessary to build/expand a/the steam network. This issue should be considered when evaluating the overall area necessary to implement the CO₂ capture process.

The mentioned technologies would increase the plant electricity demand and the possibility to provide such additional power must be verified. TSA could be a viable option, given that it is expected to return good performance with relatively low CO₂ feed concentrations. However, the low development stage of the technology and the possibility of large footprints suggest prudence in view of a short-to-medium term implementation. An interesting possibility could be the integration of a first stage based on a membrane (or PSA, even though this combination needs further validation) to a second low temperature separation stage. At the reported CO₂ feed concentration level, the hybrid concept would not necessarily achieve better performance compared to a conventional absorption system but would be beneficial in: (i) higher process flexibility, (ii) no need of steam and (iii) availability of liquid CO₂ ready for shipping transport.

Elkem Bremanger

The gas with a relatively low CO₂ concentration at atmospheric condition makes the utilization of alternative technologies likely unfeasible because of the expected footprints of the CO₂ capture units.

Eramet Sauda

An important issue to deal with is the presence of CO in the furnace gas to be processed. Currently a percentage (~20%) of the furnace gases is combusted in refractory burners and in a boiler to meet process heat requirements. The remaining fraction is flared. In view of the implementation of a CO₂ capture process, the large amount of CO should probably be handled upstream CO₂ separation. If the CO₂ separation was directly carried out on the original feed stream, the CO would need to be flared causing additional CO₂ emissions. An upstream combustion process could be designed, whether to produce additional heat (e.g., burners or boilers) or additional power (e.g., gas engines).

The simplest option is to use air as oxidant. Depending on the air excess to be used, the CO₂ concentration in the gas mixture would be decreased to some extent, making the following separation more challenging. Another option that could be explored is to use O₂-enriched air for the combustion. An air separation unit (ASU) is available on the plant site. If a spare capacity was available that could be employed to increase the O₂ content of combustion air with a beneficial impact on CO₂ dilution of the exhaust gas. Otherwise, an expansion of the ASU capacity could be considered, and its feasibility should be assessed. Moreover, if O₂-enriched air is to be used, the combustion process needs to be appropriately designed to ensure a proper flame temperature and to avoid the formation of pollutants. A certain degree of CO₂ recirculation could be necessary in this sense, increasing the complexity of the

system. It should also be pointed out that a combustion would make available exhaust gas at high temperature.

The resulting CO₂ concentration of the gas mixture influences the effectiveness of the different CO₂ capture technologies. An air-combustion would lead to medium to low CO₂ concentrations. In such case, membranes and PSA could be possible CO₂ capture technologies but with potential issues of low performance and large footprint (two-stage layouts likely required and bulky vacuum pumps). The possibility to supply the additional electricity demanded by those processes would also need to be evaluated. A low temperature separation process alone would not achieve a high capture ratio with reasonable energy efficiency. However, an integrated concept – a first stage based on a membrane or PSA separation and a second stage based on low temperature separation – could be an attractive solution. An advantage of all these processes is that they do not have heat requirements. Thus, steam has not to be generated and a steam network to be designed. Larger CO₂ concentrations due to an O₂-enriched combustion will make the alternative CO₂ capture technologies more attractive. If a high enough inlet CO₂ content of the gas is reached, membranes and PSA will become able to meet the requested gas separation duty with a single stage and potentially with competitive energy efficiencies.

Saint-Gobain Lillesand

The production process as it is now, has a too low CO₂ concentration in order to efficiently implement existing technologies for CO₂ capture. The implementation of the semi-closed furnace technology will make the plant more interesting for CO₂ capture. The medium CO₂ concentration of 5 - 7 % vol. could make a CO₂ capture process feasible.

The medium CO₂ concentration (5-7% vol.) obtained with the semi-closed furnace technology would likely make the utilization of alternative technologies less efficient in comparison to absorption. Membranes necessitate a higher CO₂ feed concentration to return competitive energy and economic performance. A similar consideration can be made for PSA and for low temperature processes, where the latter technology is that requiring the highest CO₂ concentration to reach competitiveness. Advanced process schemes involving multiple membrane stages and gas recirculation could allow to obtain higher CO₂ concentration entering the CO₂ capture unit and, therefore, better performance. However, those would entail an increased complexity and a larger footprint. Given the relatively small amount of CO₂ emissions characterizing the case study, issues regarding the size of the CO₂ capture unit should not be a main concern. Similarly, the additional electricity requirements associated with the utilization of the mentioned technologies should not be problematic to meet. No thermal energy would be requested by any of those processes, which is advantageous as there would be no need to build/expand a/the steam network or to include any other form of heat integration. An issue that needs to be considered is the necessity of vacuum regeneration for both membrane- and PSA-based systems, which could be challenging in industrial applications. As far as PSA is concerned, additional considerations with regard to the presence of water would need to be made given that water would competitively adsorb onto the most standard adsorbent materials. Either a water removal unit would have to be included (increased complexity) or more advanced adsorbent materials considered (lower technology maturity). TSA may be a potential option, but a source of heat would have to be identified for the adsorbent regeneration and a longer time frame for implementation should be envisaged due to the relatively low technology maturity. Finally, a hybrid concept - bulk separation stage (membrane or PSA) followed by a purification stage (low temperature process) - could result in a series of advantages, like: (i) higher process flexibility, (ii) no need of steam and (iii) availability of liquid CO₂ ready for shipping transport. On the

other hand, the utilization of two technologies would increase the complexity of the system and the energy performance is expected to be lower than that of a standard absorption process for the specific level of CO₂ feed concentration.

