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# Techno-economic evaluation of significant $CO_2$ emission reductions in the iron and steel industry with CCS

Antti Arasto

VTT SCIENCE 111

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**Techno-economic Evaluation of Significant $CO_2$ Emission Reductions in the Iron and Steel Industry with CCS**

# Abstract

The iron and steel industry is one of the largest emitters of industrial $CO_2$, accounting for around 6% of global anthropogenic $CO_2$ emissions each year. In Europe, the recently proposed stricter emission reduction targets for 2030 are likely to increase the price for $CO_2$ emission allowances. Various different GHG emission mitigation alternatives have been considered to enable decarbonisation of the iron and steel industry, such as energy efficiency, biogenic reducing agents, hydrogen and CCS. However, not all of these can be deployed for the most important production route – the blast furnace and basic oxygen furnace route (BF + BOF) – and all the solutions have advantages and disadvantages. CCS is currently the only mitigation option available for significantly reducing emissions from this energy-intensive industry.

A full chain assessment of carbon capture and storage (CCS) applications for the iron and steel industry was performed in order to screen technology options and build a development pathway to low carbon steelmaking for future carbon-constrained world. A techno-economic assessment of application of CCS with various technologies in the iron and steel industry was carried out to create a knowledge base for a Nordic steel producer. The assessment was conducted for two different $CO_2$ capture alternatives, namely post-combustion carbon capture and oxygen blast furnaces (OBF) with flue gas circulation. Processes were assessed by technical modelling based on the Aspen Plus process simulator and the economic evaluation toolkit CC-Skynet$^{TM}$ using two indicators: the break-even price of $CO_2$ emission allowances for CCS and the impact of CCS on steel production costs.

With the whole chain approach, including $CO_2$ capture, processing, transport and storage, the results show a significant reduction potential at an integrated steel mill for all carbon capture technologies assessed. The application of an OBF would require a larger modification of the processes of the existing steel mill than that required by the application of post-combustion capture. The staged construction and implementation of CCS in order to minimise the financial investment risk was considered and several pathways for implementation were analysed. Only transportation of $CO_2$ by ship was considered due to the coast-line location of the installation far from other emission sources, pipeline infrastructures and storage sites. Results show the cost structure and feasibility of the studied technologies. Cost break-even points for CCS at an integrated steel mill, for the plant owner and costs for globally avoided emissions are calculated. The direct site emissions were reduced by 0.28–2.93 Mt $CO_2$/a. The cases resulting in significant reductions represent 48–73% of direct site emissions. The net GHG impact of emission reductions are between 45–62% of the site emission reductions.

The cost of emission reductions are estimated from the site owner perspective, with the costs in majority of the cases being between €40–70/t $CO_2$. Oxygen blast furnace with top gas recirculation was estimated to be slightly cheaper than post-combustion capture of $CO_2$. As presented in the results of this study, BePs (break-even prices) are very sensitive to several factors which are uncertain regarding the time frame of large investments. The results also showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment, but also on the chosen system boundaries and assumptions. The assumed impacts on electricity production in the network strongly affect the amount of avoided $CO_2$ emissions in particular.

**Keywords** iron and steel industry; techno-economic evaluation; CCS; feasibility; post-combustion capture; oxygen blast furnace; Aspen Plus modelling; Skynet tool

**Teknistaloudellinen arviointi terästeollisuuden $CO_2$-päästöjen vähentämisestä CCS:llä**

# Tiivistelmä

Terästeollisuus vastaa noin 6 % globaaleista ihmisen aiheuttamista päästöistä ja on siten globaalisti yksi suurimmista teollisista $CO_2$-päästäjistä. Euroopan komission esittämät uudet, kunnianhimoisemmat päästövähennystavoitteet aiheuttavat nousupaineita päästöoikeuksien hintoihin. Lukuisia erilaisia hiilidioksidipäästöjen vähentämismenetelmiä, kuten energiatehokkuus, biopohjaiset pelkistimet, vety ja CCS, on ollut esillä terästeollisuuden hiili-intensiivisyyden vähentämiseksi. Kaikkia näistä ei kuitenkaan voida soveltaa yleisimpään teräksentuotantoprosessiin, joka perustuu masuuniin, ja kaikilla näillä vaihtoehdoilla on lisäksi hyviä ja huonoja piirteitä. CCS on tällä hetkellä ainoa vaihtoehto, jolla terästeollisuuden hiilidioksidipäästöjä voidaan merkittävästi vähentää.

Koko prosessiketjun kattavaa arviointia on tässä sovellettu hiilidioksidin talteenoton ja varastoinnin soveltamiseen terästeollisuudessa, jotta eri teknologiavaihtoehtoja voitaisiin vertailla ja luoda teknologiapolku vähähiiliseen terästuotantoon tulevaisuuden hiilivapaaseen talouteen siirryttäessä. Teknistaloudellisen arvioinnin avulla luotiin myös tietopohjaa paikallisille terästuottajille päätöksenteon tueksi. Arvio tehtiin kahdelle eri $CO_2$-talteenottoteknologialle, jotka ovat $CO_2$-talteenotto pesurilla savukaasuista ja happimasuuni savukaasun kierrätyksellä ja $CO_2$-erotuksella. Prosessit mallinnettiin Aspen Plus -prosessisimulaattorilla ja tähän perustuva taloudellinen arvio tehtiin CC-Skynet$^{TM}$-työkalulla käyttäen kahta indikaattoria: $CO_2$-päästöoikeuden rajahinta sekä CCS:n soveltamisen vaikutus teräksen tuotantokustannuksiin.

Koko CCS-ketjun kattava arviointi sisältää $CO_2$:n talteenoton, prosessoinnin, kuljetuksen ja varastoinnin. Arvioinnin perusteella voitiin todeta, että terästeollisuudessa on merkittävä tekninen $CO_2$-vähennyspotentiaali. Sovellettaessa happimasuunivaihtoehtoa tarvittiin olemassa olevaan prosessiin suurempia muutoksia kuin sovellettaessa talteenottoa savukaasuista. Erilaisia vaiheistetun soveltamisen ja investoinnin toteutuspolkuja teknologioille tarkasteltiin, jotta investoinnin riskiä saataisiin minimoitua. Vain laivakuljetusta tarkasteltiin vaihtoehtona $CO_2$-kuljetukselle, koska kohde sijaitsee rannikolla ja kaukana varastointikohteista. Tulokset näyttävät investointien kannattavuuden ja kustannusrakenteen. CCS:n soveltamisen rajahintaa arvioitiin laitoksen omistajan ja vältettyjen päästöjen näkökulmasta. Suorat päästöt vähenivät teknologioita soveltamalla 0,28–2,93 Mt $CO_2$/a. Merkittävämmät päästövähennysmäärät vastaavat 48–73 % laitoksen suorista päästöistä. Nettopäästövähenemä on noin 45–62 % laitoksen suorista päästövähennyksistä.

Päästövähennyskustannuksia arvioitiin laitoksen omistajan näkökulmasta suurimman osan ollessa 40–70 €/t $CO_2$. Happimasuuni savukaasun kierrätyksellä oli hieman halvempi kuin $CO_2$:n talteenotto savukaasuista. Kuten tuloksista selviää, päästövähennysten rajakustannukset ovat hyvin herkkiä useille kustannustekijöille, jotka ovat erittäin epävarmoja tämänkaltaisen investoinnin pitoaikana. Tuloksista selviää myös, että CCS:n soveltaminen ja sen kustannukset vaihtelevat hyvin paljon riippuen sovelluskohteesta, sen erityispiirteistä ja toimintaympäristöstä sekä myös tarkastelun rajauksista ja oletuksista. Erityisesti vaikutukset energiantuotantoon ja siten energiajärjestelmään vaikuttavat merkittävästi nettopäästövähenemiin.

**Avainsanat** terästeollisuus; teknistaloudellinen tarkastelu; CCS; hiilidioksidin talteenotto ja varastointi; kannattavuus; talteenotto savukaasuista; happimasuuni; Aspen Plus mallinnus; Skynet työkalu

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# Academic dissertation

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# List of publications

This thesis is based on the following original publications which are referred to in the text as I–V. The publications are reproduced with kind permission from the publishers.

I Arasto, Antti; Tsupari, Eemeli; Kärki, Janne; Pisilä, Erkki; Sorsamäki, Lotta. 2013. Post-combustion capture of $CO_2$ at an integrated steel mill – Part I: Technical concept analysis. International Journal of Greenhouse Gas Control. Elsevier, vol. 16, August, pp. 271–277 doi: 10.1016/j.ijggc.2012.08.018

II Tsupari, Eemeli; Kärki, Janne; Arasto, Antti; Pisilä, Erkki. 2013. Post-combustion capture of $CO_2$ at an integrated steel mill – Part II: Economic feasibility. International Journal of Greenhouse Gas Control. Elsevier, vol. 16, August, pp. 278–286 doi:10.1016/j.ijggc.2012.08.017

III Arasto, Antti; Tsupari, Eemeli; Kärki, Janne; Lilja, Jarmo; Sihvonen, Miika 2014. Oxygen Blast Furnace with $CO_2$ Capture and Storage at an Integrated Steel Mill – Part I: Technical Concept Analysis. International Journal of Greenhouse Gas Control. Elsevier, vol. 30, 1, pp. 140–147 doi: 10.1016/j.ijggc.2014.09.004

IV Tsupari, Eemeli; Kärki, Janne; Arasto, Antti; Lilja, Jarmo; Kinnunen, Kimmo; Sihvonen, Miika. 2014. Oxygen Blast Furnace with $CO_2$ Capture and Storage at an Integrated Steel Mill – Part II: Economic feasibility with sensitivity analysis. International Journal of Greenhouse Gas Control. Elsevier, vol. 32, pp. 189–196 doi: 10.1016/j.ijggc.2014.11.007.

V Onarheim, Kristin; Mathisen, Anette; Arasto, Antti. 2014. Barriers and Opportunities for Application of CCS in Nordic Industry – a Sectorial Approach. International Journal of Greenhouse Gas Control. Elsevier, vol. 36, pp. 93–105 doi:10.1016/j.ijggc.2015.02.009

# Author’s contributions

Papers I–V describe the technical and economical evaluation of the application of carbon capture and storage in the iron and steel industry. The disputant has been the leading author in Papers I and III. The disputant took a lead role in the creation of the approach and in leading and directing the work described in Papers I–V as a programme and task leader for the CCSP research programme. The disputant acted as a project manager and a team leader and his ideas for the research plan and executions were conducted in close collaboration with team members.

In Paper I the implications of the application of post-combustion carbon capture and storage on the mass and energy balance of an iron and steel mill are evaluated. The paper was mainly written by the disputant. The disputant evaluated and selected the technological solutions based on the methodology selected by the disputant. In addition to carrying the mass and energy balance simulations, he had a major role in all the simulation and mass balance calculations in the paper.

In Paper II, the economic implications of applying post-combustion carbon capture and storage in an integrated steel mill was investigated based on mass and energy balance calculations in Paper I. The economic calculations were based on the mass and energy balance calculations made by the disputant. The disputant contributed to the interpretation of the mass and energy balances as well as to the feeding into the economic model. The disputant also took part in the development and utilisation of the optimisation toolkit, the economic evaluations and the conclusions. Mr. Tsupari created the calculation spreadsheets with Mr. Kärki. Mr. Tsupari executed the economic calculations and operated the tool, based on a methodology jointly defined by the team consisting of the disputant, Mr. Kärki and Mr. Tsupari.

In Paper III, the implications of application of an oxygen blast furnace with carbon capture and storage on the mass and energy balance of an iron and steel mill are evaluated. The paper was mainly written by the disputant. The disputant evaluated and selected the technological solutions based on the methodology selected by the disputant. The disputant also carried out the mass and energy balance simulations in the paper.

In Paper IV, the economic implications of applying an oxygen blast furnace with and without carbon capture and storage in an integrated steel mill were investigated based on the mass and energy balance calculations in Paper III. The economic calculations were based on the mass and energy balance calculations made by the disputant. The disputant contributed to the interpretation of the mass and energy balances as well as to the feeding into the economic model. The disputant also took part in the development and utilisation of the optimisation toolkit, the economic evaluations and the conclusions. Mr. Tsupari created the calculation spreadsheets with Mr. Kärki. Mr. Tsupari executed the economic calculations and operated the tool, based on a methodology jointly defined by the team consisting of the disputant, Mr. Kärki and Mr. Tsupari.

Paper V, the technologies, potential and implications of applying CCS to Nordic industrial sectors were evaluated. The disputant developed the methodological approach and provided the information of the metal and forestry sectors, in addition to developing the overall conclusions and the roadmap presented in the paper.

# Contents

**Appendices**

# List of abbreviations

| | |
|---|---|
| A$ | Australian dollar, AUD |
| AACE | the Association for the Advancement of Cost Estimating International |
| ASU | air separation unit |
| BeP | break-even price |
| BF | blast furnace |
| BOF | basic oxygen furnace |
| CAPEX | capital expenditures |
| CCS | carbon capture and storage |
| CPU | compression and purification unit |
| DRI | direct reduced iron |
| EAF | electric arc furnace |
| EOR | enhanced oil recovery |
| ETS | emissions trading scheme |
| EUA | $CO_2$ emission allowances in EU ETS |
| FGR | flue gas recycling |
| GHG | greenhouse gas |
| IPCC | Intergovernmental Panel on Climate Change |
| ISBL | inside the battery limits |
| LHV | lower heating value |
| MDEA | methyldiethanol amine |
| MEA | monoethanolamine |
| O&M | Operation & management |
| OBF | oxygen blast furnace |
| OBF | oxygen blast furnace |
| OPEX | operational expenditures |

| | |
|---|---|
| OSBL | outside the battery limits |
| PCC | post-combustion capture |
| PCI | pulverised coal injection |
| Pz | piperazine |
| VPSA | vacuum pressure swing adsorption |

# 1. Introduction

IPCC [2013] states in its fifth assessment report that “human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system” and also “continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.” These statements highlight the urgency of the need for global actions in mitigating climate change.

According to IPCC, all the technological solutions are needed to meet the stringent greenhouse gas (GHG) emission targets. This highlights the importance of institutional and technological developments, and also the role of carbon capture and storage (CCS) in order to reach the 2DS scenario (the ambiguous climate target scenario, where measures are taken to limit the global temperature rise to +2 °C in comparison to pre-industrial times). “Many models could not achieve atmospheric concentration levels of about 450 ppm $CO_2$ eq. by 2100 if additional mitigation is considerably delayed or under limited availability of key technologies, such as bioenergy, CCS, and their combination (BECCS)” [IPCC 2014]. International Energy Agency (IEA) [2014b] states in its Energy Technology Perspectives report that business-as-usual is not an option if we are aiming for a “sustainable energy future”. This report also states that CCS has a crucial role in decarbonising the power sector and energy-intensive industries reducing up to 17% of world’s greenhouse gas emissions by 2050 depending on scenario.

The objective of the national climate legislation of Finland is to reduce national greenhouse gas emissions by 80% by 2050 in comparison to 1990 emission levels [HE 82/2014]. It is also acknowledged, based on extensive background work to the legislation in the Climate Roadmap of Finland [Koljonen et al. 2012, 2014], that CCS is also needed in Finland in order to economically meet the stringent targets set by the European Commission [2014].

## 1.1 General description of carbon capture and storage technology

Carbon Capture and Storage (CCS) refers to a family of technologies aiming at reducing $CO_2$ emissions into the atmosphere by capturing $CO_2$ from processes, transporting it to a suitable storage site, and storing it permanently in geological formations underground, isolated from the atmosphere [European Commission 2009]. These technologies are currently in the commercial demonstration phase and full-scale deployment is technically feasible. In this thesis, carbon capture and storage refers to the definition in the directive by the European Commission [2009], whereas wider definitions can include other storage alternatives such as in mineral carbonates or even the use of $CO_2$ in other applications.

CCS is mainly considered to be applied to stationary and large-scale emission point sources (those having $CO_2$ emissions in the order of one million tonnes per year), as the cost per tonne $CO_2$ avoided is typically considered lower for large CCS instalments than for small instalments. The sectors considered in association with CCS are heat and power production, mainly in thermal power plants, and energy-intensive industries including the iron and steel industry, cement industry, chemical industry and oil refining. These are also the largest sources of anthropogenic greenhouse gas besides transportation and agriculture.

$CO_2$ capture technologies can roughly be divided into three solution families: post-combustion capture (mainly with solvents), pre-combustion capture, and oxyfuel combustion. In addition to these, there are other $CO_2$ separation concepts, but these have either a lower technological maturity or are only suitable for certain industrial processes.

Captured $CO_2$ needs to be permanently isolated from the atmosphere in order to get the desired climate mitigation effect. If the industrial facility or power plant is not located on a storage site, the captured $CO_2$ needs to be transported either by pipeline or ship to the storage site. $CO_2$ is then injected into an underground storage formation that is permanently sealed after filling with $CO_2$. Generally, relatively pure $CO_2$ is considered to be stored in order to make the amount of stored gas smaller and to comply with international legislations preventing dumping of waste substances. The formations generally considered are porous rock formations, such as saline aquifers, that are deep enough and covered with cap rock. The injection and storage activities are carefully monitored geologically to prevent any leakage of stored $CO_2$.

## 1.2 Blast furnace-based iron making

There are two main ways of producing steel; virgin steel production by extracting iron from iron ore through a reduction process or recycling steel scrap through a melting process. The major refining process for iron production, needed to produce steel, is via the blast furnace and basic oxygen furnace route (BF + BOF), accounting for 95% of global iron production and about 60% of global steel production [IEA GHG 2011]. The direct reduced iron (DRI) route accounts for about 5% of global iron production [World Steel Association 2011]. The share of DRI is increasing largely due to increase in production in the Middle East but an increasing amount of virgin steel is needed globally, with more and more challenging ore qualities to be exploited, keeping the BF + BOF route as a major production route in future years.

Some modifications to the BF + BOF process are possible, depending on mill site, raw materials and integration opportunities. The principle behind the BF + BOF process route is illustrated in Figure 1. Iron ore fines and/or concentrates are agglomerate to make sinter or pellets in a sinter plant, in order to give it the physical properties to enable the charging of a blast furnace. Sinter pellets are then fed into the top of the blast furnace with coke produced from coal in a coking plant and limestone. In principle, also biogenic reducing agents could be utilised in the process. The hot blast containing compressed hot air and enriched oxygen is blown into the blast furnace to enable the reduction reactions. The blast is heated up in large batch-type regenerative heat exchangers called cowpers or hot stoves. They are generally heated up by firing blast furnace gas. Liquid hot metal or pig iron exits the blast furnace from the bottom and CO and $H_2$ containing gases called blast furnace top gas exit from the top of blast furnace. Blast furnace top gas can be utilised for heating up the hot stoves and energy production at a power plant on-site. Other heating value containing process gases are also collected and utilised in the heating of processes or in energy production. The carbon-rich molten pig iron (containing ~4.5% of carbon) exiting the blast furnace is converted into steel (target ~0.05% of carbon) in a basic oxygen furnace (BOF) by blowing oxygen through molten pig iron to oxidize the carbon from the melt with additives to remove impurities [Ruuska et al. 2006]. Steel exiting the converter goes to continuous casting and in the case of integrated steelworks, to rolling mills.

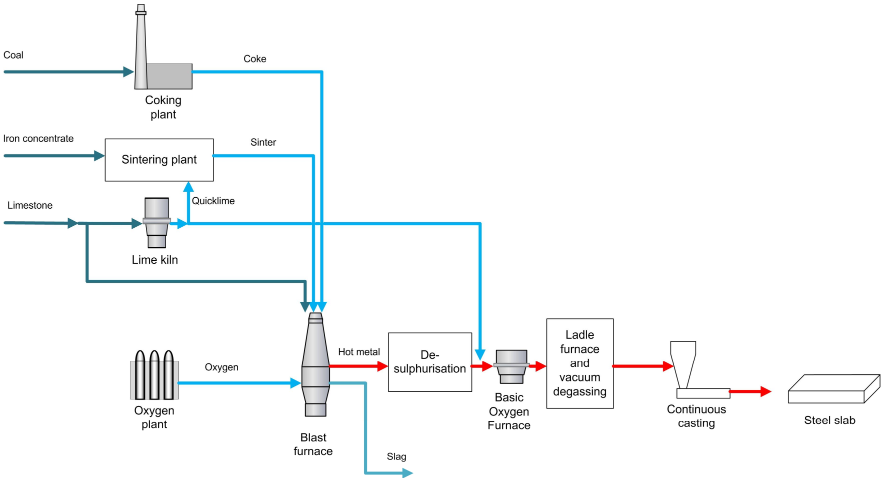

Figure 1. Principle of the blast furnace and basic oxygen (BF+BOF) furnace steelmaking process route.

The blast furnace is the main component in this most common steelmaking route. In nature, iron in iron ore is found in various forms of iron oxide. In virgin steel production process iron ore is reduced to improve its characteristics to be more suitable for construction, machinery and other uses. In the BF+BOF process route, molten iron from iron ore is further converted to steel. The primary reduction takes place first in a blast furnace and the reduction is completed in a basic oxygen furnace. A blast furnace is a counter current flow-based process. Direct reduction between carbon and iron oxide (Eq. 2) takes place, but most of the reduction takes place in the interface between solid and gaseous phases (Eq. 1) [Cottrell 1975].

$$FeO + CO \rightarrow Fe + CO_2 \tag{1}$$

$$FeO + C \rightarrow Fe + CO \tag{2}$$

$$O_2 + 2C \rightarrow 2CO \tag{3}$$

$$Fe_3O_4 + 4CO \rightarrow 3Fe + 4CO_2 \tag{4}$$

$$CO_2 + C \leftrightarrow 2CO \tag{5}$$

The overall chemical reaction using magnetite (in Eq. 4) reaction as an example is as follows: oxygen in hot blast and coke are fed into a blast furnace to form carbon monoxide (Eq. 3). Iron ore is reduced through the sequence $Fe_2O_3$ -> $Fe_3O_4$ -> FeO by mainly carbon monoxide forming carbon dioxide (Eq. 4) which further reacts with carbon to form more carbon monoxide (Eq. 5).

Most of the direct $CO_2$ emissions into the atmosphere from an integrated steel mill come from a power plant and hot stoves, as can be seen in Figure 2, which expresses the average main carbon flows of the process into and out of the mill site. These are also the biggest $CO_2$ flows from single stacks at the mill site. The majority – 94% – of the carbon entering the process is in the form of coal, entering the coking plant and directly to the blast furnace. Some 6% of the carbon enters the process in the form of limestone, $CaCO_3$, which is calcinated to CaO, forming $CO_2$ at the same time, in the lime kiln and the sinter plant. The internal carbon containing flows in the steel mill are presented in Figure 3. The carbon exiting the process is mostly in the form of $CO_2$ from various stacks on the mill site as flue gas. As can be seen, most of the carbon transferred between processes is in coke, hot metal and LHV-containing gases that can be utilised as energy source in other processes. The electricity consumption further increases the climate impact of the production.

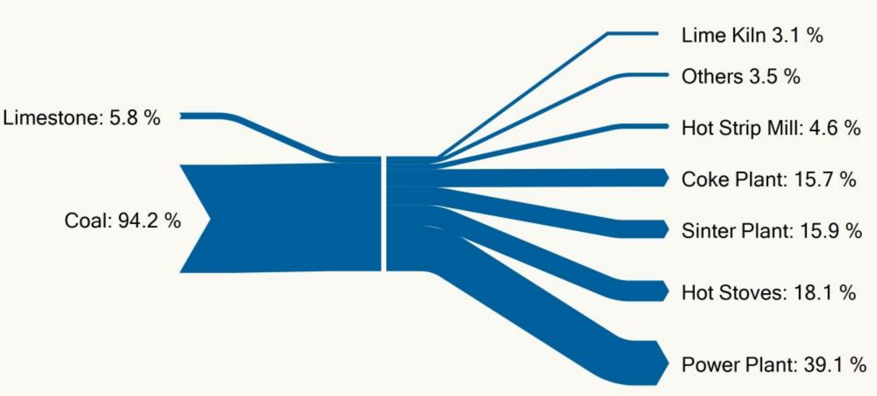

Figure 2. Sankey diagram of major carbon flows in an integrated steel mill as mass-% carbon entering the process, according to Birat [2009a].

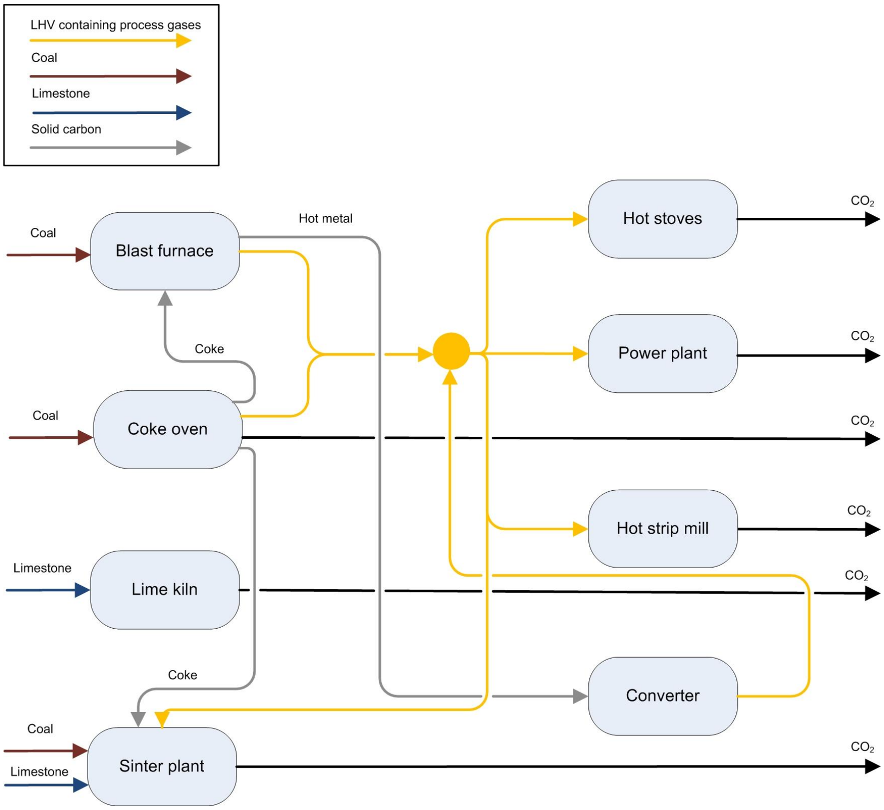

Figure 3. Main carbon flows in a typical steel mill.

## 1.3 Climate change mitigation in the iron and steel industry

Industrial sectors, such as cement, iron and steel, chemicals and refining represent 20% of total global $CO_2$ emissions currently [Oliver et al. 2013]. CCS is currently the only mitigation option available to significantly reduce emissions from these sectors [IEA 2013]. Of these, the iron and steel industry is one of the largest emitters of industrial $CO_2$, accounting for around 6% of anthropogenic $CO_2$ emissions each year [IEA GHG 2011]. In Europe, the recently proposed stricter emission reduction targets for 2030 also concern iron and steel production as it is part of the EU Emission Trading Scheme (ETS) sector [European Commission 2014]. Due to the high risk of “carbon leakage”, i.e. $CO_2$ intensive manufacturing industry moving to countries that do not have any tax or trading of $CO_2$ emissions, the iron and steel industry gets the majority of their $CO_2$ emission allowances for free [The Finnish Council of State 2008]. The amount of free allowances is based on the historical emissions of tonnes $CO_2$ per annum. However, the tightening targets will increase $CO_2$ emission allowance prices and therefore the reduction of emissions would also be of interest in the iron and steel industry. The Zero Emissions Platform (ZEP) highlights the importance of reducing emissions and deploying CCS as a technological option and considering the industrial sector being at least as important globally as the energy sector [ZEP 2014]. Based on the techno-economic scenario approach, the “Steel's Contribution to a Low-Carbon Europe 2050” report [Wörtler et al. 2013] states that the highest emission reductions in the steel sector can only be achieved by utilising CCS technologies. The European Steel Technology Platform also acknowledges CCS as a long-term opportunity to reduce GHG emissions related to steel manufacturing and use [ESTEP 2013].

Various different GHG emission mitigation alternatives have been considered to enable the decarbonisation of the iron and steel industry, such as energy efficiency, alternative smelting technologies, biogenic reducing agents, hydrogen, electrolysis and CCS [Birat et al. 2003]. However not all of these can be largely deployed to the most important production route – BF+BOF – and all of these solutions have advantages and disadvantages.

Biogenic reducing agents are currently under the spotlight [Norgate et al. 2012, MacPhee et al. 2009]. They are widely utilised in South America and represent a huge opportunity for eliminating fossil raw materials from the industry. However there are also limitations related to this solution: technical challenges, sustainability issues related to raw material, challenges in quality needed for high quality production of steel in addition to the availability and cost of biomass raw material. Also, the magnitude of incremental energy efficiency and process improvements are limited to the range of 13%, as Ribbenhead et al. [2008] conclude, whereas CCS can in theory remove all direct $CO_2$ emissions. This leaves CCS as one of the options with the greatest potential for significant GHG emission reductions in the iron and steel industry.

# 2. Literature review

## 2.1 $CO_2$ capture and storage technology

$CO_2$ can be captured from energy production or industrial process by utilising different processes, most of them known in the chemical industry. These processes can generally be divided into three categories: post-combustion capture, pre-combustion capture and oxyfuel combustion. [IPCC 2005]

Post-combustion capture refers to a family of technologies aiming at separating $CO_2$ from the flue gases or off gases that have a relatively low concentration of $CO_2$, generally in the range of 4–16 v-%. These processes are developed for the scale of CCS, generally from the processes utilised in the chemical industry. Generally, post-combustion capture technologies refer to solvent scrubbing technologies utilising chemically $CO_2$ absorbing regenerable solvents, but also adsorption processes, solid sorbents and membranes can be considered. Solvent scrubbing technologies are considered to be the most developed for the scale. Different solvents are constantly being sought in the hope of improved characteristics. The most commercially ready technologies are currently based on amine-based solvents, such as MEA, MDEA, additives like Pz and their combinations. The principle of a solvent scrubbing technology is based on the capability of solvent to selectively absorb $CO_2$ from a gas stream and desorb it later in the process. [IPCC 2005].

Pre-combustion capture removes $CO_2$ in fuel gas, such as syngas, or natural gas prior to combustion. The $CO_2$ partial pressure in the gas is generally higher than in flue gases, as the nitrogen mixed in the gas during air combustion is absent. The partial pressure of $CO_2$ can further be increased by water-gas shift reaction. Due to the higher partial pressure, solvents based on physical absorption instead of chemical absorption can be utilised. These solvents generally operate at lower temperatures and higher pressure than chemical solvents, and are sold under trade names including Selexol and Rectisol [IPCC 2005].

Oxyfuel combustion refers to a combustion process with pure oxygen resulting in the absence of nitrogen normally entering combustion with air. As a result, flue gas streams from combustion mainly comprise $CO_2$ and $H_2O$, which can be separated more easily. After the condensation of water vapour, the gas stream consists of roughly 80% $CO_2$. There are also elements of oxyfuel combustion in the oxygen blast furnace process in iron making explained in the next section [IPCC 2005].

Several advanced technologies for $CO_2$ separation with lower energy penalties associated have also been considered such as CLC (chemical looping combustion), phase change solvents, ionic liquids or membranes. However, all these are still in early development phase and not ready for commercial deployment. [González-Salazar 2015, IEA 2014a]

For transportation and storage, $CO_2$ needs to be purified and compressed. The purification step is a multistage compression and distillation process that produces at least 95% pure $CO_2$. For pipeline transportation, $CO_2$ is compressed to supercritical conditions to avoid energy losses in transportation. For ship transportation, lower pressures and temperatures are generally considered. Finally, the $CO_2$ stream is compressed to a pressure suitable for the considered storage formation [IPCC 2005].

Recently, there has been an increasing focus on utilisation of $CO_2$ in order to enable CCS deployment in commercial scale. The most significant application for $CO_2$, currently in use in commercial scale CCS demonstration is EOR, Enhanced Oil Recovery. Also other uses for $CO_2$ are in use or under consideration such as precipitated calcium carbonate production for paper fillers, use in greenhouses or use of supercritical $CO_2$ as a solvent etc. However all $CO_2$ utilisation do not result as net $CO_2$ reduction as the $CO_2$ is not permanently isolated from the atmosphere in all applications. Also the potential outside EOR seems to be limited globally. [IEA 2014a]

## 2.2 Options for $CO_2$ emission reduction in the iron and steel industry

There are different approaches to applying CCS in the iron and steel industry. Different technical solutions for capturing $CO_2$, namely post-combustion capture, pre-combustion capture and oxyfuel combustion, or technologies that can be associated with one of them can be applied to the iron and steel industry and there are numerous configurations for numerous gas streams that can be considered for the purpose [Paper V]. Two of the most applicable technologies for significant reduction of $CO_2$ emissions, post-combustion capture and oxygen blast furnace are considered more in detail below. In this section the scarce publically available literature on $CO_2$ capture from steelmaking gases and oxygen blast furnace is reviewed.

Most of the research concerning capture in the iron and steel industry discusses the energy requirements of capture solvents specifically suitable for steelmaking gas compositions and the possibilities for improvement of their regeneration energy and other properties. Carpenter [2012] describes and collects information on various options for $CO_2$ reduction in the iron and steel industry, such as fuel switch and energy efficiency improvements in addition to describing $CO_2$ separation technologies applicable to the iron and steel industry in the report. Post-combustion solvent scrubbing technologies are generally considered as technically more straightforward to apply as there is no need to alter the core process and the major impact is heat and power balance of the plant. Cheng et al. [2010] describe the application of different solvent scrubbing technologies for hot stove flue gases and the influence of technical design parameters on process efficiency. In addition, different capture solvent solutions mixes are compared. He concludes that capture properties of an alcanolamine aqueous solution were improved by adding piperazine.

Goto et al. [2011] investigate the possibilities for developing novel absorbents that are especially suitable for the properties of blast furnace gas. These absorbents were tested on a laboratory scale with as low as 3.1 MJ/kg$CO_2$ regeneration energy with as low as 2.5 MJ/kg$CO_2$ regeneration energy potential. Regeneration energy in that work was considered to be provided by steam, with temperature above 120 °C. Extensive work by Tobiesen et al. [2007a & 2007b] on solvent development also concerns gas streams related to the iron and steel industry. They also conclude that regeneration energy can be lowered by adding piperazine. By combining the best solvents and advanced internal process, integration regeneration energies of 2.2 MJ/kg$CO_2$ could be obtained with conventional blast furnace top gas.

An oxygen blast furnace can be considered as a modification of a blast furnace currently widely in use. Instead of utilising enriched air for hot blast, it utilises pure oxygen [Figure 4]. The top gas from the oxygen blast furnace is stripped of $CO_2$ and then recycled back to the blast furnace to act as reducing agent. From the carbon capture point of view, this configuration leads to less nitrogen in the system and therefore higher partial pressures of $CO_2$, enabling less energy-intensive $CO_2$ separation. Part of the top gas from the blast furnace is utilised to heat the recycled gas coming from $CO_2$ separation. Even without CCS the $CO_2$ separation or a bleed stream is needed in order to remove the inert part of the gas and to prevent build-up of gases in the system. After $CO_2$ separation the recycled gas fed back to blast furnace contains mainly $H_2$ and CO. The $CO_2$-rich stream (~92 v-% $CO_2$) is removed from the process and led to the atmosphere or purified for permanent storage in an underground reservoir for climate change mitigation [van der Stel et al. 2014].

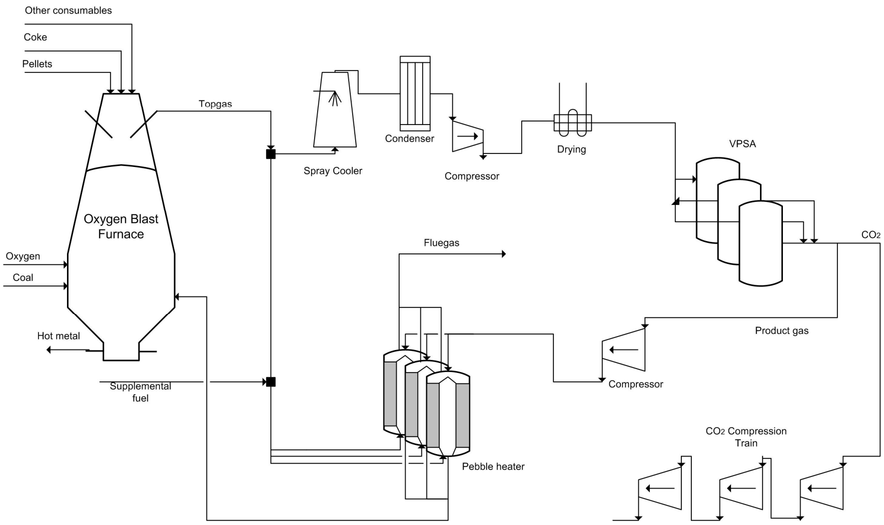

Figure 4. Schematic process configuration of an oxygen blast furnace, with flue gas recycling and carbon capture and purification.

ULCOS is an acronym for Ultra-Low Carbon dioxide ($CO_2$) Steelmaking. It is a European Commission-supported cooperative research and development initiative, with a consortium of 48 European companies and organisations to enable the reduction of $CO_2$ emissions from steel production. The aim is to reduce at least 50% of $CO_2$ emissions from blast furnaces [van der Stel et al. 2013]. They describe several technologies that have been considered and explain the benefits related to the application. They have developed and tested an oxygen blast furnace process with top gas recirculation and $CO_2$ removal with the LKAB experimental blast furnace and vacuum pressure swing adsorption (VPSA) unit. The results of the project predict a reduction of 24% of direct emissions[1] with the ULCOS oxygen blast furnace process. There are also other benefits from the deployment of this technology, such as implications for the entire steel plant, which shows a reduction of $CO_2$ emissions by 15% per tonne of hot rolled coil. With CCS technology applied, it achieves greenhouse gas reductions of over 50%, with a maximum reduction of 75% in comparison to base case reported. Overall, at the site level they have achieved a 60% reduction of direct $CO_2$ emissions from an entire steel mill site. ULCOS results show that there are several other concepts also that can achieve the targeted level of $CO_2$ reduction, CCS being an essential part of the solution [Birat and de Lassat 2009b]. The 50% target can be achieved with OBF with flue gas recycling as well as HIsarna and ULCORED process vari-

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[1] The difference between direct and indirect emission reductions is explained in Section 5.5.

ants. They also conclude that emissions related to electricity generation needed in the process have a significant impact on the GHG impact.

## 2.3 Cost of CCS for the iron and steel industry

There are in general few estimations and a limited amount of research published on the economic and environmental impacts of the application of CCS on the iron and steel industry. The few existing estimations also have very different set-ups and they are based on different assumptions. Generally the assumptions behind cost estimations, system boundary settings and the basis of cost estimations are not very well documented. The difference between $CO_2$ captured, $CO_2$ stored and $CO_2$ avoided as well as assumptions associated to theme make direct comparison of results challenging[2]. In addition, assumptions regarding transportation and storage costs are not always included in estimations

IEA [2008] summarises estimations on the costs of CCS in an iron and steel mill to be capture costs from blast furnaces of $20–25/t and total CCS costs being $40–50/t. Farla et al. [1995] estimate that capturing 2,8 Mt $CO_2$/a from blast furnace gas by MDEA solvent would cost $35/t $CO_2$ avoided. In addition to these, there are few other papers [Carpenter 2012, IPCC 2005] summarising the existing estimations.

Beyond these papers, significant contributions to the economic assessments published are summarised below.

Kuramochi [2011] concludes that CCS costs with various technological solutions for the iron and steel industry in the range of €40–65/t$CO_2$ avoided may be achieved in the short to medium-term. He also identifies possibilities for technical improvements and in the longer-term estimates that costs can be reduced to €30–55/t$CO_2$ avoided, but states that $CO_2$ capture technologies for the blast furnace-based process may not offer significant advantages over conventional ones.

In Wiley et al. [2011], estimations for 5 Mt of steel a year producing mill reductions of 7.5 Mt $CO_2$/a would cost A$77–100 from the most economic point sources on-site, before any costs of transportation and storage. The technology considered was an MEA post-combustion capture technology and the point sources considered most economic were included in the study: power plant, coke ovens, hot stoves and sinter plants.

In their work, Ho et al. [2013] have collected different solutions for the iron and steel industry with a $CO_2$ capture cost price range of A$80–250/t$CO_2$ avoided with MEA solvent scrubbing technologies applied to a conventional steel mill. The prices are estimated for different point sources around the mill site. From only the biggest point sources, such as hot stoves and power plant, and with advanced steelmaking technologies, A$65–80/t$CO_2$ cost levels can be achieved. They also

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[2] The principal difference of these terms is explained in Section 5.5.

estimate the possibility for improvements of up to 25–40% in the CCS process with vacuum pressure swing adsorption VPSA technology.

Alternative process configurations are considered to be more expensive than conventional ones [BCG 2013]. The direct reduced iron (DRI) – electric arc furnace (EAF) route enables a shift from coal-based production, but is not considered to be feasible in Europe, despite the fact that the shift is taking place in the US due to the shale gas boom. Significant emission reductions can be obtained with CCS, but these costs are also assumed to be high.

Results from ULCOS show that all alternatives considered in the publication are currently more expensive than baseline steelmaking. However, they only report on relative cost results, so no comparative conclusions can be drawn from this research [Birat and Lorrain 2009c].

Recently, IEA GHG published a very extensive study conducted together with MEFOS, Tata Steel Consulting and SINTEF Materials and Chemistry [IEA GHG 2013]. It describes a comparison of different technological options for the construction of a new BF-BOF route steel mill with a typical Western Europe configuration and access to the natural gas grid for fuel. The study comprises high level of detail on mass and energy balances and a cost breakdown with an assessment of emission impact and related costs. They conclude that $CO_2$ reductions of over 50% in blast furnace-based iron making require application of CCS. However the technology development of these CCS technologies to a commercial scale is ongoing and implementing these technologies would have significant implications on the commercial viability of a steel mill. The technologies investigated were post-combustion $CO_2$ capture with MEA and with two different levels of $CO_2$ capture rates and OBF with top gas recycling and MDEA/Pz as a solvent for $CO_2$ capture. The whole mill was modelled including sinter, coke and lime production, hot metal production and desulphurisation, the basic oxygen steelmaking process, ladle metallurgical refining, and continuous slab casting finishing mill units. The $CO_2$ delivery pressure was assumed to be 110 bar. The results show that with MEA, a reduction of 50–60% in $CO_2$ emissions avoided and with OBF a 47% reduction of $CO_2$ emissions avoided can be obtained. The costs for emissions avoided with MEA were \$74/t $CO_2$ for 50% emission reduction and \$81/t $CO_2$ for a 60% emission reduction. OBF solutions are cheaper with a price estimation of \$57/t $CO_2$, and the main reason for this is estimated to be the reduced coke consumption in the process. This work is also presented in Hooey et al. [2013].

# 3. Focus of the present thesis

Global carbon dioxide emissions from industrial processes and especially from the iron and steel industry are large. From a Nordic and a Finnish perspective, investigating the opportunities to reduce $CO_2$ emissions in the iron and steel industry are also of significance as steel mills are among the largest point sources in the region. Because of this, and the fact that other climate change mitigation options are limited, the iron and steel industry is an interesting opportunity for the application of CCS technologies.

Due to the global nature of steel markets, the economic competitiveness of the climate change mitigation solutions have to be stressed. As most of the studies reviewed above state CCS in the steel industry as being amongst the most competitive processes to apply CCS to, this was an interesting starting point. The capture cost estimations found in literature started from as low as €20/t $CO_2$ – this is well below general cost estimations associated with CCS in power production [IEA 2008, IEA 2014b, IPCC 2005, Stern 2007, Teir et al. 2011]. None of the scientifically published work is not based on comprehensive engineering work, nor addresses the process and integration consequences thoroughly. On top of this, there is no comprehensive work published on the application of CCS in an existing steel mill as opposed to greenfield installations.

The Nordic locations also constitute an interesting point of view as the transportation and storage opportunities, and therefore also the related costs are totally different from most countries considering CCS. The projects including this work referred to here are seeking answers to the question: could CCS be a viable option for Finnish carbon intensive industry?

Most of the research concerning $CO_2$ capture in the iron and steel industry addresses the energy requirements of capture solvents that are specifically suitable for steelmaking gas compositions and the possibilities for improvement of their regeneration energy and other properties, or technical improvements in the oxygen blast furnace process. Knowledge of the impact of these factors on the steel mill system, further from society's perspective and on global impacts is, however, limited or non-existent.

The objective of this thesis is to contribute to the knowledge on the feasibility of greenhouse gas mitigation technologies in the iron and steel industry. This is done by producing sound numerical data on the feasibility of these greenhouse gas mitigation solutions and to compare their technical properties and following economic implications. Furthermore the thesis contributes to knowledge of the suitability of the chosen consequential concept assessment methodology in the techno-economic assessment of climate change mitigation technology investments.

Most of the work done is presented in the five papers appended to this thesis. The work comprises two different technologies applied to an existing Finnish steel mill. The case study is based on Ruukki Metals Ltd's steel mill situated in Raahe, on the coast of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries, producing hot rolled steel plates and coils. It is also the largest $CO_2$ point source in Finland, emitting approximately 4 Mt $CO_2$/a [EMV 2011].

The two different carbon capture technology solutions considered in this thesis are a post-combustion solvent-based capture as a pure retrofit solution, and a more advanced and technically challenging technology combining an oxygen blast furnace with top gas recirculation and $CO_2$ separation. These two technology solutions are assessed in two steps following engineering and investment analysis principles:

1. First, by developing a technology concept that is suitable for the site at hand and performing mass and energy balance calculations for the concepts.
2. Second, by evaluating the economic impacts of the deployment of technologies in varying operational environments.

# 4. Mass and energy balance modelling of applications of CCS in the iron and steel industry

## 4.1 Principles of mass and energy balance calculations

Material balances are the basis of process design. Based on material balances, the quantities of raw materials required and the amount of products can be estimated. An engineering system is composed of individual process units and process streams with flows and compositions that connect them. As a whole, these form a system. The principles of chemical engineering [Peters et al. 1968, Simons 2007, Sinnot 2009] follow the fundamental laws of conservation. In non-nuclear processes these can be considered as two separate laws: conservation of matter and conservation of energy.

