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Hybrid life cycle assessment of steel production with carbon capture and storage

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Master in Industrial Ecology

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Hybrid Life Cycle Assessment of steel production with carbon capture and storage (CCS)

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MASTER THESIS

for

Hyun-Doc Choi

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Hybrid life cycle assessment of steel production with CCS
Hybridlivsløpsanalyse av stålproduksjon med CCS

Background

The iron and steel sector is the largest energy consuming manufacturing sector, accounting for nearly 20 percent of industrial energy consumption and nearly 10 percent of global CO₂ emissions. The iron making process, i.e. blast furnace and smelting reduction process, makes for the largest share of total carbon input to iron and steel plants. Carbon capture and storage (CCS) technology, which is based on the concept of capturing CO₂ from large point sources and sequestering it away from atmosphere, can therefore also be applied in conjunction with the iron and steel sector. Benchmarking the environmental performance of different options for CCS in the iron and steel industry is important to provide a solid basis for investment decisions, R&D efforts and also policy design. Life cycle assessment is the key framework for such analysis. In this work, state of the art hybrid methods will be applied to ensure consistent comparisons across a portfolio of cases.

Aim

The primary objective of this work is to assess the environmental performance of various CO₂ capture technologies for iron and steel plants. This will be undertaken using state of the art hybrid methods. The secondary objective is to benchmark these with iron and steel plants that have no CO₂ capture systems.

The analysis should include following elements:

1. Prioritization of combinations of capture technologies and iron and steel technologies to inventorize (in dialogue with supervisor and co-supervisor).
2. Development of life cycle inventories for the selected systems.
3. Development of benchmarking inventories
4. Life cycle assessment of the selected CCS and benchmarking cases.
5. Analysis and discussion.

-- " --

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- Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
 Field work

Department of Energy and Process Engineering, 1. February 2013


Olav Bolland
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Abstract

Among several Green house gases, CO₂ is a main contributor and accounts for about 60% of the greenhouse effect because of its huge emission amount. The iron and steel sector has showed one of the largest energy intensity among manufacturing sectors. 31% of CO₂ emission in the industrial sectors is caused by the production of iron and steel and the amount of CO₂ emission corresponds to nearly 6-10% of global CO₂ emission. The potential of CCS in the industrial sectors is considered to be significant to mitigate CO₂ emission to the atmosphere. IEA has estimated that, in a scenario to halve global greenhouse gas (GHG) emissions in 2050 compared to 2007 level, nearly half of all CCS deployed (up to more than 10Gt/yr) would be in industrial processes.

In the study, the environmental performance of CCS deployment in blast furnace (BF), top gas recycling blast furnace (TGRBF) and COREX processes which are technologies for producing pig iron has been evaluated by Hybrid life cycle assessment (LCA).

In terms of BF with a capture unit of chemical absorption by MEA solvent, expect for the GWP, other environmental impacts showed increases. As for TGRBF with PSA (pressure swing adsorption), while GWP and TAP decreased compared to TGRBF without CCS, the other environmental impacts were increased. COREX with physical absorption by Selexol solvent showed same trend with the BF+MEA. The net reduction of GWP was 26% in the BF+MEA, 31% in the TGRBF+PSA, and 48% in the COREX+Selexol when performing CCS technologies into pig iron production in life cycle boundary. When it comes to the change range of the environmental impacts, the BF+MEA presented the higher increases on overall environmental impact categories except for GWP than other technologies with CCS. Regardless of CCS implementation, the COREX technology showed the highest benefits for most environmental impact factors aside from IRP and POFP.

Overall, additional energy requirements by CO₂ capture unit in all technologies for pig iron production mainly contributed increases in terms of most environmental impacts. The impacts of transport and storage, and other materials such as solvent and sorbent production were negligible.

This study has shown that hybrid LCA method is a helpful tool to support the discussion about environmental effects with respect to CCS technologies depended on different ironmaking technologies.

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Trondheim, June 2013

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1. Introduction

1.1 Background

The greenhouse effect is a natural process in which the emission of infrared radiation by greenhouse gases (GHGs) in atmosphere warms a planet's surface. Nevertheless, large amount of greenhouse gases releasing to the atmosphere in a short period can lead to global warming and climate change. Among several GHGs, CO₂ is the main contributor and accounts for about 60% of the greenhouse effect because of its huge emission amount (Yang et al., 2011). According to the Intergovernmental Panel on Climate Changes (IPCC)'s the fourth assessment report, as a result of anthropogenic CO₂ emission, global atmospheric concentration has increased from a preindustrial value of ~280ppmv to 378ppmv in 2005 and ~390ppmv in currently (Metz, 2007). If businesses proceed as usual, the anthropogenic greenhouse gas (GHG) will increase the average global temperature from 1.1 to 6.4 °C during the 21st century. As a result from the increase of temperature, ecosystem may collapse and 15 to 40 percent of all species may become extinct (Shao and Stangeland, 2009).

According to the International Energy Agency (IEA)'s report, in 2008, the emission of CO₂ related global primary energy supply amounted to 29Gt and one-third of worldwide CO₂ emission are contributed to total industry and fuel transformation. As shown in Figure 1, IEA report presented several industrial sectors which generate high CO₂ emission intensity for steel, cement, refineries, and high purity sources. In particular, 31% of CO₂ emission in the industrial sectors is caused by the production of iron and steel (Figure 1). The amount of CO₂ emission corresponds to nearly 6-10% of global CO₂ emission (Kuramochi et al., 2012, Metz, 2007). The iron and steel sector is one of the largest energy intensity among manufacturing sectors. The carbon dioxide intensity of the steel sector today is around 1.9 tCO₂/t crude steel and the average energy intensity refers to 20,2GJ/ton steel (IEA, 2011).

