Techno-economic evaluation of significant CO\textsubscript{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\textsubscript{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 CO2Skynet™ tool.

Based on the assessment it can be concluded that significant CO\textsubscript{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.
Techno-economic evaluation of significant CO$_2$ emission reductions in the iron and steel industry with CCS

Antti Arasto
VTT Technical Research Centre of Finland Ltd

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in lecture room 216 (K1), at Aalto University (Otaniemi, Finland), on the 27th November 2015 at 12.00.
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$^\text{TM}$ 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\textsubscript{2}-päästöjen vähentämisestä CCS:llä

**Tiivistelmä**

Terästeollisuus vastaa noin 6 % globaaleista ihmisen aiheuttamista päästöistä ja on siten globaalisti yksi suurimmista teollisista CO\textsubscript{2}-päästääjistä. 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 vaihtoehtoilla on lisäksi hyviä ja huonoja piirteitä. CCS on tällä hetkellä ainoa vaihtoehto, jolla terästeollisuuden hiilidioksidipäästöjä voidaan merkittävästi vähentää.

Koko prosessiketjun kattava arviointia on tässä sovellettu hiilidioksidin talteenoton ja varastoinnin soveltamiseen terästeollisuudessa, jotta eri tekniologialavaihtoehtoja voitaisiin vertailla ja luoda teknologiapolku vähähiilikseen terästuvantoon tulevaisuuden hiilivaapaseen talouteen siirryttäessä. Teknistaloudellisen arvioinnin avulla luotiin myös tietopohja paikallisille terästuvantoille päätöksenteon tueksi. Arvio tehtiin kahdelle eri CO\textsubscript{2}-talteenottoteknologialle, jotka ovat CO\textsubscript{2}-talteenotto pesurilla savukaasuista ja happimasuuni savukaasun kierrätyksellä ja CO\textsubscript{2}-erotuksella. Prosessit mallinettiin Aspen Plus -prosessisimulaattorilla ja tähän perustuvaa taloudellinen arvio tehtiin CC-Skynet\textsuperscript{TM}-työkalulla käyttäen kahta indikaattoria: CO\textsubscript{2}-päästöoikeuden rajahinta sekä CCS:n soveltamisen vaikutus teräksen tuotantokustannuksiin.


Päästövähennyskustannuksia arvioitiin laitoksen omistajan näkökulmasta suurimmalla osalla eli CO\textsubscript{2}:n talteenotto savukaasualta. Kuitenkin halvempi kuin CO\textsubscript{2}:n talteenotto savukaasualta. Kuten tuloksista selviää,
päästövähennysten rajakustannukset ovat hyvin herkkiä useille kustannustekijöille, jotka ovat erittäin epävarmoja tämänkaltaisen investoinnin pitoaikana. Tuloksista selviää myös, että CCS:n sovettaminen ja sen kustannukset vaihtelevat hyvin paljon riippuen sovelluskohteesta, sen erityispiirteistä ja toimintaympäristöstä sekä myös tarkastelun rajaussista ja oletuksista. Erityisesti vaikutukset energiantuotantoon ja siten energiajärjestelmään vaikuttavat merkittävästi nettopäästövähennemiin.
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Academic dissertation

Supervising professor

Professor Mika Järvinen
Aalto University
Espoo Finland

Thesis Advisor

Dr. Sebastian Teir
VTT Technical Research Centre of Finland Ltd
Espoo, Finland

Preliminary examiners

Dr. Lawrence Hooey
Swerea MEFOS AB
Luleå, Sweden

Professor Ron Zevenhoven
Åbo Akademi University
Turku, Finland

Opponent

Dr. Lawrence Hooey
Swerea MEFOS AB
Luleå, Sweden

Professor Henrik Saxén
Åbo Akademi University
Turku, Finland
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.


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.
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Appendices

Appendix A: Cost end emission balances

Papers I–V
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 CO₂ 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
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSBL</td>
<td>outside the battery limits</td>
</tr>
<tr>
<td>PCC</td>
<td>post-combustion capture</td>
</tr>
<tr>
<td>PCI</td>
<td>pulverised coal injection</td>
</tr>
<tr>
<td>Pz</td>
<td>piperazine</td>
</tr>
<tr>
<td>VPSA</td>
<td>vacuum pressure swing adsorption</td>
</tr>
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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 CO₂ 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. Introduction

1.1 General description of carbon capture and storage technology

Carbon Capture and Storage (CCS) refers to a family of technologies aiming at reducing CO₂ emissions into the atmosphere by capturing CO₂ 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 CO₂ in other applications.

CCS is mainly considered to be applied to stationary and large-scale emission point sources (those having CO₂ emissions in the order of one million tonnes per year), as the cost per tonne CO₂ 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.