Following Simons [2007] the conservation of mass law for a box representing system boundaries is:

$$\dot{m}_{i,in} + G_i - \dot{m}_{i,out} - C_i = \frac{dm_i}{dt} \tag{6}$$

, for species, element or compound.

| | |
|---|---|
| $\dot{m}_{i,in}$ | Input is the mass of species entering the box through a system boundary |
| $G_i$ | Generation is the species produced in the system, e.g. from chemical reactions |
| $C_i$ | Consumption is the species consumed in the system, e.g. in chemical reactions |

| | |
|---|---|
| $\dot{m}_{i,out}$ | Output is the mass of species leaving the box through a system boundary |
| $\frac{dm_i}{dt}$ | Accumulation is the amount of species that adds up in the box inside system boundary |

Material can change form, for example, through chemical reactions or phases, but the total mass flow in a steady state process must equal the total mass flow out. From the design point of view, in a steady state process the accumulation should also equal zero, resulting in a simplified form of equation for the total mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{7}$$

, and individual components:

$$\dot{m}_{in} - C = \dot{m}_{out} + G \tag{8}$$

The conservation of energy law is also known as the first law of thermodynamics, and it follows the principles of conservation of mass law, with the exception that there are different types of energy that can exist: heat, mechanical energy, electrical energy, but the total energy is conserved. For a non-nuclear process these forms of energy can be classified as:

1. kinetic energy – the energy created due to the translational motion of the system
2. potential energy – the energy a system has due to a position in a potential field
3. internal energy – all other energy possessed by a system other than kinetic or potential energy.

Like mass, energy can be transferred from and to a system. There are two principles that govern how energy can be transferred:

1. heat or energy that flows through a temperature gradient
2. work, or energy that flows in response to any driving force other than a temperature gradient

The full equation for the first law of thermodynamics can be written:

$$\Delta U + \Delta E_k + \Delta E_p = Q - W \tag{9}$$

where $\Delta U$ is the difference in the internal energy of all the streams coming out of a system in relation to those coming in, $\Delta E_k$ the change in kinetic energy, $\Delta E_p$ the change in potential energy, Q the amount of heat put into the system and W the amount of work done by the system.

The conservation laws hold to any complete process or any sub-division of the process within any system boundary that can be set in an arbitrary way. The mass and energy flows that cross the system boundary are in balance according to the laws of conservation.

## 4.2 Attributional versus consequential approach to life cycle assessment

The term life cycle assessment (LCA) refers to a fair, holistic assessment for mapping all the influences of raw material production, processing, distribution use and disposal and all related actions necessary or that are caused by the existence of a product, process or service on human health and environment. There are two main principle types of approaches to a life cycle assessment problem that are, according to Finnveden et al. [2009], attributional and consequential assessment methods:

1. The attributional assessment method aims at identifying and making commensurable energy, material, emission, etc. burdens related to a production and use of a product or a service. Typically, this approach would answer the question: what are the total environmental effects of producing and utilising this product?
2. The consequential assessment method aims at identifying and making commensurable the consequences of an impactful decision or a change in a system. This approach would typically answer the question: is one option better than the other and by how much based on the environmental effects are they likely to cause?

## 4.3 Consequential approach to mass and energy balance calculations in the deployment of CCS at a steel mill

The mass and energy balance approach is applied here in the implementation of CCS technology at an iron and steel mill with a consequential approach for boundary setting. This technical evaluation can be roughly divided into two main steps:

1) Implications of the application of the CCS on a process level, and
2) Implications of the application of the CCS on the mass and energy balances on the site level.

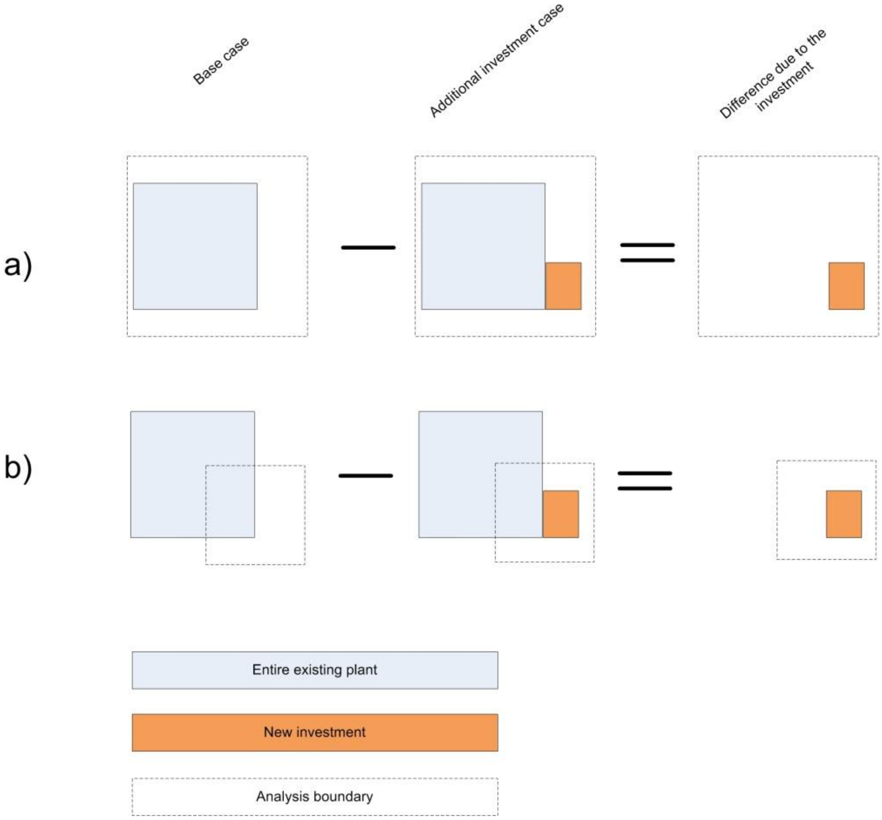

Figure 5. Illustration of a) an attributional and b) a consequential approach to mass and energy balance calculations and economic assessment.

As the investigation of applying CCS in this case is a retrofit investment to an existing site and existing production process, a common engineering approach for investments of new equipment into an existing facility is a consequential assessment type of approach on the setting of system boundaries and dealing with interactions with the surrounding facility. This results in less workload because it is a question of which option is better over another and only part of the process is changing. When considering the change, with the attributional approach this would result in a lot of calculations, which would end up being subtracted from each other and thus result in zero. With consequential assessment, only those parts affected by the investment or process alteration are considered and the result is the same. This principle is illustrated in Figure 5. The parts affected can be identified e.g. based on preliminary engineering. With the consequential approach for setting the system boundaries, we avoid excess work in calculating the entire plant site without any changes due to the investment decision. The system boundary is selected to only include the process units significantly affected by the change. This way the whole integrated steel mill does not need to be modelled and included in the economic evaluation. From an economic point of view, only those changes in the streams crossing the evaluation boundaries need to be assessed, as changes inside system boundaries define the streams crossing boundaries.

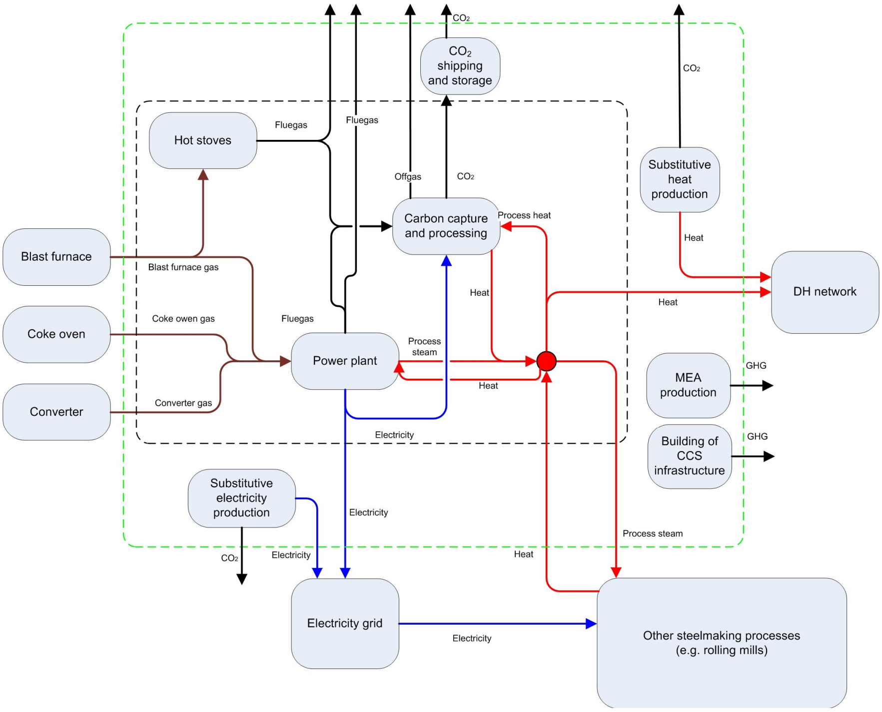

Figure 6. Example of setting analysis boundaries [Paper I].

We focus on a retrofit investment, and therefore a common engineering approach for investments of new equipment into an existing facility is a consequential assessment type of approach with the setting of system boundaries and dealing with interactions with the surrounding facility. This approach is applied to two different CCS technologies: post-combustion carbon capture and oxygen blast furnace with CCS, applied to a steel plant in order to reduce the greenhouse gas impact of the site. The parts of the steel mill under investigation and the boundaries for the evaluation are described in Figure 6.

The underlying questions at the process level are different operation assumptions of the process after investments, the selection of auxiliary processes, their energy requirements and integration in the steel mill. At the site level, the essential questions are: the overall energy balance on-site, replacing fuel usage, replacing energy production, and energy-related investments.

The study is based partly on the current operational conditions and partly on a hypothetical situation at Raahe steel mill. The sintering plant was closed in 2011, which affected the gas streams around the plant and the direct emissions of the plant site. The study investigates a situation where the current power plant at the site is renewed and converter gases are collected and utilised in the power plant. In addition, heat recovery from the steelmaking processes is improved and the production of process steam at the power plant is thus decreased. In this study, the hot stoves use only blast furnace gas as fuel. The power plant uses a mixture of gases, comprising blast furnace gas, coke oven gas and converter gas. The gases originate from fossil fuels, mostly coal and heavy fuel oil.

The basis for the entire techno-economic assessment is the modelling of the process environment, and the application of CCS technologies with auxiliaries. The $CO_2$ capture processes and the steelmaking processes were modelled using Aspen Plus® modelling software and the results were used to estimate the $CO_2$ emission reduction potential using post-combustion capture and oxygen blast furnace technologies in an integrated steel mill. As presented above, only the parts of the steelmaking processes affected by the deployment of $CO_2$ capture were investigated. Different amounts of captured $CO_2$ were investigated. The amount of $CO_2$ captured depends on solvent technology selection, solvent properties and heat available for solvent regeneration. The capture unit is sized based on the heat available for solvent regeneration in different scenarios. Different captured $CO_2$ amount cases are the result of the capture unit being sized to capture as much as possible with a 90% capture level with the available heat. Based on the energy and material balances obtained from the modelling and the technical feasibility of investigated solutions, the economic profitability is further evaluated. Emission reductions are estimated within the system boundary, i.e. from an investor’s point of view. The results from the Aspen Plus® model were used to estimate the impacts of the CCS at the site level. For these estimations, a new steel mill application was created in the MS Excel-based toolkit CC-Skynet™.

The cases with $CO_2$ capture are compared to the base case without the capture. The production of steel, the utility steam consumption and the district heating demand are assumed to remain at a constant level, also when applying $CO_2$ capture. The amount of electricity bought from or sold to the electricity grid is balanced towards the production at the power plant and the increased consumption of electricity, which depends on the amount of $CO_2$ captured. $CO_2$ crosses the system boundary either with the flue gases from the power plant and hot stoves, or as a pure stream for transportation to a permanent underground storage.

## 4.4 Application of post-combustion carbon capture

Typical carbon flows of an integrated steel mill are presented in Figure 2 to illustrate the carbon intensity of the processes and show the single biggest $CO_2$ emission sources on-site, as presented and explained in Section 1.2. As can be seen in the figure, hot stoves and the power plant are the biggest single sources of

$CO_2$ at the mill site. In the case study, there is no sintering plant on-site and the relative share of direct $CO_2$ emissions from the coke oven is smaller than that shown in Figure 2. Therefore, capture from power plant and hot stove flue gases was considered to be the design basis for the post-combustion capture at the site. Blast furnace gas represents by far the largest fuel gas stream utilised within the boundaries of this study. Since the amounts of other fuel gases used are small, there are no significant differences between the flue gases of the power plant and the hot stoves regarding composition, $CO_2$ content and impurities. Therefore, no significant advantage would be gained from treating these gas streams in separate capture units. A single capture island could be used because of the close location of the flue gas stream sources and the steady operation of both the process units that generate $CO_2$. In addition to this, only a single location suitable for constructing a capture island was found within reasonably close proximity to the sources. This also justifies the combination of the two flue gas streams into a single capture island.

Post-combustion capture (PCC, not to be confused with pulverised coal combustion or precipitated calcium carbonate) was chosen as the approach because it was considered to minimise the modifications needed to the existing core steelmaking processes. The basis of considerations for capturing carbon dioxide from the flue gases was a conventional monoethanolamine (MEA)-based solvent scrubbing process. In addition to this, the usage of two alternative solvents was investigated with a rough, conceptual study. This was performed to study the possible effects and benefits for $CO_2$ capture in the future when more advanced methods have been developed. The schematic principle of applying a post-combustion capture process is presented in Figure 7 and the connections between process units in Figure 6.

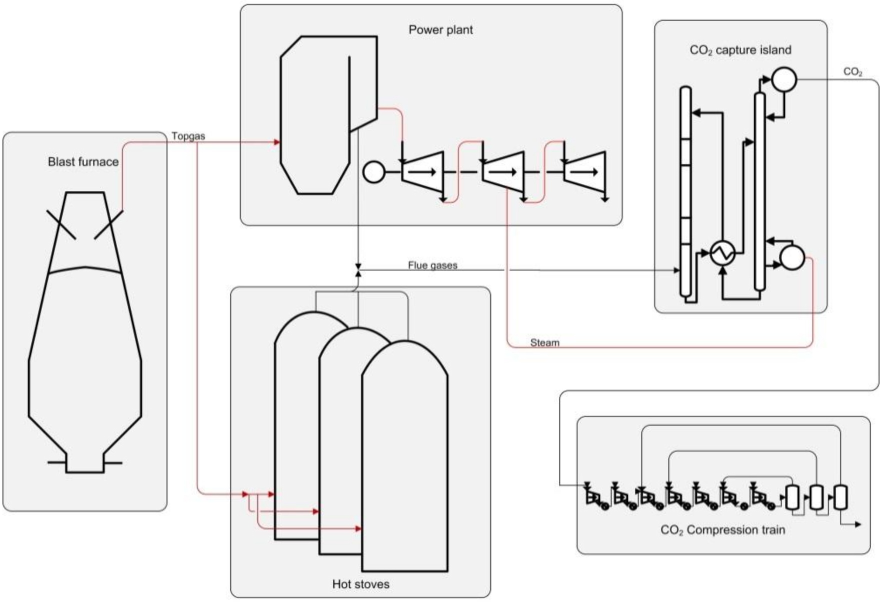

Figure 7. Schematic process configuration of applying post-combustion capture to an iron and steel mill.

The configuration of the basic regenerable solvent scrubbing process is presented in Figure 8. Flue gas from a power plant or other source is cooled down and the saturated gas is then fed into the lower part of an absorber column. Liquid solvent enters the column from the top, making a counter current contact with the gas stream. Advanced configurations of columns with several recycle streams and feed points have also been designed to improve the efficiency of the process. $CO_2$ from the flue gas is chemically absorbed by the liquid solvent. The $CO_2$-rich solvent exits the absorber column from the bottom and is fed to the stripper column via a cross heat exchanger to improve the heat recovery inside the process. The resulting $CO_2$-lean gas stream exits the column from the top of the absorber and is let into the atmosphere. Additional energy, generally in the form of steam is fed to the stripper via a heat exchanger, to break the chemical bonds between solvent and $CO_2$. This generates a $CO_2$-rich gas stream that exits from the top of the stripper and can be further compressed and transported to permanent storage. The $CO_2$-lean solvent is then recycled back to the absorber column through a cross heat exchanger [IPCC 2005].

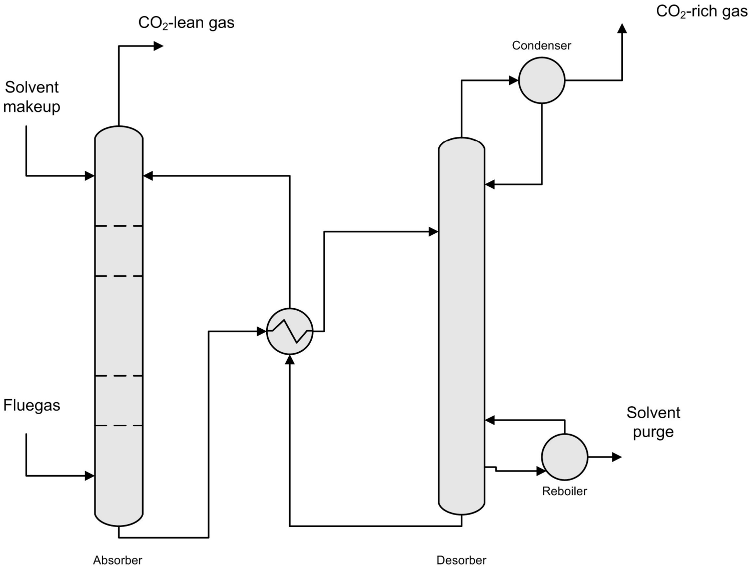

Figure 8. Schematic overview of solvent-based post-combustion carbon capture technology.

Heat integration has a significant role in integrating CCS to an iron and steel mill. Within this assessment, opportunities for the $CO_2$ capture process are based on matching the heat levels, heat sources and sinks. Heat can be recovered from steelmaking processes or generated in the boilers at the steel mill site. The heat can be utilised in electricity production and for solvent regeneration. Other utility consumptions of heat, the demand for district heat and the utilisation of process steam on-site are considered to be equal in all modelled cases. The available heat streams were divided into four categories for facilitating heat integration according to temperature and level of exergy to enable rational optimisation of utilities.

The amine capture process was modelled using a standard 30% MEA solvent. The standard capture process consists of an absorber unit and a stripper unit, pumps and heat exchangers. The process was modelled with an equilibrium model in the Aspen Plus® process simulation software. It was recognised that rate-based simulation models are known to be superior to equilibrium-state models for MEA modelling [Zhang et al., 2010, Taylor et al. 2003]. However, a simpler equilibrium model was considered to be sufficiently accurate for the accuracy needed at this level of concept analysis, where the capture process is only one component of many.

The standard MEA solvent can to some extent be considered outdated and not the best performing state-of-the-art solvent for new $CO_2$ removal processes. Because of this, two other capture processes were conceptually evaluated to reflect likely future improvements in solvent scrubbing technologies and their implications for carbon capture processes with steel mill integration. Nevertheless, MEA solvent-based processes are the most evaluated and best known processes, providing a baseline reference to compare results with other studies. However, these alternative solvent options more effectively reflect the solvent options available to a steel mill in the future. These evaluations are based partly on current operational conditions and partly on hypothetic assumptions.

The evaluation of the first of the two alternative solvents is based on public information available on the Siemens amino acid salt $CO_2$ capture technology (referred to as "advanced" later on in the text). This technology was chosen in the Fortum FINNCAP project, targeting the demonstration of $CO_2$ capture at Meri-Pori condensing power plant [Fortum 2009]. The most significant benefit with this solvent in comparison to MEA solvents is the low regeneration energy requirements of 2.7MJ/kg $CO_2$ [Fortum 2010].

The second evaluation with an alternative solvent is based on an imaginary solvent (referred to as "low-T" later on in the text), which is able to be regenerated at a significantly lower temperature than baseline MEA. This is assumed to be the result of solvent development work in the future. Having a lower regeneration temperature, even at the expense of relatively high regeneration energy, could open up new opportunities for $CO_2$ capture implementation, especially in the process industry, where low-temperature waste heat streams are readily available. The regeneration is set to occur at 70 °C, which enables a significantly larger share of the waste heat streams to be utilised for solvent regeneration and thus increases the amount of $CO_2$ that can be captured. In theory, it could be possible to develop these kinds of solvents [Zhang et al. 2010] if the advantages achieved with low temperature regeneration would compensate for other disadvantages. The regeneration energy of 3.0 MJ/kg $CO_2$ was assumed based on Zhang et al. [2010].

## 4.5 Application of oxygen blast furnace with flue gas recycling and CCS to an iron and steel mill

An oxygen blast furnace (OBF) is a blast furnace fired with pure oxygen instead of oxygen-enriched air. The schematic picture of application of OBF at a process unit level is presented in Figure 9. In principle, the process resembles a conventional blast furnace process but a part of the top gas is recycled back to the furnace to reuse the carbon in top gas as a reducing agent. This is called flue gas recycling (FGR). Because of this, the top gas of the blast furnace contains very little nitrogen. The $CO_2$ of the top gas is separated and the hydrogen and carbon monoxide is recycled back to the blast furnace to act as reductant and improve the energy balance. The separated $CO_2$ is purified, compressed and sent to a permanent storage via ship transportation.

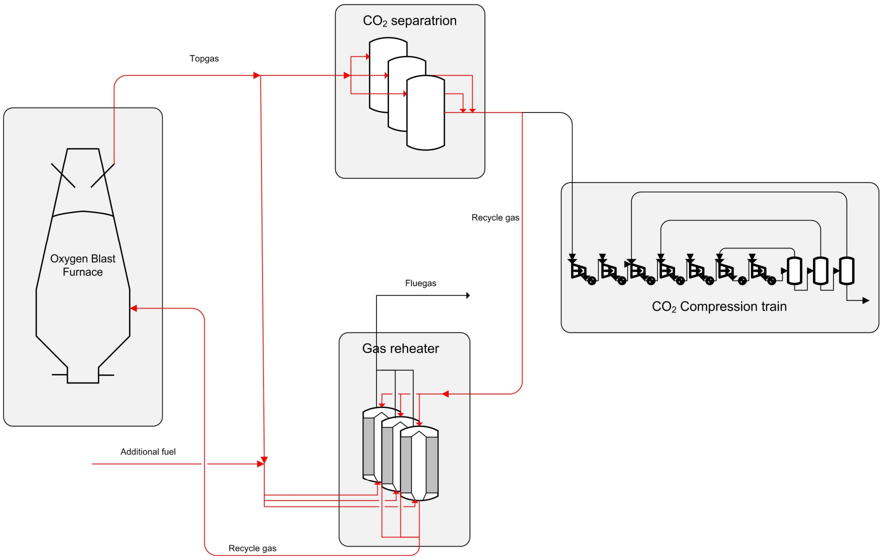

Figure 9. Schematic process configuration of application of oxygen blast furnace with top gas recycling and CCS to an iron and steel mill.

The technical evaluation is based on detailed Aspen Plus® modelling of the processes involved, such as the air separation unit, $CO_2$ separation unit as well as the compression and purification of $CO_2$. The oxygen blast furnace is modelled in this assessment as a black box. The information about input and output streams is based on experimental data provided by Ruukki. Vacuum pressure swing adsorption (VPSA) was the chosen $CO_2$ separation technology in this study. The VPSA process was chosen, as it was expected that the amount of excess steam required by MEA capture is not available on-site when removing the power production block. Oxygen for the OBF is produced by an air separation unit (ASU). The ASU utilises conventional cryogenic technology for oxygen production. Similar ASUs are currently operating on the existing site to produce oxygen, for instance, for oxygen enrichment in the conventional blast furnaces. The amount of mixed gas combusted in the preheater is estimated to be equal to the amount of mixed gas used in the power plant in the reference case in order to minimise changes in gas utilisation in the steel mill.

The most significant difference in comparison to the post-combustion capture reference case is the injection of coal (pulverised coal injection, PCI) into the blast furnace instead of extra heavy fuel oil that is assumed in the OBF base case. The differences in the reference cases have an impact on some results, but the impact is estimated to be minor when compared with overall uncertainties related to the impacts of OBF. However, the utilisation of PCI changes the composition of top gases from blast furnaces (including OBF), reduces steam consumption due to avoided oil heating, and requires inert gas for the injection of pulverised coal.

## 4.6 Technical scenario descriptions

The assessment involves several different process configurations, technologies and capture rates. These are briefly described below. More detailed information on the deployment scenarios can be found in the appended articles. Based on the approach and values presented in the previous section, the energy balance and $CO_2$ emissions could be calculated for the steel mill with three technology deployment scenarios related to post-combustion capture and three scenarios related to OBF, resulting in different $CO_2$ emissions and economics. Three different solvent solutions were varied in post-combustion capture scenarios 2 and 3.

| **Post-combustion capture (PCC) scenarios**: | |
|---|---|
| PCC 1: reference | This is the baseline scenario, with no carbon capture process in place. The plant operates according to business as usual, and the power and heat are produced at a normal rate. |
| PCC 2: Turbine back pressure operation | The size of the carbon capture installation is designed for utilising the steam available from the steam turbine in back pressure operation. This enables the capture of $CO_2$ and heat production for covering the heat demand for both the steel mill and the district heating network. In addition, some electricity generation is possible with the high pressure steam. The sizing of the capture plant is based on the amount of steam going to the low pressure section of the turbine in the baseline scenario. |
| PCC 3: No electricity production | The carbon capture plant is sized for a case where all available thermal power is utilised for the regeneration of the solvent. Only the steam and heat demands of the steel mill are satisfied and all other heat is utilised for regeneration of the solvent. In this scenario there is no on-site electricity generation. |

| **Oxygen blast furnace (OBF) scenarios:** | |
|---|---|
| OBF 1: Reference | This is the baseline scenario, with no carbon capture process in place. The plant operates according to business as usual, and the power and heat are produced based on average demand. The difference to PCC 1 is that PCI is used instead of heavy oil. |
| OBF 2: Application of oxygen blast furnace | The conventional blast furnaces are replaced with oxygen blast furnaces dimensioned to maintain the current production levels of the plant. The coking plant remains as it is in the reference case. $CO_2$ is separated from the recycled gas stream only for the operational requirements of the OBF, but there is no compression and transportation to permanent storage. There is no electricity generation on-site. |
| OBF 3: Application of oxygen blast furnace with CCS | $CO_2$ removed from the top gas stream in Scenario 2 is purified, compressed and transported to permanent storage to mitigate climate change. |

# 5. Modelling of the economic feasibility of $CO_2$ capture in the iron and steel industry

In the literature, break-even prices (BeP) and costs per avoided $CO_2$ emissions are the most common indicators used for the economic feasibility of CCS. In this study, BeP is used as one of the main indicators and it is defined as the required average price of $CO_2$ emission allowances in the EU emissions trading scheme (EU ETS) during the considered time frame to make the studied $CO_2$ emissions reduction option as feasible as the reference case.

## 5.1 AACE economic assessment classifications

The economic evaluations of investment profitability can be made for different purposes in different phases of the investment process. The assessment levels can vary from the simplest concept assessments to detailed engineering and execution design. The simplest evaluations are intended to provide an order of magnitude of understanding of the proposed investment. These are generally considered at a very early phase of an investment decision or even before actually considering investment simply for the screening of possibilities. The background information for decision making is constantly evolving to become more and more accurate as more information on the investment is gained through the design process and engineering work based on decision-making. In addition, the budget and the workload of the economic evaluation significantly increase in order to get more accurate estimations. One traditional classification of the accuracy of economic evaluation and assessment of investment costs is the AACE classification of assessments [AACE 2011, Towler et al. 2013]. AACE, the Association for the Advancement of Cost Estimating International (AACE International), is the professional association representing the cost engineering profession in the United States. The classification of economic assessment levels is presented in Table 1 and the increase in accuracy of estimations throughout the evolvement of an investment project is illustrated in Figure 10.

Table 1. Economic estimation accuracy classification [AACE 2011].

| **AACE Class** | **MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition | **END USAGE** Typical purpose of estimate | **METHODOLOGY** Typical estimating method | **EXPECTED ACCURACY RANGE** Typical variation, low and high ranges |
|---|---|---|---|---|
| **5** | 0% to 2% | Concept screening | Capacity factored, parametric models, judgment, or analogy | L: -20% to -50%<br>H: +30% to +100% |
| **4** | 1% to 15% | Study or feasibility | Equipment factored or parametric models | L: -15% to -30%<br>H: +20% to +50% |
| **3** | 10% to 40% | Budget authorisation or control | Semi-detailed unit costs with assembly level line items | L: -10% to -20%<br>H: +10% to +30% |
| **2** | 30% to 75% | Control or bid/tender | Detailed unit cost with forced detailed take-off | L: -5% to -15%<br>H: +5% to +20% |
| **1** | 65% to 100% | Check estimate or bid/tender | Detailed unit cost with detailed take-off | L: -3% to -10%<br>H: +3% to +15% |

A go/no go decision on investigating the investment opportunities further can in some cases be based on extremely simple evaluations of the feasibility of a concept, such as raw material price vs. product price estimations. More accurate evaluations might not be needed, for example if the product or raw material market price fluctuations are so high that the accurate estimation of investment costs becomes irrelevant as a negligible factor for decision-making.

The accuracy of investment estimations improves during the lifespan of an investment project (Figure 10). At the beginning of the development of a plant or other investment, rough Class 5 concept screening evaluations and “back of hand” calculations are performed to screen potential investments. As plans get more accurate and engineering proceeds, it is possible to make more accurate cost estimates. The most detailed estimations require detailed plant engineering to be completed and the estimations based on actual tender quotes from subcontractors and equipment providers. In addition, the role of contingencies and technical uncertainties with first-of-a-kind and non-commercially available plants add significant inaccuracy to cost estimations [Merrow et al. 1979]. In this context contingency is understood as a potential negative economic event which may occur in the future due to e.g. difficulties in implementation of new technologies.

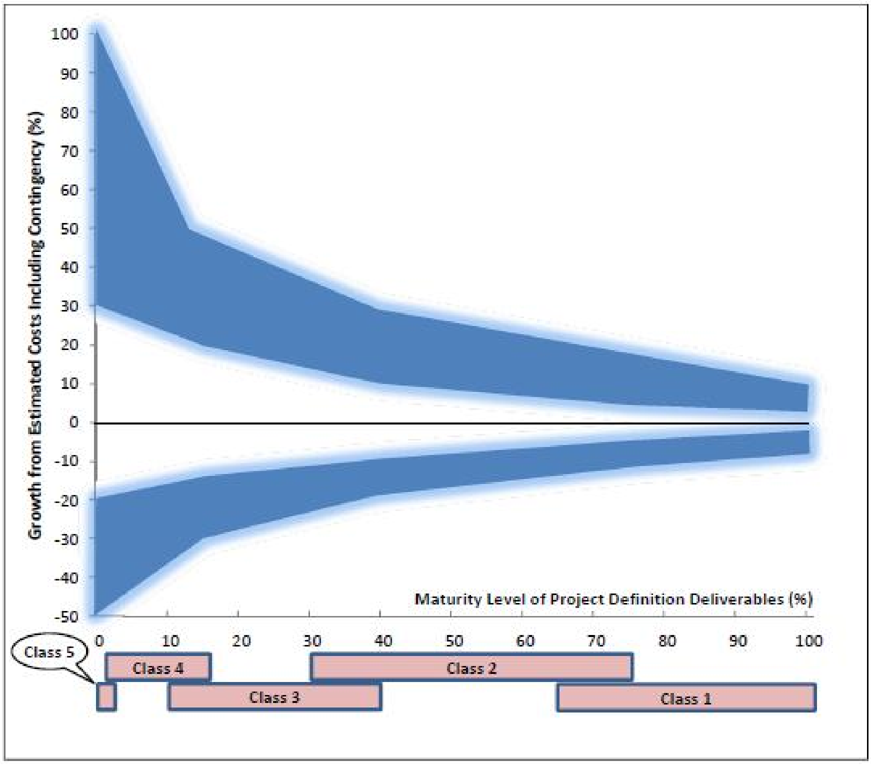

Figure 10. Example of variety of project cost estimates for the process industry [AACE 2011].

## 5.2 Principles of economic assessment of investments

The most common methods in assessing profitability of investments are net present value (NPV) and internal rate of return (IRR). These methods are also used by energy producers and the process industry, combined with various kinds of sensitivity assessments.

For the very same reason that interest rates are in use, the equal amount of payments in the future is considered less valuable than the payment taking place in the immediate future. With NPV, also known as the annuity method, the series of future payments can be made comparable. The future payments are multiplied by a discounting factor, to get their comparable net present value. If the net present value of all payments related to an investment is positive, the investment is profitable. If values of several investments are positive, the most valuable is the one with largest net present value [Brealey et al. 2003].

Engineering design projects are conducted for two primary purposes: a) to generate the actual design to enable the construction and installation of equipment, and b) to provide information for decision-making about the profitability of an investment. These estimations are made on different levels, and the estimations get more extensive and the accuracy improves as the project advances. However, the basic principles of the evaluation of investment profitability are the same. The evaluations can be based on different key figures, of which cash flow analysis and net present value (NPV) are considered here as typical approaches [Peters et al. 1968, 2002, Sinnott et al. 2009].

The net present value (NPV) of a project is the sum of the present values of the future cash flows:

$$NPV = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n} \tag{10}$$

Where

$CF_n$ = cash flow in year n

t = project life in years

i = interest rate

Cash flow for each year can be determined based on annual costs, revenues and resulting profit. For process engineering, the types of investment costs can be divided into capital costs, fixed operational costs and variable operational costs. Interest rate is considered to reflect cost of money, i.e. interest you have to pay for a loan. Discount rate however is the rate used when adjusting for the "time value of money" used in discounted cash flow analysis that can also include including also a risk or an uncertainty factor of future cash flows. Based on cash flows and net present value, a monetary value can be set for the changes between cases.

Capital investment projects in e.g. process engineering are divided into two parts, inside the battery limits (ISBL) and outside the battery limits (OSBL). ISBL constitutes the process units and the focus of the project. It can be a plant built from scratch or part of a renewal of an existing plant. OSBL is all connections that are needed to make the ISBL operational, meaning utilities, feed and product streams, etc. Fixed capital investment consists of ISBL investment, which is the cost of the plant itself, modification costs to OSBL, engineering and construction costs and contingencies. Variable costs of production are costs proportional to the plant output or operation rate, such as raw materials, fuels and utility consumables. Fixed operational costs are costs that are only incurred if production takes place, but the amount is not proportional to the amount of production. These can be costs such as labour, maintenance or taxes.

## 5.3 Boundary discussion on economics

The boundaries used for the economical evaluations are the same as those defined in the technical assessment and based on similar justifications as in Section 4.3. An example of boundaries utilised for economic assessment are presented in Figure 6. As boundaries in the technical concept assessment, following the principle of consequential assessment, the presented boundaries can be used and unchanged processes, costs and emissions can be excluded from the assessments. Capturing $CO_2$ from the flue gases from the power plant and the blast furnace hot stoves using a post-combustion capture method, or application of an oxygen blast furnace with flue gas recycle, has no effect on the core ironmaking processes outside the boundaries described. The system boundary for the LCA study is broader, because this also includes the impacts of studied cases on GHG emissions from transportation and storage as well as the production of the electricity purchased by the steel mill, for instance. These life cycle emissions are taken into account when the costs of avoided $CO_2$ emissions are estimated.

The boundary definition is multi-dimensional, as unchanged labour costs, facilities and equipment, for example, are excluded from the study even if employees currently work with the processes inside the drawn system boundary. Obviously, required additional labour expenditures due to the application of CCS are included in the study.

## 5.4 Capital cost estimation and investment cost scale-up

Investment and equipment costs can be estimated quickly based on existing knowledge or published data on the investment costs of certain equipment and on a scale that information is suitable for the purpose at hand. This requires no detailed design of process equipment and gives a reasonable investment cost estimate [Green and Perry 2008].

$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n \tag{11}$$

Where

$C_2$ = capital cost of plant or process unit with the capacity of $S_2$

$C_1$ = capital cost of plant or process unit with the capacity of $S_1$

n = scale-up exponent

Scale-up exponents are factors typically ranging from 0.6 to 0.9, depending on the type of process. These factors are published in several engineering publications including Green and Perry [2008] and Towler et al. [2013] for different types of raw materials, processes and plants.

## 5.5 Economic assessment and application of CCS in an iron and steel mill

The objective of the economic assessment was to evaluate the economic feasibility of the proposed technology investment. The approach in this work corresponds to AACE class 5 estimation accuracy in

Table 1. This was done based on two calculated parameters indicating the economic performance of applying CCS to the steel mill site. The first parameter, the break-even price (BeP) of $CO_2$, describes the feasibility of these technologies as a GHG emission mitigation tool. The second parameter, the effect of the investment on the production cost of steel, describes the feasibility of the investment from the steel manufacturing point of view. When applying CCS to an iron and steel mill, the capital expenditures (CAPEX) are higher than in the reference case. With increasing EU ETS emission allowance prices, the operational expenditures (OPEX) are rising faster in the reference case than in the CCS cases. BeP is defined as the break-even price of $CO_2$ emission allowances in the EU ETS (EUA) where CCS turns profitable over the reference case, making a CCS investment feasible. This means that the BeP is the emission allowance price that would make the annual costs of reference case equal to the CCS application case. In other words, it states what the average EU ETS allowance price should be over the investment period in order to make the investment profitable. The effect of the investment on the production cost of steel is similarly based on the cash flow analysis. In the reference case, the EU ETS allowance price brings a definable additional cost factor to steel production price that is proportional to the amount of allowances that need to be purchased. In CCS cases, the need for purchasing allowances diminishes, but larger investment costs and additional OPEX due to additional processes raise the production costs.

The difference between terms $CO_2$ captured or reduced and $CO_2$ avoided is that $CO_2$ captured does not include the impact to emissions outside system boundary. $CO_2$ captured refers to the amount of $CO_2$ that is captured and stored. $CO_2$ reduced refers to the direct impact that CCS has on reducing $CO_2$ emissions compared to not using CCS, i.e. the impact the site operator sees in relation to emissions trading scheme. $CO_2$ avoided refers to the impact that the actions have on a system level or global perspective, taking into account indirect emissions e.g. due to changes in the energy production and consumption. Direct emissions refer only to emissions emitted to the atmosphere directly from the site, whereas indirect emission reductions also take into account changes in the operational environment outside system boundaries.

In order to estimate costs and GHG emission balances throughout the overall CCS chain, a Microsoft Excel-based system model called CC-Skynet™ was used. The model has been developed at VTT Technical Research Centre of Finland since 2005 to simulate the economics of power plant operations in different operational situations. Between 2008 and 2011, the model was further developed in a project called CCS Finland to also cover investments and operation of CCS for power plants and the steel industry [VTT 2014].

Economic indicators for the various technology scenarios described in Section 4.6 were assessed in different application cases. The economic assessment is based on the assumption that the steel production of the mill in the different cases studied is constant. Electricity net purchase or sale over the system boundary is allowed from or to a national grid. The most important parameters, in terms of economic feasibility of CCS, are the prices for EUA and electricity. These two parameters were varied in the study and the most important results are presented with different prices.

Because there are only a few steel industry-based CCS approaches studied in the literature, especially based on PCC, the overall CCS investment assumptions are based on the relatively vast literature data on PCC in the power sector.

## 5.6 Break-even prices of EUAs and the impact of CCS on steel production costs

Two different indicators for the economic implications of CCS on the steel mill are calculated:

a) the break-even price (BeP) for $CO_2$, to represent the impact of technology on an actor in the EU ETS carbon allowance markets, and
b) the impact to the production cost of steel to represent the impact of technology to competition in global steel markets.

The break-even price of $CO_2$ for each scenario and case is calculated based on the annual costs and the annual emission reduction from the plant operator point of view. The costs are also estimated for the emissions avoided. That is based on the change in annual costs and the annual emissions avoided from society's point of view.

$$BEP = \frac{\Delta cost}{\Delta emissions} \tag{12}$$

where

$\Delta$cost = change in annual costs in comparison to reference case

$\Delta$emissions = change in annual emissions in comparison to reference case

The impacts of these factors on the production costs of steel are calculated based on the equation

$$P_{Steel} = \frac{Capex_{CCS} + OtherOPEX_{CCS}}{SteelProd} + P0_{Steel} + E_{CCS} \times P0_{Electricity} + P_{CO2} \times (correlation \times E_{total} + CO2_{total}) \tag{13}$$

where

$Capex_{CCS}$ = the annual capital expenditures due to required CCS investments [M€/a]
$OtherOPEX_{CCS}$ = the impact of CCS on operational expenditures other than electricity and $CO_2$ costs, such as LPG consumption and coke selling (described in previous sections) [M€/a]
SteelProd = the annual steel production [Mt/a as crude steel]
$P0_{Steel}$ = the reference steel price, i.e. the steel production cost without the costs related to $CO_2$ emissions [€/t]
$E_{CCS}$ = the additional electricity consumption due to CCS [MWh/t crude steel]
$P0_{Electricity}$ = the electricity price without the impact of $CO_2$ prices [€/MWh]
$P_{CO2}$ = the price of $CO_2$ emissions for steel mill (e.g. in the EU ETS) [€/t $CO_2$]
Correlation = the electricity price dependency on $CO_2$ price i.e. the penetration of $CO_2$ price to electricity market price [t $CO_2$/MWh]]
$E_{total}$ = the overall electricity consumption of the steel mill in each case [MWh/t crude steel]
$CO2_{total}$ = the overall $CO_2$ emissions from steel production in each case [t $CO_2$/t crude steel]

## 5.7 Cost assessment of the PCC and OBF steel mill cases

Different cases are utilised to reflect different operation situations and configurations of different technology scenarios. For the emissions balance and economic evaluations, each case is compared to the reference case. Post-combustion carbon capture cases are compared to the PCC base case and OBF cases accordingly to an OBF reference case. The difference between these reference cases was explained in Section 4.5. In general, the overall economics of CCS is strongly dependent on the energy penalty due to CCS and its implications for electricity balance over an evaluation boundary. The net electricity production of the economic system boundary is “sold” to the rest of the steel mill using the given market price for electricity, since any change in power production at the steel mill impacts on the steel mill's need to purchase electricity from the market. The entire steel mill is a net electricity consumer in any case but in cases 4 and 5, where no electricity is produced, the considered economic system is also a net electricity consumer. In addition, the amount of available district heat from the economic system boundary changes from case to case.

District heat is utilised in the premises of the mill and in the city nearby. However, there is an upper limit given for the amount of heat that is possible to sell from the system due to the limited heat consumption of the relatively small city to which the district heat network is connected. Heat supply is restricted to this limit in all of the cases with the exception of case 1 with “Low-T” solvent. The amount of combusted gases is equal in all the cases, because it is not dependent on the (post-combustion) $CO_2$ capture process or any other case variable. Therefore, the $CO_2$ formation from combustion is also equal in all the cases. The PCC processes considered with three different solvents for $CO_2$ capture and two scenarios for the heat production for solvent regeneration presented are used as a basis for the case studies. In the studied steel mill there are several options for different heat integrations available, leading to different energy penalties and economics for CCS. The most economical solution is dependent on the solvent considered, investments required for heat recovery, and future prices for electricity and EUAs, for example, which are all uncertain. Therefore, three additional cases comparing heat production options were studied for each solvent. The modelled cases included increased heat recovery from the steel mill processes suitable for solvent regeneration, resulting in higher $CO_2$ capture capacities. Only the recovery options resulting in water or steam streams at temperatures of over 130 °C were considered. The investigated OBF cases represent different technology application scenarios, as no options as in PCC cases for different heat integration options are relevant with the technologies considered.

The investigated cases are described in

Table 2, following Papers II and IV. An example of the CC-Skynet™ tool applied to the PCC cases is available at: http://www.vtt.fi/proj/ccsfinland/ccsfinland_sovelluskohdetarkastelut.jsp?lang=en.

Table 2. Case description of economic evaluation.

| Case number | Case description |
|---|---|
| PCC case 0 | The reference case without CCS, to which the CCS cases are compared. Some developments to the existing steel mill described in Section 4.4 are already implemented. |
| PCC case 1 | Small-scale CCS application, where the capacity of the $CO_2$ capture plant is determined by the regeneration heat available for the solvent using the process heat recovered from steel mill processes by additional investments. Intermediate steam from a turbine is neither used for solvent regeneration nor for district heating, because additional heat (in comparison to the reference case) is recovered for district heating using the waste heat from the capture and compression units. Therefore, power production increases and electricity production is higher than in the reference case. However, the compression stage increases plant electricity consumption and electricity output from the economic system boundary is less than in the reference case. |
| PCC case 2 | The capacity of the $CO_2$ capture plant is determined by the heat consumption of the solvent regeneration, which is set to be equal to the amount of heat in the intermediate steam available from the turbine. Therefore, condensing power is not produced. There are no investments in heat recovery in this case. |
| PCC case 3 | A combination of the previous two cases. The capacity of the $CO_2$ capture plant is determined by its heat consumption, which is set to be equal to the sum of the heat streams of cases 1 and 2. |
| PCC case 4 | The capacity of the capture plant is determined by its heat consumption, which is set to be equal to the whole steam production of the boiler. Therefore, there is no power production. Depending on the energy required for the regeneration of solvent considered, the amount of heat may be sufficient to capture all $CO_2$ emissions within the economic system boundary. There are no investments in heat recovery in this case. |
| PCC case 5 | The capacity of the capture plant is determined by its heat consumption, which is set to be equal to the sum of the heat streams of cases 1 and 4. |
| OBF case 0 | OBF reference case |
| OBF case 1 | Application of OBF without CCS |
| OBF case 2 | Application of OBF with CCS |

The economic assessment is based on a 10% interest rate and a 20-year economic lifetime of investments. Coke price is set to €300/t, the cost of electricity purchase without the impact of costs of $CO_2$ allowances is set at €60/MWh and the cost of natural gas at €40/MWh. A complete list of numbers utilised in the assessment can be found in the appended papers.

# 6. Results

## 6.1 Direct mass and energy balance implications of deployment of CCS

Technical process configurations for applying post-combustion carbon capture and oxygen blast furnace with CCS to an iron and steel mill were developed (Paper I and III). Based on the conceptual design, no major technical restrictions for applying CCS to an iron and steel mill were found. The developed technical concepts were presented in Sections 4.4 and 4.5. As a result, it is clear that it is technically feasible to capture $CO_2$ from an iron and steel mill with post-combustion solvent capture and carbon capture in connection to OBF. Both of the technological solutions of applying CCS have significant implications for the energy balance of a steel mill. The solvent regeneration requires significant amounts of heat and electricity production rates are changing due to alternative use of gases. With conventional MEA solvent, the amount of steam required to capture entire $CO_2$ emissions from two selected point sources exceeds the amount of maximum steam production without any excess fuelling in comparison to the base case. With advanced solvents the situation can be improved significantly.