Given the relatively small CO₂ emission characterizing the case study issues regarding the footprint of the CO₂ capture unit should not be a main concern. But, for the future potential, the CO₂ volume may altogether be eight times the amount described for the pilot plant.

REC Solar Kristiansand

The indicated CO₂ concentration appears to be too low for the lower TRL technologies considered.

5.3 Transport of CO₂

Saint-Gobain in Lillesand is located on a site with no immediate quay access. This fact makes CO₂ transport by ship impossible, but transport by truck is still a possibility. For all the other sites, ships seem to be the most likely transport option. The harbour facilities need further assessment in the next phase with regard to availability, capacity, maximum ship size allowed etc.

5.4 CCU: Possibilities and pitfalls

In most cases capturing the CO₂ will be necessary before any further processing of the CO₂ into useful products. The only exception is growth of algae (or other photosynthesizing organisms) by feeding them the flue gas more or less as it is. This is done at Finnfjord. Algae growth is dependent on area availability, and therefore probably not at preferred option if area is a limiting factor.

All utilization of CO₂ will need energy input and a thorough analysis of product(s) versus market. Also, CCU with a few exceptions does not provide a long-term solution to the challenge of keeping the CO₂ out of the atmosphere. Like CCS, CCU will need site specific assessment of technologies and cost, and a life cycle assessment will also provide interesting information.

5.5 Recommendations for further work

The research group will point to the need for both a broader as well as a deeper study as a natural next step for the Eyde Cluster. Deeper in the sense that the cases studied here will benefit from going into more details about both choice of capture technology, energy integration and availability, other utilities, local positioning of capture plant, CO₂ conditioning plant and other new buildings, harbour facilities etc. Also, further assessment of feasibility of CCU should be made.

Broader means that more plants within the cluster should be included to make sure the best candidates for implementation are identified.

Recommendations arrived at in a workshop 13th December 2018 suggest there is common interest from several of the industry participants to go forward with a next phase. The work could benefit from building on the competence that is being developed in the ongoing CO₂ hub Nordland study.

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7 Abbreviations

ASU: Air Separation Unit

CCS: CO₂ (or Carbon) Capture and Storage

CCU: CO₂ (or Carbon) Capture and Utilization

EOR: Enhanced Oil Recovery

MEA: Mono Ethylene Amine

MOR: Manganese Oxygen Refining

MRU: Mercury Removal Unit

NCS: Norwegian Continental Shelf

PAH: Poly Aromatic Hydrocarbons

PSA: Pressure Swing Adsorption

TRL: Technology Readiness Level (often on a scale from 1-9, where 9 means commercial)

TSA: Temperature Swing Adsorption

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A Overview of CO₂ emissions in Norway

In Norway, most of the industrial CO₂ emission are from petroleum, metal, cement industries and waste incineration plants. This chapter provides an overview of the CO₂ emission sources in Norway and their magnitude and location over the counties. Reported emission data from the European (1) and Norwegian environmental agencies (2) are used for the study. The latest data is from the 2017.

In 2017, greenhouse gas emissions only from petroleum activities corresponded to about 13.6 million tonnes (Mt) CO₂ eq (carbon dioxide equivalents). 13.2 Mt out of this was CO₂, and the rest was CH₄ (methane) (3). The petroleum sector account for about one quarter of Norway's aggregate greenhouse gas emissions and they are expected to remain fairly stable over the next few years (3).

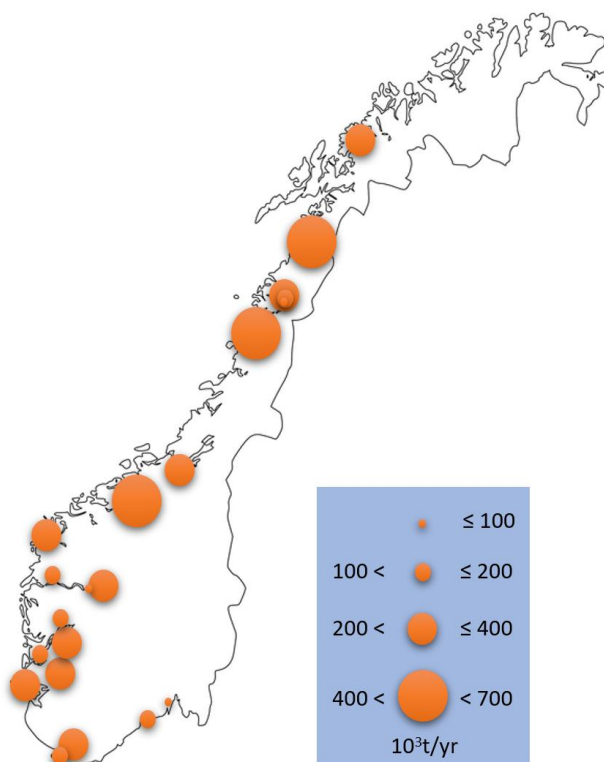


Figure A18: The location and the magnitude of CO₂ emissions from the metal production plants in Norway

The global metals sector consists of metal production facilities that smelt, refine, and/or cast ferrous and nonferrous metals, including primary aluminium, ferroalloy, iron and steel, lead, magnesium, and zinc, from ore, pig, or scrap using electrometallurgical and other methods (4). In Norway, metal industry is dominated by metal alloy and additives (for alloys) manufacturing industries and the aluminium production industry.