CO₂ 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 CO₂ separation concepts, but these have either a lower technological maturity or are only suitable for certain industrial processes.

Captured CO₂ 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 CO₂ needs to be transported either by pipeline or ship to the storage site. CO₂ is then injected into an underground storage formation that is permanently sealed after filling with CO₂. Generally, relatively pure CO₂ 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 CO₂.

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 pro-
1. Introduction

The direct reduced iron (DRI) route accounts for about 5% of global iron production [IEA GHG 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\textsubscript{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 [Ruuuska et al. 2006]. Steel exiting the converter goes to continuous casting and in the case of integrated steelworks, to rolling mills.
1. Introduction

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].

\[
FeO + CO \rightarrow Fe + CO_2 \quad (1)
\]

\[
FeO + C \rightarrow Fe + CO \quad (2)
\]

\[
O_2 + 2C \rightarrow 2CO \quad (3)
\]

\[
Fe_3O_4 + 4CO \rightarrow 3Fe + 4CO_2 \quad (4)
\]

\[
CO_2 + C \leftrightarrow 2CO \quad (5)
\]

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 Fe₂O₃ -> Fe₃O₄ -> 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 CO₂ 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 CO₂ 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, CaCO₃, which is calcinated to CaO, forming CO₂ 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 CO₂ 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].
1. Introduction

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\textsubscript{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\textsubscript{2}, accounting for around 8% of anthropogenic CO\textsubscript{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\textsubscript{2} intensive manufacturing industry moving to countries that do not have any tax or trading of CO\textsubscript{2} emissions, the iron and steel industry gets the majority of their CO\textsubscript{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\textsubscript{2} per annum. However, the tightening targets will increase CO\textsubscript{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 CO₂ 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$_2$O, which can be separated more easily. After the condensation of water vapour, the gas stream consists
of roughly 80% CO\textsubscript{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\textsubscript{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\textsubscript{2} needs to be purified and compressed. The purification step is a multistage compression and distillation process that produces at least 95% pure CO\textsubscript{2}. For pipeline transportation, CO\textsubscript{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\textsubscript{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\textsubscript{2} in order to enable CCS deployment in commercial scale. The most significant application for CO\textsubscript{2}, currently in use in commercial scale CCS demonstration is EOR, Enhanced Oil Recovery. Also other uses for CO\textsubscript{2} are in use or under consideration such as precipitated calcium carbonate production for paper fillers, use in greenhouses or use of supercritical CO\textsubscript{2} as a solvent etc. However all CO\textsubscript{2} utilisation do not result as net CO\textsubscript{2} reduction as the CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} reduction in the iron and steel industry, such as fuel switch and energy efficiency improvements in addition to describing CO\textsubscript{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/kgCO₂ regeneration energy with as low as 2.5 MJ/kgCO₂ 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/kgCO₂ 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 CO₂ 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 CO₂, enabling less energy-intensive CO₂ separation. Part of the top gas from the blast furnace is utilised to heat the recycled gas coming from CO₂ separation. Even without CCS the CO₂ 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 CO₂ separation the recycled gas fed back to blast furnace contains mainly H₂ and CO. The CO₂-rich stream (~92 v-% CO₂) 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].
ULCOS is an acronym for Ultra-Low Carbon dioxide (CO₂) 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 CO₂ emissions from steel production. The aim is to reduce at least 50% of CO₂ 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 CO₂ 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 emissions¹ 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 CO₂ 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 CO₂ emissions from an entire steel mill site. ULCOS results show that there are several other concepts also that can achieve the targeted level of CO₂ 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-

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/tCO$_2$ 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/tCO$_2$ 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$80–250/tCO$_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$65–80/tCO_2$ 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 CO₂ 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 CO₂ – 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 CO₂ 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:

\[ \dot{m}_{i,\text{in}} + G_i - \dot{m}_{i,\text{out}} - C_i = \frac{dm_i}{dt} \]  \hspace{1cm} (6)

, for species, element or compound.

- \( \dot{m}_{i,\text{in}} \): 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
4. Mass and energy balance modelling of applications of CCS in the iron and steel industry

\[ \dot{m}_{i,\text{out}} \]

Output is the mass of species leaving the box through a system boundary

\[ \frac{\text{d}m_i}{\text{d}t} \]

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:

\[ \sum \dot{m}_{in} = \sum \dot{m}_{out} \]  
(7)

, and individual components:

\[ \dot{m}_{in} - \dot{c} = \dot{m}_{out} + \dot{G} \]  
(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:

\[ \Delta U + \Delta E_k + \Delta E_p = Q - W \]  
(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.