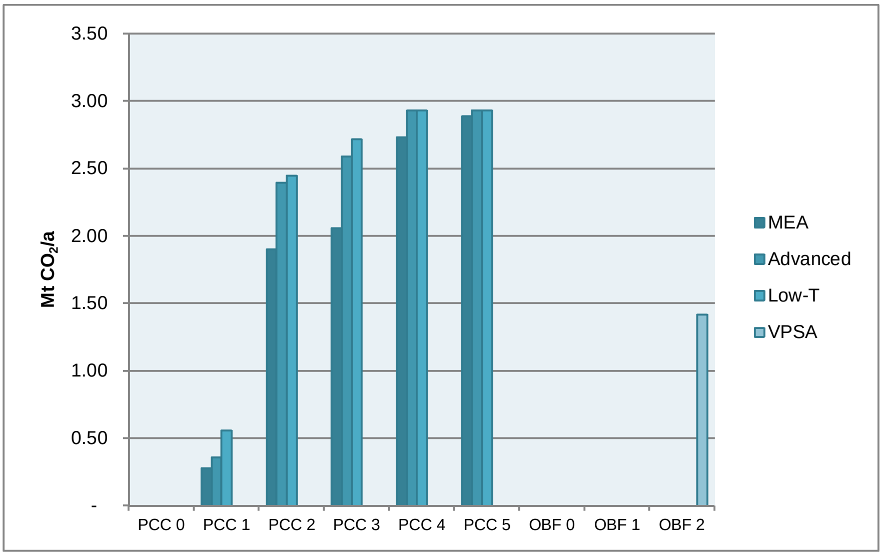

Figure 11. The captured $CO_2$ amounts in different technology scenarios with different technical solutions.

The captured $CO_2$ amounts are presented in Figure 11. The average $CO_2$ emissions during years 2008–2013 from Raahe steel works has been at the level of 4 Mt $CO_2$/a, depending on the annual production levels [Energiavirasto 2014]. The largest $CO_2$ capture amounts considered (2.9 Mt $CO_2$/a) were in the cases where all available fuel power was used for regenerating the solvent. With only low pressure steam used for solvent regeneration, the captured amounts were in the range of 1.9–2.4 Mt $CO_2$/a.

In addition to the steam consumption in solvent regeneration, power is also consumed in the capture and conditioning process. The total power consumption of CCS processes was estimated to be 0.41 MJ/kg$CO_2$ captured. This comprises of pumps, compressors and other auxiliaries. Most of this electricity is consumed in the $CO_2$ compression. The implications of the $CO_2$ capture on the electricity production of the steel mill site are presented in Figure 12. District heat sold outside the boundary was constant in every case, 300 GWh/a, which is based on the district heat demand in the nearby city.

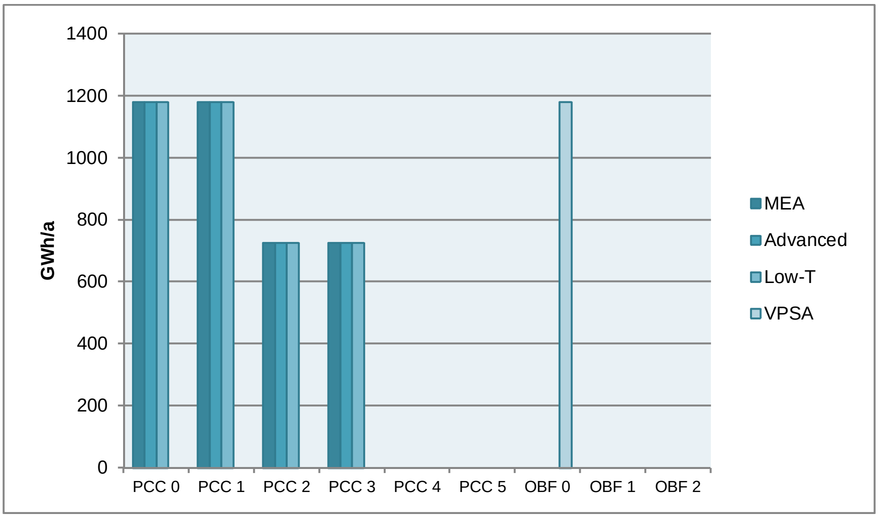

Figure 12. The amount of electricity produced on-site.

When in the post-combustion capture cases the amount of captured $CO_2$ grows, the capacity for electricity production at the power plant becomes smaller, as the steam is utilised for the regeneration of the solvent instead of being utilised in the low pressure section of the steam turbine (Figure 12). Smaller electricity production results in a need for purchasing more electricity outside system boundaries. In the reference case the annual electricity production is around 1200 GWh/a. When low pressure steam is utilised for solvent regeneration, the electricity production decreases by 40% to 730 GWh/a. When all fuel power is utilised to produce steam for regeneration, no electricity is produced on-site and this would lead to a need to purchase additional power to cover the needs of the mill site. The largest additional electricity consuming process steps related to solvent technologies are $CO_2$ purification and $CO_2$ compression. With the application of OBF, the recycling of part of the top gas will replace the gas boiler, assuming gases other than top gas previously utilised in the boiler are now used in recycled top gas reheating. The largest new energy consumers with the oxygen blast furnace with carbon capture and storage are oxygen production, $CO_2$ separation, $CO_2$ purification and $CO_2$ compression. However, some savings can be made with blowers pressurising the blast. The net change in electricity balance within the system boundary is presented in Figure 13.

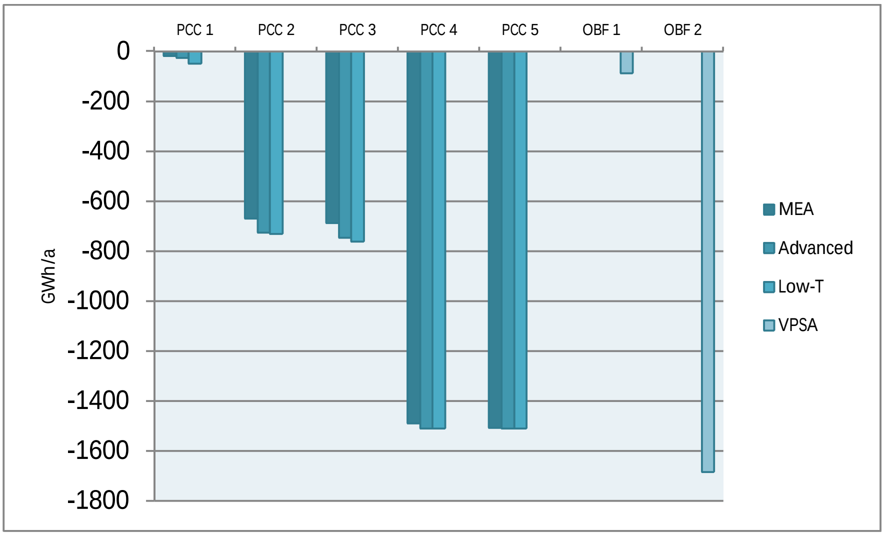

Figure 13. Changes in electricity balance within system boundary in comparison to base case.

One significant additional change between PCC scenarios and OBF scenarios is that when applying OBF (scenarios OBF 2 and 3) the coke consumption of the process decreases from 287 kg/t pig iron to 192 kg/t pig iron. OBF cases use 4.4 GJ less coke, 4.5 GJ more coal and 0.4 GJ more LPG per ton pig iron in comparison to PCC cases. This is partly due to different assumption for PCI and partly due to intensified carbon use due to top gas recirculation. LPG demand increases due to need for additional heating of hot blast in OBC cases. Change in electricity consumption within system boundary is presented in Figure 14. This is mainly due to additional compressors and blowers, e.g. equipment related to $CO_2$ separation and conditioning as no significant electricity consuming equipment are removed in any of the cases.

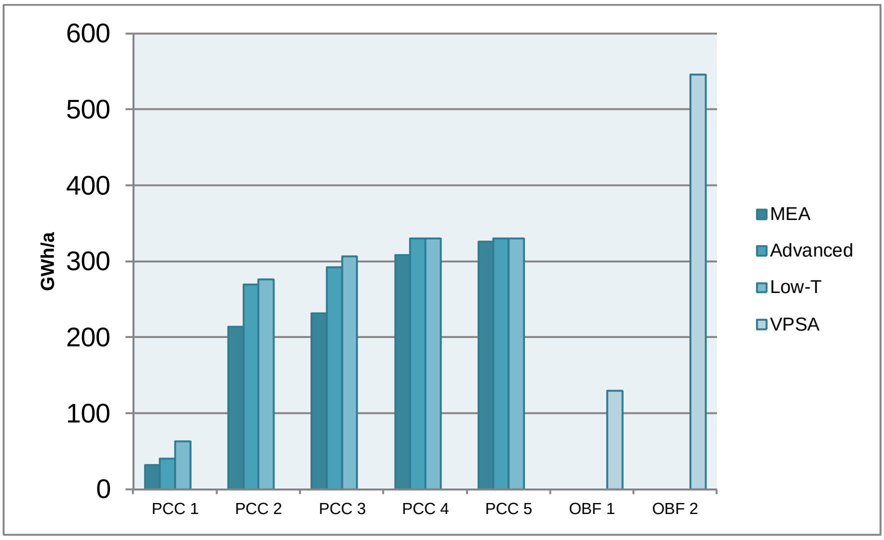

Figure 14. Changes in electricity consumption within system boundary.

## 6.2 Plant and system-level implications of deployment of CCS

Using the parameters and assumptions described earlier and modelling the energy balances impacts on the GHG emissions were calculated for the studied cases. The approach allowed for the investigation of different amounts of $CO_2$ captured. The smallest amounts captured (0.3 Mt/a) were in the cases where only recovered heat was used for the capture processes and the largest amounts (2.9 Mt/a) in the cases where all available fuel power was used for regenerating the solvent. From a global perspective the emission reductions are different from the ones that the investor or the site owner experiences in the EU emission trading scheme, for example.

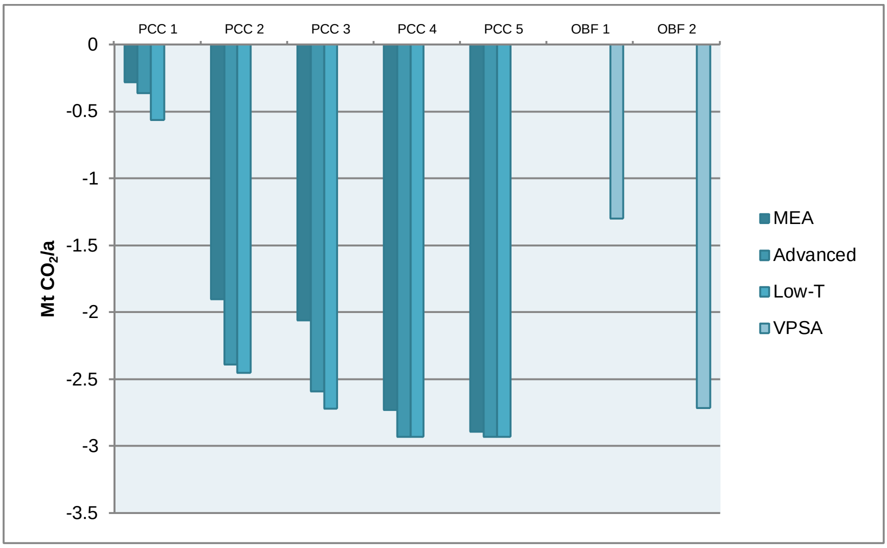

Figure 15. Impact on the site's direct $CO_2$ emissions in different cases.

The implications of direct $CO_2$ emissions from the site are presented in Figure 15. In cases PCC 1 to OBF 2 the direct site emissions are reduced by 0.28–2.93 Mt $CO_2$/a. In the OBF 1 case, the direct $CO_2$ emissions from the system are reduced from 3.2 Mt $CO_2$/a in PCC 0 to 1.96 Mt $CO_2$/a by only applying the oxygen blast furnace (i.e. no transportation or storage of $CO_2$). This is mainly due to the reduced coke consumption in the blast furnace. This is a significant reduction, considering that the production of the mill stays the same as in the reference case. With the application of CCS to the OBF system the emissions can be further reduced to 0.55Mt $CO_2$/a. The major emission source in base case scenarios PCC 0 and OBF 0 are the blast furnace gas utilised in the power plant and in the hot stoves. This only concerns a site's direct emissions and not emissions due to the replacement of electricity production outside system boundaries, for example. In other words, it represents the impact an actor or a site owner will see in relation to the EU ETS. The share of a site's direct emission reductions of total site emissions is presented in Figure 16, assuming the average $CO_2$ emissions from Raahe steel works at the level of 4 Mt $CO_2$/a [Energiavirasto 2014]. The lowest impact can be as little as 7% of the total emissions in PCC case 1, whereas all other CCS cases would reduce site direct emissions in the range of 48–73%. Applying an oxygen blast furnace without CCS would already reduce emissions by 32% in comparison to current operation.

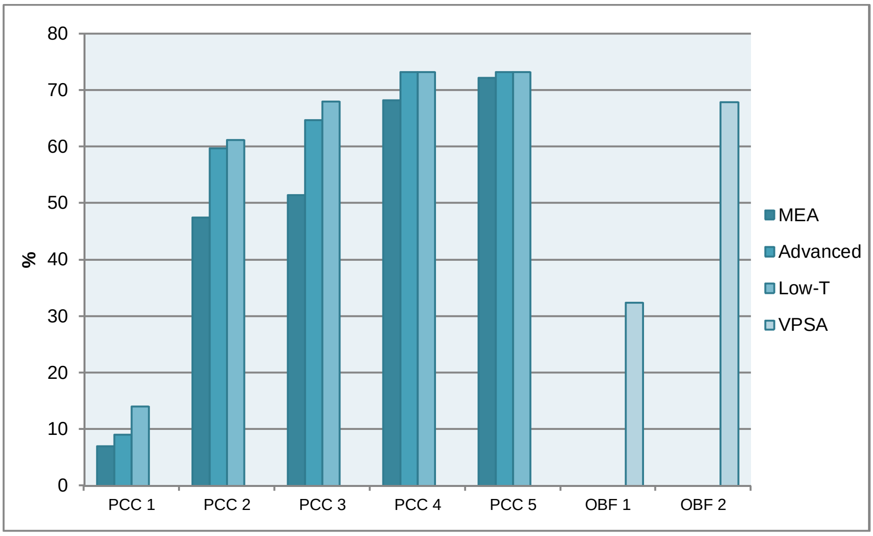

Figure 16. Share of a site’s direct emission reductions in comparison to the site emissions in of the base cases (in percentages).

The net GHG emissions avoided by deployment of technologies in different cases are presented in Figure 17. The impacts are assessed based on the assumption that the replacing energy production is coal (1000 t $CO_2/GWh_e$). As can be seen from the figure, the amount of GHG emissions avoided is much smaller than the site’s direct emission reduction. In the worst cases, the GHG emissions avoided might be only 9% of the site’s direct emission reductions as in OBF case 1. Most of the reductions fall in the 45–62% range of the site’s emission reductions, but in PCC case 1, the GHG impact reductions are between 82–93% of the direct emission reductions. This is due to the different nature of the case and also the relatively small reduction amounts have to be noted. Assumptions regarding replacing electricity production are the single biggest factor affecting the net GHG impact of application of these technologies. The relatively small GHG emission reduction in OBF 1 case is due to the fact, that in this case no $CO_2$ transportation and storage takes place, only application of oxygen blast furnace and top gas recirculation that improves the overall carbon efficiency of the process.

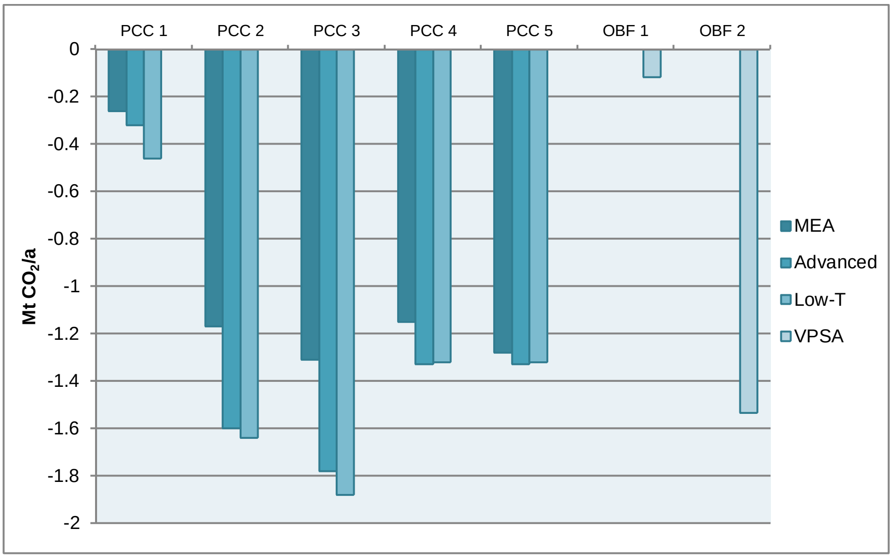

Figure 17. The GHG emissions avoided in different cases.

The economic impact of changes is strongly dependent on the prices of commodities, such as electricity and LPG. Prices should include all related variable costs, for example in the case of electricity, taxes and transmission fees should be included but not fixed costs, such as constant monthly charges, if these are not changed from one case to another. As the feasibility of OBF processes is very sensitive to prices of $CO_2$ allowances, electricity, LPG and coke, and a relatively long time frame (large uncertainty) is considered, the results are presented as graphs in the appended papers in order to get a good overall understanding of their complexity. However, for the sake of simplicity, single value-based snapshots are presented here in order to highlight some of the results. Some default values for the used prices are presented in this section but the values for other important variables are presented in conjunction with figures in the appended papers.

The cost of emission reductions is estimated from the site owner's perspective. Most of the costs fall between €40–70/t $CO_2$, OBF being slightly cheaper than post-combustion carbon capture with the €60/MWh electricity price, €60/MWh LPG price and €300/t coke price (Figure 18). However these price assumptions affect the results a lot, especially for the OBF cases as OBF as a $CO_2$ capture solution is much more sensitive to the price of electricity than that of solvent scrubbing.

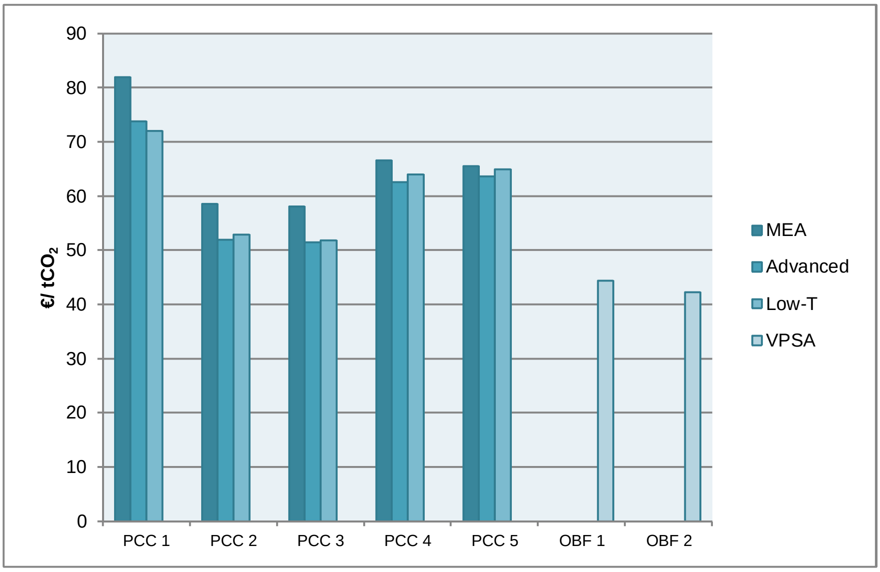

Figure 18. $CO_2$ BeP (electricity €60/MWh, LPG €60/MWh).

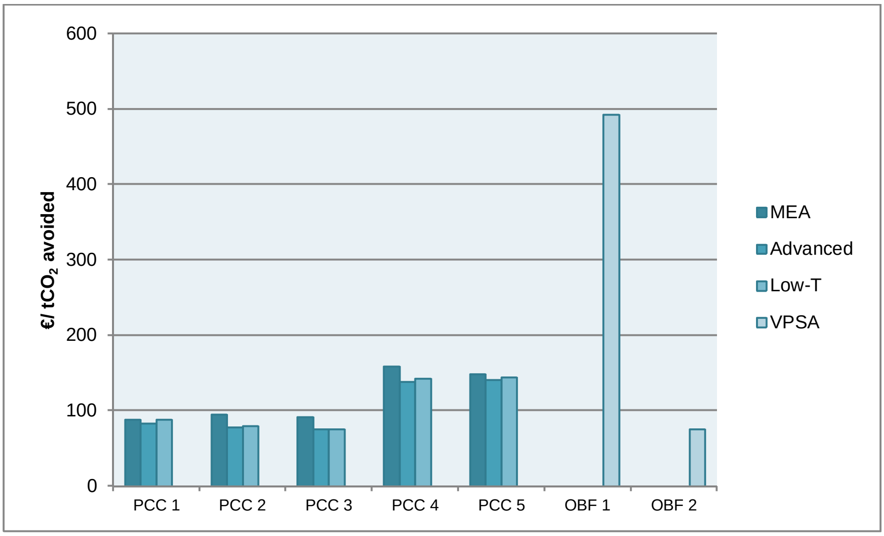

Figure 19. Cost of $CO_2$ avoided.

The magnitude of costs for avoided $CO_2$ emissions is illustrated in Figure 19. As this is not intended to be a full LCA study, this is only to highlight the differences between the prices relative to ETS and the prices in relation to e.g. reducing national or global emissions.

From an economic point of view, technical modelling shows that the most important impact of the various $CO_2$ emission reduction methods modelled are:

- increased LPG (or LNG) consumption
- decreased coke consumption (increased coke selling)
- increased electricity purchase
- decreased $CO_2$ emissions
- captured (transported and stored) $CO_2$.

Electricity purchase is increased due to both decreased production and increased consumption. Significant new consumption points, especially with regard to OBF are for example the new air separation unit (ASU) and the $CO_2$ processing unit (CPU).

Other significantly changing cost categories are:

- additional investment for OBF (including new ASU, CPU, etc.)
- Operation & management (O&M) costs of the new processes

Feedstock is a major cost in steel mills but only the difference in coke consumption impacts significantly on the economics of the cases. The default price used for selling of surplus coke is set at €300/t. Other impacted O&M costs are mainly fixed costs (labour, etc.). The additional annual fixed O&M costs are assumed to be 4% of the additional CAPEX.

Examples of cost categories that are not changed significantly due to the various $CO_2$ emission reduction measures and are therefore modelled roughly (or excluded from the system boundary) are:

- district heat selling
- O&M costs of the existing processes
- other labour costs
- feedstock to other processes
- production and selling.

At Raahe mill, district heat is produced by recovering heat from processes but during the peak demands also by steam bleed from the power plant. Heat is utilised by the buildings and service water in the mill area and by selling heat to the City of Raahe. There is potential to increase the amount of heat recovery in the mill but the annual heat demand of the city is limiting the feasibility of the required investments.

It is assumed that the O&M costs of the existing processes, other labour costs and feedstock to other processes are not changed due to OBF. This is based on the fundamental assumption that the production and sale of steel products are not changed.

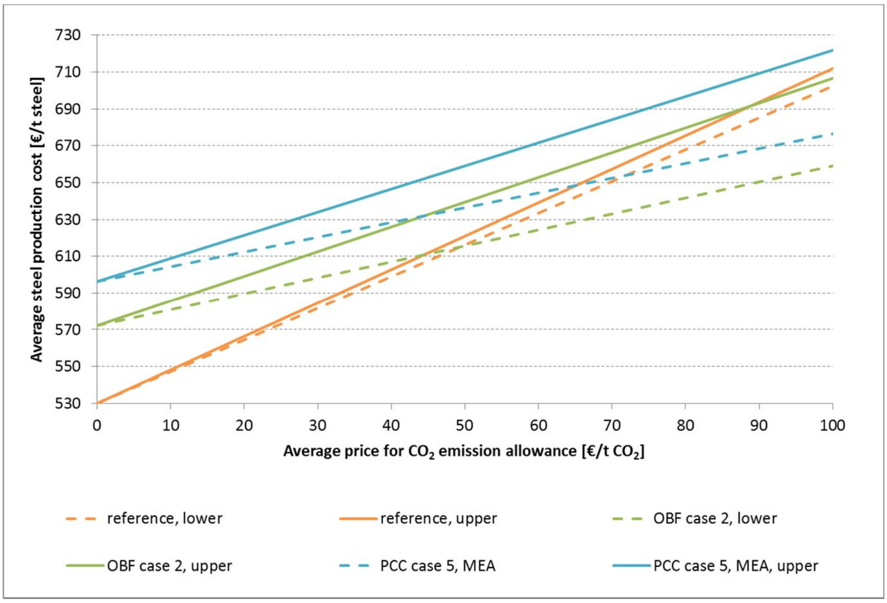

Figure 20. Effect of carbon prices on steel production costs with two different correlations assumed for $CO_2$ and electricity prices.

From the point of view of the steel mill, the production cost of steel may be the most important indicator of the feasibility of different future $CO_2$ emission reduction options. In Figure 20 the impact of different cases on the cost of steel production is presented as a function of $CO_2$ allowance prices and different impacts of the increasing $CO_2$ price on electricity price. In the upper $CO_2$ price correlation with electricity the $CO_2$ price fully penetrated to electricity market prices, assuming coal condensing power production as a marginal production. In the lower correlation half of the $CO_2$ price penetrates to electricity market price. Cases OBF 2 and PCC 5 are compared because they have a similar effect on the site's direct $CO_2$ emissions as "full capture" cases. Steel price without the costs of $CO_2$ allowances is set at €530/t based on general market prices during 2013 [Worldsteelprices 2013]. The cost of electricity purchase without the impact of costs of $CO_2$ allowances is set at €60/MWh.

As presented in Figure 20, production costs in the reference case reach production costs with OBF case 2 at a $CO_2$ price of about €50/t if a lower correlation between $CO_2$ price and electricity price is used. If a higher correlation is used, a significant difference in electricity purchase leads to a higher BeP for $CO_2$, about €90/t. The difference between OBF and PCC as solutions is due to their different electricity consumptions and effects on the plant's electricity balance. If PCC cases with remaining electricity production on-site had been compared, they would have looked better than OBF or full capture PCC.

# 7. Discussion

## 7.1 Technical concept

An integrated steel mill is a very complicated process. The application of an OBF would require a larger modification of the processes of the existing steel mill than the application of post-combustion capture would require. However, large process modifications also enable several different solutions for how to apply the OBF. In theory, concept optimisation is possible, taking into account hundreds of details and depending on prices and investments. In this study, only one technological solution for the application of an OBF was modelled and one approach presented. With the application of OBF, the recycling of part of the top gas will replace the gas boiler, with other gases than top gas previously utilised in the boiler now used in recycled top gas reheating. This would possibly enable significant improvements for the process, both economically and from the GHG perspective. If for example recycled top gas could be injected into the blast furnace at a lower temperature, the heating requirements would be reduced, and therefore the use of supplementary LPG would be minimised. However, this would most probably have an effect on the energy balance of the blast furnace, and therefore also on coke, coal and oxygen feeds. The overall impact of these improvements would, however, have to be investigated and proven experimentally. As also stated in this work, staged investment and construction could be possible – to invest first in an OBF process without CCS and if $CO_2$ prices increase further, complete the investment with CCS when feasible.

There seems to be significant opportunities for developing low temperature solvents, especially in industrial applications. Even with the assumptions considered within this work, the low temperature solvent was found to be the best $CO_2$ capture option, even though it required more regeneration energy than the advanced solvent. This is due to the higher ability to utilise low exergy heat that is widely available on-site and cannot be utilised to a large extent with other solvents considered. Significant measures are likely to be available for low temperature heat recovery that has not been mapped in the industry due to a lack of reasonable use for it. Therefore, in industrial applications, such as the steel mills in this case, where a large amount of low quality heat is available, the utilisation of a solvent that can be regenerated at low temperatures would possibly offset a number of other possible drawbacks with the specific solvent, such as a higher nominal regeneration energy, higher circulation rates or faster degradation.

In certain applications, such as in industrial processes and combined heat and power plants, significant improvements can be achieved with heat integration, for instance, for the production of district heat. The feasibility could also be optimised by using new operational options that CCS offers. For instance, $CO_2$ capture could be bypassed during periods of peak electricity prices. The optimal solution from the mill owner's point of view depends on multiple factors with electricity price and $CO_2$ price being the dominant ones. For the moment, it is often seen that the payback time for planned heat recovery investments is too long to be attractive as an investment not directly improving the core process itself.

## 7.2 Changes in and impact on the operational environment

As presented in the results of this study, BePs (break-even prices) are very sensitive to several factors which are uncertain regarding the time frame of large investments. Therefore, results are presented as figures rather than single numbers and the range of possible BePs is large. This is discussed and presented in more detail in the appended papers. There are very different estimations available for the investments required for CCS processes. Therefore, sensitivity analyses are also presented for the investments, as CCS processes are generally highly capital-intensive processes. Depending on assumed investments and used market prices for fuels, electricity and $CO_2$ emission allowances, any of the considered technology options may result in lower steel production costs in the future. There are several sources of uncertainty and ambiguous questions in the approach, technical modelling and economical assessments. For example, even if uncertainties of approach and technical modelling are not taken into account, by changing only a few economic parameters the results may look very different. What also needs to be taken into account is the interdependency of some of the parameters, e.g. carbon and electricity prices as discussed previously. Some of the sensitivities come under closer investigation in the appended papers, but parameters with a major impact on the results are discussed here as well.

At the moment, transportation and storage of $CO_2$ would be a significant cost factor for any CCS application in Finland as there is no suitable storage capacity in geologic formations in Finland [Teir et al. 2011]. In this study, the focus was on $CO_2$ capture and its impact to the steel mill process. Therefore only one price assumption method for transportation and storage was used. This value is highly uncertain and the results are very sensitive to this assumption. The uncertainty of transportation and storage costs is emphasised due to the potential to decrease the costs significantly. Transportation and storage costs in this study are in the range of €22-26/t $CO_2$, depending on the amount of $CO_2$ transported and stored, representing 28–55% of the BeP costs per t $CO_2$. For example, the storage potential in the bedrock of the Baltic Sea and the potential to utilise mineral carbonation is under research in Finland. There is a theoretical regional capacity to store 16 Gt

$CO_2$ in the sandstone formations under the South Eastern parts of the Baltic Sea [Nilsson 2014]. If significant development were to take place with these opportunities or with $CO_2$ utilisation options in Finland, the economics of the presented CCS cases would be much more favourable.

As has been stated several times in this paper, the final result of the cost estimation is driven by the relationship between $CO_2$ emission prices and electricity prices. High $CO_2$ prices increase the electricity prices, making CCS less profitable because the value gained from the carbon allowances must exceed the value of the electricity production lost in the capture process in order to make CCS feasible. Blast furnace investments are made for 20 to 30 years and the prospects of future prices for e.g. $CO_2$ emission allowances, electricity, LPG/LNG and coke are extremely uncertain. Carbon allowances, or many other $CO_2$ policy measures, connect steel manufacturing to the electricity markets even more tightly than before. If carbon prices are not penetrating electricity market prices, the conclusions concerning the merit order of proposed solutions could change significantly. This would resemble a situation with a large amount of renewable and nuclear – in other words carbon-free – capacity penetrating the electricity markets. The carbon prices would have to be high to enable penetration, but the introduction of new capacity would keep electricity prices down. This highlights the multi-variable optimisation nature of the problem, and the importance of the relationship between carbon prices and the price of electricity. As mills have been producers and huge buyers of electricity they have been in connection with the electricity markets before. However, the “Mankala” principle of buying electricity has been loosening this connection and the influence of electricity market fluctuation. The “Mankala” principle in energy production means that companies utilising energy will together own a non-profit energy company, with the purpose of providing low cost energy for owners only selling it at cost to owners. However, this study brings up the aspect of the iron and steel industry being and becoming a more and more important player in the low carbon electricity markets and the aspect of raising the importance of these issues within the industry besides the direct impacts on their core business. The magnitude of impact of these factors on a single investment on-site will also strengthen this aspect.

The magnitude of influence of different electricity production alternatives and different technical and methodological (boundary setting) approaches have a huge effect on the results of these kinds of assessments. The profitability of power and heat production or lack of it can turn the investment from being highly profitable to one that is completely unprofitable. This is a major result in comparing this study with the IEA [2013] with different assumptions for boundary setting. In the IEA study, the power and heat production scaled to balance power demands, e.g. increasing natural gas consumption and on site power production, in a way that might not be designed based on engineering design starting from scratch. This is an assumption that eases the comparison with the base case, and avoids the discussion of what the replacement energy source should be, as discussed by Soimakallio et al. [2009]. However it might lead to industrially-irrelevant solutions that might not give a correct picture for the stakeholders at hand. Of course, by having both aspects covered as in this case, drawing the right conclusions from these aspects can be ensured. The difference between the studies is that where the IEA study is based on a greenfield site, this work considers brownfield application of CCS. This also justifies to some extent the differences in boundary setting assumptions.

Following on from the discussion of boundary setting and connection to the electricity market, these two issues result in uncertainty regarding drawing conclusions about the global GHG benefits. After all, the grand purpose of deploying these technologies is to mitigate climate change. Even if direct $CO_2$ emissions are decreased significantly due to OBF and CCS, direct $CO_2$ emissions due to increased electricity consumption are higher in OBF cases. From LCA basis, impacts on the electricity production and consequent emissions are the major factor in terms of $CO_2$ emissions. In addition, the impact of coke selling may result in significant substitution credits. LCA and broader system analysis are ambiguous and strongly dependent on selected system boundaries, timeframes, etc.

However, from one point of view, $CO_2$ emissions within the European Union Emission Trading Scheme (EU ETS) cannot be decreased by individual actions as the amount of allowances to be released during the ETS period is fixed. Therefore, the impacts on $CO_2$ emissions from other processes within the EU ETS are not reasonable to estimate and direct $CO_2$ emissions only have economic value, namely the price of the $CO_2$ emission allowance. This approach was applied in the present study. From a broader perspective, more focus should be placed on any impacts outside the EU ETS, where emission reductions can be considered more valuable, whether they were to take place in Europe in sectors excluded from the ETS or regions outside Europe. It needs also to be noted that even if the author describes BeP as the point where CCS turns to more profitable option instead of paying for carbon credits, both options add costs to steel production. In other words, even if CCS is the more profitable option, it does not mean that steel production on that site would be profitable. The result of this cost burden, i.e. moving industrial activity to areas with no additional costs, is often referred to as carbon leakage.

## 7.3 Level of detail of the study

Regarding the technical and economic assessment presented, the level of accuracy obtained with AACE class 5 level assessments is limited and the limitations of this work in that respect should be noted. The purpose of level 5 studies is concept screening and initial technology assessment. The level of engineering to enable more detailed mass and energy balance calculations and the economic assessment would require more time, effort and also the site to be specified more accurately. Most technologies considered are also not mature. While there are methods to estimate the cost of technology risk, for example in Merrow et al. [1979] or Peters et al [2002], and the higher costs of first-of-a-kind plants, the cost estimation of immature technologies always includes significant uncertainty. As explained in Section 5.1 the level of accuracy increases as engineering gets more and more detailed during the project towards final investment decision and finally completion of the project

# 8. Conclusion

## 8.1 Conclusions on the technical aspects

As a technical option, it is possible to significantly lower greenhouse gas emissions from the steel industry with CCS based on the technologies covered in this study. Most of the solutions are already technically realisable in the near future; however, OBF technology does not yet seem ready to be commercially fully applied in a steel mill as opposed to post-combustion capture technologies. Nevertheless, no large scale commercial application of any of the reduction technologies studied exists yet. This calls for a demonstration of technologies on a commercial scale. The larger post-combustion capture amounts studied (2–3 Mt $CO_2$/a) account for approximately 50–75% of the $CO_2$ emissions from the site. The largest capture amounts in the OBF scenarios (1.4Mt/a) account for 35% of the direct emissions from the whole steel mill site. In total, the direct emissions could be reduced by up to 68%. With both technical solutions, a further reduction of the emissions would be technically and economically very challenging, as the remaining emissions are smaller and from various different sources around the site.

When different solvent options are considered, the low temperature solvent was found to be the best $CO_2$ capture option, even though it had higher regeneration energy than the advanced solvent. This is due to its higher ability to utilise low exergy heat that is widely available on-site and cannot be utilised to a large extent with other solvents considered. In addition, not all measures for low temperature heat recovery were mapped at the site, so it is possible that even more $CO_2$ could be captured using the low temperature solvent than that which was found in these calculations.

The technical implication of applying CCS processes to an iron and steel mill is that the mill's own electricity production decreases and consumption increases in comparison with the reference case. In addition, the consumption of LPG or LNG increases in the OBF solutions. The OBF process also enables the sale of coke due to smaller coke consumption and further savings are achieved from reduced $CO_2$ emissions, even without the application of CCS.

## 8.2 Conclusions on the economic aspects

From a plant owner's perspective, the EUA BEP (European Union Emission Allowance Break-Even Price), i.e. when CCS turns more profitable in the most competitive studied case than buying carbon credits in the reference case, is in the range of €42–82/t $CO_2$, with the assumptions in this summary. The cost for globally avoided emissions is in the range of €74–158/t $CO_2$, respectively, if coal is used as the fuel to substitute the changed electricity consumption and only CCS cases are considered. This applies to the larger amounts of captured $CO_2$ studied (2–3 Mt $CO_2$/a) which account for 50–75% of the site emissions. If a larger amount of emissions were to be captured, the costs are estimated to rise significantly in comparison to only applying CCS to the largest emission sources on-site.

The results showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment, but also on the chosen system boundaries and assumptions. The assumed impacts on electricity production in the network strongly affect the amount of avoided $CO_2$ emissions in particular. In the long term, the impacts on the electricity production system is an ambiguous issue due to complex rebound effects on fuel, electricity and EUA prices and investment decisions, among other things. As presented earlier, the feasibility of CCS in the steel industry is very sensitive to the prices of $CO_2$, electricity and replacing fuels.

The cost levels obtained in this study are some 10–20% higher than those found in the literature taking into account the challenges in directly comparing cost results in literature described earlier in this work. However, the cost level in the literature generally follows a rising trend according to the publication year, which may be partly due to the rising prices of services and material. Another reason for the higher cost levels of the present study is the long distances to storage sites and the assumption of using an offshore storage site. Comparing the present results to those for the application of CCS in a coal-firing power plant in Finland [Teir et al. 2011] that used a similar approach (system boundaries, solvents, assumptions, etc.) as the present study, the BeP for the studied steel mill application is almost €20/t lower.

Large cost ranges for applying CCS to the iron and steel industry are also reported in the literature presented at the beginning of this paper. In addition, details of integrated steel mills are very much site-specific and system boundaries selected for the studies vary. Therefore, comparison of the studies is difficult. However, the results of this study seem to fit well in the typical ranges presented in the cited studies. Taking the relatively high costs of $CO_2$ transport and storage included in the estimations into account, the presented BePs can be considered even relatively low. However, the break-even prices presented in the figures of this paper are typically the most feasible cases of numerous considered options. Despite that, the presented cases may not be optimal, as several potential improvements were identified.

The EUA prices and electricity prices predicted for the near future do not make CCS investments profitable yet. Even if CCS were to become more feasible than operations without CCS in the steel industry with higher EUA prices, the production costs of steel would rise drastically in the EU Member States, unless free EUAs are given for the industry. Assuming an EUA price of €60/t (the lower end of the presented BePs), specific $CO_2$ emissions of 1.8 t/t steel and a market price of €500/t steel, the EUA cost increase would raise the price level of steel by about 22% even when not taking the likely increase in electricity price into account.

Figure 21 below has been drawn based on the cases presented in this paper, and with the default values of this study. EUA prices and the price of electricity are the single biggest parameters in determining the economic feasibility of the solutions investigated. As these are also the two most fluctuating parameters, a diagram with areas describing operational environment for the most feasible technology was created (Figure 21). PCC case 3 with advanced solvent was chosen for comparison with OBF because it was typically the most feasible option within the varied parameters in sensitivity analysis.

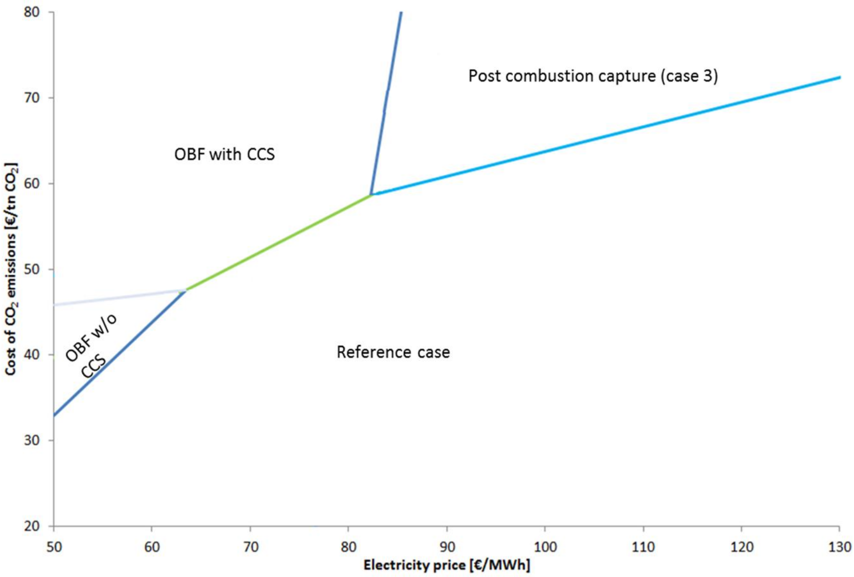

Figure 21. Feasibility map of different technologies.

This shows that any of the considered technologies may be the most feasible option in the future, depending on the price of electricity and the $CO_2$ allowance price. For example, even if the area for OBF without CCS is relatively small, the respective range for $CO_2$ price is more realistic in the near future than the prices where other considered technologies for large $CO_2$ emission reductions would be feasible. The figure does not show the consequential steel production costs, which would obviously increase if prices of electricity or $CO_2$ allowances were to significantly increase. Estimates for the increase in production costs were presented earlier in Figure 20. This leads to a situation that even if CCS investment were feasible, the steel manufacturing that is the core business would turn unprofitable.

## 8.3 Role of CCS the in iron and steel industry

There are other carbon abatement options for iron and steel production, although the $CO_2$ emission reductions that can be achieved are more limited than with the studied technologies. $CO_2$ emissions can be lowered by utilising bio char as a reducing agent, for example, and applying different energy saving measures, etc [Suopajärvi et al. 2014, Norgate et al. 2012]. The high level of integration typical in modern steel plants makes further energy-saving measures of any significant extent difficult. Large-scale bio char utilisation is restricted by constrained resources and sustainability questions [Suopajärvi et al. 2014, Norgate et al. 2012]. In addition, the suitability of bio-coke (coke produced from biomass) as a blast furnace raw material has not been proved, as several properties regarding compounds and strength are required. Generally, other $CO_2$ emission reduction options, such as electric arc furnaces or DRI processes exist, but these are only applicable for certain types of steel mills. While being important and cost-effective at best, these measures are generally of a smaller scale when compared to the order of millions of tonnes of $CO_2$ emission reductions that are possible with CCS.

Risk-taking regarding the blast furnace of an integrated steel mill is not easy, as it is the single most important and a very expensive component of the mill. Therefore, solutions involving CCS are in practice the only significant technological means of reducing the on-site emissions from virgin steel production in existing mills. It is important to note that increasing $CO_2$ prices will have a significant impact on steel production costs, whether CCS is applied or not. If these costs are increased only for some players in global markets, investment in OBF or CCS may not be feasible, even if it would be more profitable than the operation in the reference case.

We need to tackle issues related to climate change, and all sectors need to contribute. Carbon leakage is an essential question for developed countries as carbon abatement measures do not largely come without cost. This is an issue, especially for the manufacturing industry acting in global markets, as long as no global, wide participation is reached. However, there is evidence of the manufacturing industry moving back to developed countries, despite the stricter environmental rules. There are several reasons for this, but together with the involvement and technology-sharing with developing countries, there is potential for CCS in the iron and steel industry in medium to long term (2030 onwards).

## 8.4 Contribution of the work

In this work the methodology of consequential concept assessment was applied to an assessment of deployment of CCS technologies in an iron and steel mill. The process model of technical solutions was created and based on that an economic CC-Skynet tool was applied to assess the economic implications. Based on the assessment it can be concluded that significant $CO_2$ emission reductions can be obtained with these technologies at a site level. The optimal technological solution depends on the most influential parameters, prices of electricity and EUA. With future price levels of electricity and EUA, there is an operational window where each technology investment would be most feasible. The consequential approach is a practical option in the early phase technology assessment focusing on the essential factors and highlighting the internal relations of different solutions. Results are at least as credible as with the attributional approach. It minimises the impact of unessential decisions in the result that would have to be made (unlike in real investment decision) when expanding the system boundary.

The break-even price (BeP) of the EU emission allowance price and the impact on the production cost of steel, as the performance indicators used in this work, are the most important indicators for the operator taking the final investment decision. BeP reflects the impact on the actors exposed to EU ETS market prices and can be directly considered by the investor. The operator's point of view is a clear and unequivocal way of presenting results. From a society and climate point of view, the cost of emissions avoided is of most importance, and can be used as indicators in policy decision-making. Despite the fact that the essential underlying question and policy target is how to reduce global warming, the cost of emission avoided is subject to the expansion of system boundaries and is heavily dependent on assumptions regarding electricity generation, for example. It should also be acknowledged that in a cap-and-trade emissions reduction policy system, emissions will not be reduced below the cap set in the system. The merit order of emission mitigation actions will be determined by the cost aspect from the operator point of view rather than the cost of avoided emissions, if no additional policies are concerned. The impact of system-level externalities, e.g. the rising price of electricity, cannot generally be optimised within a single investment decision-making process with a single company actually taking the investment decision. At least two different aspects and motivations to operate should be clearly acknowledged and also stated when presenting the results.

## 8.5 Future work

In addition to the approach and technological solution modelled in this study, at least the following configurations could be reasonable to investigate:

- Different approaches to the deployment of technology, and their impact on the results should be investigated to improve the technical and economic feasibility of application of this technology on site

    - New or rebuilt power plant with alternative fuels
    - Alternative scenarios for a coking plant
    - Site-level optimisation of utilisation of surplus steam
- Several considerations for process improvements and differences in technology should be investigated to improve the process configurations and alternative implementation options of these technologies:
    - Application of CCS for other sub-processes
    - Oxygen enrichment in a power plant
    - Minimisation of $N_2$/air feed to OBF process
    - Optimisation of recirculation gas preheating
    - Replacement of only one BF by OBF
    - Potential of changing the recycle gas composition to be utilised for value added products
- Closer cost estimation based on more detailed engineering on all equipment enabling more accurate investment assessment to enable more accurate decision-making both in investing industrial companies and among policymaker and finally enabling decisions on demonstration and deployment of these technologies
- Detailed evaluation of the impacts of and on the electricity production system to understand the systemic nature and global impact of deployment
- According to results low temperature solvent development has significant potential, especially in energy intensive with significant amounts of waste heat and heat integration opportunities available.