The locations and the magnitude of CO₂ emissions from the metal production plants in Norway are shown in Figure A18. Most of the metal production plants are located in the eastern part of Norway, where they have easy access to harbour facilities. Quantitative summary of the all the emissions from the metal related plants in Norway are summaries in Table A3, for the year 2016 and 2017. The plants are categories in to three different groups based the products. There are 10 different plants which product metal alloys or the additives for the metal alloys. Three of them are owned by Eramet AS and produce silicone manganese and ferromanganese metal alloys in Porsgrunn, Kvinesdal and Sauda.

Table A3: CO₂ emissions from the metal and additives (for alloys) production plants in Norway

*NA- Data not available

Table A10: CO ₂ emissions from the metal and additives (for alloys) production plants in Norway					NA: Data not available	
No.	Company	Type of the industry	City	County	CO ₂ emission (10 ³ t/yr)	
					2016	2017
Metal alloys production plants						
1	Eramet Norway AS Avd Porsgrunn	Standard silicone manganese and refined ferromanganese (170,000 mt/yr)	Porsgrunn	Telemark	131	185
2	Eramet Norway AS Avd Kvinesdal	Silicone manganese (180,000 mt/yr)	Øyestranda	Vest-Agder	228	228
3	Eramet Norway AS Avd Sauda	Refined ferromanganese alloys	Sauda	Rogaland	342	320
4	Elkem ASA Avd Bjølvfossen	Ferrosilicon and magnesium-ferrosilicon master alloys (60,000 mt/yr)	Ålvik	Hordaland	172	174
5	Elkem ASA Bremanger	Metallurgic silicon-based products, specialty inoculants and ferrosilicon. (32000 mt/yr)	Svelgen	Sogn Og Fjordane	301	319
6	Elkem ASA Thamshavn	Silicon and Microsilica	Orkanger	Sør-Trøndelag	288	277
7	Elkem Rana AS Avd Rana	High purity ferrosilicon (FeSi, 90,000 mt/yr) and Microsilica (23,000 mt/yr)	Mo i Rana	Nordland	310	298
8	Elkem ASA Avd Salten Verk	Silicon with purity in the range of 96 - 99 %, Microsilica and SIDISTAR® (80,000mt/yr)	Straumen	Nordland	439	476
9	Ferroglobe Mangan Norge AS	Ferromanganese and silicone manganese (120,000mt/yr)	Mo i Rana	Nordland	88.5	137
10	Finnfjord AS	Ferrosilicon (100,000 mt/yr)	Finnsnes	Troms	300	284
Aluminum production plants						
11	Hydro Aluminium Rolled Products	Rolled aluminium products (95,000 mt/yr)	Holmestrand	Vest fold	27	24
12	Alcoa Norway ANS Avd Lista	Aluminium	Farsund	Vest-Agder	161	160
13	Hydro Aluminium AS Karmøy Aluminiumsverk	Primary aluminium (190,000 mt/yr), cast-house products (194,000 mt/yr), rolled aluminium products (75,000mt/yr), research and development	Karmøy	Rogaland	315	336
14	Hydro Aluminium Husnes	Primary Aluminium (95,000 mt/yr)	Husnes	Hordaland	141	142
15	Hydro Aluminium AS Årdal Metallverk	Primary aluminium (204,000 mt/yr), foundry products (279,000 mt/yr), anodes (172,000 mt/yr), power generation and research and development	Øvre Årdal	Sogn og Fjordane	403	300
16	Hydro Aluminium AS Høyanger Aluminiumsverk	Primary aluminium (60,000 mt/yr), foundry products (117,000 mt/yr)	Høyanger	Sogn og Fjordane	104	104
17	Hydro Aluminium, Årdal Karbon	Cast-house products, foundry alloys and carbon production	Årdal	Sogn og Fjordane	32	72
18	Hydro Aluminium AS Sunndal Aluminiumsverk	Primary aluminium (400,000 mt/yr), cast-house products (500,000 mt/yr), anodes (80,000 mt/yr)	Sunndalsøra	Møre og Romsdal	591	660
19	Alcoa Norway ANS Avd Mosjøen Prod Aluminium	Aluminium (anodes)	Mosjøen	Nordland	425	NA*
Other metal plants						
20	Tizir Titanium & Iron AS	Pig Iron and Titanium	Tyssedal	Hordaland	146	261

Total CO₂ emission from three Eramet plants is about 0.7 Mt/yr while the Elkem produce 1.5 Mt/yr CO₂ from their five different metal and additives manufacturing plants. Total emissions from the metal alloy and additive plants are around 2.7 Mt/yr which is around 51% of the total emissions from the Norwegian metal industry. This includes the emissions from the metal alloy plants operated by the Ferroglobe Mangan Norge AS and Finnfjord AS in Mo i Rana and Finnsnes.

The aluminium production plants are responsible for 42% (2.2 Mt/yr) of CO₂ emissions of the metal industry. There are seven different Hydro AS and two different Alcoa ANS, aluminium production plants are in business in Norway and emit 1.6 Mt/yr and 0.6 Mt/yr CO₂ respectively.

Apart from the metal alloys and the aluminium plants, there is a pig Iron and Titanium production plant (Tizir Titanium & Iron AS) in Tyssedal and Scrap iron and steel recycling plant (Celsa Armeringsstål AS) in Mo i Rana responsible for $261 \cdot 10^3$ t/yr and $99 \cdot 10^3$ t/yr of CO₂ emissions.