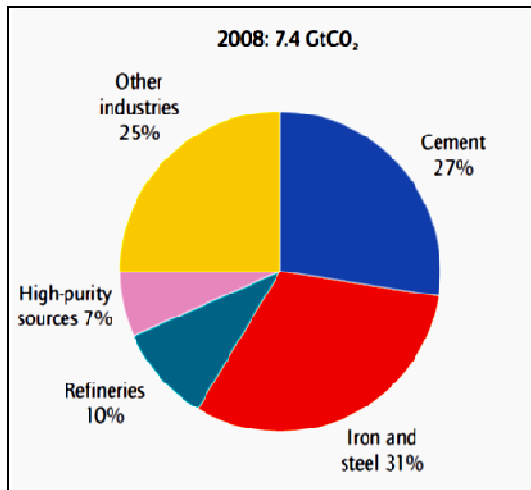


Figure 1. Industrial emission of CO₂ (IEA, 2011)

The Figure 2 presents the tendency of growth for the steel production in the world. According to the World Steel Association's statistics, total steel production in the world amounted 1.51Gton in 2012 and 1.49 Gton in 2011. The amount presented nearly 13% increased rate compared to the amount of production in 2007 and 2008. Except for the period of world economic crisis, the steel production and demand have increased gradually and some literatures have said that the world crude steel production may increase up to about 1,6Gton in 2030 (Kuramochi et al., 2012). It implies that the increased CO₂ emission for steel production is inevitable if not any actions do not measure to improve to reduce CO₂ emission.

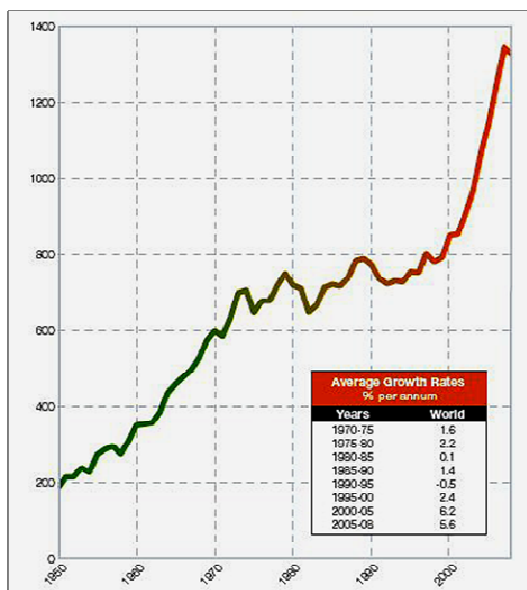


Figure 2. State of steel production in the world (Birat and Maizière-lès-Metz, 2010)

To mitigate global warming, Kyoto protocol requires that 37 industrialized nations and European Union have to reduce their greenhouse gas emission to a level 5.2% on average lower than those of 1990 during the period of 2008 to 2012. Copenhagen Accord also requests that global average temperature increase should be kept below 2 °C (Yu et al., 2012). To reduce CO₂ emission, there are several options such as efficiency improvement, increasing nuclear and renewable energy, and carbon capture and storage (CCS) systems.

The potential of CCS in the industrial sectors is considered to be significant. IEA has estimated that, in a scenario to halve global greenhouse gas (GHG) emissions in 2050 compared to 2007 level, nearly half of all CCS deployed (up to more than 10Gt/yr) would be in industrial processes (cement, iron and steel, and chemicals) and the fuel transformation sector (petroleum refineries and liquefied natural gas production)(IEA, 2011).

In the steel and iron industries, diverse projects have been implemented to reduce the CO₂ emission during production processes. ULCOS (Ultra-Low CO₂ Steel making), a consortium of 48 European companies and organization from 15 European countries to enable a drastic reduction in CO₂ emission form steel production, have suggested capturing and sequestering CO₂ with optional transportation and storage (IPPC, 2013). Additionally, the COURSE 50 (CO₂ Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) committee which is supported at the Japan Iron and Steel Federation (JISF) has included developments of technologies for separating and recovering CO₂ from iron production.

Even though the CCS can reduce high amount of direct CO₂ emission from industrial processes, the CCS process in itself has high energy requirements, additional chemicals and infrastructure. Moreover, trade-offs in environmental impacts in line with the CCS are expected and thus, it is necessary that a systemic process of evaluation for all stages of CCS and impacts related to CCS deployment. Life cycle assessment (LCA) is a useful method to better understand the human health and environmental impacts of products, processes, and activities in a systematic manner.

1.2 State of the field

As increasing importance of the CCS technology into industrial sectors, many study groups have undertaken modeling and simulation with respect to iron and steel industry with CCS.

When it comes to chemical absorption in the iron and steel industry, several studies have done process modeling. Farla et al., 1995, Gielen, 2003, Tobiesen et al., 2007, Arasto et al., 2012, Lampert and Ziebik, 2007 and Kuramochi et al., 2012 indicate the modeling data using MEA as the adsorbent to recovery CO₂ from the iron making process. Especially, Kuramochi et al., 2012 mentioned that the chemical absorption for CO₂ capture from the conventional BF process is suitable because of low partial pressure of CO₂ of BFG. (Gielen, 2003, Tobiesen et al., 2007, Arasto et al., 2012, Lampert and Ziebik, 2007, Farla et al., 1995, Kuramochi et al., 2012).

As for studies of a technology of physical adsorption using a Selexol process in the steel production, Hu et al., 2009, Ho et al., 2011, Lampert and Ziebik, 2007 have studied process modeling of CO₂ capture within COREX process. (Hu et al., 2009, Ho et al., 2011, Lampert and Ziebik, 2007).

The reports of ULCOS and IEA CCS indicated the tog gas recycling blast furnace with PSA. The ULCOS project has demonstrated the physical adsorption technology with iron and steel industry (Zuo and Hirsch, 2009, Danloy et al., 2008, IEA, 2011). XU and Cang, 2010 has recommended the employment of PSA technology in the iron and steel industry in study with respect to an overview of Low CO₂ Emission Technologies.

However, many studies have tried to evaluate CCS technologies in terms of techno-economic aspects. Power plants and fuel cycles with CCS were largely interesting in majority even if including an environmental assessment. Currently, few studies have indicated the environmental assessment based on the iron and steel sector with CCS technology. The following papers have been published in terms of iron and steel industry with CCS.

Kuramochi et al.,2012 assessed whether the deployment of CO₂ capture technologies in European industrial sector would result in emissions of air pollutants (NO_x, SO₂ , PM, and NH₃). Arasto et al., 2012) have studied different possibilities for applying post-combustion

capture at an integrated steel mill in order to reduce CO₂ emission. Nagashima et al., (2011) have performed an LCA analysis by CO₂ emission utilizing CCS in diverse industry sectors emissions and the main focus was energy supply for heat consumption to regenerate solvent to reduce own CO₂ emission from CCS.

1.3 Objective of this study

Up to date, most of the studies focus on the technical and economic parts for CCS and a few researches have carried out an environmental evaluation in iron and steel sector compared to power productions. According to literatures studied for power plants, CCS system has benefits for reducing CO₂ but trade-offs occur in terms of other environmental areas such as air quality, acidification, eutrophication, toxicity, water demand, waste management, etc (Zapp et al., 2012). Therefore, to deploy the CCS system in iron and steel sector, it is necessary to evaluate an environmental assessment as for specific iron and steel sector with CCS.