ERRATA:

Paper III: the value for the largest captured $CO_2$ amounts in the conclusions chapter should be 1.8 Mt/a instead of 1.4 Mt/a.

Paper IV: The corrected written form of formula is

$P_{Steel} = \frac{Capex_{CCS}+OtherOPEX_{CCS}}{SteelProd} + P0_{Steel} + E_{CCS} \times P0_{Electricity} + P_{CO2} \times$

$(correlation \times E_{total} + CO2_{total})$ , instead of

$P_{Steel} =$

$$\frac{Capex_{CCS}+OtherOPEX_{CCS} + P0_{Steel}+E_{CCS}\times P0_{Electricity}+P_{CO2}\times(correlation\times E_{total}+CO2_{total})}{SteelProd}$$

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PCC case 0

## Cost assessment

| | Capex | |
|---|---|---|
| **Sum** | **0** | **k€/a** |
| intrest | 10 % | |
| lifetime | 26 | a |
| *Sum* | *0* | *k€* |
| CCS | 0 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 0 | k€ |

| | Opex | |
|---|---|---|
| **Sum** | **-9 445** | **k€/a** |
| electricity | -70 824 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 0 | k€/a |
| water | 0 | k€/a |
| Other CCS Opex | 0 | k€/a |
| CO2 transportation | 0 | k€/a |
| CO2 allowances | 74 879 | k€/a |

| | Total | |
|---|---|---|
| **Sum** | **-9 445** | **k€/a** |

| **Difference to base case (0)** | | |
|---|---|---|
| **Sum** | **0** | **k€/a** |
| Opex | 0 | k€/a |
| Capex | 0 | k€/a |
| **CO2 BeP** | **-** | **€/tn** |

## Streamlined LCA

| | | |
|---|---|---|
| Sum | 1.97 | Mt/a |
| Emissions from combustion (inside battery limits) | 3.26 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | -1.18 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0 | Mt/a |
| Emissions from MEA production | 0 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0 | Mt/a |

| Comparison to 0-case | | |
|---|---|---|
| **Sum** | **0.00** | **Mt/a** |
| Emissions from combustion (inside battery limits) | 0.00 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 0.00 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.00 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.00 | Mt/a |

- €/ton CO2 avoided

PCC case 1

## Cost assessment

| | Capex | |
|---|---|---|
| **Sum** | **8 419** | **k€/a** |
| intrest | 10 % | |
| lifetime | 26 | a |
| | | |
| *Sum* | *77 123* | *k€* |
| CCS | 54 123 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 23 000 | k€ |

| | Opex | |
|---|---|---|
| **Sum** | **370** | **k€/a** |
| electricity | -69 236 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 54 | k€/a |
| water | 77 | k€/a |
| Other CCS Opex | 1 542 | k€/a |
| CO2 transportation | 14 801 | k€/a |
| CO2 allowances | 66 632 | k€/a |

| | Total | |
|---|---|---|
| **Sum** | **8 789** | **k€/a** |

| | Difference to base case (0) | |
|---|---|---|
| **Sum** | **18 234** | **k€/a** |
| Opex | 9 815 | k€/a |
| Capex | 8 419 | k€/a |
| | | |
| **CO2 BeP** | **74** | **€/tn** |

## Streamlined LCA

| | | |
|---|---|---|
| Sum | 1.65 | Mt/a |
| Emissions from combustion (inside battery limits) | 2.90 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | -1.15 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0.01 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.00 | Mt/a |

| Comparison to 0-case | | |
|---|---|---|
| **Sum** | **-0.32** | **Mt/a** |
| Emissions from combustion (inside battery limits) | -0.36 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 0.03 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.01 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.00 | Mt/a |

82 €/ton CO2 avoided

PCC case 2

## Cost assessment

| | Capex | |
|---|---|---|
| **Sum** | **21 047** | **k€/a** |
| intrest | 10 % | |
| lifetime | 26 | a |
| | | |
| *Sum* | *192 807* | *k€* |
| CCS | 192 807 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 0 | k€ |

| | Opex | |
|---|---|---|
| **Sum** | **39 019** | **k€/a** |
| electricity | -27 373 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 359 | k€/a |
| water | 515 | k€/a |
| Other CCS Opex | 3 856 | k€/a |
| CO2 transportation | 55 343 | k€/a |
| CO2 allowances | 19 819 | k€/a |

| | Total | |
|---|---|---|
| **Sum** | **60 066** | **k€/a** |

| **Difference to base case (0)** | | |
|---|---|---|
| **Sum** | **69 510** | **k€/a** |
| Opex | 48 464 | k€/a |
| Capex | 21 047 | k€/a |
| | | |
| **CO2 BeP** | **52.0** | **€/tn** |

## Streamlined LCA

| | | |
|---|---|---|
| Sum | 0.36 | Mt/a |
| Emissions from combustion (inside battery limits) | 0.86 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | -0.46 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0.05 | Mt/a |
| Emissions from MEA production | 0.001623 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

| Comparison to 0-case | | |
|---|---|---|
| **Sum** | **-1.61** | **Mt/a** |
| Emissions from combustion (inside battery limits) | -2.39 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 0.72 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.05 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

77 €/ton CO2 avoided

PCC case 3

## Cost assessment

|  | Capex |  |
|---|---|---|
| **Sum** | **24 618** | **k€/a** |
| intrest | 10 % |  |
| lifetime | 26 | a |
|  |  |  |
| *Sum* | *225 524* | *k€* |
| CCS | 202 524 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 23 000 | k€ |

|  | Opex |  |
|---|---|---|
| **Sum** | **39 964** | **k€/a** |
| electricity | -26 033 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 389 | k€/a |
| water | 557 | k€/a |
| Other CCS Opex | 4 510 | k€/a |
| CO2 transportation | 58 777 | k€/a |
| CO2 allowances | 15 264 | k€/a |

|  | Total |  |
|---|---|---|
| **Sum** | **64 582** | **k€/a** |

| **Difference to base case (0)** |  |  |
|---|---|---|
| **Sum** | **74 027** | **k€/a** |
| Opex | 49 409 | k€/a |
| Capex | 24 618 | k€/a |
|  |  |  |
| **CO2 BeP** | **52** | **€/tn** |

## Streamlined LCA

|  |  |  |
|---|---|---|
| Sum | 0.19 | Mt/a |
| Emissions from combustion (inside battery limits) | 0.66 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | -0.43 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0.05 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

| Comparison to 0-case |  |  |
|---|---|---|
| **Sum** | **-1.78** | **Mt/a** |
| Emissions from combustion (inside battery limits) | -2.59 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 0.75 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.05 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

75 €/ton CO2 avoided

PCC case 4

## Cost assessment

| | Capex | |
|---|---|---|
| **Sum** | **23 062** | **k€/a** |
| intrest | 10 % | |
| lifetime | 26 | a |
| | | |
| *Sum* | *211 266* | *k€* |
| CCS | 211 266 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 0 | k€ |

| | Opex | |
|---|---|---|
| **Sum** | **83 657** | **k€/a** |
| electricity | 19 827 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 440 | k€/a |
| water | 630 | k€/a |
| Other CCS Opex | 4 225 | k€/a |
| CO2 transportation | 64 547 | k€/a |
| CO2 allowances | 7 488 | k€/a |

| | Total | |
|---|---|---|
| **Sum** | **106 718** | **k€/a** |

| | Difference to base case (0) | |
|---|---|---|
| **Sum** | **116 163** | **k€/a** |
| Opex | 93 101 | k€/a |
| Capex | 23 062 | k€/a |
| | | |
| **CO2 BeP** | **63** | **€/tn** |

## Streamlined LCA

| | | |
|---|---|---|
| Sum | 0.62 | Mt/a |
| Emissions from combustion (inside battery limits) | 0.33 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | 0.33 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0.06 | Mt/a |
| Emissions from MEA production | 0.001987 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

| Comparison to 0-case | | |
|---|---|---|
| **Sum** | **-1.35** | **Mt/a** |
| Emissions from combustion (inside battery limits) | -2.93 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 1.51 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.06 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |
| | 136 | €/ton CO2 avoided |

PCC case 5

## Cost assessment

|  | Capex |  |
|---|---|---|
| **Sum** | **25 572** | **k€/a** |
| intrest | 10 % |  |
| lifetime | 26 | a |
|  |  |  |
| *Sum* | *234 266* | *k€* |
| CCS | 211 266 | k€ |
| Changes in the turbine | 0 | k€ |
| heat connections | 23 000 | k€ |

|  | Opex |  |
|---|---|---|
| **Sum** | **84 117** | **k€/a** |
| electricity | 19 827 | k€/a |
| district heat | -13 500 | k€/a |
| MEA | 440 | k€/a |
| water | 630 | k€/a |
| Other CCS Opex | 4 685 | k€/a |
| CO2 transportation | 64 547 | k€/a |
| CO2 allowances | 7 488 | k€/a |

|  | Total |  |
|---|---|---|
| **Sum** | **109 689** | **k€/a** |

| **Difference to base case (0)** |  |  |
|---|---|---|
| **Sum** | **119 134** | **k€/a** |
| Opex | 93 561 | k€/a |
| Capex | 25 572 | k€/a |
|  |  |  |
| **CO2 BeP** | **64** | **€/tn** |

## Streamlined LCA

|  |  |  |
|---|---|---|
| Sum | 0.62 | Mt/a |
| Emissions from combustion (inside battery limits) | 0.33 | Mt/a |
| emissions from fuel production | 0 | Mt/a |
| Effect of replacing energy production | 0.33 | Mt/a |
| Effect of replacing district heat production | -0.10 | Mt/a |
| Emissions from CO2 transportation | 0.06 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |

| Comparison to 0-case |  |  |
|---|---|---|
| **Sum** | **-1.35** | **Mt/a** |
| Emissions from combustion (inside battery limits) | -2.93 | Mt/a |
| emissions from fuel production | 0.00 | Mt/a |
| Effect of replacing energy production | 1.51 | Mt/a |
| Effect of replacing district heat production | 0.00 | Mt/a |
| Emissions from CO2 transportation | 0.06 | Mt/a |
| Emissions from MEA production | 0.00 | Mt/a |
| Emissions from construction of infrastructure (CCS, LTO:t, etc.) | 0.01 | Mt/a |
|  |  |  |
|  | 138 | €/ton CO2 avoided |

OBF cases

| Economical balance (M€/a) | BF | OBF | BF-OBF | | BF-OBF w/o C | BF-OBF w/o C |
|---|---|---|---|---|---|---|
| CO2 allowances | 74 | 12 | 62 | M€/a | 45 | 30 |
| LPG demand | 0 | 19 | -19 | M€/a | 19 | -19 |
| Light fuel oil purchase | 0 | 0 | 0 | M€/a | 0 | 0 |
| Coke selling | 0 | -74 | 74 | M€/a | -74 | 74 |
| Electricity purchase | -66 | 30 | -96 | M€/a | 19 | -85 |
| Sold district heat | | | 0 | M€/a | 0 | 0 |
| CO2 transport & storage | | 38 | -38 | M€/a | 0 | 0 |
| Capture + ASU O&M | | 2 | -2 | M€/a | 1 | -1 |
| BF feedstocks (other than coke) | 647.9 | 648.4 | -0.4 | M€/a | 648 | -0.4 |
| Capex | | 40 | -40 | M€/a | 24 | -24 |
| | | | | | | |
| **Total** | **657** | **715** | **-58.2** | M€/a | **682** | **-25.1** |
| Break-even price for EUA | | **44.42** | €/ton CO2 | | **42.37** | |

| Prices + other variables | | |
|---|---|---|
| CO2 allowances | 23 | €/tn |
| LPG, €/MWh | 60 | €/MWh |
| Light fuel oil purchase, €/MWh | | €/MWh |
| Coke selling | 300 | €/tn |
| Electricity purchase | 60 | €/MWh |
| Sold district heat | | €/MWh |
| CO2 transport & storage | 27 | €/tn |
| Capture + ASU O&M | 4 | % CAPEX |
| Investment on OBF without CCS | 60 % | of the investments on OBF with CCS |
| Total investment, M€ | 370 | M€ over the reference case |
| Discount rate | 10 % | |
| Economic lifetime | 26 | a |

PAPER I

# Post-combustion capture of $CO_2$ at an integrated steel mill – Part I: Technical concept analysis

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# Post-combustion capture of $CO_2$ at an integrated steel mill – Part I: Technical concept analysis

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ABSTRACT

In this study different possibilities for applying post-combustion capture at an integrated steel mill in order to reduce carbon dioxide emissions were studied. Implications of different amounts of $CO_2$ captured, different solvents for post-combustion capture and different heat supply options for solvent regeneration to the energy balance and greenhouse gas emissions of the steel mill are compared to that of the base case for the steel mill.

The case study is based on Ruukki Metals Ltd.'s Raahe steel mill that is situated on the coast of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. It is also the largest $CO_2$ point source in Finland emitting approximately 4 Mt/year.

Carbon capture processes were modelled using Aspen Plus process modelling software and results were used to estimate the potential for reducing $CO_2$ emissions at an integrated steel mill from a plant operator's point of view. Different heat integration options and heat utilization scenarios were investigated. The heat available for solvent regeneration varied between these heat utilization scenarios and thus partial capture of $CO_2$ was investigated with the $CO_2$ amount captured depending on the heat available for solvent regeneration in the different case studies.

The results of the study show a significant $CO_2$ reduction potential using CCS. Approximately 50–75% of the emissions from the site could be captured using post-combustion capture. Capturing a larger amount of emissions would be technically less feasible due to the large number of small stacks around the large, integrated steel mill site.

## 1. Introduction

It has been generally acknowledged that climate change is one of the most serious environmental threats that humankind is facing and that greenhouse gas emissions (GHG's) should be reduced in every field of activities. The iron and steel industry is responsible for about 10% of worldwide $CO_2$ emissions from fossil fuel use (IEA, 2008), which corresponds to about 5% of the overall global GHG emissions. $CO_2$ emissions from iron and steel industry originate mainly from the two most common steel making processes: the Blast Furnace and Basic Oxygen Furnace-based route (BF + BOF route) and the Electric Arc Furnace route (EAF route). Together these processes are responsible for about 99% of the global crude steel production (Worldsteel, 2010). The EAF route results in significantly smaller $CO_2$ emissions per ton of steel produced than the BF + BOF route, but the EAF route is often based on recycled steel and has a smaller unit size. In the previous decade, the growth in global steel production resulted mostly from the growth in production by the BF + BOF route (Worldsteel, 2010). In addition, direct reduction iron production processes (DRI) are already used commercially, but their portion of the global iron production is still minimal.

Because the BF + BOF route utilizes the iron oxide found in iron ore, a powerful reducing agent is needed in the blast furnace. A typical reducing agent is coke, which eventually results in relatively high $CO_2$ emissions (due to subsequent combustion of blast furnace gas). In addition, the production of coke results in coke oven gas and eventually in $CO_2$ emissions. Numerous improvements in the complicated BF + BOF-based steel mills are possible, but the reductions in $CO_2$ emissions are typically small in comparison to the overall $CO_2$ emissions from the mills. By Carbon Capture and Storage (CCS), $CO_2$ emissions could be reduced to a large extent. CCS is generally recognized as one of the key climate change mitigation option and the technology can be utilized in the steel industry as well. Due to large unit sizes, relatively high $CO_2$ concentrations, current utilization of pure oxygen and recoverable heat, CCS may become economically feasible in steel mills considering the likely future costs for $CO_2$, for example in the EU Emission Trading Scheme (EU ETS). In principle, each of the three main CCS technologies, namely

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post-combustion, pre-combustion and oxyfuel can be utilized in steel mills. Economically feasible options for reducing $CO_2$ emissions are of high interest to European steel producers because of the additional costs due to the EU ETS. While the market for power is typically national or regional, the market for steel is global. The additional production costs due to emission trading can therefore not be transferred to the product price in order for steel to stay competitive in the global market. Therefore, the additional costs due to CCS are even more challenging for the steel industry.

Ruukki Metal Oy's Raahe steel mill is situated on the cost of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. It is also the largest $CO_2$ point source in Finland. In 2008, before the economic down term and blast furnace revisions, the $CO_2$ emissions from the mill were 4.5 Mt/year (EMV, 2011). Replacing sinters by pellets from 2011 onwards reduced the direct $CO_2$ emissions from the site by 0.4 Mt/a.

In this study, different possibilities for reducing carbon dioxide emissions at an integrated steel mill by applying post-combustion capture (PCC) for were studied, using the Raahe steel mill as a base case. Technical implications of different post-combustion capture methods and different amounts of $CO_2$ captured as well as energy balances are presented in this paper. Based on the technical solutions described in this paper, the economics of the solutions and their net effect on the greenhouse gas emissions are assessed in the second part of the study (Tsupari et al., 2012).

## 2. Methods

### 2.1. General

The $CO_2$ capture processes and the steelmaking processes were modelled using Aspen Plus modelling software and the results were used to estimate the $CO_2$ emission reduction potential using PCC technologies at an integrated steel mill. Only the parts of the steelmaking processes affected by the $CO_2$ capture were modelled with Aspen Plus. Different $CO_2$ capture amounts were investigated with the amount captured depending on solvent properties and heat available for solvent regeneration using two different heat production solutions.

### 2.2. Boundaries of evaluation

The system boundaries that were set for the present technical evaluation are presented in Fig. 1. These boundaries were selected, since capturing $CO_2$ from the flue gas streams from the power plant and blast furnace hot stoves using post-combustion capture methods has no effect on the core iron making processes outside the boundaries. Raahe steel mill produces also district heat for use in the city nearby as well as for use onsite for the heating of premises. The power plant is connected to the national electricity grid, and thus it is possible to balance the changes in electricity demand on the site using the national grid.

The $CO_2$ from Raahe steel mill is emitted from tens of stacks spread around the site. Since two of these emission sources cover more than 70% of the total site emissions, the decision was to cover only these two largest point sources, which are the hot stoves and the power plant. In addition to being the largest $CO_2$ emissions sources, they are located close to each other, which is a benefit allowing for various technical solutions.

### 2.3. Description of the steel mill reference case

The study is based partly on the current operational conditions and partly on a hypothetical situation at the Raahe steel mill. The sintering plant was closed 2011, which affected the gas streams around the plant. The study investigates a situation where the current power plant at the site is renewed and converter gases are collected and utilized in the power plant. In addition, heat recovery from the steelmaking processes is improved and production of process steam at the power plant is thus decreased. In this study, the hot stoves use only blast furnace gas as fuel. The power plant uses mixture of gases, comprising of blast furnace gas, coke oven gas and converter gas. The mass flows and gas compositions are presented in Table 1. The gases originate from fossil fuels, mostly coal and heavy fuel oil.

**Table 1**
Fuel gas streams and compositions [v%] (based on measured data from the actual site).

| | Blast furnace gas to the power plant | Blast furnace gas to hot stoves | Converter gas to the power plant | Coke oven gas to the power plant |
|---|---|---|---|---|
| Mass flow (kg/s) | 104.1 | 49.3 | 0.8 | 6.1 |
| $CH_4$ (v%) | 0 | 0 | 0 | 23.1 |
| $C_2H_4$ v%) | 0 | 0 | 0 | 2 |
| $C_2H_6$ (v%) | 0 | 0 | 0 | 0.7 |
| CO (v%) | 23.1 | 23.1 | 69 | 5.1 |
| $CO_2$ (v%) | 22.1 | 22.1 | 16 | 0 |
| $H_2$ (v%) | 5.3 | 5.3 | 0 | 57.9 |
| $N_2$ (v%) | 45.1 | 45.1 | 15 | 6.9 |
| $O_2$ (v%) | 0.2 | 0.2 | 0 | 0 |
| $H_2S$ (ppm) | 26 | 26 | – | – |
| $SO_2$ (ppm) | 1 | 1 | – | – |
| $SO_3$ (ppb) | 36 | 36 | – | – |
| $H_2O$ (v%) | 4.3 | 4.3 | 0 | 4.3 |
| Heating value (MJ/kg) | 2.6 | 2.6 | 6.4 | 38.4 |

One of the two existing boilers is replaced with a new one in conjunction with the hypothetical power plant renewal. After the renewal, both existing boilers feed steam to a new turbine. The old, 32 $MW_{fuel}$ boiler uses blast furnace gas as fuel and the new boiler, with a capacity of 252 $MW_{fuel}$, utilizes a mixture of the gases presented earlier. The power plant renewal enables designing the steam turbine island with $CO_2$ capture in mind. Therefore, the steam turbine is designed for wide set of operation conditions. The low pressure section of the turbine can be disconnected with a clutch, in order to avoid damages when the low pressure section is running empty. The use of a generic turbine model in Aspen Plus enables the use of the same model for all the cases investigated, representing different design situations for the turbine. In addition to the steam produced from the boilers, additional steam produced at the coke oven is also directed to the turbine. The steam turbine design is presented in Fig. 2. Bleed 1 of the steam turbine is used to produce process steam for the steel mill, while steam taken from bleed 2 is used in the carbon capture process and for the production of district heat.

### 2.4. Description of the post-combustion capture cases

The parts of the steel mill under investigation and the boundaries for the evaluation are described in Fig. 1. The cases with $CO_2$ capture are compared to the base case without the capture. The production of steel, the utility steam consumption and the district heating demand are assumed to stay constant even when applying $CO_2$ capture. The amount of electricity bought from or sold to the electricity grid is balanced towards the production at the power plant and the increased consumption, which depends on the amount of $CO_2$ captured. $CO_2$ exits the system boundary either with the flue gases from the power plant and hot stoves or as a pure stream for transportation to a permanent underground storage. Besides the power plant and gas utilization renewal, the

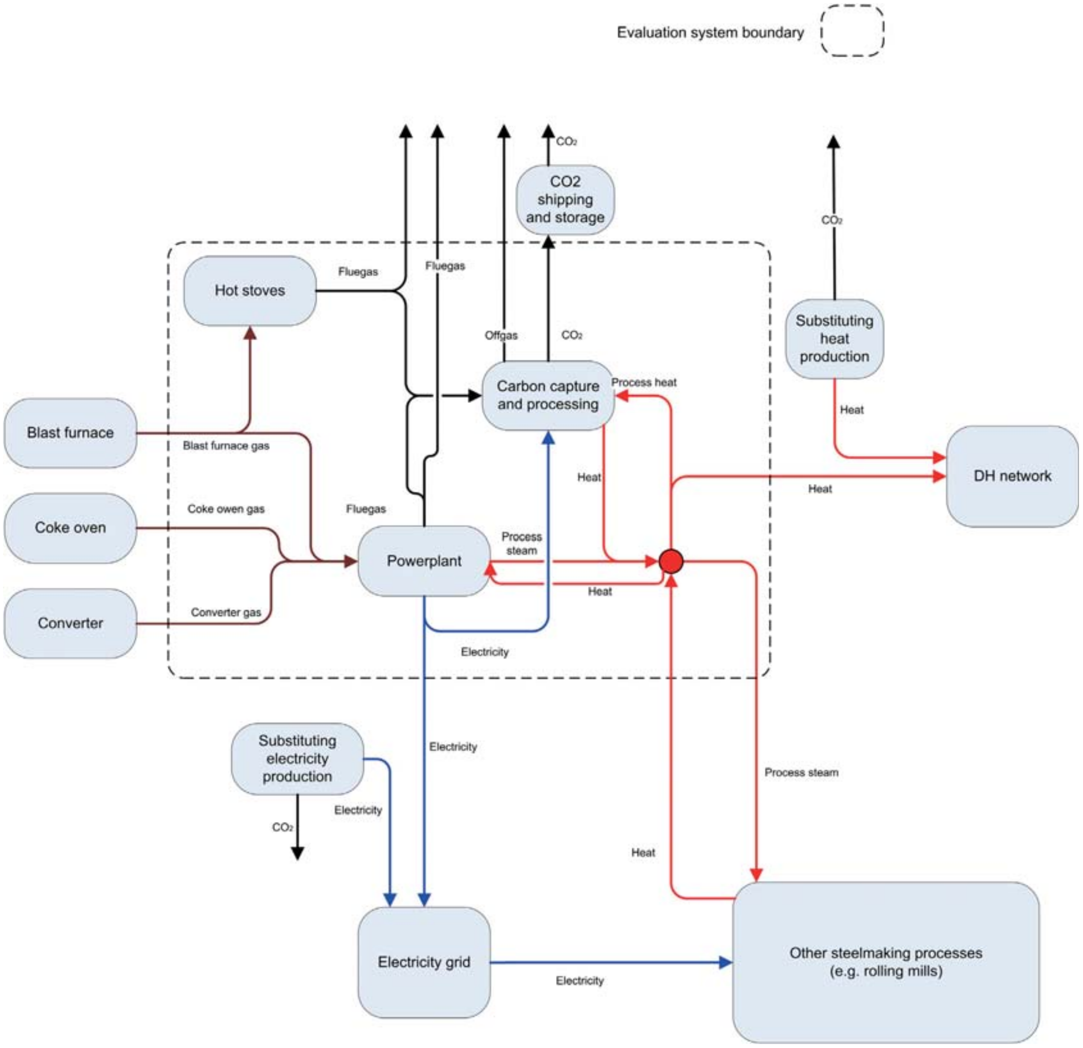

**Fig. 1.** System boundaries at Raahe steel mill for the energy balance and $CO_2$ capture study.

installation of the carbon capture island takes place in an existing site infrastructure.

Blast furnace gas represents by far the largest fuel gas stream utilized within the boundaries of this study (Table 1). Since the amounts of other fuel gases used are small, there are no significant differences between the flue gases of the power plant and the hot stoves regarding composition, $CO_2$ content and impurities (Table 3). Because of this, no significant advantage would be gained from treating these gas streams in separate capture units. A single capture island could be used thanks to the close location of the flue gas stream sources and the steady operation of the both source process units. In addition to this, only a single location suitable for constructing a capture island on could be found within a reasonably close proximity of the sources. This also justifies the combination of the two flue gas streams into a single capture island. When these flue gases are combined, the total maximum $CO_2$ flow to the capture unit is 103 kg/s. In all $CO_2$ capture cases, a 90% capture rate of the $CO_2$ in the flue gases treated was targeted for.

Heat integration opportunities for $CO_2$ capture process are based on matching the heat levels, heat sources and sinks. Heat can be recovered from steelmaking processes or generated in the boilers at the steel mill site. The heat can be utilized in electricity production and for solvent regeneration. Other utility consumptions of heat, the demand of district heat and the utilization of process steam on-site are considered to be equal in all modelled cases. As heat integrations play a significant role in the study, the available heat streams were divided into four categories for facilitating heat integration according to temperature and level of exergy (Table 2). The process steam that can be utilized in steelmaking processes is ranked as highest quality heat and set to category 1, while the lowest quality heat (that is still good for preheating the return stream from district heating) is set to category 4. The heat streams were integrated for maximizing $CO_2$ recovery, within the boundary conditions. The integration was adjusted so that the demands for process steam and district heat were always satisfied. In addition to the utilization of heat as process steam, in solvent regeneration

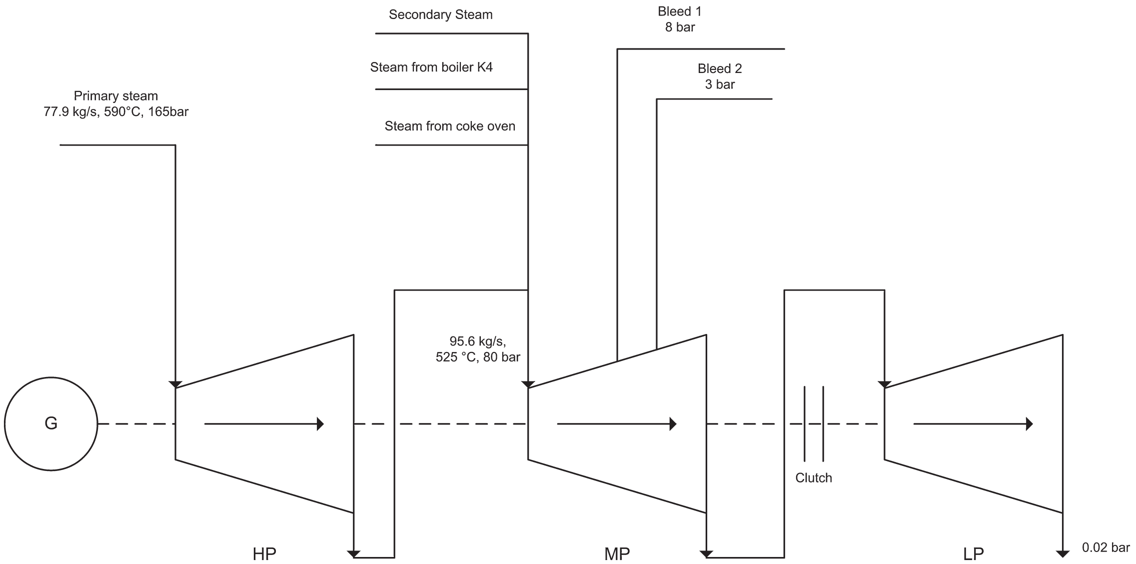

**Fig. 2.** Design parameters and turbine design for Raahe steel mill.

**Table 2**
Categorization of heat streams available based on temperature.

| Category | Temperature level | Description | Sources |
|---|---|---|---|
| 1 | Over 180 °C | Superheated 8 bar process steam | 8 bar bleed from turbine |
| 2 | Over 130 °C | MEA regeneration, district heating | 3 bar bleed, mill heat recovery (steam, hot water) |
| 3 | Over 80 °C | Advanced low temperature solvent regeneration | 3 bar bleed, mill heat recovery (steam, hot water) |
| 4 | Over 60 °C | Preheating for district heating | Mill and CCS heat recovery (steam, hot water) |

and for district heating, the heat was also utilized for preheating of boiler feed water for improving the steam and electricity production efficiency.

The starting point for capturing carbon dioxide from the flue gases was a conventional MEA based solvent scrubbing process. In addition to this, the usage of two alternative solvents was investigated with a rough, conceptual study. This was performed to study the possible effects and benefits for $CO_2$ capture in the future when more advanced methods have been developed.

Sulphur removal from the flue gases prior to the post-combustion $CO_2$ capture unit is generally required. At the steel mill, the blast furnace gas is already purified with a wet scrubber prior to utilization in the hot stoves and the power plant boiler. This leads to a rather low $SO_x$ concentration in the flue gases of the power plant and the hot stoves. The investment required for an additional $SO_2$ scrubber was considered to be a trade-off to avoid an increased MEA makeup and corrosion in the $CO_2$ scrubber. However, the $SO_2$ content in the flue gases was according to the simulations 17 ppm-v, which is in line with the level that can be found in the literature for an acceptable concentration suitable for a $CO_2$ scrubber (NETL, 2007, 2009; EPRI, 2007). Therefore, no additional sulphur removal units were needed. The sulphur content could also be further lowered slightly by improving the existing $SO_2$ removal. The simulated $NO_x$ concentration in the flue gas was very low, approximately 12 ppm.

**Table 3**
The simulated flue gas compositions [v%].

| | Power plant | Hot stoves |
|---|---|---|
| Total mass flow kg/s | 181.6 | 84.3 |
| $CH_4$ | 0 | 0 |
| $C_2H_4$ | 0 | 0 |
| $C_2H_6$ | 0 | 0 |
| CO | 0 | 0 |
| $CO_2$ | 28.1 | 28.4 |
| $H_2$ | 0 | 0 |
| $N_2$ | 64.8 | 64.7 |
| $O_2$ | 0.9 | 0.9 |
| $H_2S$ | 0 | 0 |
| $SO_2$ (ppm) | 18 | 17 |
| $SO_2$ | 0 | 0 |
| $H_2O$ | 6.2 | 6 |

### 2.4.1. *MEA capture process*

The amine capture process was modelled using a standard 30% MEA solvent. The capture process consists of an absorber unit and a stripper unit, pumps and heat exchangers. The process was modelled with an equilibrium model found in the Aspen Plus process simulation software (Fig. 3). Rate-based simulation models are known to be superior to equilibrium-state models for MEA modelling (Zhang et al., 2009; Taylor et al., 2003). However, a simpler equilibrium model was considered to be sufficiently accurate for the accuracy needed in this level of concept analysis, where the capture process is only one component of many.

The absorber was modelled using a Sulzer Mellapak structured packing. The flue gas is cooled down with a wet scrubber before the absorber unit. In the absorber, the $CO_2$ of the flue gas is absorbed by the MEA solvent to form stable chemical compounds. The absorber is operated near atmospheric pressure. According to Abu-Zahra et al. (2007) the optimum feed temperature for the solvent is 40 °C. The absorber was modelled as a packed colon with 10 ideal trays

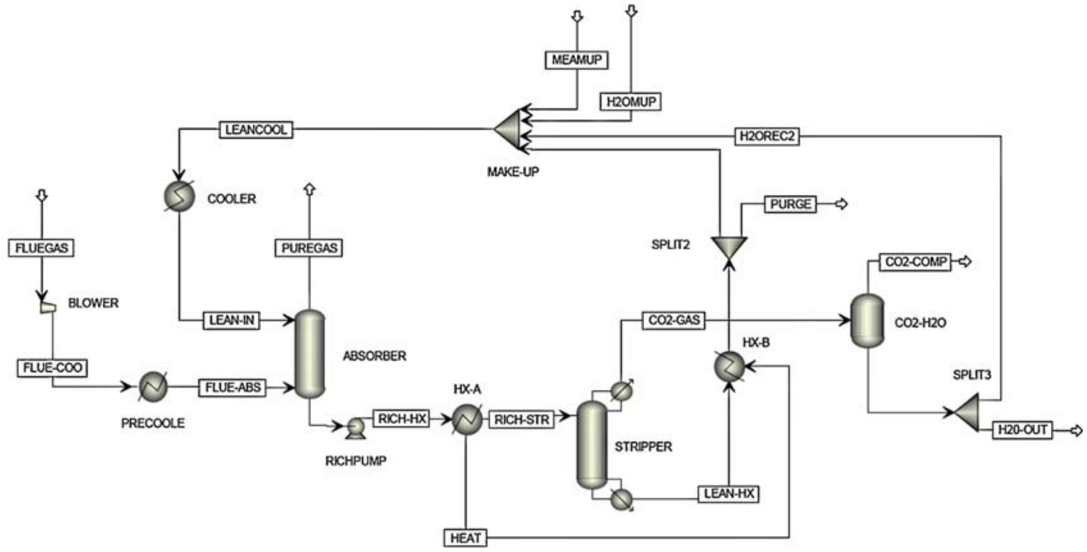

**Fig. 3.** Aspen Plus process model of MEA capture process.

and an L/G ratio of 4.2 l/m$^3$, with the solvent lean loading being 0.22 mol/mol. The rich solvent from the absorber is led into the stripper unit via a cross heat exchanger. The loading of the rich solvent was 0.49 mol/mol. In the stripper unit the chemically bound $CO_2$ is released from the solvent by heating it to 122 °C with low pressure steam at 133–160 °C (3.0–6.2 bar). The $CO_2$ exiting from the top of the stripper is led to a condenser to remove the water and solvent from the gas and return it for use in the process. Part of the water is removed from the process at this stage. The lean solvent is then led back to the absorber unit via cross heat exchanger. The stripper is operated at approximately 2 bar pressure.

A small amount of solvent and water is lost from the process with the exiting flue gas flow from the absorber unit. In addition, a small amount of solvent is removed from the system to remove impurities and degraded solvent. Because of this, water and solvent makeup is added to the process. The amount of solvent consumption was set to be 1.5 kg/$t_{\text{captured}}$ (similarly to Abu-Zahra et al., 2007).

According to the simulations, the regeneration energy needed in the process is approximately 3.4 MJ/kg captured $CO_2$. This is by far the largest energy consumer in the flue gas scrubbing process. Power is also needed in the capture process for pumps and blowers for flue gas and solvent recirculation in addition to the power needed for $CO_2$ compression.

### 2.4.2. *Alternative solvent options*

The standard MEA solvent can to some extent be considered as outdated and not the best performing state-of-the-art solvent for new $CO_2$ removal processes. Because of this, two other capture processes were conceptually evaluated to reflect likely future improvements in solvent scrubbing technologies and their implications to carbon capture processes with steel mill integration. Nevertheless, MEA solvent-based processes are the most evaluated and best known processes, providing a baseline reference to compare results with other studies. However, these alternative solvent options reflect better the solvent options available for a steel mill in the future. As the $CO_2$ concentration in the flue gas in this case is higher than in the alternative solvent studies used as reference (Fortum, 2009; Zhang et al., 2010), the results from the regeneration energy requirement calculations may be conservative in comparison to the real potential of alternative solvents in $CO_2$ capture plants in steel mills. These evaluations are based partly on current operational conditions and partly on hypothetic assumptions, and made to reflect the impact of possible future improvements in solvent scrubbing technologies in the future.

The evaluation of the first of the two alternative solvents is based on public information available on the Siemens amino acid salt $CO_2$ capture technology (referred to as “advanced” later on in the text). This technology was chosen in the Fortum FINNCAP project targeting to the demonstration of $CO_2$ capture at Meri-Pori condensing power plant (Fortum, 2009). The most significant benefit with this solvent in comparison to MEA solvents is the low regeneration energy requirements of 2.7 MJ/kg $CO_2$ (Fortum, 2010). In addition, the operational costs associated are expected to be slightly lower compared to baseline MEA. This was mainly due to a lower solvent make up consumption which was, based on the environmental impact assessment of FINNCAP project (Fortum, 2010), estimated to be only 13% of the consumption estimated for MEA.

The second evaluation with an alternative solvent is based on an imaginary solvent (referred to as “low-T” later on in the text), able to be regenerated at a significantly lower temperature than baseline MEA. This is assumed to be the result of solvent development work in the future. Having a lower regeneration temperature, even at the expense of relatively high regeneration energy, could open up new opportunities for $CO_2$ capture implementation, especially in the process industry, where low-temperature waste heat streams are readily available. The regeneration is set to occur at 70 °C, which enables a significantly larger share of the waste heat streams to be utilized for solvent regeneration and thus increase the amount of $CO_2$ that can be captured. In theory, it could be possible to develop these kinds of solvents (Zhang et al., 2010) if the advantages achieved with low temperature regeneration would compensate for other disadvantages. Regeneration energy of 3.0 MJ/kg $CO_2$ was assumed based on Zhang et al. (2010).

### 2.4.3. *$CO_2$ processing*

Since there is no capacity for geological storage of $CO_2$ in Finland the $CO_2$ has to be transported and stored outside Finland's

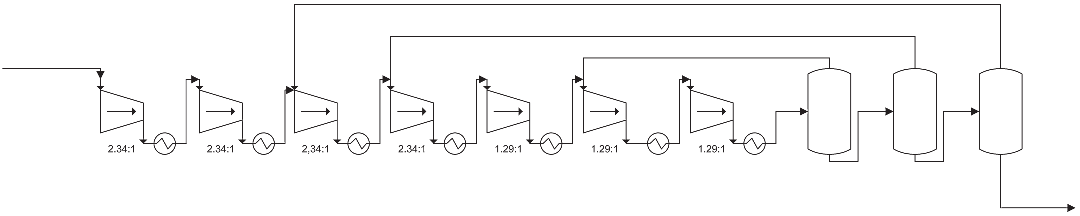

**Fig. 4.** A seven staged $CO_2$ compression train for ship transportation.

borders (Teir et al., 2011). Ship transportation from Finland is the most economical solution for transporting of $CO_2$ from a single $CO_2$ source to a storage site outside Finland (Kujanpää et al., 2011). For ship transportation $CO_2$ has to be pressurized and cooled down to approximately 6.5 bar and −52 °C. To reach these conditions with normal cooling water temperatures $CO_2$ has first to be compressed to approximately 60 bar. $CO_2$ is cooled down to −52 °C by flashing the pressurized $CO_2$ to 6.5 bar. When $CO_2$ is flashed, part of it is evaporated. The evaporated part is returned to the compression stage for the corresponding pressure level. Compression is done in seven stages, to enable an efficient heat recovery (Fig. 4). An isentropic efficiency of 0.8 was used in the compressors models. Most of the energy in $CO_2$ compression is used for liquefying $CO_2$. $CO_2$ is cooled down to 15 °C between the compression stages. Some of this low temperature level heat can be utilized to preheat the return stream from district heating network. The power requirement for ship transportation is not much smaller than that for pipeline transportation despite the pressure difference. This is because of the temperature requirements and thus recompression needed.

### 2.5. Scenarios

Using the parameters, assumptions and modelling described above, the energy balance and $CO_2$ emissions could be calculated for the steel mill. As described above, the approach allowed the investigation of energy and carbon dioxide emission balances with three different heat production scenarios resulting in different $CO_2$ capture scenarios:

*Scenario 1: no carbon capture*. This is the baseline scenario, with no carbon capture process in place. The plant operates according to business as usual, and the power and heat are produced at a normal rate.

*Scenario 2: turbine back pressure operation.* The size of the carbon capture installation is designed for utilizing the steam available from the steam turbine in back pressure operation. This enables capture of $CO_2$ and heat production for covering the heat demand for both the still mill and the district heating network. In addition, some electricity generation is possible with the high pressure steam. The sizing of the capture plant is based on the amount of steam going to the low pressure section of the turbine in the baseline scenario.

*Scenario 3: no electricity production.* The carbon capture plant is sized for a case where all available thermal power is utilized for regeneration of the solvent. Only the steam and heat demands of the steel mill are satisfied and all other heat is utilised for regeneration of the solvent. In this scenario there is no on-site electricity generation.

The implications of the $CO_2$ capture on the energy balance of the steel mill site are presented in Table 4. District heat sold from the boundary was constant in every case, 300 GWh/a, which is based on the district heat demand in the surrounding city of the mill. The largest captured $CO_2$ amounts (2.9 Mt/a) were in the cases where all available fuel power was used for regenerating the solvent. With only the low pressure steam available for solvent regeneration the captured amounts were in the range of 1.9–2.4 Mt/a. The amounts of $CO_2$ captured are presented in Fig. 5. In addition to the steam consumption in regeneration of solvent, also power is consumed in the process. The total power consumption of CCS processes was estimated to be 0.41 MJ/kg $CO_2$ captured. This comprises of pumps, compressors and other auxiliaries. Most of the electricity is consumed in the $CO_2$ compression.

**Table 4**
The calculated energy balance for different scenarios with each solvent studied.

| | Scenario 1: no carbon capture | Scenario 2: turbine back pressure operation | Scenario 3: no electricity production |
|---|---|---|---|
| Electricity generation [GWh/a] | 1180 | 726 | 0 |
| Capture island electricity consumption [GWh/a] | | | |
| MEA | 0 | 214 | 308 |
| Advanced | 0 | 270 | 330 |
| Low-T | 0 | 276 | 330 |
| Heat used for solvent regeneration [GWh/a] | | | |
| MEA | 0 | 1795 | 2581 |
| Advanced | 0 | 1795 | 2198 |
| Low-T | 0 | 2041 | 2442 |

As the amount of captured $CO_2$ gets higher, the capacity for electricity production on the power plant gets smaller, as the steam is utilized for regeneration of the solvent instead of utilized in the low pressure section of the steam turbine. In the reference case the annual electricity production is around 1200 GWh/a. When low pressure steam is utilized for solvent regeneration, the electricity production decreases by 40% to 730 GWh/a. When all fuel power is utilized to produce steam for regeneration, no electricity is produced on site.

When different solvent options are considered, the low temperature solvent was found to be the best $CO_2$ capture option, even though it had a higher regeneration energy than the advanced solvent. This is due to the higher ability to utilize low exergy heat that is widely available at site and cannot be utilized in large extent with other solvents considered. In addition, all measures for low temperature heat recovery were not mapped at the site, so it is possible that even more $CO_2$ could be captured using the low temperature solvent than what was found in these calculations. In industrial applications, such as for steel mills, where large amounts of low quality heat are available, utilization of a solvent regenerable at a low temperature would cover for a number of other possible drawbacks with the particular solvent, such as a higher nominal regeneration energy, higher circulation rates or faster degradation. In terms of the amount of $CO_2$ that could be captured, the advanced solvent proved to be almost as good as the low temperature solvent with only a minimal difference. When comparing MEA with the advanced solvent roughly 8% less $CO_2$ could be captured with the same integrations and utilization scenarios.

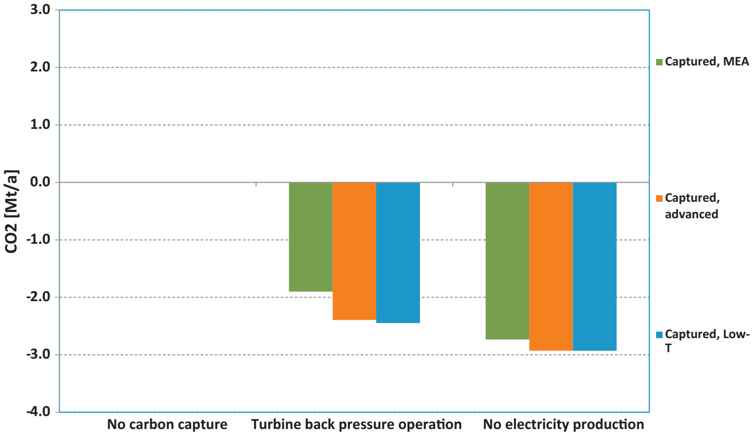

**Fig. 5.** The effect of CCS on the amount of $CO_2$ that can be captured with the studied solvents at the chosen boundary conditions.

## 3. Conclusion and discussion

As a technical option, it is possible to significantly lower greenhouse gas emissions from the steel industry with the post combustion capture technologies covered in this study. The solutions are technically realisable already in the near future. Nevertheless, no commercial application for such a large scale exists yet. The larger capture amounts studied (2–3 Mt $CO_2$/a) account for approximately 50–75% of the $CO_2$ emissions from the site. If larger amounts of emissions were to be captured it would be technically and economically significantly less feasible in comparison to only applying CCS for the largest emission sources on the site. This is due to the large number of small stacks scattered around the fairly large production site.

There are other carbon abatement options for iron and steel production. $CO_2$ emissions can be lowered for example by utilizing bio char as a reducing agent, applying different energy saving measures, etc. The high level of integration typical in modern steel plants makes further energy saving measures of any significant extent difficult. Large-scale bio char utilization is restricted by constrained resources and sustainability questions. Generally, also other $CO_2$ emission reduction options, such as electric arc furnaces or DRI processes, exists, but these are only applicable for certain types of steel mills. While being important and cost effective at best, these measures are generally of smaller scale, when compared to the order of millions of tons of $CO_2$ emission reductions that are possible with CCS.

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PAPER II

# Post-combustion capture of $CO_2$ at an integrated steel mill – Part II: Economic feasibility

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# Post-combustion capture of $CO_2$ at an integrated steel mill – Part II: Economic feasibility

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ABSTRACT

In this paper the economics of the technical possibilities presented in Part I (Arasto et al., 2013) for applying post-combustion $CO_2$ capture at an integrated steel mill were studied. Implications of different $CO_2$ amounts captured, solvents and process integration levels to the greenhouse gas balances and economics of operation are compared to the reference case without CCS trough several case studies using variable market prices of electricity and $CO_2$ emission allowances.