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

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

Vent-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 hypothetical 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.
4. Mass and energy balance modelling of applications of CCS in the iron and steel industry

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, CO₂ separation unit as well as the compression and purification of CO₂. 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 CO₂ 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. Mass and energy balance modelling of applications of CCS in the iron and steel industry

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 CO₂ 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 CO₂ emissions and economics. Three different solvent solutions were varied in post-combustion capture scenarios 2 and 3.

<table>
<thead>
<tr>
<th>Post-combustion capture (PCC) scenarios:</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC 1: reference</td>
</tr>
<tr>
<td>PCC 2: Turbine back pressure operation</td>
</tr>
<tr>
<td>PCC 3: No electricity production</td>
</tr>
</tbody>
</table>
4. Mass and energy balance modelling of applications of CCS in the iron and steel industry

<table>
<thead>
<tr>
<th>Oxygen blast furnace (OBF) scenarios:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OBF 1: Reference</strong></td>
</tr>
<tr>
<td><strong>OBF 2: Application of oxygen blast furnace</strong></td>
</tr>
<tr>
<td><strong>OBF 3: Application of oxygen blast furnace with CCS</strong></td>
</tr>
</tbody>
</table>
5. Modelling of the economic feasibility of CO₂ capture in the iron and steel industry

In the literature, break-even prices (BeP) and costs per avoided CO₂ 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 CO₂ emission allowances in the EU emissions trading scheme (EU ETS) during the considered time frame to make the studied CO₂ 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.
5. Modelling of the economic feasibility of CO2 capture in the iron and steel industry

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

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.
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 equip-
5. Modelling of the economic feasibility of CO2 capture in the iron and steel industry

ment, 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:

\[
NPV = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n}
\]  

(10)

Where

\[
\begin{align*}
    CF_n &= \text{cash flow in year } n \\
    t &= \text{project life in years} \\
    i &= \text{interest rate}
\end{align*}
\]

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\textsubscript{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\textsubscript{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].

\[
C_2 = C_1 \left( \frac{S_2}{S_1} \right)^n
\]

(11)

Where

\[
C_2 = \text{capital cost of plant or process unit with the capacity of } S_2
\]

\[
C_1 = \text{capital cost of plant or process unit with the capacity of } S_1
\]

\[
n = \text{scale-up exponent}
\]

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 CO₂, 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 CO₂ 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 CO₂ captured or reduced and CO₂ avoided is that CO₂ captured does not include the impact to emissions outside system boundary. CO₂ captured refers to the amount of CO₂ that is captured and stored. CO₂ reduced refers to the direct impact that CCS has on reducing CO₂ emissions compared to not using CCS, i.e. the impact the site operator sees in relation to emissions trading scheme. CO₂ 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.

\[
    BeP = \frac{\Delta \text{cost}}{\Delta \text{emissions}}
\]  

(12)

where

\[ \Delta \text{cost} = \text{change in annual costs in comparison to reference case} \]

\[ \Delta \text{emissions} = \text{change in annual emissions in comparison to reference case} \]

The impacts of these factors on the production costs of steel are calculated based on the equation
5. Modelling of the economic feasibility of CO2 capture in the iron and steel industry

\[
P_{\text{steel}} = \frac{\text{Capex}_{\text{CCS}} + \text{OtherOPEX}_{\text{CCS}}}{\text{SteelProd}} + P_{0}\text{steel} + E_{\text{CCS}} \times P_{0}\text{Electricity} + P_{\text{CO2}} \times (\text{correlation} \times E_{\text{total}} + \text{CO2}_{\text{total}})
\]

where

- \( \text{Capex}_{\text{CCS}} \) = the annual capital expenditures due to required CCS investments [M€/a]
- \( \text{OtherOPEX}_{\text{CCS}} \) = the impact of CCS on operational expenditures other than electricity and CO2 costs, such as LPG consumption and coke selling (described in previous sections) [M€/a]
- \( \text{SteelProd} \) = the annual steel production [Mt/a as crude steel]
- \( P_{0}\text{steel} \) = the reference steel price, i.e. the steel production cost without the costs related to CO2 emissions [€/t]
- \( E_{\text{CCS}} \) = the additional electricity consumption due to CCS [MWh/t crude steel]
- \( P_{0}\text{Electricity} \) = the electricity price without the impact of CO2 prices [€/MWh]
- \( P_{\text{CO2}} \) = the price of CO2 emissions for steel mill (e.g. in the EU ETS) [€/t CO2]
- \( \text{Correlation} \) = the electricity price dependency on CO2 price i.e. the penetration of CO2 price to electricity market price [t CO2/MWh]
- \( E_{\text{total}} \) = the overall electricity consumption of the steel mill in each case [MWh/t crude steel]
- \( \text{CO2}_{\text{total}} \) = the overall CO2 emissions from steel production in each case [t CO2/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
5. Modelling of the economic feasibility of CO2 capture in the iron and steel industry