The objective of the study assesses the environmental performance of various CO₂ capture technologies for iron and steel industry by means of the Hybrid LCA. The results will be compared to the iron and steel plants without CCS. In order to approach the objective, the study investigates technical properties of each technology of pig iron production for combination of capture technologies. In addition, the life cycle inventories for the selected systems are developed by the study. Finally, the objective of study provides the benchmarking for iron and steel industry with CCS in view of environment.

2. Technologies overview

2.1 Iron and steel production

The iron and steel industry is one of the largest energy consuming manufacturing sectors in the world. According to the IEA report, the iron and steel industry accounts for about 20% of final energy use and the CO₂ relevance is also high because of a large share of coal in the energy mix (Mandil, 2007).

In fact, the iron and steel industry has achieved significant energy efficiency, increased recycling, and materials efficiency. In particular, the energy consumption of steel sector in North America, EU, and Japan has been reduced to the extent of about 50% compared to that of 1975 through improvement of technologies (XU and Cang, 2010). However, China, India, Ukraine and the Russian Federation account for nearly half of global iron production and more than half of global CO₂ emissions from iron and steel production. Moreover, these four countries are lower efficiency of the iron and steel industries than that in OECD countries (Mandil, 2007).

Secondary production of steel which can reduce production processes and energy consumption have been increased and improved. Nevertheless, the scrap steel cannot meet the entire demand for steel both quantitatively and qualitatively. Therefore, still there is a counting demand for primary steel.

Figure 3 presents processes, materials and energy sources for the primary steel production. All of primary iron and steel production processes are based on similar chemical reaction. In iron reduction processes, Iron ore, oxidized form of iron, is reduced using a reducing agent, based on carbon and hydrogen. The process which removes oxygen from the iron ore can take place above melting point. As the result, pig iron can be produced. As seen in Figure 3, blast furnace (BF) and COREX processes indicate the production routes of pig iron. The pig iron produced in the BF is converted into steel in BOF. When it comes to Direct Reduction (DR) process, it is quite different with BF process because the principle is the removal of oxygen (reduction) from iron ores in the solid state. In addition, as for the reducing agent, natural gas is mainly used to enable this process. Direct reduction iron is applied as a feedstock of electric arc furnaces (EAF) which is the process for producing steel. In the study, the production processes of pig iron are mainly focused, therefore, the DRI production process is excluded.

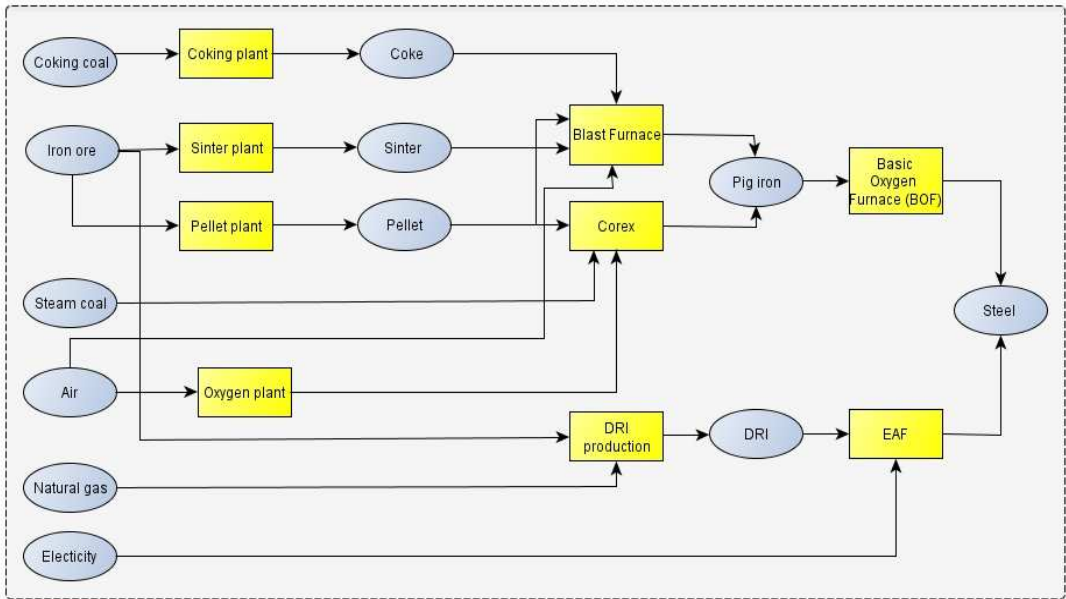


Figure 3. Primary steel production routes

Table 1 indicates compositions of flue gas from the three technologies of the BF, TGRBF and COREX based on several literatures which have carried out studies with respect to iron and steel technologies. Depending on applied technologies, the CO₂ fraction in flue gas is different. Moreover, in case performance of CO₂ capture, other impurities which affect into the capture process are also dissimilar. Therefore, the CO₂ capture technologies have to be performed by the properties of the flue gas from the reducing processes in pig iron production.

Table 1. Flue gas composition of three systems for the iron production

% volume fraction	BF ^{a)}	TGRBF ^{b)}	COREX ^{c)}
CO ₂	16-23	25-37	24-33
N ₂ + Ar	50-56	5,5-10	2-12
O ₂	0	0	0-0,5
H ₂ O	0	0	1-2
H ₂	3-3,5	8-9	17-20
CO	21-27	44-48	35-44
CH ₄	0-0,5	NA ^{d)}	1-2
SOx (ppm)	200-220	NA	20
NOx (ppm)	33	NA	NA

Source :

^{a)} (IPPC, 2012), (Gielen, 2003), (Lampert et al., 2010), (Farla et al., 1995),

^{b)} (Birat and Hanrot, 2005), (Afanga et al., 2012), (Danloy et al., 2008),

^{c)} (Hu et al., 2009), (Lampert and Ziebig, 2007), (Ho et al., 2011) ^{d)} Not available

2.1.1 Blast furnace

Conventional primary steel production follows the route from BF to basic oxygen furnace (BOF). The production route accounts for more than 65% of the world total steel production and according to the world steel report, the produced iron in 2012 was indicated as 1100Mt. (World Steel Association, 2011)

The percentage of CO₂ emission from the conventional steel production is illustrated in Figure 4 (Wiley et al., 2011). As shown in Figure 4, the Blast furnace is the main contributor as 69% of total CO₂ emission by production processes. In the BF process, the CO₂ emission is mainly due to the requirement of carbon in the reducing agents and energy such as coal, coke and etc. To feed the coke, conventional steel production needs the coking plant. Iron ore in its natural state occurs as lump ore and fine ore. Through sintering and pelletizing the ore can be agglomerated and the sinter and pellet can be feed into the BF. Therefore, the BF process route needs the coking plant, sinter plant and pellet plant to provide the materials (Daniels, 2002).