The break-even price (BEP) of $CO_2$ emissions (e.g. $CO_2$ emission allowances), where CCS becomes more profitable than the reference case, is about 72 €/t $CO_2$ with an electricity price of 100 €/MWh in the most favourable studied case using a MEA solvent. For the more advanced solvents considered, the BEP level is about 64 €/t $CO_2$. With higher prices of electricity, the costs for CCS increase rapidly. The costs for globally avoided emissions, based on a streamlined life-cycle analysis, are generally higher than the BEP's, depending on the fuels that are assumed to eventually compensate the decreased electricity production in the energy system. The amounts of captured $CO_2$ corresponding to the above presented prices in the most favourable cases are typically in the range of 2–3 Mt $CO_2$/a, which accounts for 50–75% of the site emissions.

## 1. Introduction

Climate change is considered one of the most serious environmental threats that humankind is facing. Therefore, anthropogenic greenhouse gas (GHG) emissions should be reduced in every field of activity. Iron and steel industry is responsible of about 10% of global $CO_2$ emissions from fossil fuel use (IEA, 2008), which corresponds to about 5% of the overall global GHG emissions. Numerous improvements in steel mills are possible for reducing $CO_2$ emissions, but the reductions are typically small in comparison to the overall $CO_2$ emissions from the mills (Arasto et al., 2013). Therefore, carbon capture and storage (CCS) is a key technology for significant $CO_2$ emission reductions for the steel mills. Due to the large unit sizes, relatively high $CO_2$ concentrations, existing utilization of pure oxygen and significant recoverable process heat amounts, CCS may become profitable in steel mills considering that the costs for $CO_2$ emissions would rise significantly in the future. Economically feasible options to reduce $CO_2$ emission are currently especially of interest to European steel producers, since the additional cost from EU Emission Trading Scheme (EU ETS) cannot be transferred to the product price in order for steel to be competitive in the global market.

In principle, each of the three main capture technologies, namely post-combustion capture (PCC), pre-combustion capture and oxy-fuel combustion can be utilized in the steel mills. There are only a few studies available with detailed analysis of the costs of these technologies applied to steel mills. In IPCC Special Report on CCS (IPCC, 2005) a cost of 18 US$/t $CO_2$ captured (based on Gielen (2003)) was presented for the capture stage. IEA (2008) presented costs of 20–25 €/t $CO_2$ for capture alone and 40–50 US$/t $CO_2$ with transportation and storage, based on a study by Borlée (2007). Global CCS Institute (GCCSI) has reported costs of 52 US$/t $CO_2$ captured for FOAK (first of the kind) CCS applications in the steel industry (GCCSI, 2009). In IEA Technology Roadmap (IEA, 2011) cost levels of 60–80 €/t avoided $CO_2$ are presented. GCCSI has also published an update to the economics of CCS (WorleyParsons, 2011), where a cost of 54 US$/t $CO_2$ captured is estimated for FOAK CCS plants (including transport and storage) and a range of 35–63 US$/t captured $CO_2$ for later applications, depending on the considered country. Hooey (2011) presented a cost range of 72–83 US$/t $CO_2$ avoided for end-of pipe capture and costs of about 57 US$/t $CO_2$ avoided for an OBF-MDEA process (oxygen blast furnace and $CO_2$ separation using a methyldiethanolamine solvent). According to Wiley et al. (2011), carbon capture would require a carbon price

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of at least 65 AU$ per tonne emitted to be economically attractive. Kuramochi et al. (2011) presented $CO_2$ avoidance cost of less than 50 €/t for either converting a conventional blast furnace to a top gas recycling blast furnace or for add-on $CO_2$ capture for a conventional blast furnace. Later Kuramochi et al. (2012) presented a cost range of 40–65 €/t $CO_2$ avoided for conventional capture technologies for blast furnace based process and a range of 30–55 €/t $CO_2$ avoided for advanced capture technologies. The costs for avoided emissions are very sensitive regarding the assumptions made, for example electricity prices and captured amounts of $CO_2$, which both vary in the reported studies. In general, an increasing trend can be noticed in the cost estimations as a function of the publication year.

In addition to conventional production technologies, direct reduction iron (DRI) production processes present a new type of processes for iron production. DRI processes are already used commercially, but their proportion of global iron production is still minor. According to IPCC (2005) capture from DRI process can be more feasible than from other steel making processes. Gielen (2003) has estimated costs for capture from DRI process to be around 10 US$/t $CO_2$.

Rautaruukki Ltd.'s Raahe steel mill is situated on the coast of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. It is also the largest $CO_2$ point source in Finland. In 2008, before the economic down-term the shut-down of the sintering plant and the revisions to the blast furnace, the $CO_2$ emissions from the mill were 4.5 Mt/year (EMV, 2011). Replacing sinters by pellets from 2011 onwards reduced the direct $CO_2$ emissions from the site by 0.4 Mt/a. The implications of different post-combustion capture methods and different capture amounts on technical aspects and energy balances at the Raahe steel mill have been assessed in Part I of this study (Arasto et al., 2013). In this paper, the impacts of CCS on the GHG emissions and on the economics of Raahe mill are illustrated with varying costs of $CO_2$ emission allowances in EU ETS (EUA) and varying electricity prices, using the results from the process simulation presented in Part I.

## 2. Methods

### 2.1. General

The steel mill processes studied and the technical modelling performed are presented in Part I (Arasto et al., 2013). The results obtained by that modelling were used in this paper to estimate $CO_2$ emission reduction possibilities and carbon abatement costs at an integrated steel mill from the steel mill owner's point of view. As presented in Arasto et al. (2013), flue gases from the power plant and blast furnace air preheaters (also known as "cowper stoves" or "hot stoves") were identified as the most potential streams for $CO_2$ capture as these two stacks correspond for about 75% of the overall site $CO_2$ emissions. Possibilities for partial $CO_2$ capture were investigated using different solvents and several process heat integration options for solvent regeneration. In total, five different cases for regeneration heat supply were studied for three different solvents resulting in a matrix of 15 capture cases plus a reference case without CCS. In addition, the prices of electricity and EUAs, which are the most important factors in terms of economics of CCS, were varied in all the cases.

### 2.2. Boundaries for the evaluation

The boundaries used for the economical evaluations and for the streamlined life-cycle assessment (LCA) are presented in Fig. 1. Since capturing $CO_2$ from the flue gases from the power plant and the blast furnace hot stoves using a post-combustion capture method has no effect to the core iron making processes, the presented boundaries can be used and unchanged processes, costs and emissions can be excluded from the assessments. The impact of CCS on the $CO_2$ emissions and the costs within the economic system boundary were used for calculating the break-even prices (BEPs) for EUAs where CCS turns profitable over the reference case making a CCS investment reasonable. The system boundary for the LCA study is broader, because this also includes the impacts of studied cases on GHG emissions from, for instance, transportation and storage as well as the production of the electricity purchased by the steel mill. These life cycle emissions are taken into account when the costs of avoided $CO_2$ emissions are estimated. However, in terms of CCS feasibility from the mill owner's point of view, the costs of avoided $CO_2$ emissions (as defined in this study) are not as suitable as BEP's.

### 2.3. Steel mill reference case

The study is based partly on current operating conditions at the steel mill and partly on a hypothetical situation, including some possible future improvements in the mill, which would affect the $CO_2$ emissions. The differences in the reference case compared to the existing situation are described in Part I (Arasto et al., 2013), including technical details of the reference case mill. The investments required for the assumed improvements are already included as part of the reference case and are therefore not taken further into account in this study. The improvements include a modernization of the power plant, which would have a major effect on the investments if it would have been accounted as part of the investment on CCS. In the reference case the $CO_2$ emissions of the site are 4.0 Mt/a.

### 2.4. Costs of CCS

#### 2.4.1. Description of the model

In order to estimate costs and GHG emission balances of the overall CCS chain a Microsoft Excel-based system model called CC-Skynet$^{TM}$ was used. The model has been developed at VTT Technical Research Centre of Finland since 2005 to simulate the economics of power plant operation in different operational situations. During 2008–2011 the model was further developed in a project called CCS Finland to also cover investments and operation of CCS for power plants and steel industry. In this study the goal was to evaluate the consequences of CCS in annual operational costs within the system boundary described in Section 2.2. Various cases utilizing CCS were calculated and compared to the reference case without CCS. The steel production of the mill in the different cases studied is considered to be constant. The costs are defined from the plant owner's point of view by Eq. (1). The parameters used in the cost estimations of this paper are presented in Table 1. Case specific variables/intermediate results are presented later in Table 2. The most important parameters, in terms of economic feasibility of CCS, are the prices for EUA and electricity. These two parameters were varied in the study and the most important results are presented with different prices.

$$\begin{aligned}\mathrm{CAPC_{CASE}} &= \mathrm{EAC_{CCS}} + \mathrm{EAC_{HR}} + \mathrm{EL} + \mathrm{EUA} + \mathrm{CO_{2\,trans}} + \mathrm{solvent} \\ &\quad + \mathrm{H_2O} + \mathrm{others} - \mathrm{DH} \qquad (1)\end{aligned}$$

where $\mathrm{CAPC_{CASE}}$ is the change in annual production costs [M€/a], $\mathrm{EAC_{CCS}}$ is the equivalent annual cost based on the required investment in $CO_2$ capture and further on-site processing discounted by given economic lifetime and discount rate (Table 1), $\mathrm{EAC_{HR}}$ is the equivalent annual cost based on the required investment in low temperature process heat recovery discounted by given economic

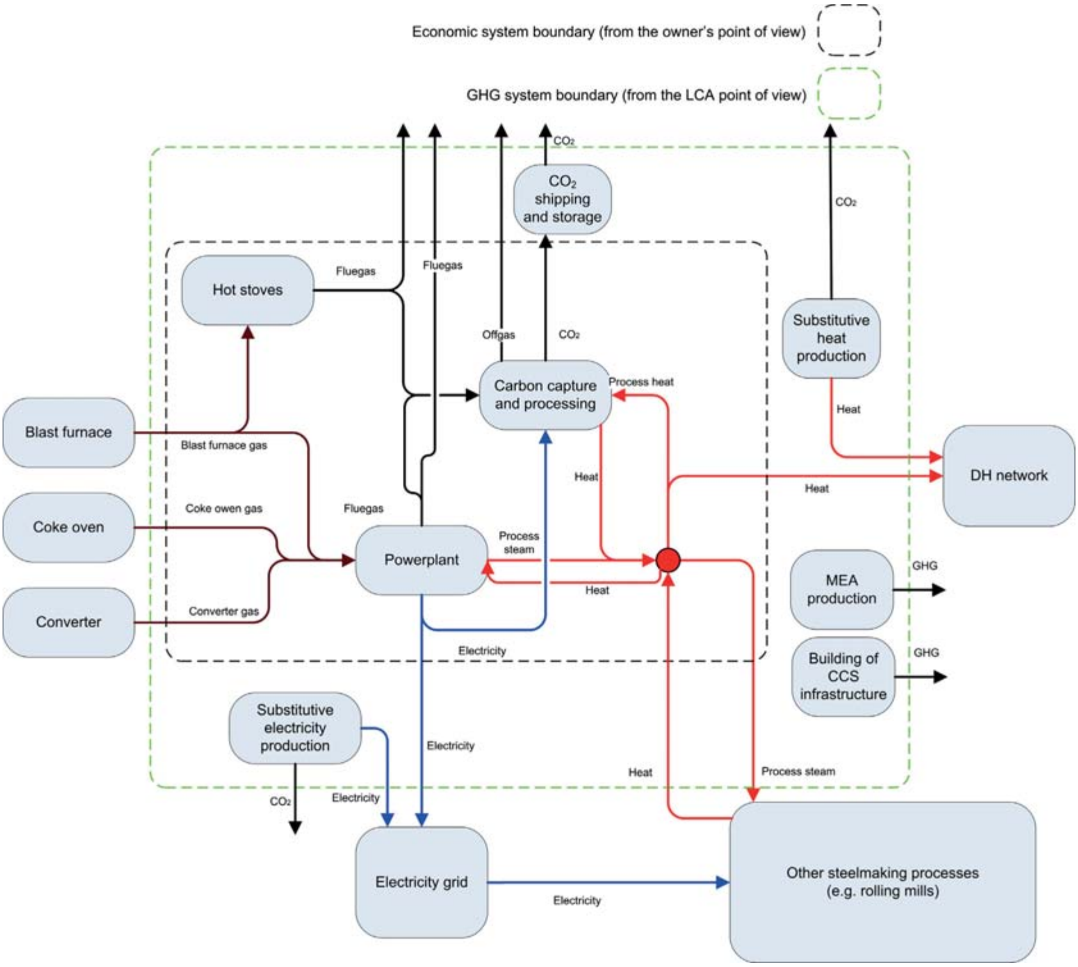

**Fig. 1.** Boundary for definition of $CO_2$ emissions and costs included in economical estimations and boundary for GHG emissions considered in streamlined LCA (avoided emissions). Only the operations impacted by application of post-combustion CCS are included to analysis.

lifetime and discount rate, EL is the electricity net purchase over the system boundary (negative for considered system boundary if more electricity is produced than consumed), EUA is the costs for EUAs corresponding to released $CO_2$ emissions inside the economic boundary, $CO_{2trans}$ is the costs for transported and stored $CO_2$, solvent is the costs for purchased solvent make-up, $H_2O$ is the water consumption due to carbon capture, Others is the other additional operating costs due to application of CCS, DH is the heat sold to city of Raahe for district heating.

Other additional operating costs are estimated to consist mainly of fixed costs because most of the variable operating costs were estimated separately. Fixed operating costs include for example personnel and maintenance costs.

Because there are only a few steel industry based CCS approaches studied in the literature, especially based on PCC, the overall CCS investment is based on relatively vast literature data on PCC at power plant sector. The selected investment level in each case is based on a PCC retrofit study published by NETL (2007) neglecting the additional $SO_x$ removal system (as justified in Part I, Arasto et al., 2013) and turbine investments (as justified in Section 2.3) presented in NETL (2007). The investment was converted to 2012 Euros using an inflation factor and 05/2012 currency exchange rate. The obtained investment ($I_{PP}$) was then scaled into a size (flue gas mass flow) for each case ($I_{case}$, M€) by Eq. (2) using the principle and scale factor presented in Green and Perry (2008):

$$I_{case} = \left(\frac{(\dot{m}_{CO_2}/CO_2 m\text{-}\%)}{\dot{m}_{FG,PP}}\right)^{SF} \cdot I_{PP} \qquad (2)$$

where $\dot{m}_{CO_2}$ is the $CO_2$ mass flow to capture plant for the current case [kg $CO_2$/s], $CO_2 m$-% is the mass fraction of $CO_2$ in the flue gases entering the capture plant [kg $CO_2$/kg], $\dot{m}_{FG,PP}$ is the flue gas mass flow in the power plant reference case [kg/s], SF is the scale factor for investments, $I_{PP}$ is the CCS investment in the power plant reference case [M€].Electricity, fuel prices and BEPs are among the numerous other indicators and variables of this kind of the case study can be defined as average future values over the economic lifetime of the investment.

**Table 1**
General cost model parameters used in the study. Data sources are indicated by footnotes below the table. The values without footnotes are based on in-house data and general assumptions. In addition to these values, the most important variables, namely EUA and electricity prices were varied in the case studies.

| Variable | Value | Unit | Data source |
|---|---|---|---|
| Basic steel mill and power plant data | | | |
| Amount of mixed gas to power plant | 2390 | GWh/a | a |
| Average emission factor for the gas combusted in power plant | 260 | g $CO_2$/$MJ_{fuel}$ | a |
| $CO_2$ formation in cowpers | 32.9 | kg/s | a |
| Annual operation hours for powerplant and cowpers | 8600 | h/a | a |
| Steam from coking plant to turbine | 440 | GWh/a | a |
| Annual operation hours for coking plant | 8700 | h/a | a |
| Turbine back pressure power production (with – without 8 bar bleed) | 83–86 | $MW_e$ | b |
| Annual need for 8 bar steam bleed from turbine | 130 | GWh/a | a |
| 8 bar steam bleed, maximum steam output | 40 | MW | a |
| Annual 3 bar bleed for district heat in reference case without CCS | 50 | GWh/a | a |
| 3 bar steam bleed, maximum steam need without CCS | 40 | MW | a |
| Effect of 3 bar bleed to power production | 0.28 | $MW_e/MW_{steam}$ | b |
| Heat recovered from steel mill for district heating in ref. case, average | 40 | MW | a |
| Heat recovered from steel mill for district heating in ref. case | 337 | GWh/a | a |
| Heat utilization for feed water preheating | 30 | MW | b |
| Upper limit for district heat consumption | 300 | GWh/a | a |
| Common variables for all CCS cases | | | |
| $CO_2$ capture rate | 90% | of $CO_2$ to capture | b |
| Additional electricity consumption incl. compression to 60 bar | 0.41 | $MJ/kg_{captured}$ | b |
| Recovered heat from $CO_2$ compression to district heating | 0.11 | $MW/kgCO_2$ | b |
| CCS water usage | 108 | $kg/t_{captured}$ | b |
| Recovered heat from flue gases | 35.8 | MW | b |
| Solvent specific variables | | | |
| Solvent regeneration energy, MEA | 3.4 | $MJ/kg_{captured}$ | b |
| Solvent regeneration energy, "Advanced" | 2.7 | $MJ/kg_{captured}$ | c |
| Solvent regeneration energy, "Low-T" | 3.0 | $MJ/kg_{captured}$ | d |
| Solvent make-up consumption, MEA and "Low-T" | 1.5 | $kg/t_{captured}$ | e |
| Solvent make-up consumption, "Advanced" | 0.2 | $kg/t_{captured}$ | f |
| Solvent make-up cost, MEA and "Low-T" | 1.0 | €/kg | e |
| Solvent make-up cost, "Advanced" | 0.75 | €/kg | |
| General economic variables | | | |
| Economic lifetime, retrofit plant | 20 | years | |
| Discount rate | 10% | | |
| Scale factor for investments in different scales | 0.65 | | g |
| Investment for PCC retrofit in power plant (434 MWe w/o capture) | 334 | M€ | h |
| Flue gas mass flow in power plant reference case | 553 | kg/s | i |
| Mass fraction of $CO_2$ in flue gases to capture plant | 0.38 | kg/kg flue gas | b |
| Price for district heat | 50 | €/MWh | |
| Cost for $CO_2$ storage | 12 | €/t | j |
| Cost for additional water usage | 2 | €/t | |
| Other additional fixed operating costs due to CCS | 2% | Of the total investment | |

[a] Personal communication with Rautaruukki Ltd, 2008–2011.
[b] Steel mill process model (model presented in Arasto et al., 2013).
[c] Siemens (2011).
[d] Zhang et al. (2010).
[e] Values for MEA from Abu-Zahra et al. (2007). These values were used also for Low-T solvent.
[f] Fortum (2010).
[g] Green and Perry (2008).
[h] NETL (2007) (Table 3-62, 368 million US$ excluding investments on FGD and turbine). Inflation from 2006 to 2012, 14.1%: http://www.usinflationcalculator.com/. Currency conversion 1.256 $/€: http://www.ecb.int/stats/exchange/eurofxref/html/index.en.html.
[i] NETL (2007) (Table 2-1, 4,390,042 lbm/h).
[j] McKinsey & Company (2008).

### 2.4.2. Processing, logistics and storing

As there is no capacity for permanent storage of $CO_2$ in Finland the $CO_2$ has to be transported and stored outside Finland. The captured $CO_2$ is assumed to be shipped to the North Sea by ships developed especially for transporting $CO_2$. The transport is assumed to be purchased as a service from a separate service provider in these studies. The storage is assumed to be an offshore saline aquifer and the overall storage price is set to 12 €/t $CO_2$ (according to McKinsey & Company, 2008).

The $CO_2$ transportation costs are assumed based on the methodology developed in CCS Finland project (Kujanpää et al., 2011). Eq. (3) was fitted to the calculation results to estimate the costs of $CO_2$ transportation [M€/a] as a function of transported (captured) amount of $CO_2$ [Mt $CO_2$/a].

$$\mathrm{COST_{trans}} = \mathrm{CO_{2\,trans}} \cdot (17.35 \cdot \mathrm{CO_{2\,trans}}^{-0.51}) \qquad (3)$$

### 2.5. Streamlined LCA

Besides the $CO_2$ emissions from the site, the direct consequences of CCS cases on the overall GHG emissions were also taken into account using system modelling and streamlined LCA. The most essential emission sources were evaluated in more detail, and for the less essential sources (e.g. construction, make-up solvent production) rough and general emission factors were used. The approach included the following GHG emission sources and emissions:

- $CO_2$ from power plant and hot stoves
- Stored $CO_2$
- $CO_2$ from substitutive electricity production
- $CO_2$ from substitutive heat production

**Table 2**
The modelled energy balance and GHG emissions in different cases with different solvents.

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| Change in gross electricity generation [GWh/a] | 14 | −454 | −454 | −1180 | −1180 |
| Capture plant el. consumption [GWh/a][a] | | | | | |
| MEA | 32 | 214 | 232 | 308 | 326 |
| "Advanced" | 40 | 270 | 292 | 330 | 330 |
| "Low-T" | 63 | 276 | 307 | 330 | 330 |
| Heat used for solvent regeneration [GWh/a] | | | | | |
| MEA | 269 | 1795 | 1944 | 2581 | 2730 |
| "Advanced" | 269 | 1795 | 1944 | 2198 | 2198 |
| "Low-T" | 465 | 2041 | 2268 | 2442 | 2442 |
| Captured $CO_2$ [Mt/a] | | | | | |
| MEA | 0.28 | 1.90 | 2.06 | 2.73 | 2.89 |
| "Advanced" | 0.36 | 2.39 | 2.59 | 2.93 | 2.93 |
| "Low-T" | 0.56 | 2.45 | 2.72 | 2.93 | 2.93 |
| Net GHG effect [Mt/a] | | | | | |
| MEA | −0.26 | −1.17 | −1.31 | −1.15 | −1.28 |
| "Advanced" | −0.32 | −1.60 | −1.78 | −1.33 | −1.33 |
| "Low-T" | −0.46 | −1.64 | −1.88 | −1.32 | −1.32 |

[a] Including compression.

- $CO_2$, $CH_4$ and $N_2O$ from avoided/additional production and supply of fuels
- Construction of CCS plant
- $CO_2$ transport (ship construction, fuel consumption, $CO_2$ cooling splits)
- Solvent production and transportation

Relatively definite emission factors for direct $CO_2$ emissions from substitutive external combustion processes (i.e. combustion at a plant outside of the steel mill) are based on national fuel classification data (Statistics Finland, 2011). More ambiguous is the question about what type of fuels are those that in certain cases are eventually substitutive ones. In this paper, changes in electricity and heat sold/purchased over the system boundary are assumed to be substituted by coal and oil, respectively. In the Nordic electricity market (Nordpool) the base load is produced mainly by hydropower, nuclear and combined heat and power (CHP). Coal-fired power plants are used mostly during periods of high electricity prices (i.e. during high consumption or reduced hydropower). Therefore, changes in electricity consumption can be assumed to impact mostly coal-fired power production (Nordpool, 2012). Benefits from oil substitution are minor, because already in the reference case the steel mill could supply more district heat than the city consumes and in the district heat network oil is used only for reserve and peak load production (Raahen Energia, 2010).

General factors (literature sources) were used for evaluating GHG emissions from fuel production and supply (Kirkinen et al., 2008; Neste Oil, 2010), GWP (global warming potential) factors for a 100-year time horizon for $CH_4$ and $N_2O$ emissions (IPCC, 2007), CCS plant construction (Pehnt and Henkel, 2009) and MEA (monoethanolamine) production (Ecoinvent, 2009). GHG emissions from MEA production (3.4 $CO_2$-equiv. t/t MEA) were also used as an estimate for GHG emissions from the production of other solvents due to their small contribution to the overall GHG emissions.

Emissions from ship transportation were calculated based on the estimated ship capacity and transportation time (based on the methodology presented in Kujanpää et al. (2011)). The fuel consumption at sea is linearly interpolated, based on the deadweight of a 20,000 $m^3$ tanker used as a reference, consuming 0.6 t of heavy fuel oil per hour (Aspelund et al., 2006). During mooring, loading and discharging, the ship engines are assumed to run on 20% capacity. The amount of vented boil-off $CO_2$ per day from the ship tanks is based on IEA (2004). Ship weight is calculated based on the deadweight coefficient presented by Molland (2008) and assumed to consist of steel only. The total $CO_2$ emissions resulting from production of this steel is estimated to 1.97 t $CO_2$/t steel (Hu et al., 2006).

### 2.6. Studied cases

In general, the overall economics of CCS is strongly dependent on the energy penalty due to CCS. The PCC processes considered with three different solvents for $CO_2$ capture and two scenarios for the heat production for solvent regeneration were presented in Part I (Arasto et al., 2013). Those scenarios are used also as basis for the case studies of this paper (cases 2 and 4). The solvents considered are MEA, an "Advanced" solvent based on Siemens amino acid salt $CO_2$ capture technology (Siemens, 2011) and a solvent presented by Zhang et al. (2010), which could be regenerated in lower temperatures than the other solvents ("Low-T").

In the steel mill studied there are several options for different heat integrations available, leading to different energy penalties and economics for CCS. The most economical solution is dependent on, for example, the solvent considered, investments required for heat recovery, and future prices for electricity and EUAs, which are all uncertain. Therefore, three additional cases comparing to heat production options presented in Part I were studied for each solvent. The modelled cases included increased heat recovery from the steel mill processes suitable for solvent regeneration, resulting in higher $CO_2$ capture capacities. Only the recovery options resulting water or steam streams at over 130 °C temperature were considered.

In order to ease the reading of the results, the cases have been put in such an order that the amount of captured $CO_2$ increases as the number of the case increases. The cases are described as follows:

- Case 0: the reference case without CCS to which the CCS cases are compared. In case 0 some developments to the existing steel mill are already implemented as presented in Arasto et al. (2013). A small, intermediate steam bleed is needed for district heating peak loads.
- Case 1: small scale CCS application, where the capacity of the $CO_2$ capture plant is determined by the regeneration heat available for the solvent using the process heat recovered from steel mill processes by additional investments (23 M€, 120 GWh/a hot water and 146 GWh/a steam. GWh values are expressed at 60 °C reference temperature). Intermediate steam from turbine is neither used for solvent regeneration nor for district heating, because additional heat (in comparison to the reference case) is recovered for district heating using the waste heat from the capture and compression units. Therefore, power production increases and

electricity production is higher than in the reference case. However, compression stage increases plant electricity consumption and electricity output from the economic system boundary is less than in the reference case.
- Case 2: the capacity of the $CO_2$ capture plant is determined by the heat consumption of the solvent regeneration, which is set to be equal to the amount of heat in the intermediate steam available from the turbine. Therefore, condensing power is not produced. There are no investments in heat recovery in this case.
- Case 3: combination of previous cases. The capacity of the $CO_2$ capture plant is determined by its heat consumption, which is set to be equal to the sum of the heat streams of cases 1 and 2
- Case 4: the capacity of the capture plant is determined by its heat consumption, which is set to be equal to the whole steam production of the boiler. Therefore, there is no power production. Depending on the energy required for the regeneration of solvent considered, the amount of heat may be sufficient to capture all $CO_2$ emissions within the economic system boundary. There are no investments on heat recovery in this case.
- Case 5: the capacity of the capture plant is determined by its heat consumption, which is set to be equal to the sum of the heat streams of cases 1 and 4.

The net electricity production of the economic system boundary is "sold" to the rest of the steel mill (see Fig. 1) using the given market price for electricity, since any change in the power production at the steel mill impacts on the steel mill's need to purchase electricity from the market. The entire steel mill is a net electricity consumer in any case but in cases 4 and 5, where no electricity is produced, also the considered economic system is a net electricity consumer. In addition, the amount of available district heat from the economic system boundary changes from case to case. District heat is utilized in the premises of the mill and in the city nearby. However, there is an upper limit given for the amount of heat that is possible to sell from the system due to the limited heat consumption of the relatively small city to which the district heat network is connected. Heat supply is restricted to this limit in all of the cases with the exception of case 1 with "Low-T" solvent. The amount of combusted gases is equal in all the cases, because it is not dependent on the (post-combustion) $CO_2$ capture process or any other case variable. Therefore, the $CO_2$ formation from combustion is also equal in all the cases.

## 3. Results

### 3.1. Energy balance and GHG emissions

Using the earlier described parameters, assumptions and modelling the energy balances and impacts on the GHG emissions were calculated for the studied cases. The most important impacts on the energy streams and GHG emissions are presented in Table 2 for each of the modelled solvents. As our approach allowed investigation of different amounts of $CO_2$ captured, the smallest amounts captured (0.3 Mt/a) were in the cases where only recovered heat was used for the capture processes and the largest amounts (2.9 Mt/a) in the cases where all available fuel power was used for regenerating the solvent.

As presented in Table 2, the same heat sources can be utilized to a larger extent in the case of the "Low-T" solvent. This is mostly due to a better utilization of low temperature process heats in liquid phase. For example, from the same 130 °C hot water stream, almost five times more energy can be utilized for regeneration of the low temperature solvent than for regeneration of MEA. Due to smaller specific regeneration energy, more $CO_2$ can be captured with the same energy sources also by "Advanced" solvent than by MEA. The lowest overall GHG emissions are achieved using the "Low-T" solvent in case 3, where recovered process heat is utilized, but only low pressure steam is needed from the turbine. The effect of CCS on the GHG emissions from the LCA system of the considered cases is illustrated in Fig. 2 for the MEA solvent.

### 3.2. Costs of CCS

In Table 3 the effect of CCS on the annual costs and incomes within the economic system boundary are presented using EUA price of 50 €/t and electricity price of 80 €/MWh for different cases using the MEA solvent. The results from the calculations show that all CCS cases are less profitable than operation without CCS.

In Fig. 3 the effect of CCS on the total costs in comparison with the reference case are presented using an EUA price of 80 €/t and electricity price of 100 €/MWh for all three solvents. With these

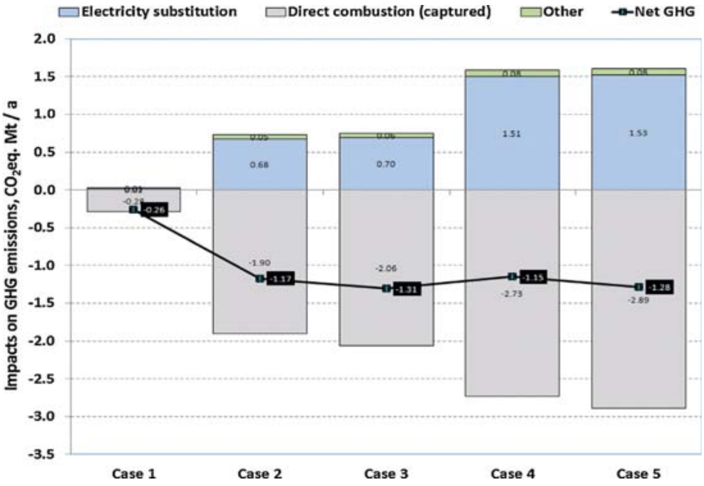

**Fig. 2.** The impact of studied cases on related system's GHG emission levels with MEA as a solvent. The lowest overall GHG emissions are achieved in case 3, where recovered process heat is utilized, but only low pressure steam is needed from the turbine.

**Table 3**
The impact of CCS on the annual costs of the steel mill with EUA price of 50 €/t and electricity price of 80 €/MWh for different cases with MEA solvent.

| [M€/a] | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| Electricity purchase | 1.5 | 53.5 | 54.9 | 119.1 | 120.5 |
| $CO_2$ allowances | −14.2 | −95.1 | −102.9 | −136.7 | −144.5 |
| $CO_2$ transport and storage | 12.8 | 46.6 | 49.4 | 61.2 | 63.9 |
| Other OPEX | 1.9 | 6.6 | 7.5 | 8.9 | 9.6 |
| CAPEX | 8.2 | 19.5 | 23.2 | 24.5 | 27.5 |
| Total | 10.1 | 31.1 | 32.1 | 76.9 | 77.0 |

prices CCS cases 2 and 3, with any of the studied solvents, would be more profitable than the reference case. Case 1 with MEA as a solvent yields to slightly higher overall costs and other studied solvents slightly smaller costs than the reference case. The most economic option would be "Low-T" solvent in case 3 but in general the results with "Advanced" solvent and "Low-T" solvent are near to each other. With high electricity prices cases 4 and 5 would not be feasible.

Vast uncertainty lies in EUA–electricity price interaction in the future and under estimated price range where CCS could be feasible. However, it can be assumed that increasing EUA price leads to climbing electricity prices. If we compare the economics of operation for different CCS cases to that for the base case steel production as presented in Fig. 3 but with varying costs of electricity, we can define trends for EUA BEPs where CCS turns profitable over the reference case. In Fig. 4 the EUA BEPs are presented as a function of electricity price for MEA and "Advanced" solvents in cases 1 and 3. The BEPs are lower with "Advanced" solvent than with MEA mainly due to the more efficient utilization of heat sources. With high electricity prices, BEPs in case 1 reach case 3 prices and eventually become lower. BEP values for "Low-T" solvent are close to those of "Advanced" solvent.

In the cases studied using the "Low-T" solvent, the cost for avoided $CO_2$ varies between 84 and 169 €/t using an electricity price of 80 €/MWh and between 93 and 192 €/t using an electricity price of 100 €/MWh. For the MEA solvent the respective costs are between 94–186 €/t and 95–212 €/t. The levels of cost of avoided $CO_2$ are heavily dependent not only on the characteristics of the facility and the operational environment (e.g. electricity price) but also on the chosen system boundaries and assumptions, such as the type of substitutive electricity generation. For example, if we consider natural gas-based electricity as marginal production instead of coal, the cost level of avoided $CO_2$ decrease, especially in the cases with a higher amount of $CO_2$ captured, so that with an electricity price of 80 €/MWh the costs are between 72 and 113 €/t for the "Low-T" solvent and between 84 and 119 €/t for the MEA solvent.

## 4. Conclusion and discussion

From a plant owner's perspective, the EUA BEP, i.e. when CCS turns more profitable in the most competitive studied case than buying carbon credits in the reference case, is in the range of 58–78 €/t $CO_2$, if only electricity prices between 80 and 150 €/MWh are considered. The cost for globally avoided emissions is in the range of 84–114 €/t $CO_2$, respectively, if coal is used as the fuel to substitute the changed electricity consumption. This applies to the larger amounts of captured $CO_2$ studied (2–3 Mt $CO_2$/a) which account for 50–75% of the site emissions. If a larger amount of emissions were to be captured, the costs are estimated to rise significantly in comparison to only applying CCS for the largest emission sources on site. This is due to the large number of small stacks around the large production site.

The results showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment, but also on the chosen system boundaries and assumptions. Especially the assumed impacts on electricity production in the network affect strongly the amount of avoided $CO_2$ emissions. In the long term, the impacts on the electricity production system is an ambiguous issue due to, for instance, complex rebound effects on fuel, electricity and EUA prices and investment decisions. On the contrast, GHG emissions from ship transportation are only about 2% of the captured emissions and GHG emissions due to the capture plant construction even smaller. The cost levels obtained in this study are slightly higher than that of the literature.

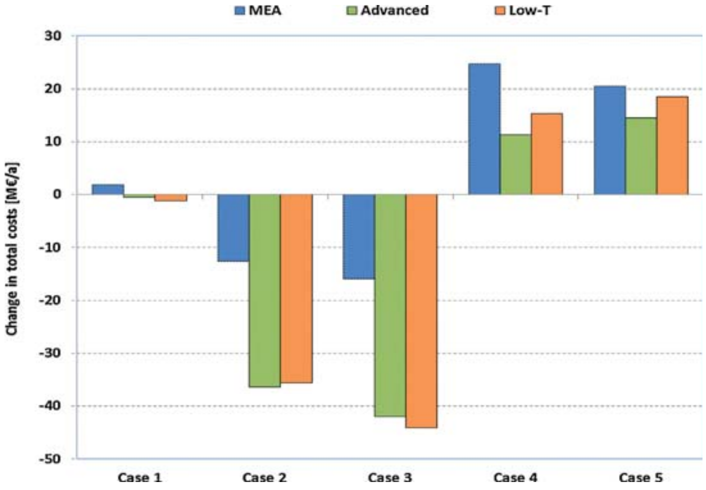

**Fig. 3.** The impact of CCS on the total costs in comparison with the reference case using different solvents and electricity price 100 €/MWh and EUA price 80 €/t.

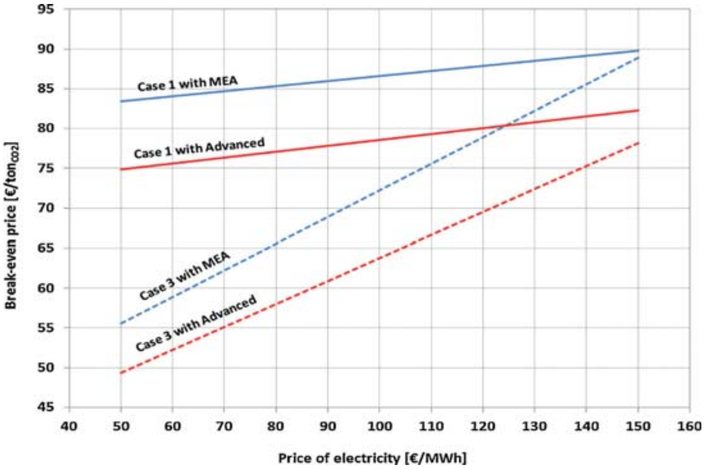

**Fig. 4.** The EUA break-even price for MEA and advanced solvents in cases 1 and 3.

However, the cost level in literature generally follows a rising trend according to the publication year, which may be partly due to the rising prices of services and material. Another reason for the higher cost levels of the present study is the long distance to a storage site and the assumption of using an offshore storage site. Comparing the present results to those for application of CCS in coal-firing power plant in Finland (Teir et al., 2011), that used similar approach (system boundaries, solvents, assumptions etc.) as the present study, the BEP for the studied steel mill application is almost 20 €/t lower.

Capturing and storing smaller amounts of $CO_2$ (in the range of 0.3 Mt $CO_2$/a), could be realized with very low operational costs, due to the waste heat available at the site of the steel mill. However, the total costs would still be in the same range as with the larger amounts captured due to the relatively higher investment costs for the smaller size equipment and higher transportations costs per ton of $CO_2$. The cost optimum depends on various factors, but in general, heat integration is a major contributor to the overall efficiency and economics of CCS installation.

Capture processes using more developed solvent processes were the most feasible solutions studied. A solvent, which could be regenerated using low temperature process heat, would probably result in significant advantages in the overall economics of CCS in the process industry, where substantial amounts of process heats are available in liquid phase. The figures presented in this study are based on the mapped heat recovery potential in the studied steel mill. Because extensive utilization of low temperature heat streams in the mill has not been relevant issue before, the amount of recoverable heat streams, especially in low temperatures, are unknown as well as the related investments. If the studied “Low-T” solvent could be developed and commercialized, even more low level waste heat could be available in the mill in comparison to heat streams above 130 °C that were considered in this study. This might lead to improvements in the feasibility of CCS if heat recovery can be implemented with low investment.

The EUA prices and electricity prices prospected for the near future do not turn the CCS investment profitable yet. Even if CCS would become more feasible than operation without CCS in the steel industry with higher EUA prices, the production costs of steel would rise drastically in the EU member states, unless free EUAs are given for the industry. Assuming an EUA price of 60 €/t (the lower end of the presented BEPs), specific $CO_2$ emissions of 1.8 t/$t_{steel}$ and a market price of 500 €/$t_{steel}$, the EUA cost increase would raise the price level of steel about 22% even when not taking the likely increase in electricity price into account.

In certain applications, such as in industrial processes and combined heat and power plants, significant improvements can be achieved with heat integration, for instance, in the production of district heat. The feasibility could also be optimized by using new operational options that CCS brings. For instance, $CO_2$ capture could be bypassed during periods of peak electricity prices. The optimal solution from the mill owner’s point of view depends on multiple factors with electricity price and $CO_2$ price being the dominant ones. The final result of the cost estimation is driven by the relationship between $CO_2$ emission prices and electricity prices. High $CO_2$ prices increase the electricity prices making the CCS less profitable because the value gained from the carbon allowances must exceed the value of the electricity production lost in the capture process in order to make CCS feasible.

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PAPER III

# Oxygen Blast Furnace with $CO_2$ Capture and Storage at an Integrated Steel Mill – Part I: Technical Concept Analysis

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# Oxygen blast furnace with $CO_2$ capture and storage at an integrated steel mill—Part I: Technical concept analysis

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ABSTRACT

In this study application of OBF with and without CCS to an integrated steel mill is investigated. The study is based on the real, Ruukki Metals Ltd.'s existing steel mill, located in the city of Raahe, Finland. Implications of application of OBF to energy and mass balances at the site are studied. Based on the technical evaluation, costs and feasibility for carbon capture are estimated. The energy and mass balance basis is presented in this first part of the series of two papers. Costs, feasibility and sensitivity analysis are assessed in the second part of the series (Tsupari et al. 2014. Int. J. Greenhouse Gas Control).

The impact of applying OBF at an integrated steel mill is evaluated based on a consequential assessment following the methodology of Arasto et al. (2013). Int. J. Greenhouse Gas Control 16 (August) pp. 271–277 concentrating only on the parts of the steelmaking processes affected by the deployment of OBF and $CO_2$ capture. The technical processes, $CO_2$ capture and the steelmaking processes affected were modelled using Aspen Plus process modelling software and the results were used to estimate the $CO_2$ emission reduction potential with OBF technology at an integrated steel mill.

The results show that the $CO_2$ emission from an iron and steel mill can be significantly reduced by application of an oxygen blast furnace and CCS. By applying only the blast furnace process, the emissions can already be reduced by 1.2 Mt/a without storing the separated $CO_2$. If captured $CO_2$ is also purified and stored permanently, the emission can be further reduced by an additional 1.4 Mt/a. This is a significant reduction considering that the production of the mill stays the same as in the reference case. In addition to carbon footprint of the production, application of oxygen blast furnace also has significant impact on coke consumption and energy balance on the site.

## 1. Introduction

Iron and steel industry is a significant contributor to global $CO_2$ emissions with up to 10% share of emissions from use of fossil fuels (IEA, 2008). In Europe, the recently proposed more strict emission reduction targets for 2030 also concern iron and steel production as it is part of the ETS sector (European Commission, 2014). Due to the high risk of carbon leakage, iron and steel industry seems to get majority of their emission allowances for free. However the tightening targets will bring the carbon prices higher and therefore the reduction of emissions would also be of interest in the iron and steel industry.

An oxygen blast furnace (OBF) is one technology for enabling carbon capture and storage (CCS) to an integrated iron and steel mill. Other options for reducing $CO_2$ emissions at the plant producing virgin steel, based on blast furnace + basic oxygen furnace (BF + BOF) route, are other $CO_2$ capture solutions, alternative fuels and energy efficiency measures. CCS is one of the only means possible for large reduction of $CO_2$ emissions from the plant site. However, application of OBF reduces coke consumption in blast furnace and therefore also $CO_2$ emissions even without CCS.

Recently, extensive work on development of OBF concept and technology has been conducted in ULCOS project (van der Stel et al., 2013). However, in addition to results of ULCOS projects (Birat et al., 2009; Birat and Lorrain, 2009), very few estimations of economic impact of application of OBF in steel mills are available. Recently, IEA GHG published a study conducted together with MEFOS and Tata Steel (IEA GHG, 2013). It should be noted that the study presented by IEA GHG is based on comparison of different technological options for construction of a new steel mill

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and it includes also other notable differences in assumptions and approach in comparison with this study, such as the use of a smaller coking plant and a natural gas fired power plant in the case of OBF.

In this study application of OBF with and without CCS to an integrated steel mill is investigated. The objective of the two series paper is to compare different process configurations and alternatives, their GHG impacts and costs related to an existing steel mill site. First one in the series is to describe technical concept and its direct implications. The second paper addresses the greenhouse gas impact and costs on site level (Tsupari et al., 2014). This also includes sensitivity analysis based on the technology described. The study is based on the real existing steel mill, located in city of Raahe, Finland. Implications of application of OBF to energy and mass balances at the site are studied. Based on the technical evaluation costs, feasibility and sensitivity analysis are assessed in the second part of the series. Similar methodology has been used as in the evaluation made in the CCS Suomi project for application of post combustion $CO_2$ capture to Ruukki Metal Oy's Raahe Steel Mill (Arasto et al., 2013; Tsupari et al., 2013), enabling comparison of results, both technical and economical between that study and the present study.

Ruukki Metal Oy's Raahe steel mill is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. In 2008, before the economic down term and blast furnace revisions, the $CO_2$ emissions from the mill were 4.5 Mt/year (EMV, 2011). Replacing sinters by pellets from 2011 onwards reduced the direct $CO_2$ emissions from the site by 0.4 Mt/a.

This paper describes the technical assessment of application of OBF with CCS to the Raahe steel mill. In addition, background information, used assumptions and approach for economic estimations are presented as well as examples of results based on the selected parameters.

## 2. Methods

### 2.1. General

The basis for the entire techno-economic assessment is the modelling of process environment, and application of oxygen blast furnace (OBF) with auxiliaries. Based on the energy and material balances obtained from the modelling and the technical feasibility of solutions the economic profitability is further evaluated (Tsupari et al., 2014). Emission reductions are estimated within the system boundary (i.e. from an investor's point of view).

The impact of applying OBF at an integrated steel mill is evaluated based on a consequential assessment following the methodology of Arasto et al. (2013) concentrating only on the parts of the steelmaking processes affected by the deployment of OBF and $CO_2$ capture. The technical processes, $CO_2$ capture and the steelmaking processes affected were modelled using Aspen Plus process modelling software and the results were used to estimate the $CO_2$ emission reduction potential with OBF technology at an integrated steel mill.

### 2.2. Reference case

It is realistic to assume that investment in CCS applications in Raahe would not take place before 2020. Therefore also the reference case of this study (without OBF) includes some future improvements, even if it is uncertain whether these improvements take place in reality. To enable comparison with results from the CCS Suomi project (Arasto et al., 2013; Tsupari et al., 2013), the reference case and related background data were kept as similar as possible to those in the CCS Suomi project and the same input data has been utilised where applicable. However, some modifications to the reference case were decided for this study as described below. The evaluation is based on a normal yearly production of 2600,000 t of hot metal and the annual operation of 8600 h for most of the units. The capacity of the current two blast furnaces is replaced by oxygen blast furnaces.