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.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Case description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC case 0</td>
<td>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.</td>
</tr>
<tr>
<td>PCC case 1</td>
<td>Small-scale CCS application, where the capacity of the CO₂ 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.</td>
</tr>
<tr>
<td>PCC case 2</td>
<td>The capacity of the CO₂ 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.</td>
</tr>
<tr>
<td>PCC case 3</td>
<td>A combination of the previous two cases. The capacity of the CO₂ 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.</td>
</tr>
<tr>
<td>PCC case 4</td>
<td>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 CO₂ emissions within the economic system boundary. There are no investments in heat recovery in this case.</td>
</tr>
<tr>
<td>PCC case 5</td>
<td>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.</td>
</tr>
<tr>
<td>OBF case 0</td>
<td>OBF reference case</td>
</tr>
<tr>
<td>OBF case 1</td>
<td>Application of OBF without CCS</td>
</tr>
<tr>
<td>OBF case 2</td>
<td>Application of OBF with CCS</td>
</tr>
</tbody>
</table>

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 CO₂ 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.
6. Results

The captured CO$_2$ amounts are presented in Figure 11. The average CO$_2$ emissions during years 2008–2013 from Raade 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/kgCO$_2$ 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.
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.
6. Results

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 OBF 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 CO₂ separation and conditioning as no significant electricity consuming equipment are removed in any of the cases.
6. Results

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.
6. Results

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.
6. Results

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\textsubscript{2}/GWh\textsubscript{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\textsubscript{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.
6. Results

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 17. The GHG emissions avoided in different cases.
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.
6. Results

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 \( \text{CO}_2 \) emission reduction methods modelled are:

- increased LPG (or LNG) consumption
- decreased coke consumption (increased coke selling)
- increased electricity purchase
- decreased \( \text{CO}_2 \) emissions
- captured (transported and stored) \( \text{CO}_2 \).

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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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 CO₂ 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 CO₂ 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, CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂, depending on the amount of CO₂ transported and stored, representing 28–55% of the BeP costs per t CO₂. 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
7. Discussion

CO₂ in the sandstone formations under the South Eastern parts of the Baltic Sea [Nilsson 2014]. If significant development were to take place with these opportuni-
ties or with CO₂ 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 esti-
mation is driven by the relationship between CO₂ emission prices and electricity
prices. High CO₂ 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 feasi-
ble. Blast furnace investments are made for 20 to 30 years and the prospects of
future prices for e.g. CO₂ emission allowances, electricity, LPG/LNG and coke are
extremely uncertain. Carbon allowances, or many other CO₂ policy measures,
connect steel manufacturing to the electricity markets even more tightly than be-
fore. 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 be-
fore. However, the “Mankala” principle of buying electricity has been loosening this
connection and the influence of electricity market fluctuation. The “Mankala” prin-
ciple 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 im-
portance 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

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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 CO₂ emissions are decreased significantly due to OBF and CCS, direct CO₂ 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 CO₂ 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, CO₂ 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 CO₂ emissions from other processes within the EU ETS are not reasonable to estimate and direct CO₂ emissions only have economic value, namely the price of the CO₂ 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
7. Discussion

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 CO₂, with the assumptions in this summary. The cost for globally avoided emissions is in the range of €74–158/t CO₂, 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 CO₂ studied (2–3 Mt CO₂/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 CO₂ 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 CO₂, 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 CO₂ 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.

![Feasibility map of different technologies.](image)

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\textsubscript{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\textsubscript{2} emission reductions that can be achieved are more limited than with the studied technologies. CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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. Conclusion

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
8. Conclusion

- 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 N₂/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 policymakers 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 CO₂ 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

\[ P_{\text{Steel}} = \frac{\text{Capex}_{\text{CCS+OtherOPEX}}}{\text{SteelProd}} + P_{0,\text{Steel}} + E_{\text{CCS}} \times P_{0,\text{Electricity}} + P_{\text{CO₂}} \times (\text{correlation} \times E_{\text{total}} + \text{CO₂}_{\text{total}}) \]

instead of

\[ P_{\text{Steel}} = \frac{\text{Capex}_{\text{CCS+OtherOPEX}} + P_{0,\text{Steel}} + E_{\text{CCS}} \times P_{0,\text{Electricity}} + P_{\text{CO₂}} \times (\text{correlation} \times E_{\text{total}} + \text{CO₂}_{\text{total}})}{\text{SteelProd}} \]
References


HE, 82/2014. Finland’s Governments proposal for a climate law (Hallituksen esitys eduskunnalle ilmastolaiksi).