Table A4, provides a quantitative summary of all the onshore CO₂ emission sources in Norway. Here, the CO₂ emissions are reported quantitatively from the year 2016 and 2017, with and without the emissions of bio CO₂. The Norwegian CO₂ sources, which are smaller than $15 \cdot 10^3$ t/yr are excluded from the table. All the emissions sources from the Table A4 are shown in Norwegian county maps based on the location and the magnitude, from Figure A19 to Figure A35.

Table A4: Sources of on shore CO₂ emissions in Norway

No	Company	Type of the industry	City	County	CO ₂ emission (10 ³ t/Yr)		CO ₂ emission (T/Yr)	
					2016	2017	2016	2017
					With bio CO ₂	Without bio CO ₂	With bio CO ₂	Without bio CO ₂
1	Eramet Norway AS Avd Porsgrunn	Standard silicone manganese and refined ferromanganese (170,000 mt/yr)	Porsgrunn	Telemark	131	131	185	185
2	Norcem AS Sementfabrikk Dalen	Cement, lime and plaster	Brevik		840	742	877	783
3	Noretyl AS	Ethylene and propylene	Stathelle		426	426	432	432
4	Yara Norge AS Avd Hydrovegen Porsgrunn	Ammonia, Nitric acid, and NPK-based fertilizers	Porsgrunn		678	678	487	487
5	Inovyn Norge AS	Chlorine and vinyl chloride monomer (VCM)	Herre		84	84	93	93
6	RHI Normag AS	Magnesite calcination & refractory material production	Porsgrunn		84	84	29	29
7	Esso Norge AS Avd Raffineriene Slagen Og Valøy	Refined petroleum products	Tolvsrød	Vestfold	259	259	330	330
8	Norgips Norge AS	Plaster board	Svelvik		30	30	31	31
9	Hydro Aluminium Rolled Products	Rolled aluminium products	Holmestrand		27	27	24	24
10	Borregaard AS Avd Spesialcellulose	Pulp and fibrous materials	Sarpsborg	Østfold	174	85,6	166	81
11	Frevar - Fredrikstad Vann Avløp Og RenovASjonsselskap Forbrenning - Prosessdamp/Adm	Waste incineration	Fredrikstad		114	46,5	110	45
12	Norske Skog Saugbrugs AS	Pulp, paper and paperboard	Halden		160	1,72	178	0,43
13	Borregaard - Forbrenningsanlegget	Chemicals for coating, plastic, paper catalyst	Sarpsborg		55,6	36	51,5	33,5
14	Rockwool, Moss	Insulation material	Moss		33	33	39	39
15	Kronos Titan AS	Dyes and pigments	Fredrikstad	Oslo	30,5	30,5	31	31
16	Fortum Oslo Varme AS Avd Klemetsrudveien	Waste incineration	Oslo		375	150	385	186
17	Haraldrud Energigjenvinningsanlegg	Waste incineration	Oslo		121	48,2	118	47
18	Leca Norge AS Avd. Rælingen	Non-metallic mineral products	Rælingen	Akershus	35	35	37	37
19	Dynea, Lillestrøm Fabrikker	Base plastics	Skedsmo		15	15	17	17
20	Alcoa Norway Ans Avd Lista	Aluminium	Farsund	Vest-Agder	161	161	160	160
21	Eramet Norway AS Avd Kvinesdal	Silicone manganese (180,000 mt/yr)	Øyestranda		228	228	228	228
22	Elkem solar Norway AS Avd Kristiansand	Solar cell silicon	Kristiansand		58	46,5	58	46,5
23	Saint Gobain Ceramic Materials AS	Ceramic product	Lillesand	Aust-Agder	47,5	47,5	55	55
24	3b-Fibreglass AS Norway AS	Fibre glass product	Birkenes		22	22	21,5	21,5
25	Eramet Norway AS Avd Sauda	Refined ferromanganese alloys	Sauda	Rogaland	342	342	320	320
26	Gassco AS Avd Kårstø Prosessanlegg	Extraction of natural gas	Kårstø		1115	1115	1206	1206
27	Hydro Aluminium AS Karmøy Aluminiumsverk	Primary aluminium (190000 mt/yr), cast-house products (194000 mt/yr), rolled aluminium products (75000mt/yr), research and development	Karmøy		315	315	336	336
28	Skangas LNG Production AS	LNG production	Sola	Eigersund	25	25	29	29
29	Egersund Sildoljefabrikk	Processing and preserving of fish and fish products	Eigersund		19	19	19	19