**Table 1**
Raw material consumptions for BF and OBF [kg/t hot metal].

| | BF | | OBF | |
|---|---|---|---|---|
| | kg/t Hot metal | t/a | kg/t Hot metal | t/a |
| Coke | 287 | 746,200 | 192 | 499,200 |
| Pellets | 1388 | 3608,800 | 1388 | 3608,800 |
| Briquettes | 100 | 260,000 | 100 | 260,000 |
| Quartz | 13 | 33,800 | 21 | 54,600 |
| BOF slag | 60 | 156,000 | 60 | 156,000 |
| Limestone | 44 | 114,400 | 48 | 124,800 |
| PCI | 180 | 468,000 | 180 | 468,000 |

As in the CCS Suomi project, the reference case of this study is based on the Raahe steel mills with additional improvements: the sintering plant was stopped, collection of converter gas to a new gas holder, and utilisation of the converter gas as mixed gas in a new power plant. Due to these improvements the reference case is slightly different from the present situation in the real steel plant. For example, electricity production in reference case is higher than at present in the real plant.

The most significant difference in comparison to the CCS Suomi reference case is injection of coal (PCI) to blast furnace instead of extra heavy fuel oil. This change was made in order to get a better comparison of the results with the ULCOS project (van der Stel et al., 2014) using experimental data provided by Ruukki based on PCI utilisation (Nevalainen, 2011). The differences in the reference cases have an impact on some results, but the impact is estimated to be minor when compared with overall uncertainties related to the impacts of OBF. However, utilisation of PCI changes composition of top gases from blast furnaces (incl. OBF), reduces steam consumption due to avoided oil heating and requires inert gas for injection of pulverised coal.

The difference between the steam consumptions in these two reference cases is partly compensated by different assumptions regarding investments on heat recovery from rolling mills. In the CCS Suomi reference case it was assumed that consumption of 30 bar and 10 bar steam is satisfied by heat recovery investments. In the reference case of this study, these investments in heat recovery are not executed, since 30 bar steam is not consumed because of heavy fuel oil replacement by PCI.

### 2.3. System boundary

The replacement of a normal blast furnace with OBF affects many of the processes at an integrated steel mill, but not all of them. The system boundary is selected to only include the process units significantly affected by the change. This way the whole integrated steel mill does not need to be modelled and included in the economic evaluation. From an economic point of view, only changes in the streams crossing the evaluation boundaries need to be assessed. Table 1 shows the raw material consumptions used for the reference case blast furnace (BF) and for the OBF case.

Based on Table 1 it can be concluded that the most important impact of the OBF on the blast furnace raw materials is the change in coke consumption. As consumptions of other materials are not significantly changed or these streams are purchased from external vendors or from other units or operators in the mill area (e.g. limestone), production or processing of these substances are not included in modelling. However, a more significant change in consumption of some materials could have other impacts as well,

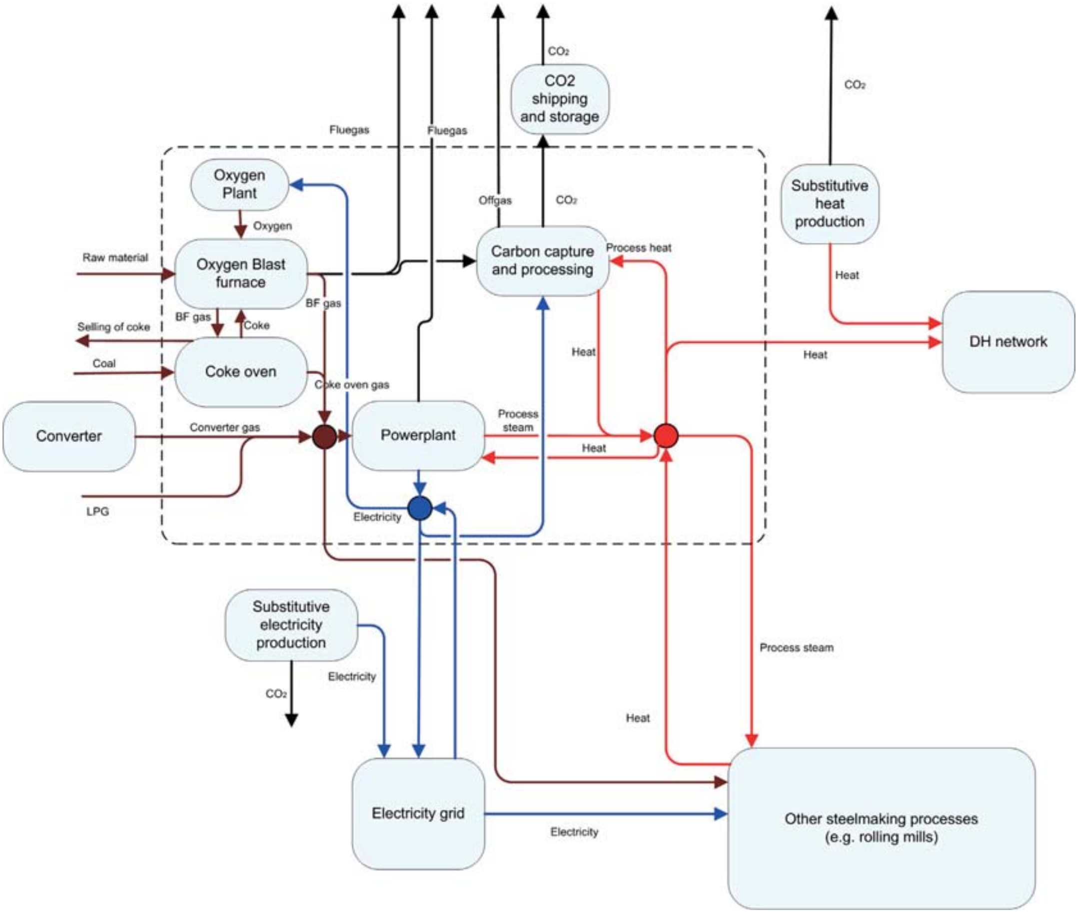

**Fig. 1.** Evaluation system boundaries utilised in the study. Dashed black line (inner boundary) indicates the economic system boundary. This boundary is utilised also in the case of break-even prices for $CO_2$ emission allowances from the investor's point of view. Dashed green line (outer boundary) indicates the impacts on the emissions from global/society's point of view.

for example on the amount of mixed gas sold to lime kilns (Fig. 1).

In the case of the OBF the following three scenarios for implications of decreased coke consumption were identified and discussed:

1. decreased coke production in coke ovens,
2. different coal properties (higher share of volatiles) and
3. similar utilisation of coke ovens and coke selling to markets.

Options (1) and (2) would have major impacts on the gas balances of the steel plant, coking plant feedstock as well as on operation and by-products from the coking plant. These impacts and technical limitations are partly unknown and therefore option (3) was chosen for modelling. However, options (1) and (2) could offer some benefits which are further discussed in the end of this report.

Based on the earlier presented assumptions, the system boundaries described in Fig. 1 can be assumed for calculations.

### 2.4. Technical evaluation

Technical evaluation can be roughly divided into two main parts:

(1) Implications of the application of the OBF on a process level and
(2) implications of the application of the OBF to the mass and energy balances on the site level.

Underlying questions on process level are different operation assumptions of the OBF process, selection of auxiliary processes, their energy requirements and integration to the steel mill. On site level the essential questions are: the overall energy balance on the site level, replacing fuel usage, replacing energy production and energy related investments.

The technical evaluation is based on detailed Aspen Plus modelling of the processes involved, such as the air separation unit, $CO_2$ separation unit as well as compression and purification of $CO_2$. Vacuum pressure swing adsorption (VPSA) was the chosen $CO_2$ separation technology in this study. The VPSA process was chosen as the capture technology, as it was expected that the amount of

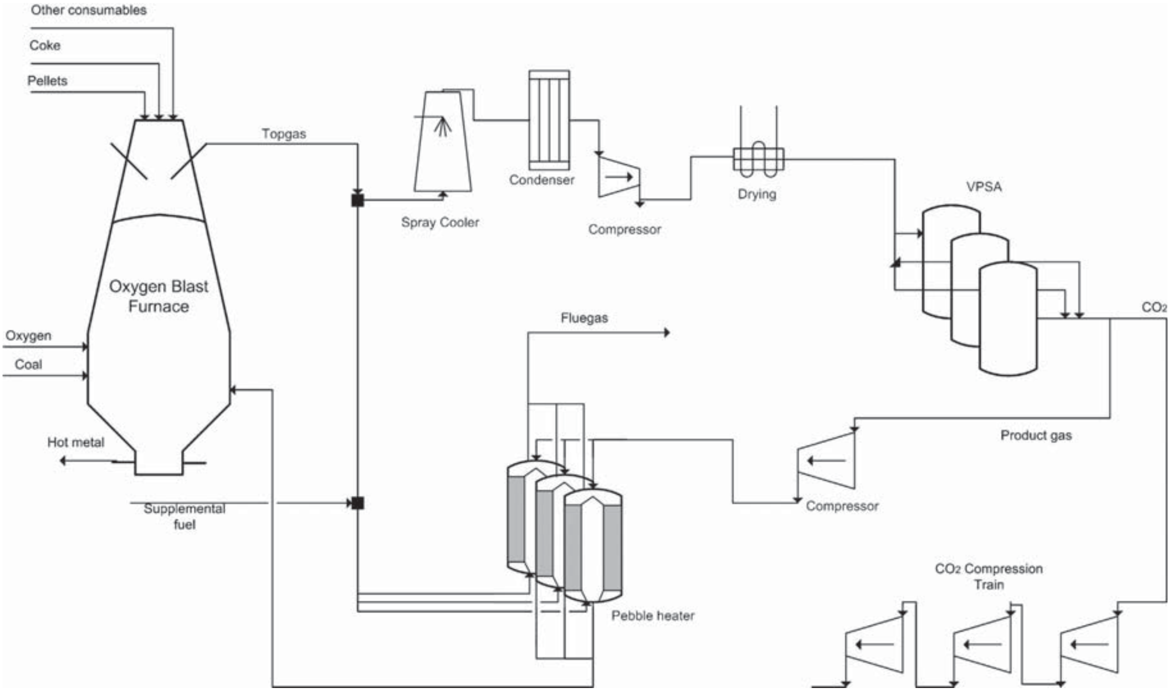

**Fig. 2.** Schematic process diagram of oxygen blast furnace process with CCS.

excess steam required by MEA capture is not available on site when removing the power production block. The results from the Aspen Plus model were used to estimate the impacts of the OBF on site level. For these estimations, a new steel mill application was created in the MS Excel based toolkit CC-Skynet$^{TM}$. More information about CC-Skynet$^{TM}$ is given for example in (Tsupari et al., 2013).

### *2.4.1. Detailed Aspen Plus modelling*

Process units and islands were modelled with an equilibrium model of the Aspen Plus process simulation software to get information on the plant level implications on mass and energy balances of the investigated. The process units and sections were modelled following the interconnections presented in schematic flow sheet in Fig. 1 and the information collected for balance calculations in CC-Skynet$^{TM}$ [Fig. 3]. Ambient conditions of 1.01325 bar and 10 °C were utilised for the steady state modelling. Conventional components based on PURE 24 database with PENG-ROB property method and STEAM-TA for free water method were used in Aspen Plus modelling.

OBF is a blast furnace fired with pure oxygen instead of oxygen enriched air. The schematic picture of application of OBF on a process unit level is presented in Fig. 2. In principle the process resembles a conventional blast furnace process but a part of the top gas is recycled back to the furnace to re-use the carbon in top gas as a reducing agent. Because of this the top gas of the blast furnace contains very little nitrogen. The $CO_2$ of the top gas is separated and the hydrogen and carbon monoxide recycled back to the blast furnace to act as reductant and improve the energy balance. The separated $CO_2$ is purified, compressed and sent to a permanent storage via ship transportation. Transportation costs have been assessed in a previous study (Kujanpää et al., 2011).

The blast furnace and oxygen blast furnace are modelled in this assessment as a black box with a yield block. The information about input and output streams is based on experimental data provided by Ruukki. The input and output gas compositions are presented in Table 2 and utility consumptions in Tables 1, 5 and 6. The injection temperature of recycle gas is estimated to be 900 °C.

Oxygen for the OBF is produced by an air separation unit (ASU). The ASU is utilizing conventional cryogenic technology for oxygen production. Similar ASUs are currently operating on the existing site to produce oxygen, for instance, for oxygen enrichment in the conventional blast furnaces. The current oxygen consumption of blast furnaces is 70 $Nm^3$/tHM and the oxygen consumption is estimated to rise to 220 $Nm^3$/tHM with an oxygen blast furnace (Nevalainen, 2011). Electricity consumption of the existing ASU is about 400 kW h/t $O_2$. The respective consumption of modern ASU technologies is 260 kW h/t $O_2$ (Hannula et al., 2013). Therefore, in OBF case, it is assumed that the new ASU is designed to fulfil the entire $O_2$ consumption of blast furnaces, therefore also replacing a share of the production of existing ASU. Electricity consumption and heat recoveries are diminished accordingly. The ASU is modelled with Aspen Plus process modelling software with RADFRAC distillation blocs on three different pressure levels and intercooling. It is assumed that utilisation of OBF technology does not have an impact on the oxygen consumption of (or production for) other processes (BOF converters etc.).

**Table 2**
Input gas flows and compositions (Nevalainen, 2011).

| | Top gas | $CO_2$ rich Gas | Product gas |
|---|---|---|---|
| $Nm^3$/t HM | 1276 | 457 | 819 |
| CO % | 46.1 | 6.3 | 68.3 |
| $H_2$% | 8.3 | 0.7 | 12.5 |
| $CO_2$% | 35.8 | 92 | 4.4 |
| $N_2$% | 9.8 | 1 | 14.7 |

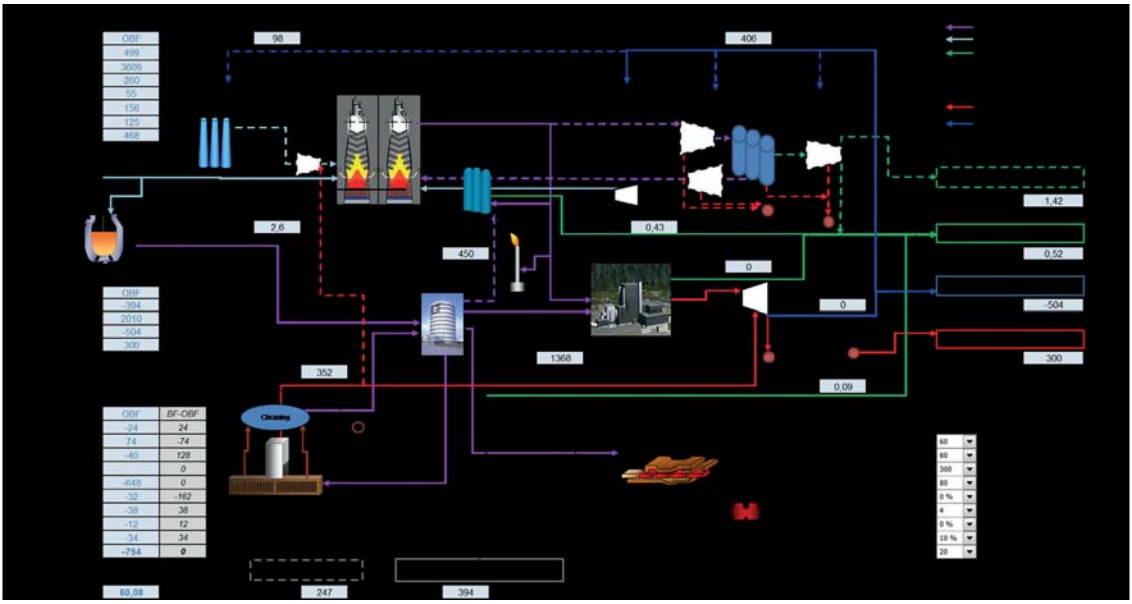

**Fig. 3.** Steel mill application built in CC-Skynet$^{TM}$ toolkit (OBF case study).

Cooling of process gas streams is done at three temperature levels in this assessment. The cooling above 110 °C is for steam production and above 60 °C for district heat production. The rest of the cooling is carried out using cooling water, typically down to 30 °C.

The top gas exiting from the OBF and going to the VPSA for $CO_2$ separation is cooled down to 30 °C before the compressors. Before cooling down, 10% of the top gas is taken to combustion to heat up the recycle gas stream before injection to the blast furnace. Hot gas is directed to the combustion to take advantage of the sensible heat in the gas.

Vacuum pressure swing adsorption (VPSA) is a technology used to separate some gas species from a mixture of gases under pressure according to the species' molecular characteristics and affinity for an adsorbent material. It operates at near-ambient temperatures and thus differs from cryogenic distillation techniques of gas separation. In addition to the adsorption vessels operated cyclically, the VPSA system consists of a compressor and a vacuum pump.

The VPSA process is modelled in Aspen Plus based on experimental data provided by Ruukki (Nevalainen, 2011). The modelling is explained in detail in Mondino (2013). The pressure before the adsorption vessel is 3.5 bar and the vacuum pressure at the exit of the vessel is 0.015 bar. The compressor before adsorption has one stage and the vacuum pump operates in two stages.

The $CO_2$ stream exiting from the VPSA is not pure enough for storage purposes and needs to be purified. Purification is done by cryogenic distillation at 26 bar similar to oxyfuel $CO_2$ purification processes developed (Pikkarainen et al., 2007; Tourunen, 2011). This produces $CO_2$ with a purity of 99.0%. After purification $CO_2$ is compressed to meet the conditions needed in ship transportation (−52 °C, 6.5 bar). Cooling of the $CO_2$ stream is done by first pressurizing the stream up 64.3 bar and flashing the stream to 6.5 bar in several stages (Arasto et al., 2013). The evaporated part is recirculated back to the compressors.

Purified and recycled top gas needs to be heated before injected into the blast furnace to secure the process conditions in the blast furnace. The gas is heated with a pebble heater from 88 °C to 900 °C. In Aspen Plus model, the pebble heater was modelled with a RSTOIC combustor block with heat exchangers on the flue gas side. The gas boiler is fuelled with blast furnace top gas (10% side stream), mixed gas (from coke ovens and converter) and LPG for additional fuel. LPG consumption for preheating is significant and therefore LNG may be utilised if it will be available in the future.

The amount of mixed gas combusted in the preheater is estimated to be equal to the amount of mixed gas used in the power plant in the reference case in order to minimise changes in gas utilisation on steel mill. The option to capture $CO_2$ from mixed gas, top gas or LPG combusted in the pebble heater was not modelled in this

**Table 3**
High and medium pressure steam consumption in OBF case (annual basis).

| | T1 [C] | P1 [bar] | qm [kg/s] | H [kJ/kg] | T2 [C] | P2 [bar] | qm [kg/s] | H [kJ/kg] | P [MW] | Q [MW h] |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steam production** | | | | | | | | | | |
| Coke oven line 1 | | | | | 479 | 84 | 5.1 | 3341 | 17 | 146,597 |
| Coke oven line 2 | | | | | 493 | 79.4 | 7.1 | 3383 | 23.9 | 205,169 |
| **HP steam consumption** | | | | | | | | | | |
| Turbo blower | 519 | 82.2 | 4 | 3443 | 25 | 0 | 4 | 105 | 13.4 | 114,820 |
| Vacuum | 519 | 82.2 | 1.9 | 3443 | 50 | 1 | 1.9 | 209 | 6.2 | 52,930 |
| 8 bar Steam production potential from leftover HP steam | | | | | | | 7.7 | 2886 | 22.2 | 191,292 |

study. Because the recycle gas needs to be heated as hot as 900 °C, there will be a lot of lower quality heat (below ~400 °C) available that cannot be utilised for heating of the recycle gas. This makes the effective efficiency (heat transferred to recycle gas divided by heat of combustion) of the heating of the recycle gas less than 50%. Additional heat losses in the pebble heater are assumed to be 5%. Part of the flue gas is directed to PCI drying and the heat left in rest of the flue gases recovered as low pressure steam. PCI drying by flue gases would replace PCI drying by flue gases of hot stoves in reference case. The heat requirement of drying is 390 TJ/a (Sihvonen et al., 2012).

In the reference case one blower runs with electricity, while the other runs with steam. Consumption of the steam driven compressor is 240 GW h/a 84 bar steam (Kinnunen, 2012) leading to compression work of 8.6 MW. It is assumed that the compression work needed in the other compressor is similar to this. The efficiency of an electricity driven compressor is assumed to be 85%, thus leading to electricity consumption of 10.1 MW (87 GW h/a).

In the OBF case oxygen from ASU is compressed instead of air, which leads to significant reduction in compressed volumes. The pressure of $O_2$ exiting ASU is assumed to be 1 bar. The steam driven compressor is assumed to be utilised for the compression of the oxygen stream leading to both blast furnaces, as there is an overcapacity of compressors and steam in the OBF case. As the steam compressor is assumed to be more suitable to higher pressures needed in the OBF, the existing electric compressor is left as a redundant one. This is at least a reasonable approximation for the utility consumption of turbo blowers [Table 5]. The pressure for oxygen going to OBF is 6 bar.

### 2.4.2. Implications on site level

The implications on site level (also taking into consideration processes excluded from the Aspen model) were assessed using the steel mill application built into the CC-Skynet$^{TM}$ toolkit [Fig. 3] in the CCS Suomi project (Tsupari et al., 2014). The fuel gas and heat de Kinnunen, K., 2012. Personal communication with Ruukki Metals by e-mail19.10.2012 mands of the processes outside the system boundaries were assumed equal between the reference case and OBF case. Based on this assumption and the results from the Aspen model (e.g. gas demand in OBF preheating and steam balance), overall demands for steam and additional fuels could be calculated.

The energy content of the mixed gas originates to 81% of energy from coke oven gas (COG) and 19% from converter gas (CNG). The mixed gas includes also 50 TJ/a of blast furnace gas in the reference case (Arasto et al., 2013). In the OBF case the amount of available mixed gas is therefore smaller because of the utilisation in heating the recycle gas. This is assumed to increase LPG consumption in rolling mills by 50 TJ/a. The amount of mixed gas combusted in power plant in reference case (450 TJ/a) is utilised for preheating of recirculation gas in OBF case. Most of the mixed gas is used in processes outside the system boundary of this study (rolling mills, coking plant). These processes are considered unchanged.

In the OBF case, the steel mill power plant will be significantly impacted. The amount of combustible gases will collapse and steam demand on site may be changed. In this study, high and medium pressure steam balances (82 bar and 8 bar, respectively) are estimated for the OBF case [Table 3] on an annual basis. Low pressure steam and heat consumptions are not studied in detail because there are already several sources of low pressure steam available in the mill and even more heat recovery can be utilised if an OBF with CCS is applied [Table 4]. The amount of steam available for reduction to 8 bar was calculated by decreasing the steam consumption of turbo blowers and reduction for vacuum from available HP steam. This was compared with 8 bar steam demand for which the same value as in the CCS Suomi project (130 GW h/a) was used (Arasto et al., 2013). The amount of steam available from the coking plant is enough to respond to the demand around the site [Table 3] and even some surplus high pressure steam would be available on an annual basis.

**Table 4**
Potential for heat recovery and cooling demands (MW as average power).

| Potential for heat recovery and needed additional cooling | | | |
|---|---|---|---|
| | Reference case | OBF | |
| **Flue gases** | | | |
| PCI drying | 12.6 | 12.6 | MW |
| Steam | 16.2 | 28.5 | MW |
| DH | 7 | 3.0 | MW |
| **VPSA compressors** | | | |
| Steam | 0 | 4.7 | MW |
| DH | 0 | 8.2 | MW |
| Cooling | 0 | 4.4 | MW |
| **CPU cooling** | | | |
| DH | 0 | 13.4 | MW |
| Cooling | 0 | 31.9 | MW |
| **Topgas cooling** | | | |
| Steam | 0 | 9.8 | MW |
| DH | 0 | 5.3 | MW |
| Cooling | 0 | 3.1 | MW |
| **ASU cooling (extra unit)** | | | |
| DH | 0 | 6 | MW |
| Cooling | 0 | 3 | MW |
| Steam total | 16.2 | 44.2 | MW |
| DH total | 7 | 35.9 | MW |
| Cooling total | 0 | 42.3 | MW |

Steam production values from the coking plant are considered as net output and therefore internal steam consumption of the coking plant is not taken into account separately in the steam consumption assessment [Table 3].

### 2.5. Scenarios

Based on the approach and values presented in the previous section, the energy balance and $CO_2$ emissions could be calculated for the steel mill with three scenarios resulting in different $CO_2$ emissions and economics:

### 2.5.1. Scenario 1: Reference

This is the baseline scenario, with no carbon capture process in place. The plant operates according to business as usual, and the power and heat are produced based on average demand.

### 2.5.2. Scenario 2: Application of oxygen blast furnace

The conventional blast furnaces are replaced with oxygen blast furnaces dimensioned to maintain the current production levels of the plant. The coking plant remains as it is in the reference case. $CO_2$ is being separated from the recycle gas stream only for the operational requirements of the OBF, but there is no compression and transportation to permanent storage. There is no electricity generation on the site.

### 2.5.3. Scenario 3: Application of oxygen blast furnace with CCS

$CO_2$ removed from the top gas stream in Scenario 2 is purified, compressed, and transported to permanent storage to mitigate climate change.

## 3. Results

The implications from the deployment of technologies on the energy consumption and production within the system are presented in Tables 5 and 6. The electricity production within the system is reduced from 137.2 MW to zero when applying oxygen blast furnace. The largest new energy consumers in Scenario 3,

**Table 5**
Changes in process gas streams.

| Impacted gas streams | Reference case | OBF | OBF with CCS | |
|---|---|---|---|---|
| **Oxygen to BF** | 70 | 220 | 220 | Nm3/tHM |
| | 7.6 | 23.9 | 23.9 | kg/s |
| | 270 | 0 | 0 | MW |
| **BF/OBF gas** | | | | |
| —to power plant | 270 | 0 | 0 | MW |
| —to preheaters | 129 | 53 | 53 | MW |
| —flaring/vent gas | 3.2 | 0 | 0 | MW |
| —to mixed gas | 1.6 | 0 | 0 | MW |
| **LPG (or LNG)** | | | | |
| —to OBF preheaters | – | 34.9 | 34.9 | MW |
| | – | 0.7 | 0.7 | kg/s |
| —replacement of BF gas in mixed gas | – | 1.6 | 1.6 | MW |
| **Coke oven gas (COG)** | | | | |
| —to power plant | 11.8 | 0 | 0 | MW |
| | 0.3 | 0 | 0 | kg/s |
| —to OBF preheaters | 0 | 11.8 | 11.8 | MW |
| | 0 | 0.3 | 0.3 | kg/s |
| **Converter gas (CNG)** | | | | |
| —to power plant | 2.8 | 0 | 0 | MW |
| | 0.4 | 0 | 0 | kg/s |
| —to OBF preheaters | 0 | 2.8 | 2.8 | MW |
| | 0 | 0.4 | 0.4 | kg/s |

**Table 6**
Changes in energy balances on process unit level.

| | Reference case | OBF | OBF with CCS | |
|---|---|---|---|---|
| Electricity consumption | | | | |
| Oxygen production | 11 | 22.4 | 22.4 | MWe |
| VPSA | 0 | 21.9 | 21.9 | MWe |
| BF air blower | 10.1 | 0 | 0 | MWe |
| Recirculation gas compressors | 0 | 3.5 | 3.5 | MWe |
| CPU | 0 | 0 | 21.8 | MWe |
| Impacted processes, total | 21.1 | 69.6 | 69.6 | MWe |
| Electricity production | | | | |
| | 137.2 | 0 | 0 | MW |
| Steam consumption | | | | |
| Turbo blower | 27.9 | 13.4 | 13.4 | MW |
| Heating required | | | | |
| Heat to recycle gas | 0 | 53.4 | 53.4 | MW |

oxygen blast furnace with carbon capture and storage, are oxygen production, $CO_2$ separation, $CO_2$ purification and $CO_2$ compression. However, some savings can be made with blowers pressurising the blast as explained in Section 2.4.1. The heat utilisation for district heating remains the same in all scenarios as new consumption cannot be justified (there is already a surplus of heat production in the reference case).

The implications on $CO_2$ emissions of the system are presented in Table 7 and closer break-out of the emissions from recycle gas heating are presented in Table 8. In Scenario 2, the direct $CO_2$ emissions from the system are reduced from 3.2 Mt/a in Scenario 1 to 1.96 Mt/a by only applying the oxygen blast furnace (i.e. no transportation or storage of $CO_2$). This is mainly due to the reduced coke consumption in the blast furnace. Nevertheless the on-site electricity production is also reduced to zero at the same time. With application of CCS to the system the emissions can be further reduced to 0.55 Mt/a. This is a significant reduction considering that the production of the mill stays the same as in the reference case. The major emission source in Scenario 1 is the blast furnace gas utilised in the power plant and in the hot stoves. In Scenarios 2 and 3, the blast furnace gas remains as the main origin of the $CO_2$ emissions to the air, being significantly smaller in Scenario 3.

## 4. Discussion

An integrated steel mill is a very complicated process. Application of an OBF would require a larger modification of the processes of the existing steel mill than the application of post combustion capture would require. However, it also enables several different solutions for how to apply the OBF. In theory, concept optimisation is possible taking into account hundreds of details and depending on prices and investments. In this study, only one technological solution for application of an OBF was modelled and one approach presented.

In addition to the approach and technological solution modelled in this study, at least the following configurations could be reasonable to investigate:

New or rebuilt power plant with alternative fuels.
Application of CCS also for other sub processes.
Oxygen enrichment in power plant.
Alternative scenarios for coking plant.
Minimisation of $N_2$/air feed to OBF process.
Optimisation of recirculation gas preheating.
Site level optimisation of utilisation of surplus steam.
Replacement of only one BF by OBF.
Potential in changing the recycle gas composition to be utilised for value added products.

These configurations are shortly discussed below.

In the case of the OBF, the power plant can be completely replaced by electricity purchase from the market (as in this study) or it could be rebuilt for different fuels. A rebuilt or new power plant could be smaller than the existing one and based at least partly on renewable fuels, which would probably improve economics in comparison to fossil fuels assuming high prices for $CO_2$ emission allowances in the future. Anyhow, at least some kind of reserve power plant may be required due to temporal variation in production and consumption of power and heat, and to secure steam and electricity supply in the mill.

Oxyfuel combustion and CCS facilities could be applied for other sub processes than only for the OBF, for example for OBF preheaters (and the power plant if utilised), bringing some potential benefits from the economy of scale and avoided $CO_2$ emissions. On the other

**Table 7**
$CO_2$ emissions from the system boundary.

| | Reference case | Oxygen blast furnace w/o CCS | Oxygen blast furnace with CCS | |
|---|---|---|---|---|
| Captured $CO_2$ | 0 | 0 | 1418 | kt/a |
| $CO_2$ to air from utilised BF gas | 3161 | 1814 | 396 | kt/a |
| $CO_2$ to air from flared/vented BF gas | 26 | 15 | 15 | kt/a |
| $CO_2$ to air from mixed gas combustion | 47 | 34 | 34 | kt/a |
| $CO_2$ from increased LPG consumption | – | 76 | 76 | kt/a |
| Total | 3.234 | 1.939 | 0.521 | Mt/a |

**Table 8**
Fuel utilisation in heating of recycle gas and related $CO_2$ emissions [kg/s].

| | Fuel use | $CO_2$ emissions |
|---|---|---|
| Top gas | 11.2 | 12.8 |
| COG | 0.3 | 0.5 |
| LPG | 0.7 | 1.9 |
| CNG | 0.4 | 0.5 |
| Total | 12.6 | 16.2 |

hand, investment and electricity consumption would increase and some processes may become more complicated. Utilisation of partial oxyfuel (oxygen enrichment) in the power plant would bring some benefits with fuels with low heating value and smaller post combustion equipment for power plant flue gases.

It could also be possible to optimise the temperature of preheated gas or even to avoid preheating of recirculation gas preheating entirely. This depends on the OBF process design. In this study, only one configuration was investigated with 10% of the top gas utilised for preheating. The optimal solution is dependent on for example prices of LPG and $CO_2$ emissions, but the share of top gas utilised in preheating could be larger to reduce the need for purchasing LPG.

In the modelled case, some surplus high pressure steam would be available in annual level. However, due to temporal peak demands of steam, a steam boiler or power plant may be required. On the other hand, some electricity could be produced by this high pressure steam. In that case, the modelled high pressure steam reduction to 8 bar could be replaced by expansion of the steam in a turbine to produce electricity. On the other hand, also other modelled electricity-driven compressors or blowers could be replaced by steam-driven compressor using the surplus high pressure steam. These options are not taken into account in this study and these could improve economics, especially with high electricity prices. In the case of the OBF, more surplus steam would be available also in low pressure levels. Utilisation of this energy in, for example, district heating or biomass drying would benefit the OBF case in terms of economics. However, the low heat consumption in the city located nearby the plant is limiting the potential utilisation of district heating and therefore additional benefits in comparison to reference case are not taken into account. Also additional heat recovery from, for example, rolling mills is possible. With high electricity prices it might be feasible to produce additional steam by recovered heat and invest in steam-driven compressors instead of electricity-driven.

## 5. Conclusions

In general, it is possible to significantly reduce greenhouse gas emissions from an integrated iron and steel mill by applying an oxygen blast furnace and CCS. However the OBF technology does not seem yet to be ready to be commercially applied in full scale to a steel mill. The largest capture amounts in the scenarios (1.8 Mt/a) account for 35% of the direct emissions from the whole steel mill site. In total the direct emissions could be reduced by up to 68%. Further reduction of the emissions would be technically and economically very challenging, as the remaining emissions are of smaller and from various different sources around the site.

The means for significant greenhouse gas emission reductions for an iron and steel mill producing steel from virgin raw materials are limited. Emission reduction could be obtained by deploying biomass as fuel and raw material for the processes, but in order to reach the levels discussed here, a very large amount of sustainable biomass would have to be deployed to the site, with additional costs associated to the raw material supply (Suopajärvi et al., 2014; Norgate et al., 2012). In addition, the suitability of bio-coke (coke produced from biomass) as a blast furnace raw material is not proven as several properties regarding compounds and strength are required. Risk-taking regarding the blast furnace of an integrated steel mill is not easy, as it is the single most important and a very expensive component of the mill. Therefore solutions involving CCS are in practice the only significant technological means to reduce the on-site emissions from virgin steel production of existing mills.

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PAPER IV

# Oxygen Blast Furnace with $CO_2$ Capture and Storage at an Integrated Steel Mill – Part II: Economic feasibility with sensitivity analysis

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# Oxygen blast furnace with $CO_2$ capture and storage at an integrated steel mill – Part II: Economic feasibility in comparison with conventional blast furnace highlighting sensitivities

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ABSTRACT

This article is part II of the series of two papers regarding the application of oxygen blast furnace (OBF) in Ruukki Metals Ltd.'s existing steel mill, located in city of Raahe, Finland. The economic assessment presented in this paper is based on the technical modelling presented in part I of the study. OBF with CCS would lead to large reductions in $CO_2$ emissions but also OBF without CCS would decrease emissions significantly due to decreased coke consumption. From economic point of view, other important consequences of OBF process are increased LPG or LNG (liquefied petroleum gas or liquefied natural gas) consumption, decreased electricity production (increased purchase from markets), required investments and $CO_2$ transportation and storage costs. As CCS processes typically, especially application of OBF is a trade-off between decreased electricity production and decreased emissions. Therefore a correlation between $CO_2$ price development and electricity price development is of interest. In this paper, several sensitivity analyses are presented with different prices for $CO_2$, electricity and other parameters. The results present the sensitivity of different options in terms of economic feasibility for large $CO_2$ reductions in the integrated steel mill based on blast furnace process.

## 1. Introduction

This article is part II of the series of two papers regarding the study about application of oxygen blast furnace (OBF) in Ruukki Metals Ltd.'s existing steel mill, located in city of Raahe, Finland. The OBF process utilizes oxygen separated from air and in the process blast furnace gas is recycled back to blast furnace. Therefore the process is also known as Top Gas Recycling Blast Furnace (TGRBF) or Nitrogen free BF process. OBF with CCS would lead to large reductions in $CO_2$ emissions but also OBF without CCS would decrease emissions significantly. Both of these options are included in the analysis. Background information and technical description is published in part I of the study (Arasto et al., 2014) including the results of the technical concept analysis. In this article, methodology used in the economic assessment is described and selected results of economic analysis are presented. The results include also comparison of feasibility of OBF with authors' previous study regarding application of post combustion $CO_2$ capture (PCC) in Raahe steel mill (Arasto et al., 2013; Tsupari et al., 2013). The objective of the study was to compare the feasibility of different technologies for large $CO_2$ emission reductions in Raahe mill with sensitivity analyses for main market variables.

In the literature, break-even prices (BeP) and costs per avoided $CO_2$ emissions are the most common indicators used for the economic feasibility of CCS (e.g. ZEP, 2011; IEA, 2008). In this study, BeP is used as one of the main indicators and it is defined as the required average price of $CO_2$ emission allowances in EU emissions trading scheme (EU ETS) during the considered time-frame to turn studied $CO_2$ emissions reduction option as feasible as the reference case. Some results of publications regarding feasibility of CCS in steel mills are presented in Tsupari et al. (2013) and those are not repeated here. In general, a rising trend in the cost estimations as a function of publication year was noticed, and the range of the estimations varied significantly, being typically between 30–80 €/t avoided $CO_2$ (IEA, 2008; GCCSI, 2009; IEA, 2011; WorleyParsons, 2011; Hooey, 2011; Wiley et al., 2011).

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Recently IEA GHG published a study conducted together with MEFOS and Tata Steel including extensive cost analysis (IEA GHG, 2013). They presented cost analysis for two post combustion capture cases as well as for OBF with MDEA/Pz $CO_2$ capture. Estimated costs (by default values) per avoided $CO_2$ tonne without transportation and storage costs are US$ 74–81/t $CO_2$ for PCC cases and US$ 57/t $CO_2$ for OBF case. The cost evaluation was developed in 2010 US$ with exchange rate 1.34 US$/€ (IEA GHG, 2013). Thus the respective costs as €/tonne $CO_2$ are 55–60 for PCC and 43 for OBF. The study includes also some sensitivity analysis and therefore also much broader possible cost range is presented. However, it should be noted that the study presented by IEA GHG is based on comparison of different technological options for construction of a new steel mill and it includes also other notable differences in assumptions and approach in comparison with this study, such as the use of a smaller coking plant and a natural gas fired power plant in the case of OBF. These fundamental differences have significant impact on the results and therefore all the results of these studies are not comparative as such.

Another recent study regarding CCS in iron and steel industry was presented by Ho et al. (2013). Wide range of costs was presented for various steel production and CCS technologies, including also different $CO_2$ sources of the mills. Application of CCS in some sources was identified expensive for example due to the lack of the economy of scale (cost per avoided $CO_2$ over A$200/t). Typical cost range for PCC with MEA process was 60–80 A$/t $CO_2$ excluding costs of transportation and storage. Capture costs with VPSA for the respective processes were lower, about A$40/t avoided. TGRBF process was identified more economical than conventional blast furnace with PCC in both cases, utilizing MEA and VPSA. Ho et al. (2013) reported costs in 2010 dollars. According to Bank of Finland (BoF, 2014), the average exchange rate in 2010 was about 1.44 AUD/€. Consequently, the presented costs as €/t $CO_2$ avoided are 42–56 for MEA process and 28 for VPSA.

In addition, steel mill CCS has been included in broader studies regarding emission reductions of different regions and countries. For example, recently Saygin et al. (2013) estimated future $CO_2$ abatement potentials of energy efficiency and CCS for the Dutch industry. The range of 39–94 €/t $CO_2$ avoided was presented for the iron and steel sector.

## 2. Methods

The impacts of applying OBF at an integrated steel mill are evaluated based on a consequential assessment following the methodology presented in, for example, Arasto et al. (2013), Tsupari et al. (2013) and Arasto et al. (2014). The approach is to focus only on the parts of the steelmaking processes affected by the deployment of OBF and $CO_2$ capture and exclude rest of the steel mill from the analysis. The boundary definition is multi-dimensional, as for example unchanged labour costs, facilities and equipment are excluded from the study even if for example employers would physically work with the processes inside the drawn system boundary. Obviously, required additional labour expenditures due to application of OBF are included in the study.

The economic assessment is based on the technical modelling presented in part I of the study (Arasto et al., 2014). The background data presented in part I is significantly based on the results of ULCOS Programme. In addition, some background data obtained from Ruukki's experts are used regarding for example prices. The idea of the economic assessment is to recognize the significant differences between the OBF process and reference case from the economic point of view and focus on these differences. Several cost categories, which may be very significant in terms of annual incomes or outcomes of steel mill operation, are excluded from the study or estimated roughly, if the difference in these categories is assumed to be minor between OBF case and the reference case. Emission reductions are estimated within the system boundary including only impacted $CO_2$ emissions relevant in EU ETS from the operator's point of view, i.e. any kind of life-cycle-analysis is not included. More detailed definition for the reference case is presented in Arasto et al. (2014).

**Table 1**
Annual net balance of the most impacted substances in system boundary.

| | BF | OBF w/o CCS | OBF with CCS |
|---|---|---|---|
| LPG [GWh/a] | 0 | −314 | −314 |
| Coke [GWh/a] | 0 | 2010 | 2010 |
| Electricity [GWh/a] | 1094 | −316 | −504 |
| $CO_2$ emissions [Mt/a] | 3.2 | 1.9 | 0.5 |
| $CO_2$ trans.&stor. [Mt/a] | 0 | 0 | 1.4 |

Negative values mean net consumption inside the boundary, positives mean net production.

This paper mainly focuses on two $CO_2$ emission reduction options, namely

(1) OBF with CCS
(2) OBF without CCS

These technologies are compared with reference case but in addition also with one post combustion $CO_2$ capture option presented in authors' previous study (Arasto et al., 2013; Tsupari et al., 2013). BeP's have been calculated by Eq. (1).

$$\text{BeP} = \frac{(\text{Profit}_{\text{reference}} - \text{Profit}_{\text{case}})}{(\text{CO}_{2\,\text{reference}} - \text{CO}_{2\,\text{case}})} \tag{1}$$

where, Profit means operator's profit excluding the purchase of $CO_2$ allowances and $CO_2$ stands for on-site $CO_2$ emissions (in respect of EU ETS). The incomes and expenditures not impacted by application of considered $CO_2$ reduction options are subtracted from Eq. (1).

### 2.1. Important cost categories

From the economic point of view, the most important results from technical modelling of OBF process are:

- increased LPG (Liquefied Petroleum Gas) or LNG (Liquefied Natural Gas) consumption
- decreased coke consumption (increased coke selling)
- increased electricity purchase
- decreased $CO_2$ emissions
- captured (transported and stored) $CO_2$

Electricity purchase is increased due to both, decreased production and increased consumption. Significant new consumption points are for example new air separation unit (ASU) and $CO_2$ processing unit (CPU). The impacts of OBF on these categories are presented in part I of the study (Arasto et al., 2014). Assuming annual operation time of 8600 h/a for average capacity, the following annual net balance of these substances can be calculated (Table 1).

The economic impact of the changes presented in Table 1 is strongly dependent on the prices of these substances. Prices should include all related variable costs, for example in the case of electricity also taxes and transmission fees but exclude fixed costs, such as constant monthly charges, if these are not changed from case to another. As the feasibility of OBF processes are very sensitive for prices of $CO_2$ allowances, electricity, LPG and coke, and relatively long timeframe (large uncertainty) is considered, results are presented as graphs rather than by single values. Some default values for used prices are presented in this section but the values for other important variables are presented in conjunction with figures. Prices are presented as 2013 Euros without any inflation corrections. For $CO_2$ transportation and storage a fixed value of 27 €/t is used in the figures, based on the same equation that used in earlier studies for Raahe mill (Tsupari et al., 2013). Originally, the equation is based on the modelling work presented by Kujanpää et al. (2011). The cost of $CO_2$ transportation and storage is highly uncertain and dependent on several factors, for example the location of storage site, the development of Nordic $CO_2$ transportation infrastructure and available options for (partial) utilization of $CO_2$ (including enhanced oil recovery, EOR), mineral carbonation etc. The default value is based on transportation to North Sea. However, it should be noted that storage potential for example under Baltic Sea is under research (Nieminen et al., 2011). Storage under Baltic Sea would decrease transportation costs from Finland.

Other significantly changing cost categories in the case of OBF are:

- Additional investment for OBF (incl. new ASU, CPU, etc.)
- Operation and maintenance (O&M) costs of the new processes

This study is based on the assumption that OBF is built when BF renovation is needed. Therefore for example production losses during construction time are not accounted for and the investment is defined as additional investment in comparison with BF renovation in the reference case. The investment on OBF itself can be even smaller than investment on BF in the reference case due to smaller dimensions of OBF (IEA GHG, 2013) but OBF with CCS requires large investments also on other units, such as ASU and CPU. Therefore overall investment is probably significantly greater in OBF case (with and without CCS) than in the reference case.

In the figures presented in this article the default value of 370 M€ is used for the additional investment required for OBF with CCS in comparison to the reference case. This is based on the experience of Ruukki regarding blast furnace renovations as well as unpublished estimations presented by ULCOS and equipment suppliers. The value is uncertain and therefore some sensitivity analysis is included in this article. The higher the assumed investment is the greater is the impact of given interest rate and economic lifetime on the feasibility of OBF. In this article, 10% interest rate and 20 years economic lifetime are used. The default value for additional investment required for OBF without CCS was assumed to be 60% of the additional investment of OBF with CCS. The presented values for additional investments are assumed to include all required auxiliaries. For example dust removal from blast furnace top gas and the separation of the gas components are important parts of OBF process.

The difference between consumption of BF and OBF feedstocks were presented in part I (Arasto et al., 2014). These feedstocks are a major cost in steel mills but only the difference in coke consumption impacts significantly on the economics between BF and OBF case. The market price of coke has varied significantly (Steelonthenet.com, 2013) and therefore some sensitivity analysis is presented also for coke prices in the figures of this article. The default price used for selling of surplus coke is set to 300 €/t. Other impacted O&M costs are mainly fixed costs (labour, etc.). The additional annual fixed O&M costs are assumed to be 4% of the additional CAPEX.

### 2.2. Less impacted cost categories

The examples of cost categories, which are not changed significantly and are therefore modelled roughly (or excluded from the system boundary) are:

- district heat selling
- O&M costs of the existing processes
- other labour costs
- feedstocks to other processes
- production and selling

At Raahe mill, district heating is produced by recovering heat from processes but during the peak demands also by steam bleed from the power plant. Heat is utilized by the buildings and service water in mill area and by selling heat to city of Raahe. There is potential to increase the amount of heat recovery in the mill but annual heat demand of the city is limiting the feasibility of the needed investments.

It is assumed that O&M costs of the existing processes, other labour costs and feedstocks to other processes are not changed due to OBF. This is based on the assumption that production (quantity and quality) and selling of steel products are not changed. This assumption is fundamental.