The BF process consists of a shaft furnace and feeds of the iron-containing materials such as sinter, pellet, and iron ore and coke are needed. Hot air is injected into the furnace through tuyères and a reducing reaction with the coke take place. The BF process is a very energy-efficient, counter-current (Daniels, 2002). It is operated in extremely high temperature. According to the IPPC report, the BF process can be divided into six temperature zones as top, shaft, belly, bosh, tuyères and hearth. In a case of tuyères zone, temperature here can

exceed 2000°C and the iron oxide is completely reduced (IPPC, 2012). Hence, to operate the BF process, significantly the energy consumption is needed

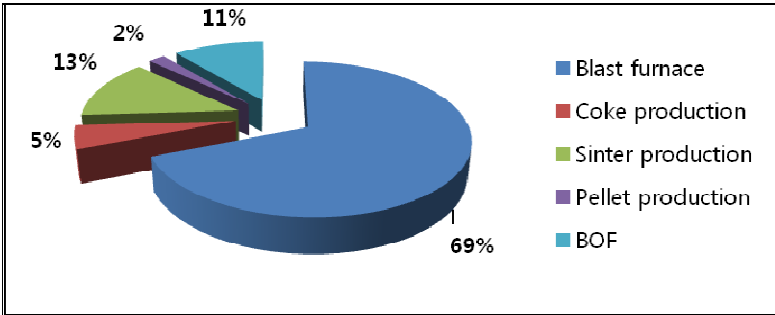


Figure 4. Contribution of CO₂ emission in conventional steel production

Blast furnace gas (BFG) contains about 20-28% CO, 1-5% H₂, inert compounds (50-55% N₂, 17-25% CO₂), some SO_x, NO_x, and large amounts of dust from burdens. If the CO₂ emitted from the BF is captured and stored, the total CO₂ emission from a steel plant can be significantly reduce (Birat and Hanrot, 2005, XU and Cang, 2010, IPCC, 2012).

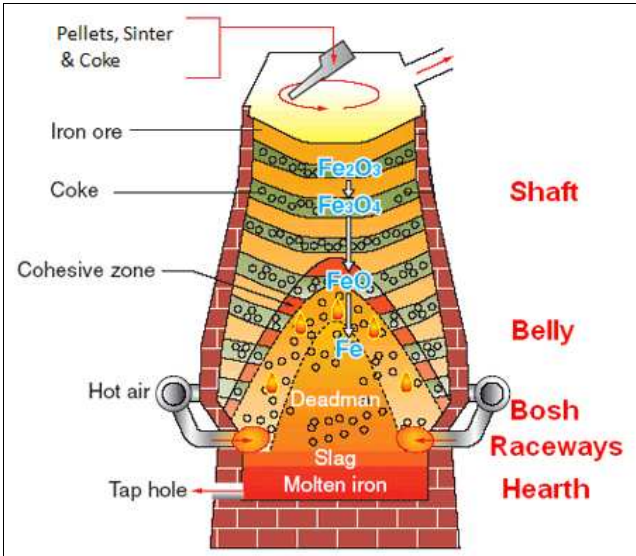


Figure 5. Simplified scheme of blast furnace

2.1.2 Top gas recycling blast furnace (TGRBF)

Typically, the BF process produces approximately 1200-2000Nm³ of BFG per tonne of hot metal. As mentioned in the BF technology, the BFG consists of about 20-28% CO and 1-5%

H₂. These CO and H₂ can be the potential energy source or reducing agent. TGRBF technology has been studied for decades to reduce coke consumption and has been evaluated for commercialization by ULCOS program. Since the technology is based on modification of conventional BF technology, it is possible to be commercialized in short term and midterm. The technology suggested from the several projects and roadmaps is oxygen-blown TGRBF with CCS (Kuramochi et al., 2012, Schmöle and Lungen, 2004, IEA, 2011).

Four versions of the TGRBF concepts have been considered. The common features of the different TGRBF processes are the use of the oxygen instead of hot air, the CO₂ removal and the re-injection of the recycled CO-rich gas into BF. In version 1, the de-carbonated top gas is recycled both coldly at main tuyères and hotly at the stack tuyères. The recycled top gas can be injected into the main tuyères only, version 3 or shaft/stack tuyères, version 4 (Danloy et al., 2008). Figure 6 presents the TGRBF technology for the version 3 and 4. Other processes and feedstock are identical with conventional BF technology.

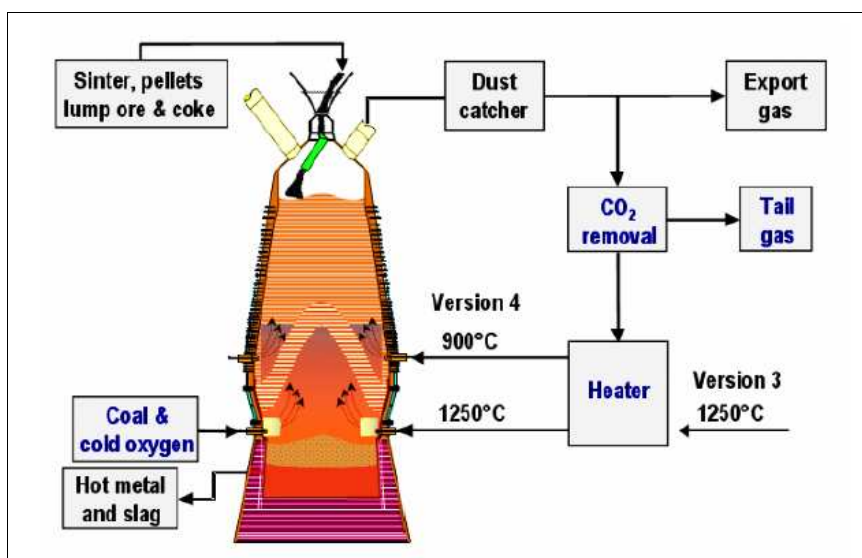


Figure 6. Process flows of TGRBF

2.1.3 COREX

COREX is another producer of pig iron and a smelting reduction process alternative to the BF. The COREX technology does not require the coke and thus non-coking coal is used as a source of energy and reducing agents. Therefore, the COREX technology is environmental friendly than the BF technology. Besides, the COREX technology can use the lump ore and pellets as the feedstock. Therefore, the COREX process can reduce coking plant and the

process for sinter production. Unlikely with BF, the technology use the oxygen as an oxidizing agent instead of air.