## Appendix A

### Cost and emission balances

#### PCC case 0

<table>
<thead>
<tr>
<th>Cost assessment</th>
<th>Capex</th>
<th>Opex</th>
<th>Total</th>
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<td>Sum -9 445 k€/a</td>
<td>Sum -9 445 k€/a</td>
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<td>MEA 0 k€/a</td>
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<td>CO2 transportation 0 k€/a</td>
<td>Capex 0 k€/a</td>
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<td>CO2 allowances 74 879 k€/a</td>
<td>CO2 BeP - €/tn</td>
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#### Streamlined LCA

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<tbody>
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<td>Emissions from fuel production 0 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing energy production -1.18 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing district heat production -0.10 Mt/a</td>
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<tr>
<td>Emissions from CO2 transportation 0 Mt/a</td>
</tr>
<tr>
<td>Emissions from MEA production 0 Mt/a</td>
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<tr>
<td>Emissions from construction of infrastructure (CCS, LTO,t, etc.) 0 Mt/a</td>
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Comparison to 0-case

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<th>Sum 0.00 Mt/a</th>
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<td>Effect of replacing district heat production 0.00 Mt/a</td>
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<td>Emissions from CO2 transportation 0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from MEA production 0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO,t, etc.) 0.00 Mt/a</td>
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- €/ton CO2 avoided
## Cost assessment

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<tr>
<th></th>
<th>Capex</th>
<th>Opex</th>
<th>Total</th>
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<tbody>
<tr>
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<td>8 419 k€/a</td>
<td>370 k€/a</td>
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<tr>
<td>interest</td>
<td>10 %</td>
<td></td>
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</tr>
<tr>
<td>lifetime</td>
<td>26 a</td>
<td></td>
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</tr>
<tr>
<td>Sum</td>
<td>77 123 k€</td>
<td>54 k€/a</td>
<td>81 667 k€</td>
</tr>
<tr>
<td>CCS</td>
<td>54 123 k€</td>
<td>1 542 k€/a</td>
<td>55 665 k€/a</td>
</tr>
<tr>
<td>Changes in the turbine</td>
<td>0 k€</td>
<td>14 801 k€/a</td>
<td>14 801 k€/a</td>
</tr>
<tr>
<td>heat connections</td>
<td>23 000 k€</td>
<td>66 632 k€/a</td>
<td>66 632 k€/a</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Opex</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>Changes in the turbine</td>
<td>0 k€</td>
<td>0 k€/a</td>
</tr>
<tr>
<td></td>
<td>heat connections</td>
<td>23 000 k€</td>
<td>23 000 k€/a</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<tr>
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</tbody>
</table>

### Streamlined LCA

<table>
<thead>
<tr>
<th>Sum</th>
<th>-0.32 Mt/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions from combustion (inside battery limits)</td>
<td>-0.36 Mt/a</td>
</tr>
<tr>
<td>emissions from fuel production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing energy production</td>
<td>0.03 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing district heat production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from CO2 transportation</td>
<td>0.01 Mt/a</td>
</tr>
<tr>
<td>Emissions from MEA production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO,t, etc.)</td>
<td>0.00 Mt/a</td>
</tr>
</tbody>
</table>

82 €/ton CO2 avoided
## Cost assessment

<table>
<thead>
<tr>
<th></th>
<th>Capex</th>
<th>Opex</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum</td>
<td>Sum</td>
<td>Sum</td>
</tr>
<tr>
<td></td>
<td>21 047 k€/a</td>
<td>39 019 k€/a</td>
<td>60 066 k€/a</td>
</tr>
<tr>
<td>interest</td>
<td>10 %</td>
<td>-27 373 k€/a</td>
<td>359 k€/a</td>
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<tr>
<td>lifetime</td>
<td>26 a</td>
<td>-13 500 k€/a</td>
<td>515 k€/a</td>
</tr>
<tr>
<td>Sum</td>
<td>192 807 k€</td>
<td>55 343 k€/a</td>
<td>69 510 k€/a</td>
</tr>
<tr>
<td>CCS</td>
<td>192 807 k€</td>
<td>38 56 k€/a</td>
<td>48 464 k€/a</td>
</tr>
<tr>
<td>Changes in the turbine</td>
<td>0 k€</td>
<td>-52.0 €/tn</td>
<td></td>
</tr>
<tr>
<td>heat connections</td>
<td>0 k€</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Difference to base case (0)

- Capex: 21 047 k€/a
- Opex: 48 464 k€/a
- Total: 69 510 k€

### Streamlined LCA

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

<table>
<thead>
<tr>
<th>Sum</th>
<th>-1.61 Mt/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions from combustion (inside battery limits)</td>
<td>-2.39 Mt/a</td>
</tr>
<tr>
<td>emissions from fuel production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing energy production</td>
<td>0.72 Mt/a</td>
</tr>
<tr>
<td>Effect of replacing district heat production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from CO2 transportation</td>
<td>0.05 Mt/a</td>
</tr>
<tr>
<td>Emissions from MEA production</td>
<td>0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.)</td>
<td>0.01 Mt/a</td>
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</table>