### 2.3. Correlations between prices

There are some correlations between the development of prices of fuels, electricity and $CO_2$ emission allowances. These correlations should be taken into account even if the correlations are ambiguous. In general, if fuel prices or $CO_2$ emission prices increase, also electricity price will increase.

In this study, upper and lower estimations are used to illustrate the impact of $CO_2$ price development on electricity price. Upper limit is estimated based on the $CO_2$ emissions from a coal fired power plant with moderate efficiency, representing higher end of the $CO_2$ emissions from typical marginal electricity production in Nordic electricity market (Nordpool) at present. Specific $CO_2$ emission of 850 g/kWh is assumed for this limit (corresponding about 40% net efficiency if marginal production is assumed to be solely coal firing). Therefore increase of 1 EUR/tonne in $CO_2$ price would increase electricity price by 0.85 €/MWh. Lower limit is assumed to be 20% of the upper limit. This can be considered to represent energy system where impact of $CO_2$ emission allowances on electricity price is small. Such a system could be for example future energy system where share of renewables (and/or nuclear) is increased and/or share of natural gas in marginal production is higher. It can also be considered to simulate the impact in the existing energy system if it is assumed that the impact on electricity price is not directly dependent on the emissions of coal power, especially with high $CO_2$ prices. However, the impacts of these correlations on steel production costs are presented in Fig. 1, where the production costs ($P_{\mathrm{Steel,ETS}}$) are calculated by Eq. (2)

$$P_{\mathrm{Steel,\,ETS}} = \frac{(\mathrm{Capex}_{\mathrm{CCS}} + \mathrm{OtherOPEX}_{\mathrm{CCS}})}{\mathrm{SteelProd.}} + P0_{\mathrm{Steel}} + E_{\mathrm{CCS}} * P0_{\mathrm{Electricity}} + P_{\mathrm{CO_2}} * (\mathrm{correlation} * E_{\mathrm{total}} + \mathrm{CO_{2,\,total}} \tag{2}$$

where, $\mathrm{Capex}_{\mathrm{CCS}}$ is the annual capital expenditures due to required CCS investments [M€/a]; $\mathrm{OtherOPEX}_{\mathrm{CCS}}$ is the impact of CCS on other operational expenditures than electricity purchase and $CO_2$ emissions, such as LPG consumption, coke selling and $CO_2$ transportation & storage (described in previous sections) [M€/a]; SteelProd. is annual steel production [Mt/a as crude steel]; $P0_{\mathrm{Steel}}$ is reference steel price, i.e. the steel production cost without the costs related to $CO_2$ emissions [€/t]; $E_{\mathrm{CCS}}$ is the additional electricity consumption due to CCS [MWh/t crude steel]; $P0_{\mathrm{Electricity}}$ is electricity price without the impact of $CO_2$ prices [€/MWh]; $P_{\mathrm{CO2}}$ is the price

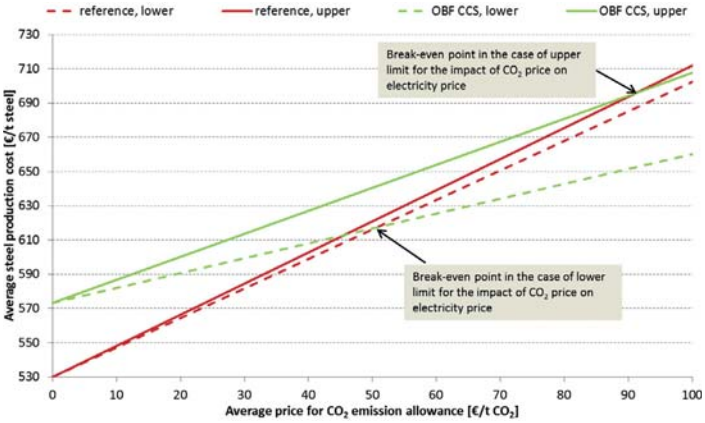

**Fig. 1.** Production costs of steel with different $CO_2$ prices and different impacts of $CO_2$ price on electricity price, in reference case and in the case of oxygen blast furnace (OBF) with CCS. Price for LPG purchase 60 €/MWh and for coke selling 300 €/t. *Note*: Production costs are based on the earlier presented general market price and therefore these costs do not present directly the production costs in Raahe mill.

of $CO_2$ emissions for steel mill (e.g. in EU ETS) [€/t $CO_2$]; correlation is the electricity price dependency on $CO_2$ price (described above); $E_{total}$ is the overall electricity consumption of the steel mill in each case [MWh/t crude steel]; $CO_{2,total}$ is the overall $CO_2$ emission from steel production in each case [t $CO_2$/t crude steel].

In the reference case, $Capex_{CCS}$, $OtherOPEX_{CCS}$ and $E_{CCS}$ are zero and can be neglected.

Other correlations between the most significant prices, for example between LPG, coke and electricity are not taken into account in this article as obvious correlations do not exist. Correlations between the development of prices of $CO_2$, LPG and coke are considered too ambiguous to be taken into account in this study.

## 3. Results

From the steel mill point of view, the production cost of steel may be the most important indicator about the feasibility of different future options. In Fig. 1 the production cost of steel in the reference case and in the case of OBF with CCS are presented with different $CO_2$ allowance prices and different impacts of increasing $CO_2$ price on electricity price. Steel price without costs of $CO_2$ allowances is set to 530 €/t based on general market prices during 2013 (Worldsteelprices, 2013). Cost of electricity purchase without the impact of costs of $CO_2$ allowances is set to 60 €/MWh.

As presented in Fig. 1, production costs in the reference case reach production costs with OBF at $CO_2$ price about 50 €/t if lower correlation between $CO_2$ price and electricity price is used. If higher correlation is used, large difference in electricity purchase leads to higher BeP for $CO_2$, about 90 €/t.

The BeP for $CO_2$ emission allowances can be presented also as a function of electricity price (Fig. 2). Because in the case of OBF the difference in net electricity consumption is large in comparison to the reference case, unknown future electricity price is probably the most significant factor of uncertainty in terms of OBF feasibility. In Fig. 2, also the sensitivity of BeP for the selected LPG price, coke selling price and investment can be seen. In addition, the sensitivity for the interest rate or economic lifetime can be estimated based on the sensitivity for investment.

In authors' previous study (Tsupari et al., 2013) feasibility of post combustion $CO_2$ capture in Raahe mills was estimated. Based on case 3 of (Tsupari et al., 2013) and default values of this study, the following figure (Fig. 3) can be drawn. From the previous study, case 3 with advanced solvent was chosen for comparison because it was typically the most feasible option within the varied parameters in sensitivity analysis.

Fig. 3 shows that any of the considered technologies may be the most feasible option in future, depending on electricity price and $CO_2$ allowance price. For example, even if the area for OBF without CCS is relatively small, the respective range for $CO_2$ price is more realistic in near future than the prices where other considered technologies for large $CO_2$ emission reductions would be feasible. The figure does not show the consequent steel production costs, which obviously would increase if prices of electricity or $CO_2$ allowances would significantly increase. Increase in production costs can be estimated for example based on Fig. 1.

The results are very sensitive for many of the parameters. There are several sources of uncertainty and ambiguous questions in the approach, technical modelling and economical assessments. For example, even if uncertainties of approach and technical modelling are not taken into account, by changing only few economic parameters the results look very different. In Fig. 4, similar graph than presented in Fig. 3 is drawn but with the following changes in parameters:

- Additional investment on OBF with CCS (over the reference case blast furnace renovation) would be 20% lower than default value (296 M€). This can be the consequence of technology development, investment subsidies, etc.
- Investment on OBF process without CCS would be 50% of the investment required for OBF with CCS (instead of 60% assumed in Fig. 3).
- LPG or LNG could be purchased by the price of 40 €/MWh. At present natural gas is not available in Raahe, but this could be the case for example due to published plans to invest on LNG terminal in Northern Finland (Torniomangalng, 2013).

According to Fig. 4, OBF without CCS would be economically the most feasible option at $CO_2$ allowance prices from about 20 €/t to 45 €/t, if electricity price remains relatively low. This can be considered as realistic range of $CO_2$ prices for the future. If $CO_2$ price would increase over 50 €/t, OBF with CCS would be the most feasible option according to Figs. 3 and 4. In this kind of scenarios, it could be possible to invest first on OBF process without CCS and if $CO_2$ price increases further, complete the investment with CCS when feasible.

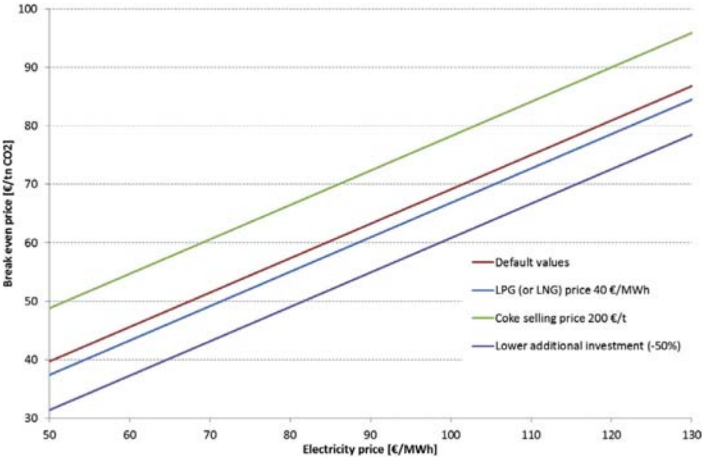

**Fig. 2.** Break-even price for $CO_2$ emission allowances, where Oxygen Blast Furnace (OBF) with CCS turns feasible over the reference case as a function of electricity price. Default values for LPG purchase 60 €/MWh and for coke selling 300 €/t. Default additional investment (in comparison to investments required in reference case) 370 M€.

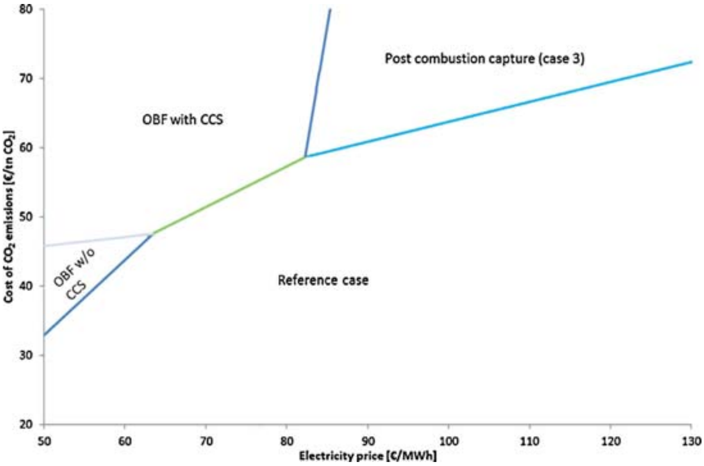

**Fig. 3.** The map of the most feasible technology options considered for Raahe mills with different market prices for electricity and $CO_2$ emission allowances in the future. OBF stands for Oxygen Blast Furnace, with or without (w/o) CCS. Default prices and investments (OBF with CCS 370 M€, investment without CCS 60%, LPG 60 €/MWh, coke selling 300 €/t).

However, the selling price for coke could be also lower than assumed 300 €/tonne, especially in the case of high $CO_2$ prices. If the selling price for coke would be 200 €/tonne, the feasibility of OBF would be much lower (Fig. 5). However, in that case different scenarios regarding coking mill and consequent impacts on the steel mill would be reasonable as well. In addition, LNG and lower investments could take place also in the scenario where coke price is low, improving the feasibility of OBF.

## 4. Discussion

Integrated steel mill is very complicated process and several technical scenarios with thousands of details are possible to analyze. Some potential improvements are listed in Part I of the study (Arasto et al., 2014) which would impact on the economics as well. In this part of the study, the focus was on the economics which introduces an additional dimension of the complexity and uncertainty on the results. Blast furnace investments are made for 20–30 years and prospects of future prices for, for example, $CO_2$ emission allowances, electricity, LPG/LNG and coke are extremely uncertain. In this article, only selected scenarios are possible to present.

As presented in the results of this study, BePs are very sensitive for several factors which are uncertain regarding the timeframe of large investments. Therefore results are presented as Figures rather than single numbers and the range of possible BePs is large. Large ranges are reported also in the literature presented in the introduction of this paper. In addition, details of integrated steel mills are very much site-specific and system boundaries selected for the studies vary. Therefore the comparison of the studies is difficult. However, the results of this study seem to fit well in the typical ranges presented in the cited studies. Taking into account relatively high costs of $CO_2$ transport and storage included in our estimations, the presented BePs can be considered even relatively low. If only capture costs would be included, BeP's would decrease significantly. For example in Fig. 3 with electricity price 80 €/MWh, BeP for OBF would decrease from 57 €/t to 44 €/t. The difference

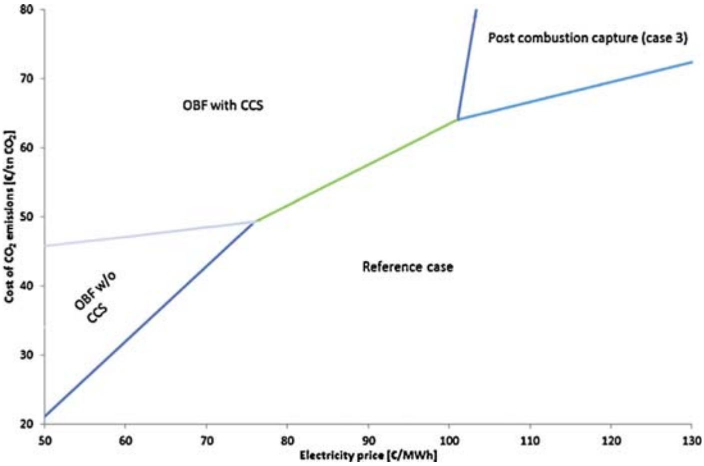

**Fig. 4.** Example of the sensitivity of the economics of different technology options for large scale $CO_2$ reductions (“Optimistic price scenario for Oxygen Blast Furnace, OBF”: OBF with CCS 296 M€, investment without CCS 50%, LPG/LNG 40 €/MWh, coke selling 300 €/t).

in OBF case is not directly the cost of transportation and storage (27 €/t) as $CO_2$ emissions are decreased also due to decreased coke consumption in OBF.

The break-even prices presented in the figures of this paper are typically the most feasible cases of numerous considered options. Despite of that, the presented cases may not be optimal, as several potential improvements were identified. Among the potential improvements listed in part I, electricity production by surplus high pressure steam available in the mill after the changes assumed due to application of OBF was discussed. By this steam, electricity production of about 122 GWh/a would be possible, if suitable turbine is available. If the turbine assumed for reference case could be utilized (no additional investment is assumed) the feasibility of OBF would improve as presented in Fig. 6.

At the moment, transportation and storage of $CO_2$ would be a significant cost factor for all Finnish CCS cases as there is no suitable storage capacity in Finland. In this study, the focus was on the $CO_2$ capture and steel mill process and therefore only one price for transportation and storage was used for OBF case. This value is highly uncertain and the results are very sensitive for this assumption. The uncertainty of transportation and storage costs is emphasized due to potential to decrease the costs significantly. For example storage potential under the Baltic Sea and the potential to utilize mineral carbonation is under research in Finland (Nieminen et al., 2011; Fagerlund et al., 2009). If remarkable development will take place with these opportunities or with $CO_2$ utilization options in Finland, the economics of presented CCS cases would be much better.

In this study, both of the existing blast furnaces at the mill are replaced by OBF. If only one BF would be replaced, the solution could be more economic with moderate $CO_2$ prices and with low coke selling price. The required investment (and risk) would be lower and blast furnace gas would be available for preheating and power (and steam) production. This would lead to significant savings in LPG consumption and electricity purchase. In addition, also electricity consumption would be smaller due to smaller

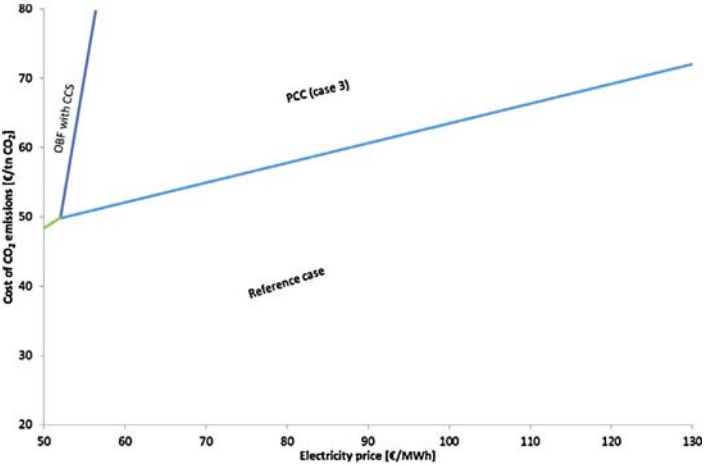

**Fig. 5.** Example of the sensitivity of the economics of different technology options for large scale $CO_2$ reductions (“Pessimistic price scenario for Oxygen Blast Furnace, OBF”: OBF with CCS 370 M€, investment without CCS 60%, LPG 60 €/MWh, coke selling 200 €/t). PCC means post-combustion capture.

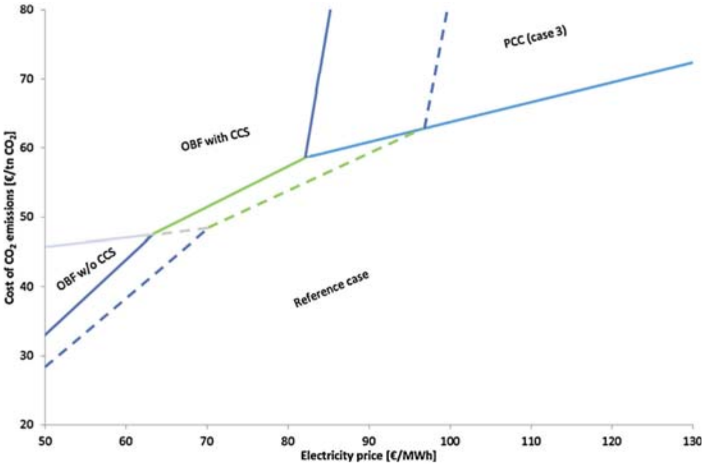

**Fig. 6.** The impact of additional electricity production by surplus steam available from coking plant and Oxygen Blast Furnace (OBF) preheater. Solid lines presents the break-even prices with default values as in Fig. 3 and dashed lines break-even prices with additional electricity production. PCC means post-combustion capture.

oxygen consumption and smaller amount of processed $CO_2$. However, smaller size of ASU, VPSA and other $CO_2$ processing equipment would result some drawbacks in terms of economy of scale and smaller reduction in $CO_2$ emissions and coke consumption would be achieved in comparison to modelled case. However, it is possible that replacement of both blast furnaces by OBF is more economical solution only with very high $CO_2$ prices.

Due to new ASU, it could be possible to gain some additional income from sold argon and nitrogen. This is not included in the economic analyses of this study. However, this impact is probably small in comparison to main cost categories of this study (Perander, 2010).

In theory, chemical looping combustion (CLC) could be applicable for blast furnace air or OBF recirculation gas preheating or for oxygen production to blast furnace. There are different options which could be applicable in steel mill with or without $CO_2$ capture.

Even if direct $CO_2$ emissions are decreased significantly due to OBF and CCS, indirect $CO_2$ emissions due to increased electricity consumption are higher in OBF cases. However, these emissions are not taken into account in economical assessments as these emissions are not from the processes of Ruukki and thus not equally relevant in terms of feasibility of OBF from investor's point of view. From LCA basis, impacts on the electricity production and consequent emissions are the major factor in terms of $CO_2$ emissions. Also the impact of coke selling may result in significant substitution credits. LCA and broader system analysis are ambiguous and strongly dependent on selected system boundaries, timeframes, etc. For example, emissions related to electricity purchase are very ambiguous, and the challenge is emphasized in Nordic countries. The average $CO_2$ emission of electricity production in Nordpool electricity market varies depending on seasonal precipitation but is typically very low, between 50 and 200 g/kWh. This estimate is based on country specific emissions presented by Soimakallio and Saikku (2012). Average specific emissions are low due to high shares of hydropower, biomass, other renewables and nuclear in the system. However, even if hydropower is used for short term regulation, coal fired plants are typically operating in marginal production and therefore the changes in electricity consumption impact mainly on the coal consumption in annual level. Specific $CO_2$ emissions up to 900 g/kWh have been presented for typical current marginal electricity production in an average precipitation year in the Nordic electricity markets (Soimakallio et al., 2009). Of course, Nordic energy markets are not isolated but imports and exports need to be taken into account as well. Relatively high specific $CO_2$ emissions are realistic to assume for marginal production also for example in Central Europe and Russia. The impact of selection of average or marginal emission factor for electricity is therefore significant (multifold) in all system and LCA studies considering Nordic countries, especially in the case of CCS where electricity penalty plays important role. This can be the case also in Central Europe in the future if share of renewables in the system increases. Further analysis about the complexity of determination of $CO_2$ emissions of purchased electricity is presented for example in Soimakallio et al. (2009).

However, from one point of view, $CO_2$ emissions within EU ETS cannot be decreased by individual actions as the amount of allowances to be released during the ETS period is fixed. Therefore the impacts on $CO_2$ emissions from other processes within EU ETS are not reasonable to estimate and direct $CO_2$ emissions have only the economic value, namely the price of $CO_2$ emission allowance. This approach was applied in this study. From broader perspective, more focus should be paid on any impacts outside of EU ETS, where emission reductions can be considered more valuable, whether those would take place in Europe in sectors excluded from ETS or regions outside Europe.

In the case of OBF there would be even more low temperature steam and hot water available for district heating than in the reference case. Benefit of the additional heat from OBF and CCS processes is that the heat would probably be available with relatively constant capacity. Heat has relatively high economic value in Finland but the consumption of the city is limiting the amount of district heat selling and therefore this potential is not taken into account in this study. However, during the previous years there have been plans about integration of biomass drying terminal to the steel mill (Cleantech News, 2012). This is an example of the processes where additional low temperature heat could be utilized.

## 5. Conclusions

As presented earlier, the feasibility of OBF (or CCS in steel industry in general) is very sensitive for the prices of $CO_2$, electricity and replacing fuels. In OBF process, electricity production decreases and consumption increases in comparison with the reference case. Also consumption of LPG or LNG increases. OBF process enables selling of coke due to smaller coke consumption and further savings are achieved from reduced $CO_2$ emissions even if CCS would not be applied. If CCS is applied, economic savings due to avoided purchase of $CO_2$ emission allowances would be significant, depending on price of the allowances. However, utilization of CCS would introduce additional costs due to electricity consumption in $CO_2$ compression and costs of transportation, which is emphasized in Finland.

There are very different estimations available for the investments required for CCS processes. Therefore sensitivity analyses are presented also for the investments. Depending on assumed investments and used market prices for fuels, electricity and $CO_2$ emission allowances, any of the considered technology options may result on lowest steel production costs in the future. Essential question is also the correlation between $CO_2$ price development and electricity price development.

Finally, it is important to notice, that increasing $CO_2$ prices will have a significant impact on steel production costs, whether CCS is applied or not. If these costs are increased only for some players in global markets, investment on OBF or CCS may not be feasible even if it would be less unprofitable than the operation in the reference case.

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PAPER V

# Barriers and Opportunities for Application of CCS in Nordic Industry – a Sectorial Approach

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# Barriers and opportunities for application of CCS in Nordic industry—A sectorial approach

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ABSTRACT

The potential for implementing carbon capture in Nordic industry sectors such as iron and steel production, cement and lime production, onshore and offshore oil and gas activities and pulp and paper production has been addressed. In Norway, much of the $CO_2$ is emitted from the oil and gas sector. In Denmark the power and heat production comprises the largest share while in Sweden and Finland biomass based industry such as power and heat production in CHP plants and pulp and paper production generates most of the $CO_2$ emissions. Iceland emits most $CO_2$ from metal industry, in particular non-ferrous metal production. In a Nordic perspective, the oil and gas industry has a high potential for implementation of CCS along with iron and steel production and cement production. Only cement production and pulp and paper production industries seem to have potential to decrease the $CO_2$ emissions close to zero. Capturing biogenic $CO_2$ from pulp and paper production could remove $CO_2$ from the atmosphere and create a carbon sink. Clustering of emission sources and implementing a joint CCS (Carbon Capture and Storage) chain could possibly lower the CCS unit costs. Process alterations and industry specific solutions due to the implementation of CCS in industry could improve existing processes. However, the possibility for carbon leakage could decrease the competitiveness of Nordic industries significantly as long as there is no global agreement on reduction of $CO_2$ emissions.

## 1. Introduction

During the last 200 years the atmospheric concentration of $CO_2$ has increased from about 280 ppm to around 400 ppm (Scripps Institution of Oceanography, 2014), of which an approximate increase of 80 ppm has taken place within the last 40 years alone (NOAA, 2013). As a response to increased concern about the ensuing climate change, several nations have committed to strategically prioritise the reduction of $CO_2$ emissions, among other greenhouse gas emissions. For instance, the European Union has committed to reduce emissions by 20% below 1990 levels by 2020 (European Commission, 2013).

In the Energy Technology Perspectives from IEA (Energy Technology Perspectives, 2014), various approaches are suggested in order to constrain global warming to 2 °C. Of these, Carbon Capture and Storage (CCS) accounts for about 21% of the required reduction. Beyond the oil and gas industry, where capture technologies were mainly developed for the purpose of enhanced oil and gas recovery, coal-fired power production has traditionally been the target of research and development of $CO_2$ capture. However, other industries also emit significant amounts of $CO_2$. In the Nordic countries there are four major industrial $CO_2$ emission sectors in addition to power and heat production: pulp and paper production, oil and gas activities, iron and steel production and cement and lime production. Waste treatment incineration, the chemical industry and non-ferrous metal production also emit significant amounts of $CO_2$ each year in the Nordic countries (NORDICCS, 2014).

In the Nordic Energy Technology Perspectives (IEA, 2013), the IEA states that “Decarbonisation is vital in the areas of electricity generation and energy use in industry, transport and buildings; it also requires deployment of carbon capture and storage (CCS)

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*Abbreviations:* ASU, air separation unit; BAU, business as usual; BF, blast furnace; BOF, basic oxygen furnace; CA, chilled ammonia; CCS, carbon capture and storage; CHP, combined heat and power; CLC, calcium looping cycle; DRI, direct reduced iron; EAF, electric arc furnace; EOR, enhanced oil recovery; GHG, greenhouse gases; LPG, liquefied petroleum gas; MEA, monoethanolamine; Mt, million tonne; MtC, metric tonne carbon; NGCC, natural gas combined cycle; NGL, natural gas liquids; NIMBY, not in my backyard; OBF, oxygen blast furnace; t, metric tonne; ULCOS, ultra-low $CO_2$ steelmaking.

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for cost-effective reduction of greenhouse-gas (GHG) emissions" and "Carbon capture and storage (CCS) accounts for more than 25% of industry emissions reduction and is also applied in electricity generation".

The only industrially implemented full CCS chain in the Nordic countries to be found today is in the Norwegian oil and gas industry, where initiatives to capture and store $CO_2$ were prompted by the national carbon taxes implemented in 1991.

The purpose of this paper is to discuss the potential and general challenges of implementing CCS in industrial sectors typical for the Nordic countries. The objective is to bridge the gap between system analysis and regional targets in EU and scenario work (IEA, 2013; Lehtilä et al., 2014) and technical assessments on application of CCS. The focus for the industry sectors in this discussion will be on large plants in the Nordic context. The additional value of combining information of solutions on different industrial sectors, national industrial structures and national targets is to enable a holistic view of the opportunities and prospects in Nordic countries in the medium and long term perspective. The power and heat sector has not been the focus in this discussion, as other industrial sectors seem to be the source of fossil $CO_2$ in Nordic countries in the longer perspective (IEA, 2013). However, as part of the whole picture, the power sector has occasionally been referred to for comparison or information. An introduction to the different carbon capture technologies is outside the scope of this discussion.

National policies and energy strategies differ significantly in the Nordic countries. Denmark aims to reduce GHG emissions by 30% by 2020 relative to 1990 levels and has indicated an approach towards the EU objective of 80%–95% reduction by 2050. CCS is not regarded as an important tool for $CO_2$ reduction initiatives towards 2020 in Denmark, partly due to the planned phase out of fossil fuels in the energy sector. Onshore storage of $CO_2$ in Denmark is not an option at least until 2020. There is, however, some interest in enhanced oil recovery (EOR), and permitting offshore $CO_2$ storage in the North Sea is currently ongoing (Anthonsen, 2014; The Danish Government, 2013; DOEA, 2014; The Danish Government, 2011).

Finnish energy policy is largely consistent with EU climate targets. Finland aims to use 38% renewable energy by 2020, including a 20% share of liquid biofuels in transport fuels. The overall political target for reduced GHG emissions by 2050 is 80%. The main approach to reaching this target is to reduce the use of coal by replacing it with renewable fuels for energy production. Furthermore, Finland is currently expanding its nuclear power production. As a consequence, and because the majority of industrially related $CO_2$ emissions in Finland are biogenic, the need for CCS is regarded as small and consequently not specifically supported by government policies. Finland has in addition no possibilities for domestic large scale storage of $CO_2$ and will have to rely on export of $CO_2$ for storage from any large scale capture facility (Nieminen, 2014; FMEE, 2013).

Sweden has a national target of 40% reduction in GHG emissions relative to 1990 levels, including a 50% share of renewable energy in the energy mix and a 10% share of renewable energy in transportation fuels. For 2050, the target is a near-zero net GHG emissions scheme, including a fossil free transportation fleet by 2030. With power production mainly based on hydropower and nuclear power, a significant share of $CO_2$ emissions in Sweden are generated by industry. CCS is regarded as one of the requirements for reaching the 2050 goal, however, no large scale onshore storage of $CO_2$ is allowed in Sweden. This means that Sweden is currently dependent on transportation of captured $CO_2$ to offshore storage sites, both national and international (Johnsson, 2014; The Swedish Government, 2012; Riksdag, 2014).

Norway has committed to a renewable energy share of 67.5% of overall energy consumption (equivalent) by 2020 (Ministry of Petroleum and Energy, 2013), a GHG reduction of 20% by 2020 and to be carbon neutral by 2030 (Røkke, 2014). Norway is in a slightly different situation than the previously mentioned Nordic countries, as most of its power production is based on hydropower (Ministry of Petroleum and Energy, 2013; Røkke, 2014). In addition, being heavily dependent on the oil and gas industry, the offshore $CO_2$ tax imposed in 1991 has spurred research into CCS. Norway currently has two full scale CCS plants storing about 1.5 Mt $CO_2$/a plus two test centres (catch and release) in operation (Røkke, 2014). The Norwegian government has a history of funding CCS projects through various sources although the full-scale CCS in the natural gas-fired cogeneration plant at Mongstad is currently cancelled.

Table 1
Nordic $CO_2$ emissions by sector in 2011 (NORDICCS, 2014).

| Sector | $CO_2$ emissions (Mt/a) |
|---|---|
| Pulp and paper production | 44.4 |
| Oil and gas activities | 22.6 |
| Iron and steel production | 11.8 |
| Waste treatment and incineration | 7.7 |
| Cement and lime production | 6.5 |
| Non-ferrous metal production | 3.8 |
| Production of chemicals | 3.6 |

Iceland is also in a unique situation compared to the other Nordic countries. Most of the energy production in Iceland is based on renewable geothermal energy. Some 80% of the primary energy supply is renewable (Ministry of Industries and Innovation, 2014), but there are still $CO_2$ emissions both from energy production and industrial processes. Historically, the Icelandic government has funded CCS research, partly ambitiously, but the current government is unclear in its policy and government funding is limited. Iceland, as part of the North Atlantic ocean ridge, has significant reactive basalt where $CO_2$ can be stored as solid magnesium or calcium carbonates, and extensive field scale $CO_2$ injection is currently ongoing in connection to the Hellisheiði geothermal power plant (Matter et al., 2009; Orkuveita, 2015). No capture or storage initiatives have been made for industrial $CO_2$ emissions in Iceland.

## 2. Industrial $CO_2$ emissions

In 2011 the total $CO_2$ emissions from point sources larger than 100,000 t/a reached more than 100 Mt/a in the Nordic countries alone (NORDICCS, 2014). Power and heat production is not included in these numbers and was out of the scope of this discussion. As shown in Table 1, the single largest industrial sector in terms of $CO_2$ emissions is pulp and paper production. The Nordic countries produce around 58–64 Mt of pulp and 45–47 Mt of paper yearly (FAOSTAT, 2013), accounting for 47% and 12.4% of the global production, respectively (Finnish Forest Industries Federation, 2013). The majority of the Nordic pulp and paper industry is located in Finland and Sweden, with a few plants in Norway. More than 90% of the $CO_2$ emissions related to the pulp and paper sector are of biogenic origin (NORDICCS, 2014). Table 2.

Table 2
The ten largest industrial point source emissions in the Nordic countries (>1 Mt/a) in 2011 (NORDICCS, 2014).

| Facility | Sector | Location | $CO_2$ emissions (Mt/a) |
|---|---|---|---|
| SSAB Europe | Iron and steel | Raahe, Finland | 4.0 |
| Neste Oil Oyj | Oil and gas | Porvoo, Finland | 3.0 |
| Stora Enso Oy | Pulp and paper | Imatra, Finland | 2.6 |
| SSAB Oxelösund AB | Iron and steel | Oxelösund, Sweden | 2.2 |
| Statoil ASA Mongstad | Oil and gas | Mongstad, Norway | 2.1 |
| Södra Cell Mönsterås | Pulp and paper | Mönsterås, Sweden | 1.9 |
| Preemraff Lysekil | Oil and gas | Lysekil, Sweden | 1.7 |
| Cementa AB | Cement and lime | Slite, Sweden | 1.7 |
| Aalborg Portland | Cement and lime | Aalborg, Denmark | 1.7 |
| UPM-Kymmene Oyj | Pulp and paper | Pietarsaari, Finland | 1.7 |

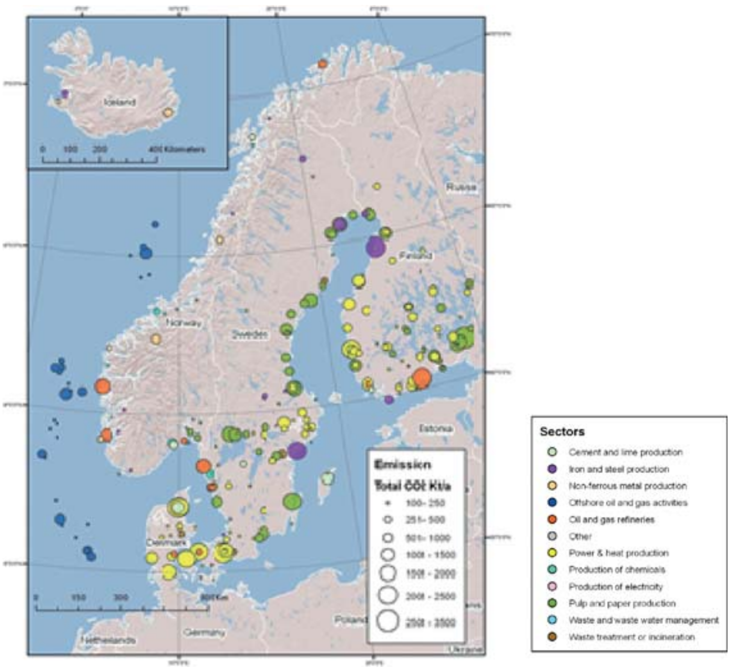

**Fig. 1.** Nordic $CO_2$ emissions by sector and size, including emissions from fossil, inorganic and biogenic sources (NORDICCS, 2010).

Although Norway is the main exporter of fossil fuels, oil and gas activities, including both offshore activities and onshore refineries, are present in all Nordic countries except Iceland. About 62 Mt of crude oil is processed each year at refineries in the Nordic countries (Refinery home pages, in press). Offshore oil and gas recovery activities are located mainly in the North Sea (Norway and Denmark). Sweden also has a small share of offshore oil and gas activity in the Baltic Sea. Onshore oil and gas refineries comprise the majority of $CO_2$ emissions from this sector.

The average production of crude steel in the Nordic countries amounts to about 10 Mt each year (2010) (World Steel Association, 2013). The main steel product is hot rolled plates. There are two major steel works in the Nordic countries: The SSAB Europe Raahe steel mill in Finland and the SSAB EMEA mill in Luleå, Sweden. Situated geographically close to each other and with similar production processes, these plants could potentially create a platform for a $CO_2$ transport cluster in the northern reaches of the Gulf of Bothnia. In addition, there are few smaller plants in Finland, Norway and Sweden and one plant in Iceland.

Approximately 7.4 Mt of cement is produced in the Nordic countries annually (USGS, 2013). The total production capacity is slightly higher than this reported amount, as production rates vary according to demand. The largest cement production plant, owned by Aalborg Portland A/S, is situated in Aalborg, Northern Jutland in Denmark. In Norway, the largest plant is owned by Norcem AS, located just across the Skagerrak Strait. In Sweden there is a large cement plant on the east coast of the island of Gotland. The plant is owned by the same corporation as the Norcem AS plant in Norway, Heidelberg Cement Group.

The cement plants in Norway and Denmark, together with the Preemraff refineries on Sweden's west coast, could potentially incorporate a larger $CO_2$ transport cluster as all plants are situated on the coast, which facilitates transport both by pipeline and tanker. Distance to potential storage sites below the sea bed in the North Sea would be relatively short for this cluster. In addition to the Utsira formation in the North Sea a potential storage site, Gassum, has recently been identified in the Skagerrak Basin (CCS in the Skagerrak/Kattegat Region, 2012). For this potential cluster the average transport distances would be approximately 180–560 km for storage in the Gassum formation and approximately 560–1650 km for storage in the Utsira formation (Kjärstad et al., 2014).

A major issue concerning the implementation of CCS in industry is the potential for carbon leakage. This is of special concern for industries that operate and compete for market shares worldwide such as iron and steel production, pulp and paper production, non-ferrous metals and chemical production. The additional cost of CCS will be met by the consumer, either directly through taxes or through subsidy schemes. This will potentially lower the competitiveness of Nordic industries in the market unless same regulations apply globally. Oil and gas activities and waste treatment and incineration are also vulnerable to additional production costs. Combined power and heat production, as well as cement and lime production, are targeted mostly at local markets within the individual countries or neighbouring countries. As a consequence, the effect of additional costs for CCS implementation in these industry sectors is smaller. Market prices will increase as a consequence, but there will not be the situation where there are competition advantages for some of the producers. Fig. 1.

## 3. Nordic industry sites

In this paper the major industrial $CO_2$ emitting sectors in the Nordic countries have been identified and evaluated. The sectors identified are: iron and steel production, cement and lime production, oil and gas activities, pulp and paper production, aluminium production and the chemical industry.

### 3.1. Iron and steel

Globally, iron and steel production accounts for around 6% of anthropogenic $CO_2$ emissions each year (IEAGHG, 2013a). The iron and steel industry is one of four major emitters of industrial $CO_2$ in the Nordic countries, with a total of almost 12 Mt $CO_2$/a. The largest single source emission of $CO_2$ in the Nordic countries is an iron and steel mill.

There are two main methods for producing steel: by extracting iron from iron ore through a reduction process or recycling steel scrap through a melting process. Steel production from crude iron ore is preceded by iron production. The major refining process for iron production is via the blast furnace and basic oxygen furnace method (BF + BOF), accounting for 95% of global iron production and about 70% of global steel production (IEAGHG, 2013a). The direct reduced iron (DRI) method accounts for about 5% of global iron production (World Steel Association, 2011). Steel scrap and steel recycling is performed in an electric arc furnace, where the steel or solid iron from a direct reduced iron process is melted by electric power. Around 30% of global steel is produced via this method (IEA Clean Coal Centre, 2012; Bureau of International Recycling, 2012). Currently, the main iron production process represented in the Nordic countries is the BF + BOF route in an integrated steel mill. In the future, the Nordic iron and steel production technologies might change for more novel concepts, such as the plan is for the TiZir ilmenite upgrading facility in Tyssedal, Norway, (Grande, 2013), but only blast furnace based processes have been considered in this paper.

The blast furnace process extracts iron from crude iron ore ($Fe_2O_3$) by heating the ore and melting the metal fractions to liquid pig iron. In order to extract the oxygen from the iron ore, an efficient reduction process is required. This is obtained by adding a reducing agent, typically coke, to the blast furnace. The carbon reacts with the iron oxide and produces carbon monoxide, which again reduces the iron oxides to pure iron during a combustion process ($Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$). The coke is typically coal that has been pyrolyzed in an oxygen-free atmosphere in order to drive off volatile matter.

Iron and steel production processes vary significantly and depend on production site, quality of iron ore and fuel availability and cost (mainly natural gas and coal). A modern, integrated steel mill is a complex system consisting of various individual process steps. The result is a number of scattered $CO_2$ emissions sources, which makes the capture of $CO_2$ more challenging compared to $CO_2$ capture from a single stack. Typically, about 1.8 t of $CO_2$ is generated per tonne of liquid steel produced (ArcelorMittal, 2011). The majority of the $CO_2$ emissions are generated during iron production and end up in the flue gases. This allows for the possibility of implementing post-combustion $CO_2$ capture without altering the existing processes. However, the different off-gases vary widely in composition and conditions and as a consequence, the flue gases cannot be directly accumulated into one central $CO_2$ capture unit. Typical $CO_2$ concentrations in process and flue gases in an integrated steel mill are 20–25 vol% in blast furnace off-gas, 16 vol% in converter off-gas, 25–30 vol% in power plant flue gas and ±30 vol% in hot stoves flue gas. Off-gas from coke ovens contains little or no $CO_2$ at all. Additional carbon content in flue gases is found mainly in the form of CO. Typical CO concentrations are 20–25 vol% in blast furnace off-gas, 60–70 vol% in converter off-gas and around 5 vol% in coke oven off-gas. Coke oven off-gas contains in addition around 20–25 vol% methane (Arasto et al., 2013). Off-gases from blast furnaces, coke ovens and converters are usually not emitted directly, but combusted in the power plant for production of power and heat. As a result, the most significant $CO_2$ streams from an integrated iron and steel plant are flue gases from the power plant, the hot stoves and possible CCS processes.

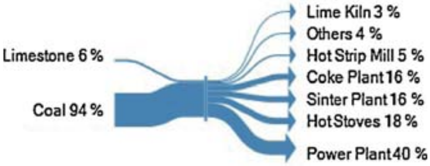

**Fig. 2.** Carbon flow in a typical integrated steel plant.

The major source of $CO_2$ originates from the coal used as reducing agent in the blast furnace. As of today, there are no real alternatives to reducing agents. Torrefied biomass could be utilised to replace coal injection and even coke to some extent, but current costs exceed coal prices. Theoretically, it is possible to use hydrogen instead of CO, but the technology is not currently ready for industrial implementation. Experiments with waste plastic and animal waste have been performed, but substituting conventional coal will in any case alternate the furnace balance and might affect the production process. Fig. 2.

### 3.2. Cement

The main raw material of cement is limestone ($CaCO_3$). After being quarried, the limestone is transported to the cement plant, ground to powder and mixed with correction materials. This is to ensure the right quality of the cement end-product. The powder mix is heated to 1000 °C in multistage cyclone pre-heaters by hot exhaust gas. In the precalciner, the powder mix is heated further and the limestone is reduced to CaO and $CO_2$. The mixture then enters the rotating kiln where it is heated gradually as it moves down the kiln, finally reaching a temperature of 1450 °C. The powder mixture is sintered together and small balls called clinker are formed during this process. After cooling, the clinker, together with additives like plaster, lime, slag and fly ash, is ground to cement in mills. The $CO_2$ concentration of the exhaust gas depends on the air leakage in the process and can consequently vary between 12–30 vol%.

In addition to being the raw material of cement, limestone has many other uses, for instance in the manufacture of steel, paper, glass, and as a neutralising agent. The quality of the limestone will in some cases dictate its use. For instance, the limestone quarried at Nordfrakalk's facility in Norway is utilised in the making of high quality paper due to its white colour and purity, while the limestone quarried in Brevik, Norway, is used in cement production. Between 0.6–1.0 t of $CO_2$ is generated per tonne of cement produced (IEA Clean Coal Centre, 2012; OECD/IE.A, 2007). The emission rate will vary depending on the limestone quality, type of fuel used, energy efficiency and on the share of clinker in the cement (type of cement). Generally, about 60% of $CO_2$ emissions originate from the calcination process, while the remaining 40% is related to fuel consumption, usually coal. The future demand for cement in the Nordic region is difficult to predict as it is highly dependent on the activity level in the construction market, which again is dependent on the global economic situation. A recent survey by IEAGHG (IEAGHG, 2013b) showed that there is awareness towards CCS and an understanding of the relevancy of CCS in the cement industry. This is also reflected in the number of past and current research and pilot projects on CCS in the cement industry. Fig. 3.

**Fig. 3.** Carbon flow in a typical cement plant.

### 3.3. Oil and gas refineries

There are $CO_2$ emissions related to oil and gas recovery operations offshore, mainly from the combustion of natural gas for power generation. In addition to emissions directly connected to recovery operations, there are also emissions related to the refinement of crude oil and natural gas. These emissions are the focus of this paper.

Crude oil refineries are complex processing plants, and defining a standard layout is challenging as the type of processing units at a refinery will depend on the composition of the crude oil received and the number of refining steps involved. The products are mainly used for fuel, but some are processed further in petrochemical plants to produce chemical products. Different hydrocarbon molecules have different chain lengths, and they can be separated based on their boiling points. As a result, the major unit in a refinery is the crude oil distillation tower. Heat is generated as a result of superheated steam, and the distillation takes place at atmospheric pressure. The crude oil is heated up to just below 400 °C and starts to boil before it enters the distillation tower. In the tower, the lighter hydrocarbons evaporate and are separated by condensing out the vapours at different stages as they rise up the tower. The lightest fractions with the lowest boiling points exit at the top of the tower while the heavy hydrocarbons are removed as bottom fractions. Commonly, the bottom fractions are further treated through vacuum distillation. The different fractions are treated further to remove impurities. Many of the distillates need further processing, or cracking, in order to produce the desired petrochemical products. Cracking is a process that breaks longer complex hydrocarbons down into simpler fractions. The most common cracking methods are thermal (temperature about 800 °C), catalytic (fluid catalysts, temperature about 500 °C) and hydrocracking (combination of catalytic cracking and hydrogenation in the presence of hydrogen).

$CO_2$ emissions related to oil refining depends on many factors such as crude oil composition, the refining process method, energy efficiency and the type of fuel. CONCAWE (CONCAWE Refinery Management Group, 2011) reported that on average, 200 kg of $CO_2$ per tonne of crude oil is emitted from European refineries. An investigation into $CO_2$ emissions from oil refineries in the Nordic countries yielded a widely varying result; 63–153 kg $CO_2$ emission per tonne of crude oil processed (CCS in the Skagerrak/Kattegat Region, 2012).