All metallurgical processes take place in a reduction shaft and a smelter gasifier. Coal enters the smelter gasifier and is converted to char under 1100-1150°C temperature. High pressure oxygen, blown into the smelter gasifier produces reduction gas by reaction with coal. After cooling to 800-850 °C, the gas is injected into reduction shaft. In the shaft, pellet and lump ore can be reduced. Compared with BFG, COREX gas contains high CO₂ composition in volume. The COREX gas consists of about 35-44% CO, 7-12% H₂, 24-35% CO₂, and 2-12% N₂. Since the gas has high energy potential, the gas has been studied as other energy sources or generation of electricity. (Lampert et al., 2010, Ho et al., 2011, Kuramochi et al., 2012)

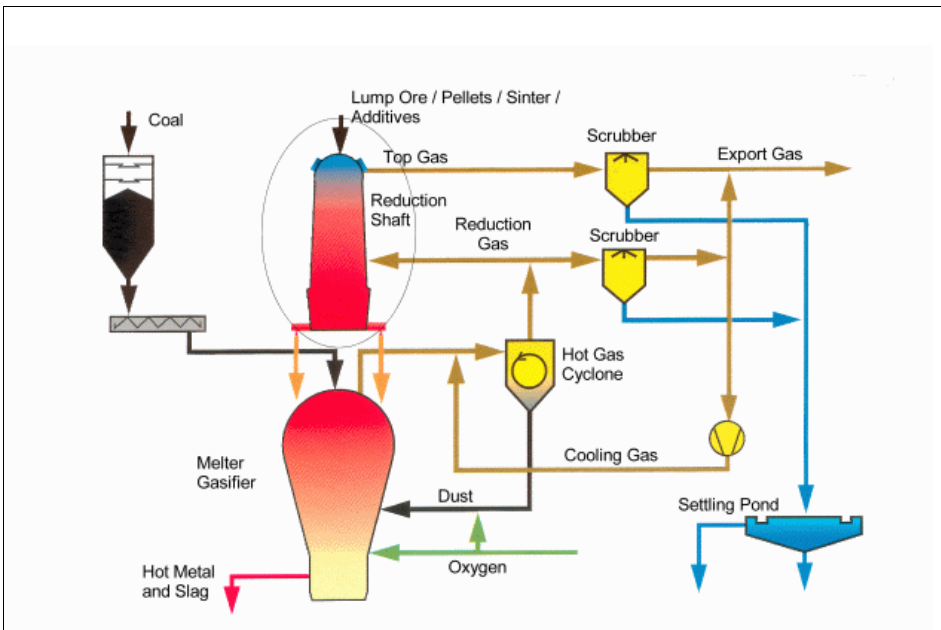


Figure 7. Schematic diagram of the COREX process

2.2 CO₂ capture technology

In terms of the CCS technology, there are generally three step processes: (1) capture and compression from combustion, (2) transportation, (3) utilization and storage. The CO₂ capture stage could account for 70-90% of total operating costs of a CCS system. In particular, the capture technology in power generation sectors has been much researched (Spigarelli and Kawatra, 2013). While the power plants release CO₂ through combustion of fossil fuels, in the iron making processes, the major part of CO₂ generation is related to the

reduction of the iron ore. As the reason, the CO₂ capture technologies in the iron and steel industry do not exactly match the existing capture categories such as post combustion, pre combustion and oxyfuel (Birat and Maizière-lès-Metz, 2010). However, the CO₂ separation technologies within power plants could be applicable to CO₂ capture from the iron and steel industry. In general, when exploring capture options in industrial processes, it is important to take note of impurities such as NO_x, SO_x, particulate matter, partial pressure of CO₂ and volume of flue gas, and temperature of inlet flue gas stream (Spigarelli and Kawatra, 2013).

2.2.1 Chemical absorption

Chemical absorption is based on a reversible character of the reaction of CO₂ and other acid gases with liquid solvent or absorbent. It is the preferred method for capturing CO₂ from flue gas streams containing low to moderate partial pressure of CO₂ (3-20%). When choosing solvents or absorbents, the solubility of the gaseous component in the absorbent and reactive properties of the gaseous component and the absorbent. For the CO₂ gas which is an acid gas, alkaline absorbents is desirable. The cooled flue gas of a furnace in the iron-making process comes into contact with the liquid absorbent and is absorbed from the gas phase into the liquid phase in absorber. The flue gas is then washed to remove water and solvent droplets/vapor. The CO₂-rich solvent is subsequently transferred to the top of stripper column and then CO₂ is freed at a temperature between 100 and 140 °C using heat which is generated from steam in a reboiler. The gas leaving the stripper contains CO₂ and water and can be hydrated and compressed before being sequestered. After the CO₂ is stripped, the lean solvent is cooled in the heat exchanger before it is recycled back to the absorber (Veltman et al., 2010, Peeters et al., 2007). The regeneration energy for CO₂ capture from the iron production process lies from 2.6 to 4.4 GJ/ton CO₂ (Tobiesen et al., 2007, Kuramochi et al., 2012, Arasto et al., 2012). In this process, most energy consumption comes from the solvent regeneration step, occupying about 60% of the required energy (Yu et al., 2012).

Alkanolamines are widely used as the absorbent for chemical CO₂ capture. The structure of alkanolamines can be classified as primary, secondary, and tertiary amines containing at least one OH and amine group such as monoethanolamine (MEA), diethanolamine (DEA) and N-methyldiethanolamine (MDEA). Among the amine solvents, MEA is widely used and reacted strongly and quickly in low CO₂ partial pressure (Shao and Stangeland, 2009). The degradation of alkanolamine is an important issue in chemical absorption processes because it causes economic, operational, and environmental problems. Degradation can generally be classified into three types which are thermal degradation, carbamate polymerization, and oxidative degradation. Thermal degradation requires the operation at high temperatures, generally above 200°C. The degradation does not occur for dealing with

the iron production exhausted gases because the operation temperature in thermal regeneration is not at high. Oxidative degradation is mainly resulted from reaction with flue gas impurities such as SO_2 , NO_2 , and O_2 and occurs by fragmentation of the amine solvent. The degradation products of MEA are mainly formate, hydroxyethyl formamide, hydroxyethyl imidazole and oxalate, glycolat and acetate are also present, however, are in low concentrations. Carbamate polymerization requires the presence of amine at high temperatures so that it typically occurs in the stripper during the thermal regeneration (Yu et al., 2012).