77 €/ton CO2 avoided
## Cost assessment

<table>
<thead>
<tr>
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<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum 24 618 k€/a</td>
<td>Sum 39 964 k€/a</td>
<td>Sum 64 582 k€/a</td>
</tr>
<tr>
<td>interest</td>
<td>10 %</td>
<td>electricity -26 033 k€/a</td>
<td>Difference to base case (0)</td>
</tr>
<tr>
<td>lifetime</td>
<td>26 a</td>
<td>district heat -13 500 k€/a</td>
<td>Opex 49 409 k€/a</td>
</tr>
<tr>
<td>Sum</td>
<td>225 524 k€</td>
<td>MEA 389 k€/a</td>
<td>Capex 24 618 k€/a</td>
</tr>
<tr>
<td>CCS</td>
<td>202 524 k€</td>
<td>water 557 k€/a</td>
<td>CO2 BeP 52 €/tn</td>
</tr>
<tr>
<td>Changes in the turbine</td>
<td>0 k€</td>
<td>Other CCS Opex 4 510 k€/a</td>
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</tr>
<tr>
<td>heat connections</td>
<td>23 000 k€</td>
<td>CO2 transportation 58 777 k€/a</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>CO2 allowances 15 264 k€/a</td>
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</tr>
</tbody>
</table>

## Streamlined LCA

<table>
<thead>
<tr>
<th></th>
<th>Sum</th>
<th>Comparison to 0-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions from combustion (inside battery limits)</td>
<td>0.19 Mt/a</td>
<td>-1.78 Mt/a</td>
</tr>
<tr>
<td>Emissions from fuel production</td>
<td>0.66 Mt/a</td>
<td>Emissions from combustion (inside battery limits) -2.59 Mt/a</td>
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<tr>
<td>Effect of replacing energy production</td>
<td>-0.43 Mt/a</td>
<td>Effect of replacing energy production 0.75 Mt/a</td>
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<tr>
<td>Effect of replacing district heat production</td>
<td>-0.10 Mt/a</td>
<td>Effect of replacing district heat production 0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from CO2 transportation</td>
<td>0.05 Mt/a</td>
<td>Emissions from CO2 transportation 0.05 Mt/a</td>
</tr>
<tr>
<td>Emissions from MEA production</td>
<td>0.00 Mt/a</td>
<td>Emissions from MEA production 0.00 Mt/a</td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.)</td>
<td>0.01 Mt/a</td>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.) 0.01 Mt/a</td>
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</table>

75 €/ton CO2 avoided
## Cost assessment

<table>
<thead>
<tr>
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<th>Opex</th>
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<tbody>
<tr>
<td>Sum</td>
<td>Sum</td>
<td>Sum</td>
</tr>
<tr>
<td></td>
<td>83 657 k€/a</td>
<td>106 718 k€/a</td>
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<tr>
<td>interest</td>
<td>electricity</td>
<td>district heat</td>
</tr>
<tr>
<td>10 %</td>
<td>19 827 k€/a</td>
<td>-13 500 k€/a</td>
</tr>
<tr>
<td>lifetime</td>
<td>MEA</td>
<td>water</td>
</tr>
<tr>
<td>26 a</td>
<td>440 k€/a</td>
<td>630 k€/a</td>
</tr>
<tr>
<td></td>
<td>Other CCS Opex</td>
<td>4 225 k€/a</td>
</tr>
<tr>
<td></td>
<td>CO2 transportation</td>
<td>64 547 k€/a</td>
</tr>
<tr>
<td></td>
<td>CO2 allowances</td>
<td>7 488 k€/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Difference to base case (0)</td>
</tr>
<tr>
<td>Sum</td>
<td>Opex</td>
<td>Capex</td>
</tr>
<tr>
<td>211 266 k€</td>
<td>93 101 k€/a</td>
<td>23 062 k€/a</td>
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<tr>
<td>CCS</td>
<td>Other CCS Opex</td>
<td>4 225 k€/a</td>
</tr>
<tr>
<td>211 266 k€</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changes in the turbine</td>
<td>0 k€</td>
<td></td>
</tr>
<tr>
<td>heat connections</td>
<td>0 k€</td>
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</tr>
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</table>

## Streamlined LCA

<table>
<thead>
<tr>
<th>Comparison to 0-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
</tr>
<tr>
<td>Emissions from combustion (inside battery limits)</td>
</tr>
<tr>
<td>emissions from fuel production</td>
</tr>
<tr>
<td>Effect of replacing energy production</td>
</tr>
<tr>
<td>Effect of replacing district heat production</td>
</tr>
<tr>
<td>Emissions from CO2 transportation</td>
</tr>
<tr>
<td>Emissions from MEA production</td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.)</td>
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</table>