30	Tine Sa Tine Meieriet Jæren	Dairy food products	Hå		16	16	17	17
31	Karmsund Fiskemel AS	Processing and preserving of fish and fish products	Karmøy		13,5	13,5	16	16
32	BIR Avfallsenergi AS	Waste incineration	Bergen		218	73	216	72
33	Elkem ASA Avd Bjølvfossen	Ferrosilicon and magnesium-ferrosilicon master alloys (60000mt/yr)	Ålvik		172	156	174	153
34	Hydro Aluminium Husnes	Primary aluminium (95000 mt/yr)	Husnes		141	141	142	142
35	Equinor ASA Avd Raffineri Mongstad	Refined petroleum products	Mongstad	Hordaland	1954	1954	2356	2356
36	Tizir Titanium & Iron AS	Pig iron and titanium	Tyssedal		146	146	261	261
37	Equinor Stureterminalen	Oil refinery	Hellesøy		76	76	73	73
38	Gassco AS, Kollsnes Prosessanlegg	Extraction of natural gas	Tjeldstø		63	63	63	63
No	Company	Type of the industry	City	County	CO ₂ emission (10 ³ t/Yr) 2016	CO ₂ emission (T/Yr) 2017	No.	Company
39	Elkem ASA Bremanger	Metallurgic silicon-based products, specialty inoculants and ferrosilicon. (32000 mt/yr)	Svelgen		301	228	319	245
40	Hydro Aluminium AS Årdal Metallverk	Primary aluminium (204000 mt/yr), foundry products (279000 mt/yr), anodes (172000 mt/yr), power generation and research and development	Øvre Årdal	Sogn Og Fjordane	403	403	300	300
41	Hydro Aluminium AS Høyanger Aluminiumsverk	Primary aluminium (60000 mt/yr), foundry products (117000 mt/yr)	Høyanger		104	104	104	104
42	Hydro Aluminium, Årdal Karbon	Cast-house products, foundry alloys and carbon production	Årdal		32	32	72	72
43	Hydro Aluminium AS Sunndal Aluminiumsverk	Primary aluminium (400000 mt/yr), cast-house products (500000 mt/yr), anodes (80000 mt/yr)	Sunndalsøra	Moere And Romsdal	591	591	660	660
44	Equinor ASA Avd Tjeldbergodden	Methanol (900,000 mt/yr) from LNG and Atmospheric oxygen	Kjørsvikbugen		339	339	312	312
45	Elkem ASA Thamshavn	Silicon and Microsilica	Orkanger		288	222	277	213
46	Wacker Chemicals Norway AS	Silicon (50,000 mt/yr)	Kyrksæterøra	Sør-Trøndelag	281	256	274	248
47	Rockwool, Trondheim	Production of insulation material	Trondheim		16	16	18	18
48	Statkraft Varme- Avfallsforbrenning	Waste incineration	Trondheim		99	99	97	97
49	Norske Skog Skogn AS	Manufacture of pulp, paper and paperboard	Skogn	Nord-Trøndelag	263	10	203	9
50	Norfrakalk AS	Manufacture of cement, lime and plaster	Verdal		178	178	167	167
51	Verdalskalk Hylla	Production of lime and plaster	Inderøy		53,5	53,5	58,5	58,5
52	Alcoa Norway Ans Avd Mosjøen Prod Aluminium	Aluminium (anodes)	Mosjøen		425	425	NA*	NA*
53	Elkem Rana AS Avd Rana	High purity ferrosilicon (FeSi, 90,000 mt/yr) and Microsilica (23,000 mt/yr)	Mo I Rana		310	300	298	281
54	Elkem ASA Avd Salten Verk	Silicon with purity in the range of 96 - 99 %, Microsilica and SIDISTAR® (80000mt/yr)	Straumen	Nordland	439	314	476	324
55	Norcem AS Sementfabrikk Kjøpsvik	Manufacture of cement, lime and plaster	Kjøpsvik		304	289	401	388
56	Celsa Armeringsstål AS	Scrap iron and steel recycling	Mo I Rana		91,5	91,5	99	99
57	SMA Mineral AS	Lime and gypsum production	Mo I Rana		77	77	79,5	79,5
58	Ferroglobe Mangan Norge AS	Ferromanganese and silicone manganese (120,000mt/yr)	Mo I Rana		88,5	88,5	137	137
59	Finnfjord AS	Ferrosilicon (100,000 mt/yr)	Finnsnes	Troms	300	290	284	268
60	Statoil ASA Avd Hammerfest LNG Snøhvit	Extraction of natural gas	Melkøya	Finnmark	1065	1065	997	997

61	Elverum Fjernvarme AS	Bioenergy plants	Elverum	Hedmark	2,2	2,2	386	386
62	Longyearbyen Lokalstyre, Longyear Energiverk	Coal-fired cogeneration plant	Spitsbergen	Svalbard	70	70	73	73
63	Barentsburg Kraftverk Trust Arcticugol	Coal fired power plant	Spitsbergen		68	68	61	61