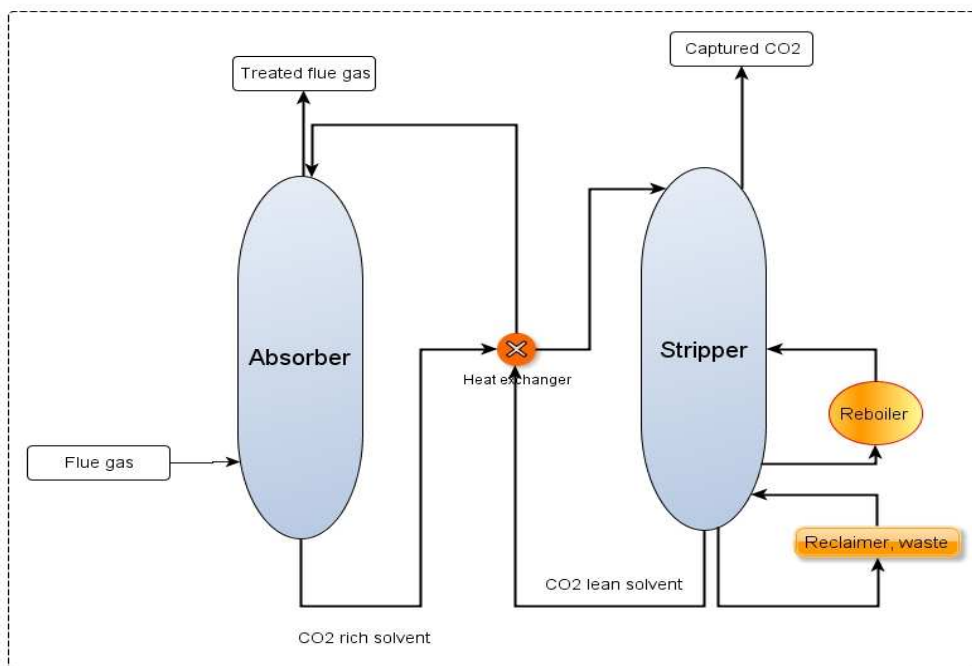


Figure 8. Flow diagram of chemical absorption for CO₂ capture

2.2.2 Physical absorption

Physical absorption is based on Henry's Law. In the case of raw gas containing more than 10% of CO₂, CO₂ removal by physical absorption processes allows to keep the energy demand on a reasonable level with high potential in large industrial scale. CO₂ in flue gas is absorbed under a high pressure and a low temperature, and desorbed at reduced pressure and increased temperature (Spigarelli and Kawatra, 2013). The Physical absorption has been widely used in natural gas, synthesis gas, and hydrogen production with high CO₂ content. Existing commercial processes are Selexol process, Rectisol process, Purisol process, Morphosob process and Fluor process. The most frequently encountered solvent in CO₂ removal applications is Selexol (Yu et al., 2012).

The Selexol process has been in use since the 1960s for natural gas sweetening. The process can be applied to remove both CO₂ and sulfur compounds without degrading solvent. The solvent is a mixture of dimethylether polyethylene glycol with the formulation of CH₃(CH₂CH₂O)_nCH₃ with “n” ranging from 3 to 9. In the Selexol process, the flue gas contacts the solvent in an adsorption column at about 450psi and 0-5°C. The regeneration of the original solvent is accomplished by flash desorption or stripping of the CO₂ loaded solvent. The CO₂ gas stream obtained is then compressed and stored and the solvent is recycled back to the column. The advantage of the Selexol process is that there are no chemical reaction, no need of thermal solvent regeneration, noncorrosive process. However, the process is most efficient at elevated pressure (Spigarelli and Kawatra, 2013, Ho et al., 2011). When it comes to studies the Selexol process in the steel production, Hu et al., 2009, Ho et al., 2011, Lampert and Ziebig, 2007 have studied process modeling of CO₂ capture within COREX process. (Hu et al., 2009, Ho et al., 2011, Lampert and Ziebig, 2007).

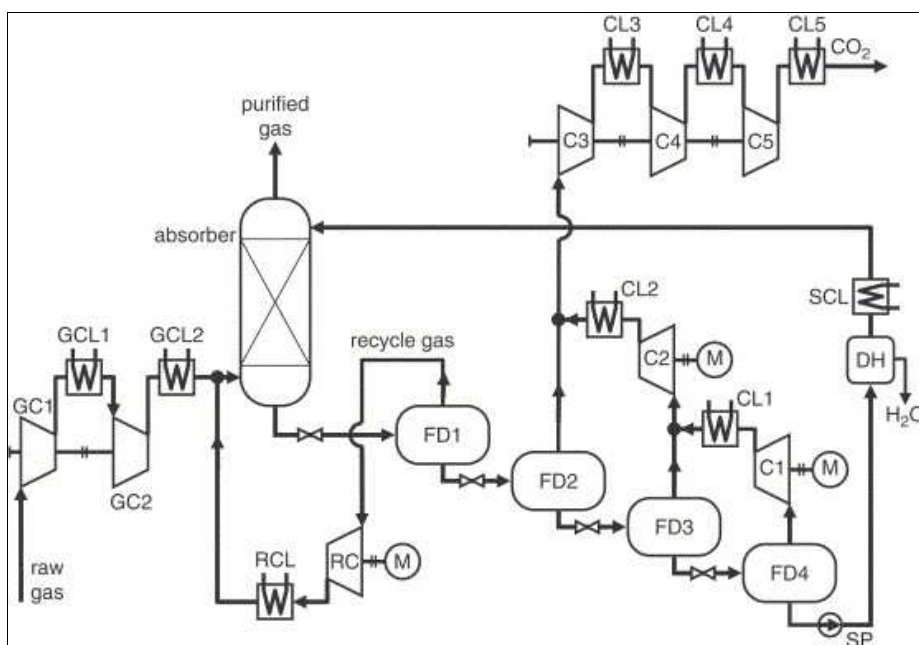


Figure 9. Flow diagram of Selexol process for CO₂ capture (CG, C : gas compressor, GCL : gas intercooler, CL : cooler, FD : flash drum, RC : recycle gas compressor, RCL : water cooler)