136 €/ton CO2 avoided
## Cost assessment

### Capex

<table>
<thead>
<tr>
<th>Item</th>
<th>Sum</th>
<th>€/a</th>
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</thead>
<tbody>
<tr>
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<td>25 572</td>
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<tr>
<td>interest</td>
<td>10%</td>
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</tr>
<tr>
<td>lifetime</td>
<td>26 a</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>234 266</td>
<td>€</td>
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<tr>
<td>CCS</td>
<td>211 266</td>
<td>€</td>
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<tr>
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<tr>
<td>heat connections</td>
<td>23 000</td>
<td>€</td>
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### Opex

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<th>€/a</th>
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<tbody>
<tr>
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<tr>
<td>electricity</td>
<td>19 827</td>
<td></td>
</tr>
<tr>
<td>district heat</td>
<td>-13 500</td>
<td></td>
</tr>
<tr>
<td>MEA</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>630</td>
<td></td>
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<tr>
<td>Other CCS Opex</td>
<td>4 685</td>
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<tr>
<td>CO2 transportation</td>
<td>64 547</td>
<td></td>
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<td>CO2 allowances</td>
<td>7 488</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>119 134</td>
<td>€</td>
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### Total

<table>
<thead>
<tr>
<th>Item</th>
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<tbody>
<tr>
<td>Sum</td>
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### Difference to base case (0)

<table>
<thead>
<tr>
<th>Item</th>
<th>Sum</th>
<th>€/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>119 134</td>
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</tr>
</tbody>
</table>

### Streamlined LCA

<table>
<thead>
<tr>
<th>Item</th>
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<th>Mt/a</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<tr>
<td>Emissions from fuel production</td>
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<tr>
<td>Effect of replacing energy production</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Effect of replacing district heat production</td>
<td>-0.10</td>
<td></td>
</tr>
<tr>
<td>Emissions from CO2 transportation</td>
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</tr>
<tr>
<td>Emissions from MEA production</td>
<td>0.00</td>
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<tr>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.)</td>
<td>0.01</td>
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### Comparison to 0-case

<table>
<thead>
<tr>
<th>Item</th>
<th>Sum</th>
<th>Mt/a</th>
</tr>
</thead>
<tbody>
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</tr>
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</tr>
<tr>
<td>Emissions from fuel production</td>
<td>0.00</td>
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<tr>
<td>Effect of replacing energy production</td>
<td>1.51</td>
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</tr>
<tr>
<td>Effect of replacing district heat production</td>
<td>0.00</td>
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</tr>
<tr>
<td>Emissions from CO2 transportation</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Emissions from MEA production</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Emissions from construction of infrastructure (CCS, LTO:t, etc.)</td>
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</table>

138 €/ton CO2 avoided
### Cost and Emission Balances

#### OBF Cases

<table>
<thead>
<tr>
<th>Economical Balance (M€/a)</th>
<th>BF</th>
<th>OBF</th>
<th>BF-OBF</th>
<th>BF-OBF w/o CBF-OBF w/o C Prices + Other Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 allowances</td>
<td>74</td>
<td>12</td>
<td>62</td>
<td>M€/a</td>
</tr>
<tr>
<td>LPG demand</td>
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<td>M€/a</td>
</tr>
<tr>
<td>Light fuel oil purchase</td>
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<td>0</td>
<td>0</td>
<td>M€/a</td>
</tr>
<tr>
<td>Coke selling</td>
<td>0</td>
<td>-74</td>
<td>74</td>
<td>M€/a</td>
</tr>
<tr>
<td>Electricity purchase</td>
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<td>30</td>
<td>-96</td>
<td>M€/a</td>
</tr>
<tr>
<td>Sold district heat</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>M€/a</td>
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<tr>
<td>CO2 transport &amp; storage</td>
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<td>-38</td>
<td></td>
<td>M€/a</td>
</tr>
<tr>
<td>Capture + ASU O&amp;M</td>
<td>2</td>
<td>-2</td>
<td>-2</td>
<td>M€/a</td>
</tr>
<tr>
<td>BF feedstocks (other than coke)</td>
<td>647.9</td>
<td>648.4</td>
<td>-0.4</td>
<td>M€/a 648 -0.4</td>
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<td>Capex</td>
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<td>-40</td>
<td>-40</td>
<td>M€/a</td>
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<tr>
<td>Total</td>
<td>657</td>
<td>715</td>
<td>-58.2</td>
<td>M€/a 682 -25.1</td>
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<tr>
<td>Break-even price for EUA</td>
<td></td>
<td></td>
<td></td>
<td>44.42 €/ton CO2 42.37</td>
</tr>
</tbody>
</table>