*NA- Data not available

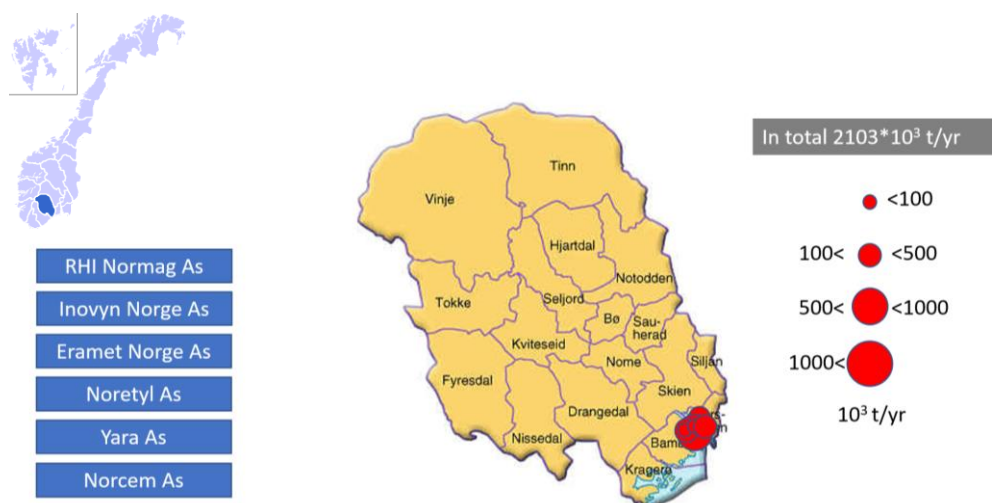


Figure A19: CO₂ emissions in Telemark



Figure A20: CO₂ emissions in Vestfold

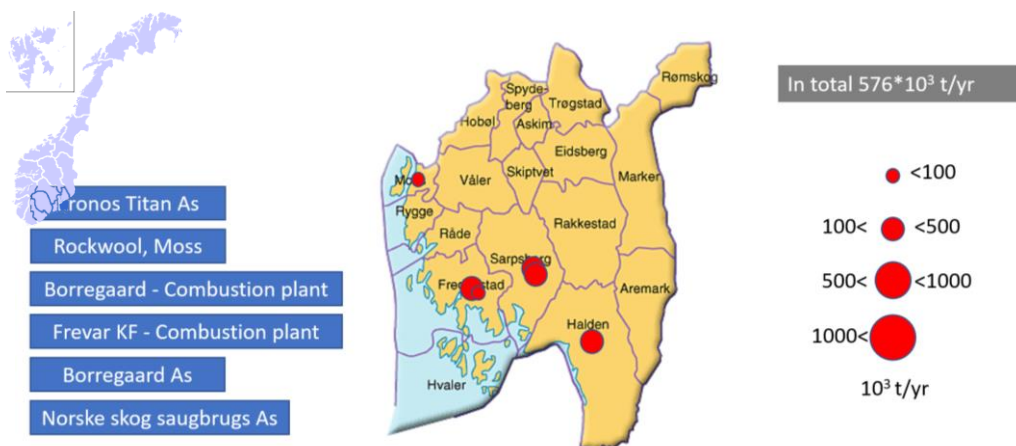


Figure A21: CO₂ emissions in Østfold



Figure A22: CO₂ emissions in Oslo



Figure A23: CO₂ emissions in Akershus

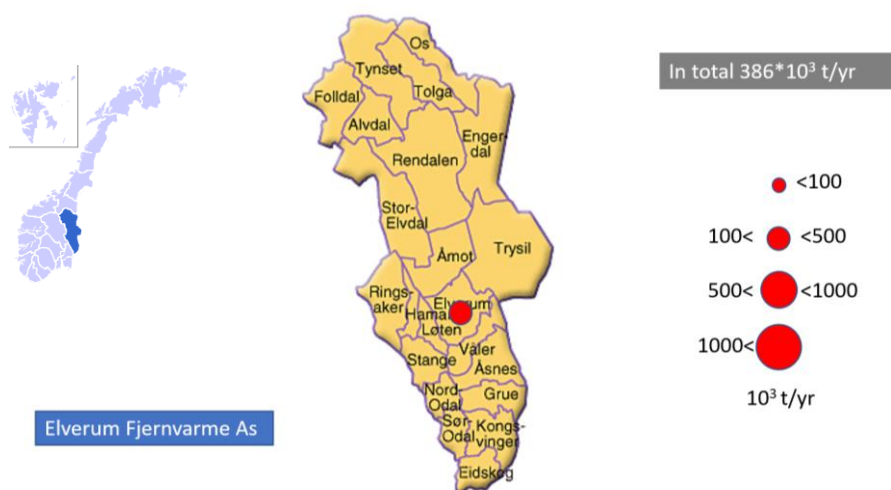


Figure A24: CO₂ emissions in Hedmark