2.2.3 Adsorption

Adsorption process is that CO₂ is separated from a gas stream by use of a solid material. The gaseous component comes into contact with the solid and is adsorbed from the gas phase onto the solid surface. The solid material used for adsorption is often referred to as the

adsorbent and the gas species being adsorbed is referred to as the adsorbate. When selecting the adsorbent for CO₂ capture, it is important to consider the adsorbent's qualities such as high CO₂ adsorption capacity, High surface area, fast kinetics, high CO₂ selectivity, mild regeneration conditions, stability during the adsorption and desorption cycle, tolerance to impurities, and low cost. In CO₂ adsorption processes, after reducing impurities such as SO_x, NO_x, and water vapor in the gas stream using pretreatment process, the gas can be cooled to round room temperature before the adsorption stage. Most adsorbents exhibit a drastic decrease of adsorption capacity as elevated temperature (100°C)(Yu et al., 2012, Spigarelli and Kawatra, 2013). In terms of adsorbents which can be commonly used in CO₂ capture process, carbonaceous sorbents such as activated carbon, Zeolites, Silica support-based sorbents, and polymer can be presented (Samanta et al., 2011). CO₂ adsorption capacity can be seen that low CO₂ selectivity is the major drawback for most physical adsorbents. According to several studies, a Zeolite-based adsorbent, especially 13X zeolite, is selected as adsorbent to assess the CO₂ capture system because it has high selectivity for CO₂ over N₂ compared to other adsorbents. (Hasan et al., 2012, Ho et al., 2008, Samanta et al., 2011).

During desorption, the CO₂ is taken off adsorbent and the adsorbent is regenerated into the process. As the most common approaches, there are pressure swing adsorption (PSA) and vacuum swing adsorption (VSA), and temperature swing adsorption (TSA). PSA and VSA use adsorption or desorption at two fixed pressure levels, and TSA uses adsorption or desorption at two fixed temperature levels. Historically, while the PSA has been widely used in oxygen enrichment, air separation, H₂ purification, CO₂ separation, and the other industrial areas, the VSA and TSA are not used relatively. PSA processes can be categorized as pressurization and adsorption which are merged into one group called "adsorption" and depressurization/blowdown and evacuation which are grouped into "desorption" (Ho et al., 2008). Figure 10 presents the shortcut of general PSA processes.

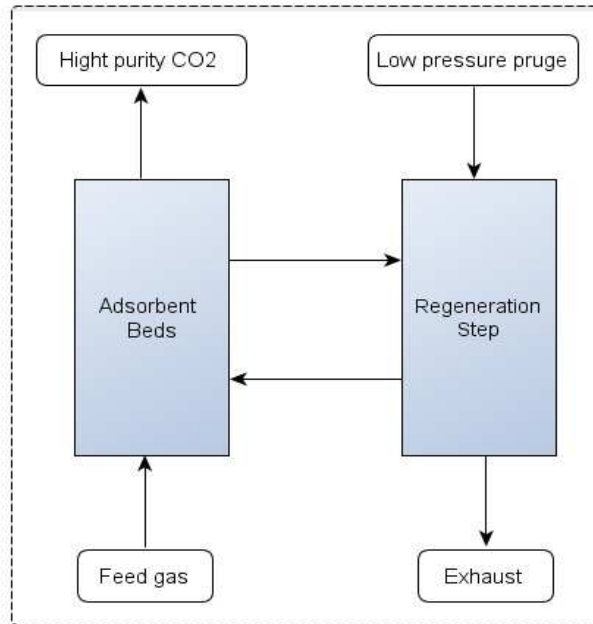


Figure 10. Schematic diagram of general PSA process

2.3 CO₂ Transport and Storage

CO₂ captured from an industrial sector must be transported to a storage site, because suitable storage sites are rarely located near the CO₂ source. There are several options such as pipeline, shipping, and road and railway transportation; however, for an industrial scale application only pipeline and shipping are viable. In the case of road and railway transportation, it is not enough to fulfill the needed capacity and cannot be realistically seen as cost effective option for CCS infrastructure (Teir et al., 2010)

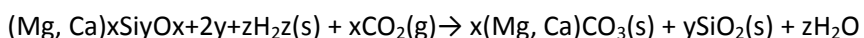
In terms of applying pipelines, in order to avoid to two-phase flow and increase the density of the CO₂, gaseous CO₂ must be dried and compressed to a pressure above 8Mpa, thereby making it easier and less costly to transport. Pipeline can be designed for onshore and offshore CO₂ transport. Onshore is similar to construction of hydrocarbon pipelines which is based on engineering experience. In general, onshore pipeline are buried to depth of 1m, and the offshore pipelines are almost buried in shallow water. As other equipment for operation and maintenance, there are valves, compressors, pumps, tanks, monitoring points, and block valves. The pipeline has to be carefully designed for reliable operation and best achievable cost effectiveness. The CO₂ flows need to be well known beforehand, especially in case of a trunk line with multiple connected CO₂-sources, in order to determine the optimal pipeline size (Teir et al., 2010).

The shipping transport is a developing stage. CO₂ can be transported as the phase of liquid in ship tanker which keeps the CO₂ as properly to transport in a storage site by insulation at a temperature well below ambient and high pressure (Singh et al., 2011a)

As the end of the CCS chain, the storage of CO₂ can be carried out to be store safely for a long period of time in isolation for the atmosphere. Because of the large amount of CO₂ that needs to be stored, only few options can be considered.

Firstly, the geological formation technology has been considered as one option. Sedimentary basins potentially suitable for CO₂ storage are distributed around the globe, both onshore and offshore. The most promising formations are nearly depleted or depleted oil and gas reservoirs, deep saline formations, and un-minable coal beds. In each case, CO₂ could be injected in compressed form into a rock formation at depths greater than 800 m, where the CO₂ is in a liquid or supercritical state because of the ambient pressures. The reservoir needs to have certain characteristics that will ensure that the CO₂ remains trapped underground, such as a well-sealed cap rock on top of the reservoir.