**Discount rate** 10%

**Economic lifetime** 26 a
## Title

**Techno-economic evaluation of significant CO₂ 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 CO₂, accounting for around 8% of global anthropogenic CO₂ emissions each year. In Europe, the recently proposed stricter emission reduction targets for 2030 are likely to increase the price for CO₂ 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 CO₂ 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™ using two indicators: the break-even price of CO₂ emission allowances for CCS and the impact of CCS on steel production costs. With the whole chain approach, including CO₂ 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 CO₂ 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 CO₂/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 CO₂. Oxygen blast furnace with top gas recirculation was estimated to be slightly cheaper than post-combustion capture of CO₂. 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.
### Teknistaloudellinen arviointi terästeollisuuden CO₂ -päästöjen vähentämisestä CCS:llä

#### Tekijät

Antti Arasto

#### Tiivistelmä

Terästeollisuus vastaa noin 6 % globaaleista ihmisen aiheuttamista päästöistä ja on siten globaalisti yksi suurimmista teollisista CO₂-päästijästä. Euroopan komission esittämät uudet, kunniainhimoisemat päästövähennystavoitteet aiheuttavat noussuojain- ja päästööljyjen hintoihin. Luksuisia erilaisia hiilidioksidipäästöjen vähentämismenetelmiä, kuten energiatehokkuus, biopohjaiset pelkistimet, vety ja CCS, on ollut esillä terästeollisuuden hiilintensiivisyyden vähentämiseksi. Kaikia näistä ei kuitenkaan voida soveltaa yleisimminä teräsentuotantoprosessiin, joka perustuu masuuniin, ja kaikilla näillä vaihtoehtoilla on lisäksi hyviä ja huonoja piirteitä. CCS on tällä hetkellä ainoana vaihtoehtona, joilla terästeollisuuden hiilidioksidipäästöjä voidaan merkittävästi vähentää.

Koko prosessiketjun kattava arviointi on tässä sovellettu hiilidioksidin talteenoton ja varastoinnin soveltamiseen terästeollisuudessa, jotta eri teknologianvaihtoehtojen voitaisiin vertailla ja luoda teknologiapolitiikan vähähiiliseen terästukentoon tulevaisuuden

- Hiilivapaaseen talouteen siirryttäessä. Teknistaloudellisen arviinnin avulla luotiin myös
tietopohjaa paikallisille terästutajille päätöksenteon tukeksi. Arvio tehtiin kahdelle eri
CO₂-talteenottoteknologialle, jotka ovat CO₂-talteenotto pesurilla savuasuaista ja
happimasuuni savuasuaan kierrätyksellä ja CO₂-erotuksella. Prosessit mallinnettiin Aspen
Plus -prosessimitaloilla ja tähän perustuva talouden arvio tehtiin CC-SkyNETTM-
yökalulla käyttäen kahta indikaattoria: CO₂-päästöoikeuden rajahinta sekä CCS:n
soveltamisen vaikutus teräksen talteenoton tulevaisuudessa.

Koko CCS-ketjun kattava arviointi sisältää CO₂:n talteenoton, prosessoinnin, kuljettuken ja
varastoinnin. Arvioinnin perusteella voitetaan todeta, että terästeollisuudessa on merkittävä
 tekninen CO₂-vähennyspotentialia. Solvelletussa happimasuunivaihtoehtoa tarvittiin
olemassa olevaan prosessiin suurempia muutoksia kuin solvelletussa talteennotosta
savuasuaista. Erilaisia vaiheistetun soveltamisen ja investoinnin toteutuspolkuja
- terästeollisuuden hiilidioksidipäästöjen vähentämiseksi.

Päästövähennyskustannuksia arvioitiin talteenoton lomakkeen omistajan näkökulmasta
suurimman osan ollessa 40–70 €/t CO₂. Happimasuuni savuasuaan kierrätyksellä oli hieman
halvempi kuin CO₂:n talteenotto savuasuaista. Kuten tuloksista selviää, päästövähennysten
rajakustannukset ovat hyvin herkkä useille kustannustekijöille, jotka ovat erittäin
epävarmoja tämänkaltaisen investoinnin pitoaikana. Tuloksista selviää myös, että CCS:n
soveltaminen ja sen kustannukset vaihtelevat hyvin paljon riippuen solveluksen muotoista
ja terästen piirteistä ja toimintaympäristöstä sekä myös tarkastelun rajakustannus ja
oletukset.

Erityisesti vaikuttavat energiantuloutuotoon ja siten energiayarjestelmiin vaikuttavat
merkittävästi nettopäästövähennyksiin.

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### Julkaisija

Teknologian tutkimuskeskus VTT Oy

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Techno-economic evaluation of significant CO₂ 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 CO₂ 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 CO₂ 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.