In addition to the crude oil distillation tower and vacuum distillation, Preem's refinery in Lysekil, Sweden also has catalytic and hydro cracking. The final products are gasoline, diesel, propane, propylene, heavy fuel oil and bunker oil. $CO_2$ is generated from the burning of fossil fuels to produce the energy needed for the various refining steps. Some 97% of the $CO_2$ is emitted through four stacks and the $CO_2$ concentration of the flue gases varies between 6.7 to 24 vol% (CCS in the Skagerrak/Kattegat Region, 2012).

Natural gas mainly consists of methane. However, other hydrocarbons and impurities may be present to a varying degree, depending on the gas field from which it is extracted. The processing of natural gas is less complicated than crude oil refining. Nevertheless, several operations are required before the natural gas is ready for sale. Before the hydrocarbons in natural gas are separated, impurities like $CO_2$, $H_2S$ and water are reduced to achieve the required specifications. Natural gas liquids (NGL) can then be recovered through cryogenic absorption or adsorption, the former being most frequently used. NGLs are absorbed using absorption oil. The methane and ethane exit from the top of the tower and the NGLs exit from the bottom of the tower together with the absorption oil. The oil is recovered by heating the mixture to above the boiling point of the NGLs. In cryogenic extraction, the natural gas is cooled down to approximately −85 °C. The temperature drops rapidly and all of the hydrocarbons except methane and some of the ethane are condensed out. After this first separation process, the NGLs are fractionated by utilising the difference in boiling point of the hydrocarbons as the hydrocarbons are boiled off one by one. These steps are called de-ethanisation, de-propanisation, de-butanisation and de-isobutanisation.

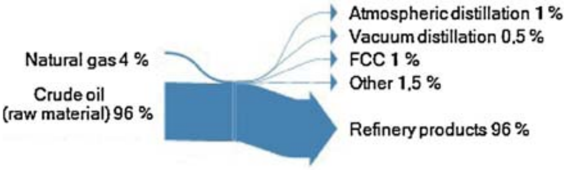

**Fig. 4.** Carbon flow in a typical oil refinery.

$CO_2$ is currently separated from two installations on the Norwegian Continental Shelf. The Sleipner West field produces natural gas with a $CO_2$ content of between 4–9 vol%, which is above the sales specification at 2.5%. The excess $CO_2$ is removed and injected into the Utsira formation at a maximum annual injection rate of 0.9 Mt $CO_2$. The other installation is at Melkøya, where natural gas from the Snøhvit field is cooled and compressed to liquefied natural gas (LNG). Before cooling, the $CO_2$ (5–8 vol%) is removed from the natural gas. The $CO_2$ is stored offshore in the Tubåen formation at a maximum annual injection rate of 0.7 Mt $CO_2$.

It is likely that there will be an increased need for separation of $CO_2$ from the natural gas if fields with a $CO_2$ content higher than 2.5% is to be produced. The Norwegian Petroleum Directorate (Halland, 2014) reports that gas fields discovered on the Norwegian Continental Shelf can vary greatly in $CO_2$ concentration, up to 20 vol%, with the majority being below 10 vol%. Fig. 4.

### 3.4. Pulp and paper

The majority of pulp produced in the Nordic countries today is produced via the chemical pulping process, or more specifically by the Kraft process. The Kraft process emits about three times as much $CO_2$ as the mechanical pulping process and is also the main process used in Nordic pulp and paper mills. Consequently, only Kraft process pulp production has been assessed in this paper.

In the Kraft process, raw wood chips are digested under elevated temperature and pressure in an alkali environment typically applying sodium sulphide ($Na_2S$) and sodium hydroxide (NaOH). After dissolving most of the wood fibres, the pulp is extracted and further processed for paper or cardboard production. The spent cooking liquid, together with dissolved lignin and hemicellulose fractions, is concentrated by evaporating most of the water. The remaining black liquor is combusted in the recovery boiler, converting the organic part into energy (heat) while the inorganic part is recovered as sodium sulphide and sodium carbonate ($Na_2CO_3$). Sodium sulphide can be directly returned to the wood chip digesters, while the sodium carbonate reacts with calcium hydroxide (CaO) to regenerate sodium hydroxide. This enables the recovery of the cooking chemicals and the energy content in the cooking residues. A by-product of the causticising process is calcium carbonate ($CaCO_3$). This is converted into reusable calcium hydroxide and $CO_2$ under high temperatures in the lime kiln.

Depending on the installation, $CO_2$ emissions from pulp and paper mills are scattered around the site in several stacks, but the recovery boiler is usually the major source of $CO_2$ emissions. Typically, 1 t of $CO_2$ is generated per tonne of pulp produced (ZEP, 2012). Contrary to most other industrial processes, up to 90–100% of the total $CO_2$ emissions from a Kraft pulp mill are biogenic (Carbo,

**Fig. 5.** Carbon flow in a typical modern integrated pulp and paper mill.

2011). The biogenic $CO_2$ emissions mainly originate from the recovery boiler. Fig. 5.

### 3.5. Aluminium

Aluminium is a light-weight metal and is the most widely used non-ferrous metal. Approximately 2 Mt is produced in the Nordic countries annually (USGS, 2013). The raw material of aluminium is bauxite from which alumina (aluminium oxide) is extracted. Alumina has a high smelting point (about 2000 °C), and aluminium production is therefore a highly energy intensive process. The energy comes in the form of electric power. The current technology is based on the electrolytic smelting of alumina, known as the Hall–Héroult process. In this process, alumina is dissolved in molten cryolite, $Na_3AlF_6$ (electrolyte), and reacted with carbon in cells at temperatures of between 950 °C and 980 °C. The number of cells varies depending on the size of the plant. A typical aluminium plant usually has hundreds of cells. The carbon acts as an anode with negative charge, which is continuously depleted. As a consequence, it has to be replaced. The aluminium is deposited in pots that are lined with carbon. These act as cathodes and are positively charged. The reaction equation for the reduction is $2Al_2O_3 + 3C + \text{energy} \rightarrow 4Al + 3CO_2$. According to the equation, the process gas from aluminium production should mainly consist of $CO_2$. However, this is not the case. The current cell design requires that a large amount of air is supplied to the cells as a mean of temperature control. Consequently, the process gas is diluted and typically has a $CO_2$ concentration of only 0.8–1 vol% (Arasto et al., 2013). Fig. 6.

$CO_2$ emissions from aluminium production are process-related due to the continuously depletion of the carbon anode. Approximately 4 t of $CO_2$ equivalent is produced per tonne of aluminium. Of this, about 2.2 t $CO_2$ equivalent originates from the anode production, electrolysis and anode effects. In addition, the process is very energy intensive as it is based on electric power input. Hydro Aluminium (Gassnova and Mott MacDonald, 2012) reports a typical electricity consumption of 13.5 kWh per kg of aluminium produced. In Norway and Iceland this electricity is taken from the national grid. The electricity supplied to the grid is generated almost exclusively from hydropower or geothermal power. As a consequence, there are no $CO_2$ emissions associated with the energy consumption for aluminium production in these countries. Aluminium plants that do not have the option of connecting to the national grid generate their own electricity in dedicated gas or coal-fired power plants. In such cases, the $CO_2$ emissions will be 10 and 17.5 t per tonne of aluminium for gas and coal, respectively (Gassnova and Mott MacDonald, 2012).

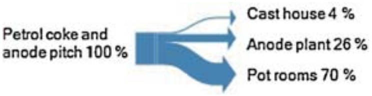

**Fig. 6.** Carbon flow in a typical aluminium plant.

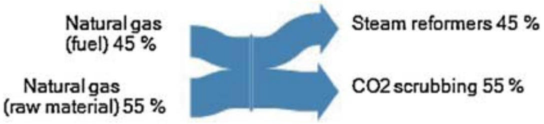

**Fig. 7.** Carbon flow in a typical ammonia plant.

### 3.6. Chemical industry—ammonia

Ammonia has many uses, but is mostly used in fertilisers. The first step in an ammonia plant is the cracking of natural gas (methane) or liquefied petroleum gas (LPG) into hydrogen gas in a process called catalytic steam reforming. Before the gas enters the reformer it is preheated to 520 °C and pressurised to 34 bar. Out of the reformer the temperature is 800 °C and the pressure is 29 bar. In the next step, the gas enters a secondary reformer together with air. In this step, the temperature in the flame zone reaches 1300 °C. In the reactions taking place in the flame zone, CO is formed and nitrogen is released. The gas then passes through a catalyst layer where the reactions yield $H_2$, CO and $CO_2$. CO is converted to $CO_2$, which takes place over several steps. CO reacts with water and produces $CO_2$, $H_2$ and heat. After this step, the $CO_2$ is removed. There are several methods that can be used, such as absorption by aqueous amine solutions and pressure swing adsorption. At the Yara plant in Porsgrunn, Norway, $CO_2$ is removed from the syngas ($CO_2$ concentration 20 vol%) in a water wash (CCS in the Skagerrak/Kattegat Region, 2012). The water absorbs $CO_2$ from the $H_2$ and $N_2$. The $CO_2$ is then released from the water in an air stripping tower. Further processing might be needed for final removal of CO and $CO_2$. Finally, $H_2$ and $N_2$ are converted to ammonia through the Haber-Bosch process. The conversion takes place at high pressures, 150–300 bar, and at temperatures between 350–650 °C, depending on the design used.

Between 1.5 and 3.1 t of $CO_2$ is emitted per tonne ammonia produced, depending on the feedstock (OECD/IE.A, 2007). The Yara plant emits approximately 825,000 t $CO_2$/a (Gassnova and Mott MacDonald, 2012). The $CO_2$ recovered from the water wash amounts to about 200,000 t and is purified and sold as food grade $CO_2$ (the $CO_2$ concentration is between 95–97 vol% before purification). Not all of the $CO_2$ recovered from the water wash is sold and the rest is vented to the atmosphere. The other $CO_2$ emissions are off-gas from the air stripping tower with a $CO_2$ concentration of 8 vol% and the $CO_2$ originating from the steam production for the reformers with a typical $CO_2$ concentration of 13 vol% (CCS in the Skagerrak/Kattegat Region, 2012). Fig. 7.

Fig. 8 shows the annual Nordic $CO_2$ emissions from the industry sectors covered in this section. Speculations about the future emissions in these sectors are hard to make as both the cement industry and metal industries are especially sensitive to the activity level in the construction market, which again depends on the current economic situation. Also the pulp and paper industry is sensitive to the global market situation.

## 4. CCS potential

The industry sectors covered in this paper are the main emitters of $CO_2$ in the Nordic countries. The production processes of each sector vary significantly and require individual CCS solutions for optimal $CO_2$ capture. Table 3 summarises the main industrial sectors and provides a general overview of the reduction potential and associated costs. As shown in the table, the costs can vary significantly, and the comments below the table should be taken into consideration when assessing the costs. The cost range refers to the $CO_2$ reduction potential. Generally, large scale capture of

**Table 3**
General overview of CCS technologies applicable to industrial sectors and costs related to the CCS implementation.

| | Technology | Carbon intensity without CCS t $CO_2$/t prod. | Reduction potential with CCS, %[25] | Cost range €/t stored | Cost range €/t avoided | References |
|---|---|---|---|---|---|---|
| **Iron and steel** | BF + BOF<br>Top-gas recycling | 1.5–2.2<br>0.7–0.8 | 85–95<br>60 | 17.5–40[10,12,13] | 26–150[9],<br>55–250[26,27],<br>55–85[29]<br>45–55[28] | (IEAGHG, 2013a; IEA Clean Coal Centre, 2012; ArcelorMittal, 2011; Fujita et al., 2010; IEA, 2006; Farla et al., 1995; Gordon et al., 2012)<br>(Gielen, 2003; IEA ETSAP, 2010; IEA, 2009; Ho et al., 2013; Tsupari et al., 2012)<br>(IEAGHG, 2013a; Meier and Zeilstra, 2011; Gordon et al., 2012; Gielen, 2003; van der Stel, 2011; Midrex Technologies Inc., 2013; Asia Pacific Partnership for Clean Development and Climate, 2010; IEAGHG, 2013c) |
| **Cement and lime** | Lime, shaft kiln<br>Cement, dry process | 0.75<br>0.6–1 | 85 | 34.3–59.6[5,6,8] | 40.2–107.4[5,6] | (OECD/IE.A, 2007)<br>(OECD/IE.A, 2007; World Business Council for Sustainable Development, 2012; Tel-Tek, 2009; IEAGHG, 2008) |
| **Oil and gas/refineries** | Oil refining<br>Gas processing | 0.063–0.2[24] | 80[27] | 67–84[7], 74.5[8]<br>69[8] | 90–120[11]<br>40–263[11] | (CCS in the Skagerrak/Kattegat Region, 2012; CONCAWE Refinery Management Group, 2011; Tel-Tek, 2009; van Straelen et al., 2010)<br>(Gassnova and Mott MacDonald, 2012; Tel-Tek, 2009; Johansson et al., 2013) |
| **Pulp and paper** | Kraft process pulping | 0.1–1.4[1,2] | 85[31,32]–91[31,33] | 19–26[14a,15] | 20–65[14b,15,16,17,18a,19,20,21,22,18b] | (OECD/IE.A, 2007; Vos and Newell, 2009; CEPI, 2007; Möllersten et al., 2004; Ekström et al., 1997; Hektor, 2008) |
| **Aluminium** | Hall–Héroult process renewable electricity | 1.8[3,30] | 0–85[4] | 75[8], 60.4[23] | | (OECD/IE.A, 2007; Gassnova and Mott MacDonald, 2012; Tel-Tek, 2009; Mathisen et al., 2012) |
| **Chemical industry, ammonia** | Ammonia Haber-Bosch process | 1.5–3.1 | 85 | 55[8,11]–89[11] | | (CCS in the Skagerrak/Kattegat Region, 2012; OECD/IE.A, 2007; Gassnova and Mott MacDonald, 2012; Tel-Tek, 2009) |

[1] When energy is supplied from CHP plants applying on average 50% bio-based fuels.
[2] Coated paper production.
[3] $CO_2$ equivalent.
[4] With current production technologies $CO_2$ capture is probably unrealistic, but future alternative methods may offer new possibilities.
[5] Five stage pre-heater with pre-calciner dry process.
[6] Five stage pre-heater with pre-calciner dry process, oxy-combustion in pre-calciner only.
[7] Depending on the complexity of the refinery and level of cooperation with other emitters on capture and storage.
[8] Capture cost only.
[9] MtC.
[10] Based on Selexol capture and implementation of a shift reaction to convert CO into $CO_2$ and $H_2$, including electricity consumption, investment, operational and management costs, storage and $CO_2$ emission electricity production costs. Enriched $H_2$ is used for power production.
[11] Does not include the capture of the near pure $CO_2$ flow.
[12] Capture only in new-design, oxy-fuel BF, physical adsorption.
[13] Capture from BF, including transport and storage.
[14] Integrated pulp and paper mill (MEA post-combustion), [a] Transportation distance 500 km, [b] Transportation distance 700 km.
[15] Market pulp mill (MEA post-combustion).
[16] Pre-combustion.
[17] Four different scenarios for energy market parameters including near future, BAU, moderate change and sustainable. Scenarios are described further in (Ådahl and Harvey, 2007).
[18] Biofuel boiler ([a] MEA, [b] CA).
[19] NGCC–CHP (MEA).
[20] Excess steam, biofuel (MEA).
[21] Excess steam, NGCC (MEA).
[22] Heat pump (MEA).
[23] Capture cost only, modified process with a flue gas $CO_2$ concentration of 4 vol%.
[24] Electricity consumption in the cells only, excluding energy consumption related to alumina and anode production, and casting/rolling.
[25] The reduction potential is based on a realistic evaluation of direct emission capture from the entire site (technically the number will be higher, but this would be economically unrealistic).
[26] Commercial MEA solvent in conventional iron and steel mill, all point sources.
[27] Depends largely on the specific site and process configuration.
[28] MEA post-combustion capture.
[29] MEA post-combustion capture from on-site power plant and blast furnaces.
[30] The $CO_2$ that originates from the aluminum production only and emitted through the process gas.
[31] Including $CO_2$ emissions originating from increased fuel consumption due to $CO_2$ capture.
[32] Integrated pulp and paper mill with biofuel or coal boiler using MEA.
[33] NCGG CHP configuration.

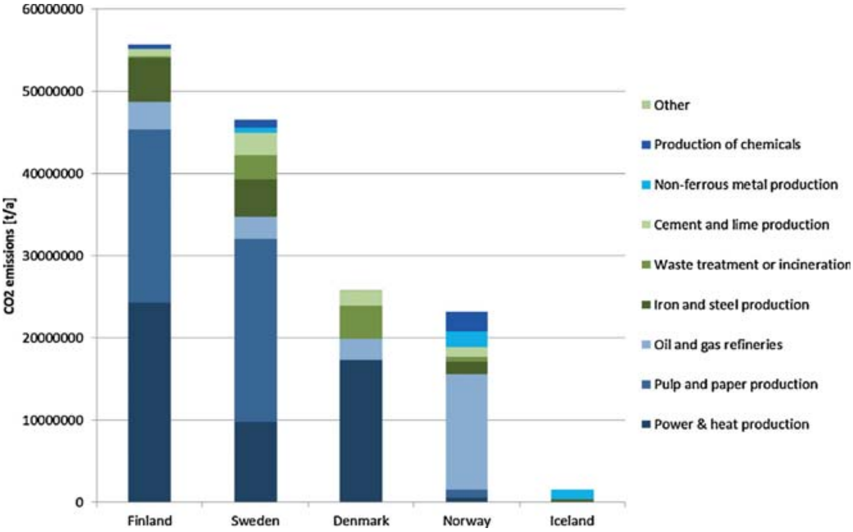

**Fig. 8.** Nordic industrial point source $CO_2$ emissions (>100,000 t/a) by country. Numbers are based on emissions from 2011 (Onarheim et al., 2014; EEA, 2014).

site-specific $CO_2$ emissions requires more energy than capturing smaller shares of emissions. Costs must also be seen in light of the time of research. For details on the CCS chain costs the original reference should be addressed.

Nordic iron and steel mills are highly efficient compared to global steelmaking plants (Kerkhoff, 2011), and the waste heat available has usually already been profoundly exploited. This leaves fewer opportunities for profitable heat integration when implementing energy-intensive $CO_2$ capture technologies. Pre-combustion and oxy-fuel combustion would in theory be possible at an integrated steel mill, but the effect of these capture technologies on overall $CO_2$ emissions would most probably be smaller than with post-combustion capture. The reason is that these technologies can only be applied to a limited part of the steel making process. Additionally, the long life expectancy of a blast furnace and the major modifications needed for implementing pre-combustion into a conventional steel production route would not favour this transition. Major modifications are also needed for transition into an oxy-fuel based production process. In addition, the oxy-blast furnace concept still has technology issues that must be resolved before industrial implementation. Combustion with oxygen instead of air would, however, benefit an amine-based post-combustion capture system by excluding most of the amine-degrading nitrogen from a conventional process.

The iron and steel industry in the Nordic countries has made significant efforts to reduce $CO_2$ emissions. The European ULCOS Consortium has identified breakthrough technologies that combined with conventional CCS technology can significantly reduce $CO_2$ emissions from iron and steel production. One of these technologies is the top-gas recycling process, where part of the blast furnace off-gas is purified and returned to the blast furnace as a reducing agent. As a result, the coke input to the iron production process is reduced (ULCOS, 2013). A pilot plant has tested the process successfully at SSAB in Luleå, Sweden, but plans to construct a demonstration plant in Florange, France, through the NER300 were discontinued in 2012 (Reuters, 2012).

Another promising technology for reducing $CO_2$ emissions in the iron and steel industry is the HIsarna process, also developed in the ULCOS project. The HIsarna process is based on direct feeding of powdered coal and iron into a modified blast furnace, a HIsarna bath smelter. This omits the need for coal coking and pig iron production (ULCOS, 2013). A process pilot has been constructed at Tata Steel in IJmuiden, the Netherlands, which shows indications that when combined with conventional CCS technology, the process could reduce $CO_2$ emissions by up to 80% (20% without CCS technology) (Meier and Zeilstra, 2011).

Cement production is a highly $CO_2$-intensive industry. In addition to being an energy-intensive process, the raw material for cement production contains $CO_2$. The industry is favourable for post-combustion $CO_2$ capture due to the high concentration of $CO_2$ in the flue gas (15–22 vol%). A challenge concerning implementation of post-combustion capture in cement plants is the need for additional energy, mainly in the form of steam, as there is usually no power plant at a cement production site. Flue gas contaminants, especially dust, will also represent a significant challenge for certain capture technologies. Reduction methods to cope with these challenges are available and in some cases already installed due to national $CO_2$ emission constraints.

Some cement plants are continuing to increase the share of bio and waste fuel to reduce the $CO_2$ footprint. Other options for $CO_2$ reductions are increased energy efficiency and clinker substitution (limited by the type of cement), i.e. using less carbon-intensive components with similar properties. Fly ash is commonly used for this purpose. Excess energy can be extracted from the process and utilised to cover part of the energy demand for $CO_2$ capture processes.

Tests have shown promising results from oxy-fuel combustion in cement production. An additional air separation unit (ASU) would be required, increasing capital expenses. Due to the nature of the cement production process, it is also possible to implement a calcium looping cycle (CLC) for $CO_2$ capture. This is believed to have a lower efficiency penalty than amine-based post-combustion capture, since the heat for calcination is offset by heat released during carbonation. In addition, it is possible to exploit lime purge materials from the CLC process as a raw material substitute. A natural limitation with the CLC process is the upper limit of the capture efficiency, connected to the carbonation reaction equilibrium. Pre-combustion is a possible CCS technology for capturing $CO_2$ from the combustion process, but not from the calcination process.

The European Cement Association (ECRA) started a CCS research project in 2007. The project has five phases, of which phases I, II and III have been completed. Phase IV is currently on-going (ECRA, 2007). The focus of phase IV is oxy-fuel combustion. The previous studies concluded that post-combustion (considered for both retrofit and greenfield plants) and oxy-combustion (considered for greenfield plants only) capture technologies are the best options for cement plants, while pre-combustion technologies will need fundamental changes in the clinker burning process (ECRA, 2013). There is experience with oxy-enriched combustion in both Russia and the United States. In these cases the purpose was to increase production capacity rather than to reduce $CO_2$ emissions. Skyonic's SkyMine technology has been pilot tested at Captiol Aggeregates' cement mill in Texas, United States. The post-combustion pilot plant project at the Norcem Heidelberg cement plant in Brevik, Norway, was granted funding in early 2013. In this project, one to three $CO_2$ capture technologies relevant for cement production will be tested (Global CCS Institute., 2013).

In a report on carbon capture and storage in the Skagerrak region (CCS in the Skagerrak/Kattegat Region, 2012), three Nordic oil refineries were evaluated for CCS. The $CO_2$ concentrations of the flue gases from heaters (furnaces and boilers) that provide the energy needed to refine the crude oil varies between 7 vol% and 24 vol%, and up to nine different emission points were identified at one plant. Oil refineries are generally complex plants and typically have limited space available for a $CO_2$ capture plant. Still, post-combustion $CO_2$ capture can be implemented, but site-specific considerations must be taken into account. A flexible approach to the implementation of CCS should be adopted, including capturing the $CO_2$ from the easiest accessible emission points. As energy in the form of heat is generated on-site at the refinery, it could be possible to increase the capacity of the energy production to cover energy needed for $CO_2$ capture as well. The report also found that in some cases a considerable amount of excess energy can be extracted from the existing process. However, with the current focus on energy efficiency, work is ongoing to increase the efficiency internally while other plants sell this energy in the form of district heating.

The Test Centre Mongstad (TCM) is in operation in Norway and currently both amine-based and ammonia-based post-combustion capture technologies are being tested on a pilot scale. The flue gas is supplied both from the refinery and from a gas-fired power plant. At the Valero Port Arthur Refinery in the United States, about 1 Mt $CO_2$ from two of the existing methane steam reformers began operation in April 2013 (Air Products, 2013). The $CO_2$ will be utilised in enhanced oil recovery (EOR).

The Nordic pulp and paper sector has a significant potential for $CO_2$ reduction in Sweden and Finland based only on emission rates. As the majority of $CO_2$ from pulp and paper production is biogenic, the sector theoretically has the potential to function as a carbon sink and to produce zero-emission paper leading to negative emissions. This could possibly be more profitable than fossil CCS under specific conditions (Arasto, 2013). However, there is currently no incentive for pulp and paper producers to implement CCS (ZEP, 2012; Directive, 2003) and taking into account the status of global market competition the potential for $CO_2$ capture from pulp and paper production on a Nordic and European level is estimated to be moderate (Arasto et al., 2011).

As the major $CO_2$ emissions from a Kraft mill originate from combustion processes, all major capture technologies (pre- and post-combustion and oxy-fuel combustion) are theoretically possible to implement. Of these, post-combustion capture is probably the most viable option, as both pre- and oxy-fuel combustion would require significant process modifications, both in the case of retrofit and greenfield plants. In favour of the post-combustion capture option is the potentially high $CO_2$ concentration in the flue gases (10–25 vol%) and the possibility of retrofitting without affecting the core process. In addition, there is typically both process water and steam available at the mills. One drawback with post-combustion capture is the presence of significant amounts of amine inhibitors such as dust, NOx, SOx and heavy metals in the flue gases. Furthermore, the point sources are small, and joining the recovery boiler and lime kiln flue gases into a central capture unit would have to take into account the fact that the flue gas compositions are relatively different. The site-specific treatment of odorous gases may also affect a possible post-combustion $CO_2$ capture process. A high concentration of sulphur components is harmful to the amine solvent and would require a desulphurization process upfront.

With current production processes, the implementation of CCS in the aluminium industry is unlikely due to the very low $CO_2$ concentration. However, $CO_2$ can be captured from the power plants that generate electricity for the production process. Further development on the Hall–Héroult process to lower electricity consumption (10 kWh per kg of aluminium) is being undertaken by Hydro Aluminium. In addition, methods of increasing the $CO_2$ concentration up to 4 vol% are being explored which will make the implementation of $CO_2$ capture more attractive. There are technical challenges associated with this as an increase in the $CO_2$ concentration will lead to increased temperature in the cell, which again affects the mechanical and automation equipment and components of the process. An advantage of the increased temperature could be to recover the excess energy from the flue gas for utilisation in $CO_2$ capture (Gassnova and Mott MacDonald, 2012). Developing a CCS-ready production process for aluminium is likely to take time, but it might become a viable alternative in the future.

For ammonia, capturing the high $CO_2$ concentration emission, which is not sold as food grade $CO_2$, could be a low threshold opportunity; however, the volume is small. The impact of capturing this amount is limited, but could still be a starting point for CCS in ammonia production. It should be noted that the capture costs reported in Table 3 for ammonia production do not represent the cost of capturing this concentrated $CO_2$ flow. As removal of $CO_2$ is an integrated part of the ammonia production process these plants have experience in capturing and handling $CO_2$.

A limited number of studies have been carried out on the implementation of CCS in industry and evaluating the cost associated with these processes. An overview of these costs is presented in Table 3. As there are currently few implemented CCS processes, these studies have been compiled based on assumptions and to a large extent theoretical principles. As a result, evaluation results can be highly hypothetical and studies can lead to results that deviate significantly from each other. Furthermore, even if assumptions were to be quite similar, both industry processes and carbon capture technologies are different in nature. Even within the industry sector, conditions may be very different from site to site. Most industrial processes are sensitive to local conditions (physical, political and socio-economic), raw material, plant age, fuel costs and fuel availability, to mention a few. Different ways of integrating a plant, either individually or in combination with other plants/processes, also affect the outcome. As a consequence, cost estimations can be rather uncertain so it is important to be aware of the preconditions for the studies. The cost of $CO_2$ capture is also a question of energy cost, which again is affected by the type and degree of integration, and in the MEA post-combustion case also on the absorbent performance (Hektor, 2008; Rao and Rubin, 2006).

From Table 3 it can be concluded that the Nordic industry sectors represent a variety of different technologies. Only pulp and paper production and cement production have similar technologies across the borders. The target when implementing carbon capture technologies is typically to reduce the $CO_2$ emissions by 90% or more. The cost estimations in Table 3 are on the lower end of CCS cost estimations in general, and depending on technology

**Table 4**
Potential of CCS implementation in different industries.

| Sector | Conclusions | Potential | Impact |
|---|---|---|---|
| **Iron and steel** | Current processes are dependent on coal<br>Scattered emissions on site<br>Waste heat available (?)<br>Complex integrated plant<br>Little effect on existing processes | 8% of Nordic emissions*<br>Mainly Sweden and Finland<br>Large point source emissions<br>Combustion with $O_2$ facilitates CCS<br>Alternative reducing agents<br>Alternative process routes<br>Biomass/biogenic $CO_2$ | Difficult |
| **Cement and lime** | No alternative to raw material<br>High $CO_2$ concentration<br>Waste heat available | 5.1% of Nordic emissions*<br>All Nordic countries except Iceland<br>No project experience<br>Post-combustion pilot in operation at Norcem Brevik<br>Biomass/biogenic $CO_2$ | Possible, individual considerations needed |
| **Oil and gas** | Both onshore and offshore activities are limited by space for installations<br>Refineries usually have scattered emissions<br>Potentially high $CO_2$ concentration<br>Waste heat available | 23.7% of Nordic emissions*<br>Onshore activities in all Nordic countries except Iceland<br>Offshore activities in Norway and Denmark<br>Large emissions<br>Some project experience | Difficult, individual considerations needed |
| **Pulp and paper** | Potentially high $CO_2$ concentration<br>Scattered emissions on site<br>Lack of incentives for biogenic $CO_2$ | 28% of Nordic $CO_2$ emissions*<br>Mainly Sweden and Finland<br>Carbon sink/Biogenic $CO_2$<br>Alternative process routes | Possible |
| **Aluminium** | Current process is dependent on carbon cathodes<br>Potential for limited number of emissions on-site<br>Low $CO_2$ concentration | 3.8% of Nordic emissions* (non-ferrous metal production)<br>Mainly Norway, Iceland and Sweden<br>No project experience<br>Alternative process methods | Difficult with current technology |
| **Chemical industry** | Hydrocarbon feedstock<br>Scattered emissions<br>Potentially high $CO_2$ concentration<br>Waste heat available | 3.2% of Nordic emissions*<br>Mainly Norway, Sweden and Finland<br>Some project experience<br>Limited industrial initiative | Limited, individual considerations needed |

* Industrial $CO_2$ emissions > 0.1 Mt/a.

the cost per tonne avoided can be very different per tonne stored. It is also difficult to make a conclusion for the cost of per tonne avoided, because the presumptions regarding the energy systems vary significantly from case to case. Additionally, transportation and storage might have been assessed individually. This shows that there is a need for studies that are comparable in spite of the different nature of these industry sectors, where common presumptions are clearly laid out.

Individual considerations are needed when assessing the opportunity for $CO_2$ capture in the different industrial sectors, as the number of emissions and their size can vary from plant to plant within the same sector. Such examples can be found in the oil refining and cement sector. While it can generally be said that oil refineries have scattered emissions, there are plants (often newer ones) that have dedicated energy plants that supply energy to all the refining steps. At such sites it is easier to facilitate $CO_2$ capture. In the cement industry, plant sizes vary greatly. Larger plants usually have several emission points, many of these substantial. Table 4 gives an overview of the potential of implementing CCS in different industry sectors. The impact column describes whether it is possible to decrease the $CO_2$ emissions, taking into account both social, economic and technical aspects.

## 5. Discussion

In general, Nordic industry sites might be less suitable for CCS than industry sites in other regions. In Sweden and Finland there are no options for $CO_2$ storage, except from a theoretical possibility in the Faludden formation located in the southern Baltic Sea. This storage site is, however, unlikely to be realised in the near future. The formation has not yet been fully mapped and assessed for storage capacity and the location and its geological features extend over several national borders. Disregarding this option, $CO_2$ captured in Sweden and Finland will have to be transported over long distances, either to the North Sea, Skagerrak or to the Barents Sea.

Norway has a range of possible storage locations with very high storage capacities, such as the Utsira Formation. Norway, on the other hand, has lower $CO_2$ emissions from industrial sources than other Nordic countries.

Denmark has little heavy industry. Only about 8–9 Mt yearly $CO_2$ emissions originate from industry processes, the rest is to a great extent from power and heat production. As a result, most of the $CO_2$ sources in the ETS sector are power plants, which makes industrial CCS less relevant in Denmark.

More than half of the point source $CO_2$ emissions from Finland originate from heavy industry processes, and several large industrial emission sources would be suitable for CCS application. The largest emitters are the iron and steel industry and the pulp and paper industry. Both industries trade commodities globally, and thus transferring the costs to end-product prices would be a significant burden on competitiveness and viability. In oil refining the transfer of costs could possibly be slightly easier, as these producers typically take advantage of their geographic location and serve local markets. Emissions from the pulp and paper industry are mainly biogenic and are thus considered to be carbon neutral. This has reduced the interest in capturing $CO_2$ to low or non-existent levels. Finland's geographic location and the lack of large scale storage capacity will increase transportation costs. With no possibilities for EOR, this could possibly make the total cost of CCS higher than in other Nordic countries. Cement production sites in Finland are small-scale installations that also increase the costs of capture and transportation.

Large industrial $CO_2$ emissions in Sweden resemble the emission profile of Finland, with similar problems in transferring $CO_2$ prices to global markets. Potential offshore storage sites within the country's borders could make CCS more attractive for Sweden. Most of the large industrial installations, such as many of the pulp mills, are situated at the coast, unlike in Finland, which makes transport of $CO_2$ easier than for sites located inland. Cement manufacturing is on a larger scale than in Finland and thus offers a larger potential and less expensive application targets than the corresponding Finnish cement production sites. Considering the storage potential, refineries on the west coast of Sweden are better situated than most of the other Swedish industrial $CO_2$ emitters. If storage in the southern Baltic Sea were to become an option, this could lower transportation costs from the east coast of Sweden and from southern Finland as well (Elforsk/SLR Global Environmental Solutions, 2014).

Industrial $CO_2$ sources in Norway are large-scale oil refineries with sufficient capacity to consider CCS. Most of the remaining emissions originate from offshore oil and gas activities. These are technically and economically less advantageous targets for applying CCS. The only advantage considered is the proximity to storage sites, and distance to the population that could facilitate the implementation with regard to “Nimbyism”. Currently, there are two full-scale CCS projects in operation in Norway as a result of the $CO_2$ tax on Norwegian offshore activities. Natural gas from some of the fields on the Norwegian continental shelf contain more $CO_2$ than the limit of 2.5% and consequently the excess $CO_2$ must be removed before it can be sold to Europe. In order to avoid the $CO_2$ tax, $CO_2$ is removed from natural gas and injected for permanent storage in the Utsira Formation and in a formation in the Snøhvit reservoir. In 2013 this $CO_2$ tax was 450 NOK/t $CO_2$ (~54.5 €/t in September, 2014) (Norwegian Directorate for Oil and Energy, 2013).

## 6. Conclusion

All the industrial sectors considered in this paper represent large installations and are thus large $CO_2$ point sources with technical potential for deploying CCS. These sectors are also the largest industrial sectors in the Nordic countries from an economic perspective.

Typical industrial emission point sources in the Nordic countries are larger than emissions from power production plants (except some cases in Denmark). Technically it would be possible (and perhaps also attractive) to implement CCS in these industry sectors. It could even be economically more attractive and/or technically easier to implement CCS in some of these industries than in power and heat production in the Nordic countries. At any rate, it is clear that in order to be able to compare the different industries in terms of the cost and realistic GHG impact of $CO_2$ capture (as far as the sectors can be compared), new studies are needed where an open, consistent approach to presumptions concerning for instance energy systems enables a relevant comparison.

From a Nordic perspective, the most significant technical potential is in the oil and gas sector, iron and steel production and in cement production. The pulp and paper industry has also a significant potential if biogenic emissions are considered. The national distribution of industry segments and storage sites varies significantly between the Nordic countries. Finland and Sweden are closely situated and more alike with an extensive heavy industry sector. The iron and steel industry and the pulp and paper industry are the most significant and highest-potential industries in Finland with regard to CCS, although the majority of $CO_2$ emissions from the pulp and paper industry are of biogenic origin and therefore considered climate-neutral. Capturing and storing biogenic $CO_2$ emissions would theoretically enable the removal of $CO_2$ from the atmosphere and create a carbon sink. The largest $CO_2$ emitter in Norway is the oil and gas industry, including oil refineries and natural gas processing. $CO_2$ capture and storage has been implemented at two production sites due to the $CO_2$ tax on Norwegian offshore activities. Industrial $CO_2$ emissions in Iceland originate mostly from aluminium production and in Denmark the oil and gas sector is the largest emitter together with cement production.

A significant reduction of $CO_2$ emissions from large Nordic industry sectors is currently not possible without the implementation of CCS (Nordic Energy Technology Perspectives, 2013; Teir et al., 2010). There are different technologies that can be deployed in relation to different industries, and although the principles are similar, these technologies and their implications might differ significantly from the ones considered for application in the power and heat production sector. Technology-wise industrial solutions could provide opportunities, along with technologies that cannot be considered in connection with power and heat production, as these might offer opportunities for new process inventions. These process alternatives, or other industry-specific solutions, might also improve the existing production process and therefore bring other than negative effects due to the financial and energy-consuming penalty of capture processes.

There is a significant potential for carbon leakage and decrease in the competitiveness of Nordic industries in connection with the implementation of CCS. Most of these industries compete in global markets where any additional $CO_2$ cost burden is unaccounted for due to the lack of a global $CO_2$ emission reduction treaty. This concerns the iron and steel, pulp and paper and oil and gas sectors in particular, as they primarily operate in global markets. Norway is at this point the only Nordic country with sufficient fiscal incentives in place to enable the implementation of CCS in at least some emission sources. Furthermore, EU ETS prices and future price estimations do not currently motivate for investment in CCS technology.

Although only the largest $CO_2$-emitting industry sectors have been covered in here, these emission sources are still small in terms of CCS. They are also geographically spread over a large area with varying physical challenges such as mountain ranges and large sea areas, in many cases complicating or even prohibiting a straightforward CCS chain. Establishing smaller clusters for cooperation on $CO_2$ transport and storage would clearly be an advantage in terms of CCS chain operation and associated costs, in particular concerning transport and storage. This could facilitate the CCS operations for smaller emission sites that have little or no experience with $CO_2$ transport and storage and that require access to international storage sites. However, this coordination of CCS could also lead to risks in competitiveness. The energy strategies and policies on CCS and/or $CO_2$ emissions differ in all the Nordic countries, and industries remain heavily dependent on a common Nordic political will to cooperate and coordinate the Nordic CCS chains in order not to lose their competitiveness.

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|---|---|
| Title | **Techno-economic evaluation of significant $CO_2$ emission reductions in the iron and steel industry with CCS** |
| Author(s) | Antti Arasto |
| Abstract | The iron and steel industry is one of the largest emitters of industrial $CO_2$, accounting for around 6% of global anthropogenic $CO_2$ emissions each year. In Europe, the recently proposed stricter emission reduction targets for 2030 are likely to increase the price for $CO_2$ emission allowances. Various different GHG emission mitigation alternatives have been considered to enable decarbonisation of the iron and steel industry, such as energy efficiency, biogenic reducing agents, hydrogen and CCS. However, not all of these can be deployed for the most important production route – the blast furnace and basic oxygen furnace route (BF + BOF) – and all the solutions have advantages and disadvantages. CCS is currently the only mitigation option available for significantly reducing emissions from this energy-intensive industry. A full chain assessment of carbon capture and storage (CCS) applications for the iron and steel industry was performed in order to screen technology options and build a development pathway to low carbon steelmaking for future carbon-constrained world. A techno-economic assessment of application of CCS with various technologies in the iron and steel industry was carried out to create a knowledge base for a Nordic steel producer. The assessment was conducted for two different $CO_2$ capture alternatives, namely post-combustion carbon capture and oxygen blast furnaces (OBF) with flue gas circulation. Processes were assessed by technical modelling based on the Aspen Plus process simulator and the economic evaluation toolkit CC-SkynetTM using two indicators: the break-even price of $CO_2$ emission allowances for CCS and the impact of CCS on steel production costs. With the whole chain approach, including $CO_2$ capture, processing, transport and storage, the results show a significant reduction potential at an integrated steel mill for all carbon capture technologies assessed. The application of an OBF would require a larger modification of the processes of the existing steel mill than that required by the application of post-combustion capture. The staged construction and implementation of CCS in order to minimise the financial investment risk was considered and several pathways for implementation were analysed. Only transportation of $CO_2$ by ship was considered due to the coast-line location of the installation far from other emission sources, pipeline infrastructures and storage sites. Results show the cost structure and feasibility of the studied technologies. Cost break-even points for CCS at an integrated steel mill, for the plant owner and costs for globally avoided emissions are calculated. The direct site emissions were reduced by 0.28–2.93 Mt $CO_2$/a. The cases resulting in significant reductions represent 48–73% of direct site emissions. The net GHG impact of emission reductions are between 45–62% of the site emission reductions. The cost of emission reductions are estimated from the site owner perspective, with the costs in majority of the cases being between €40–70/t $CO_2$. Oxygen blast furnace with top gas recirculation was estimated to be slightly cheaper than post-combustion capture of $CO_2$. As presented in the results of this study, BePs (break-even prices) are very sensitive to several factors which are uncertain regarding the time frame of large investments. The results also showed that the costs for CCS are heavily dependent not only on the characteristics of the facility and the operational environment, but also on the chosen system boundaries and assumptions. |
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| | |
|---|---|
| Nimeke | **Teknistaloudellinen arviointi terästeollisuuden $CO_2$ -päästöjen vähentämisestä CCS:llä** |
| Tekijä(t) | Antti Arasto |
| Tiivistelmä | Terästeollisuus vastaa noin 6 % globaaleista ihmisen aiheuttamista päästöistä ja on siten globaalisti yksi suurimmista teollisista $CO_2$-päästäjistä. Euroopan komission esittämät uudet, kunnianhimoisemmat päästövähennystavoitteet aiheuttavat nousupaineita päästöoikeuksien hintoihin. Lukuisia erilaisia hiilidioksidipäästöjen vähentämismenetelmiä, kuten energiatehokkuus, biopohjaiset pelkistimet, vety ja CCS, on ollut esillä terästeollisuuden hiili-intensiivisyyden vähentämiseksi. Kaikkia näistä ei kuitenkaan voida soveltaa yleisimpään teräksentuotantoprosessiin, joka perustuu masuuniin, ja kaikilla näillä vaihtoehdoilla on lisäksi hyviä ja huonoja piirteitä. CCS on tällä hetkellä ainoa vaihtoehto, jolla terästeollisuuden hiilidioksidipäästöjä voidaan merkittävästi vähentää.<br>Koko prosessiketjun kattavaa arviointia on tässä sovellettu hiilidioksidin talteenoton ja varastoinnin soveltamiseen terästeollisuudessa, jotta eri teknologiavaihtoehtoja voitaisiin vertailla ja luoda teknologiapolku vähähiiliseen terästuotantoon tulevaisuuden hiilivapaaseen talouteen siirryttäessä. Teknistaloudellisen arvioinnin avulla luotiin myös tietopohjaa paikallisille terästuottajille päätöksenteon tueksi. Arvio tehtiin kahdelle eri $CO_2$-talteenottoteknologialle, jotka ovat $CO_2$-talteenotto pesurilla savukaasuista ja happimasuuni savukaasun kierrätyksellä ja $CO_2$-erotuksella. Prosessit mallinnettiin Aspen Plus -prosessisimulaattorilla ja tähän perustuva taloudellinen arvio tehtiin CC-SkynetTM-työkalulla käyttäen kahta indikaattoria: $CO_2$-päästöoikeuden rajahinta sekä CCS:n soveltamisen vaikutus teräksen tuotantokustannuksiin.<br>Koko CCS-ketjun kattava arviointi sisältää $CO_2$:n talteenoton, prosessoinnin, kuljetuksen ja varastoinnin. Arvioinnin perusteella voitiin todeta, että terästeollisuudessa on merkittävä tekninen $CO_2$-vähennyspotentiaali. Sovellettaessa happimasuunivaihtoehtoa tarvittiin olemassa olevaan prosessiin suurempia muutoksia kuin sovellettaessa talteenottoa savukaasuista. Erilaisia vaiheistetun soveltamisen ja investoinnin toteutuspolkuja teknologioille tarkasteltiin, jotta investoinnin riskiä saataisiin minimoitua. Vain laivakuljetusta tarkasteltiin vaihtoehtona $CO_2$-kuljetukselle, koska kohde sijaitsee rannikolla ja kaukana varastointikohteista. Tulokset näyttävät investointien kannattavuuden ja kustannusrakenteen. CCS:n soveltamisen rajahintaa arvioitiin laitoksen omistajan ja vältettyjen päästöjen näkökulmasta. Suorat päästöt vähenivät teknologioita soveltamalla 0,28–2,93 Mt $CO_2$/a. Merkittävämmät päästövähennysmäärät vastaavat 48–73 % laitoksen suorista päästöistä. Nettopäästövähenemä on noin 45–62 % laitoksen suorista päästövähennyksistä.<br>Päästövähennyskustannuksia arvioitiin laitoksen omistajan näkökulmasta suurimman osan ollessa 40–70 €/t $CO_2$. Happimasuuni savukaasun kierrätyksellä oli hieman halvempi kuin $CO_2$:n talteenotto savukaasuista. Kuten tuloksista selviää, päästövähennysten rajakustannukset ovat hyvin herkkiä useille kustannustekijöille, jotka ovat erittäin epävarmoja tämänkaltaisen investoinnin pitoaikana. Tuloksista selviää myös, että CCS:n soveltaminen ja sen kustannukset vaihtelevat hyvin paljon riippuen sovelluskohteesta, sen erityispiirteistä ja toimintaympäristöstä sekä myös tarkastelun rajauksista ja oletuksista. Erityisesti vaikutukset energiantuotantoon ja siten energiajärjestelmään vaikuttavat merkittävästi nettopäästövähenemiin. |
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# Techno-economic evaluation of significant $CO_2$ emission reductions in the iron and steel industry with CCS

In this dissertation, the methodology of consequential concept assessment was applied to an evaluation of CCS technologies deployed in an iron and steel mill. Two different carbon capture technology solutions were considered: a post-combustion solvent-based capture as a pure retrofit solution, and a more advanced and technically challenging technology combining an oxygen blast furnace with top gas recirculation and $CO_2$ separation.

These two solutions were assessed in two steps following engineering and investment analysis principles. First, a technology concept was developed that was customized for the site at hand. Mass and energy balance calculations were carried out for the concepts using the Aspen Plus® process simulator. In the second step, the economic impacts of the deployment of technologies in varying operational environments were evaluated with the CC-Skynet™ tool.

Based on the assessment it can be concluded that significant $CO_2$ emission reductions can be obtained with these technologies at a site level. The optimal technological solution depends on the price of electricity and carbon allowances, which were identified as the most influential parameters.

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