Figure A25: CO₂ emissions in Vest-Agder



Figure A26: CO₂ emissions in Aust-Agder

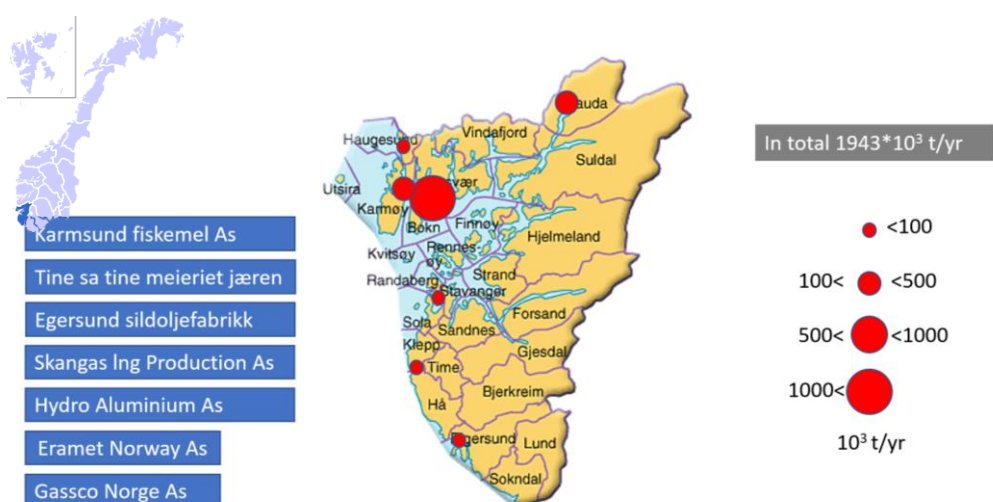


Figure A27: CO₂ emissions in Rogaland

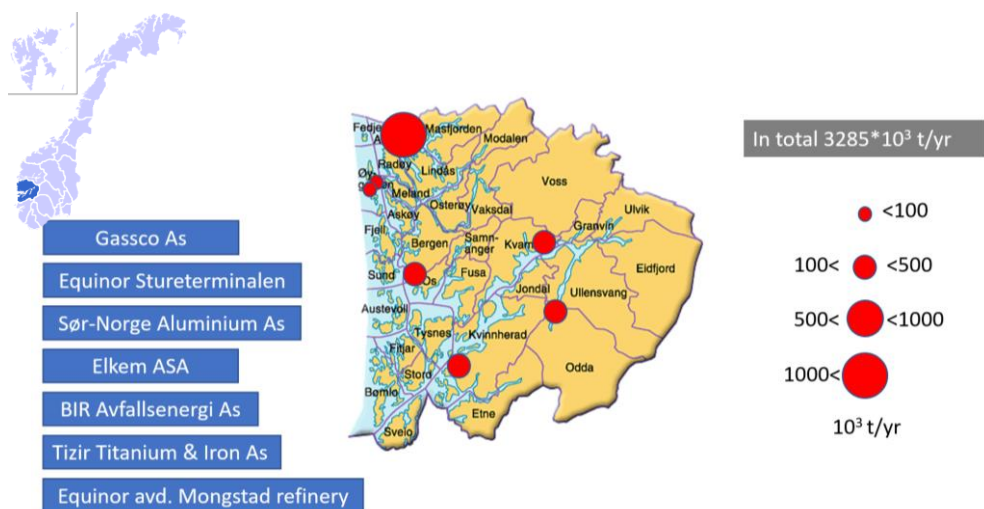


Figure A28: CO₂ emissions in Hordaland



Figure A29: CO₂ emissions in Sogn and Fjordane

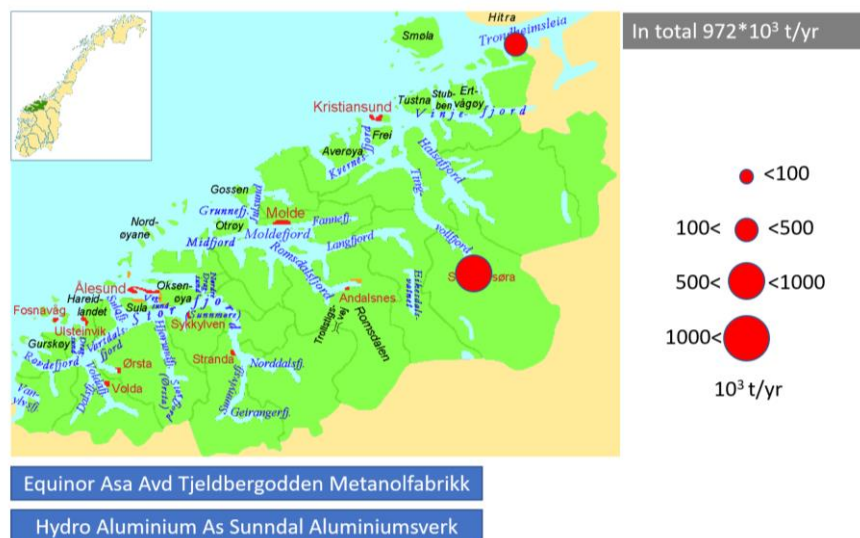


Figure A30: CO₂ emissions in Møre and Romsdal

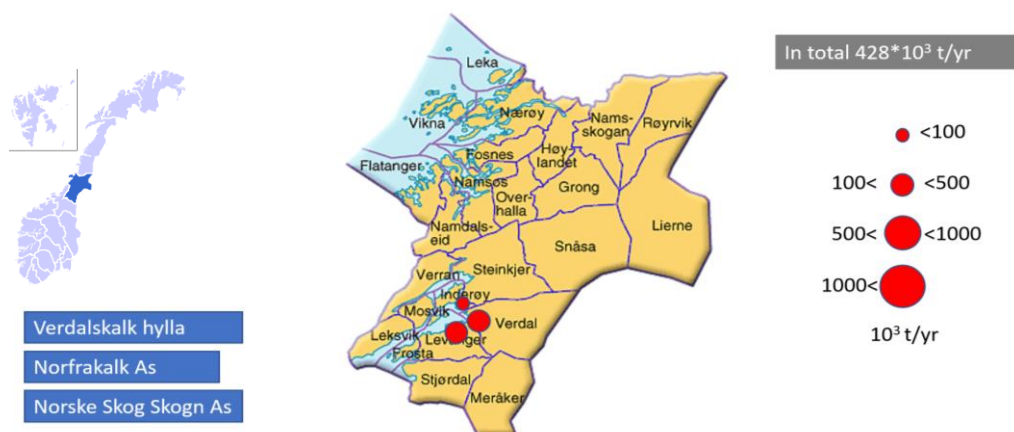


Figure A31: CO₂ emissions in Nord-Trøndelag



Figure A32: CO₂ emissions in Sør-Trøndelag

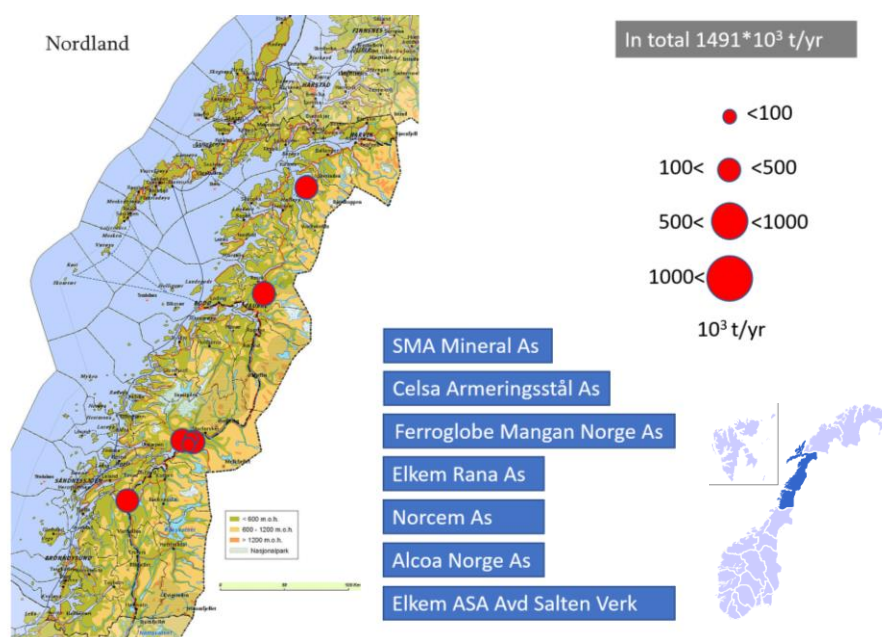


Figure 33: CO₂ emissions in Nordland

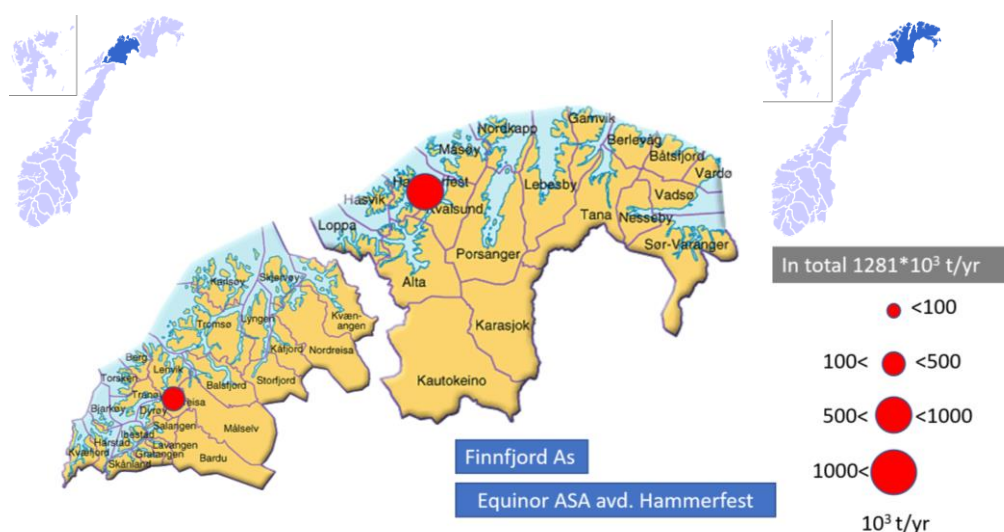


Figure A34: CO₂ emissions in Troms and Finnmark

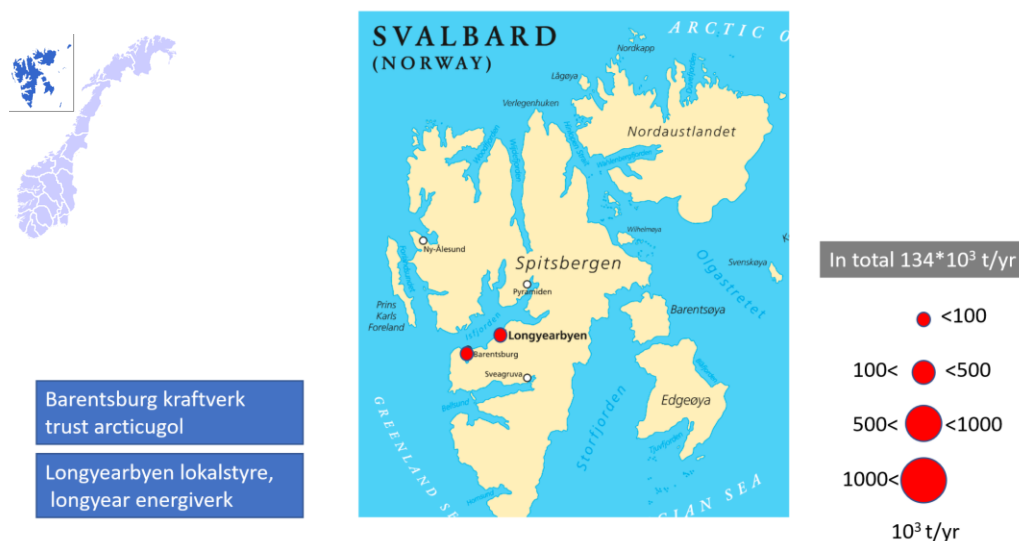


Figure A35: CO₂ emissions in Svalbard

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