The other option is mineralization of CO₂. The concept for storage of CO₂ as calcium and magnesium carbonate minerals is commonly referred to as mineral carbonation. These carbonates are poorly soluble in water and environmentally harmless minerals that could provide a permanent storage solution for CO₂. The net reaction equation for carbonation by using calcium- or magnesium-containing silicate minerals can be generalized as



Since the naturally occurring mineral carbonation process is very slow, it is needed to be accelerated to be viable for CO₂ storage. A commercial process would require mining, crushing, and milling of the mineral-bearing ores and their transport to a processing plant receiving a concentrated CO₂ stream from the capture plant. Except for the geological formation, and mineralization of CO₂, ocean storage and industrial uses of CO₂ are possible; however, ocean storage is not feasible because of the ecologic uncertainties thereof. Also recent laws prevent storage of CO₂ in the ocean. In terms of industrial use of CO₂, the typical lifetime of CO₂ storage by industrial processes is only few days to months and do not contribute meaningfully to climate change mitigation (Teir et al., 2010, Singh et al., 2011b).

3. Methodology

3.1 Life Cycle Assessment (LCA)

The main objective of Life Cycle Assessment (LCA) is generally to perform consistent comparison of technological systems related to their environmental impacts throughout their life cycle. The term of 'life cycle' implies that all stages of product or technology's life which includes resource extraction, manufacture, and distribution, use, and end disposal are taken into account. In particular, it quantifies energy and resource inputs and outputs from cradle to grave and identifies and assesses the associated impacts. According to cases, their system boundaries can be changed as from cradle to cradle or from cradle to gate. There is a series of international standard for LCA, ISO 14040-14044. ISO standard 14040 describes the principles and framework for LCA. ISO standard 14044 specifies requirements and provides guidelines for LCA. Generally, the standard framework for LCA consists of the following four components: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation.

In the goal and scope definition stage, the purpose and system boundaries of a study in terms of functional unit are decided. The functional unit is a quantitative measure of the function that is to be delivered by products or services. The stage depends on subject and intended use and goal of the study and must be clearly specified (Gaidajis and Angelakoglou, 2011).

In inventory analysis stage, an analytical list of data components including all inputs (materials and energy) and outputs (solid waste and emissions into air and water) is developed according to the system boundary to meet the goal of the study. The LCI of amount of resource use and pollutant emission of the system also can be calculated in relation to the functional unit. The data must be confidential as possible (Singh et al., 2011b).

Life Cycle Impact Assessment (LCIA) provides information to understand and assess the magnitude and potential environmental impact associated with the inventory results. In the first step that is 'classification', the inventory parameters are assigned to different environmental issues according to their contributions. The second step is 'characterization' that the inventory items can be multiplied with characterization factors to obtain environmental impact through the relative contribution of the emissions and resource consumption. As the optional steps, there are 'Normalization and Weighting' after the 'Characterization' step. The normalization step provides that characterization results are calculated relatively to the actual magnitude of each impact in the region in which the products is produced and used. In the weight step, single score by considering the

multiplication factor that reflects the social importance of different impact categories is presented (Singh et al., 2011a).

In the interpretation stage, the most important contributions to impacts from the inventory, process, life cycle phases, and sub-systems are identified. The stage provides conclusions and recommendations based on the results of the inventory and impact assessment. Sensitivity analysis and uncertainty analysis are important aspects in the stage (Gaidajis and Angelakoglou, 2011).

3.2 Hybrid Life Cycle Assessment for this study

Even though the application of LCA provides systematic understanding to evaluate environmental impacts of products and technologies, the limitation of the LCA has been introduced in terms of the incomplete system boundaries. Therefore, to avoid underestimation of environmental impacts, the combined method of economic input-output (IO) and process based LCI, referred as ‘hybrid life cycle assessment’ has been studied. Conventional LCA has good detail on foreground processes but suffer from incomplete system boundaries. The IO based assessments will suffer from aggregation errors; however they have good system boundary completeness. Hybrid LCA seeks to combine these two in such a manner that the best of the two methods are kept while the weaknesses are left out (Strømman and Hertwich, 2004, Treloar et al., 2000).

In the study, a tiered Hybrid LCA is used as the methodology. For all LCA calculation, it is needed to establish normalized requirement matrix, ‘A’, containing a combination of physical and monetary units.

$$A = \begin{bmatrix} A_{ff} & \mathbf{0} & \mathbf{0} \\ A_{pf} & A_{pp} & \mathbf{0} \\ A_{nf} & \mathbf{0} & A_{nn} \end{bmatrix} \dots (1)$$

As the equation (1), a tiered hybrid LCA is performed as a conventional process based LCA, with a foreground system, A_{ff} , and requirements, A_{pf} from a background LCA database, A_{pp} , which are presented by physical units. In addition to this, requirements to the foreground system, A_{nf} , from an IO data set, A_{nn} are added. This introduces an extra background system indicated as monetary units. Basically, the idea is that LCI data missed out in the process based LCI can be covered from the IO system; therefore, truncation error would be minimized. Flows from foreground to background processes and economy are set to zero, as the product flows related to the functional unit are negligible compared to the national level flows. Some of LCI data come from Best Available Techniques (BAT) Reference Document for Iron and Steel Production published by IPCC in 2012 (IPCC, 2012) for

foreground data and Ecoinvent v2 database is used for the background process and EXIOPOL table is used for background economy (Tukker and Heijungs, 2007). The EXIOPOL is an integrated project funded by the European Commission under the 6th framework program. The established objective of EXIOPOL is to provide a new environmental accounting framework using externality data and input-output tools for policy analysis.

3.3 Life Cycle Impact Assessment (LCIA)

To present the LCIA, there are two approaches which are midpoint approach and endpoint approach. A number of methods convert the emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level, while others use impact category indicators at the endpoint level (Goedkoop et al., 2009). One of the key differences between midpoint and endpoint approaches is the way in which the environmental relevance of category indicators is taken into account. In the midpoint approach, the environmental relevance is generally presented in forms of qualitative relationships, statistics and review articles; however, it could similarly be quantified using endpoint methods to provide insights to the decision maker. In endpoint approaches there is no need to deal separately with the environmental relevance of the category indicators, because the indicators are chosen at an endpoint level and are generally considered more understandable to the decision makers. As a result, different types of results are presented to the decision maker (Bare et al., 2000).

ReCiPe 2008 is a method providing results to indicate a LCIA at both midpoint and endpoint levels. ReCiPe 2008 builds on the Eco-indicator 99 and the CML Handbook on LCA (2002). A nearly complete restructuring of the CML baseline midpoint method and the Eco-indicator 99 endpoint method was undertaken to fulfill a need to harmonize midpoint and endpoint LCIA impact categories. The midpoint of ReCiPe 2008 provides eighteen impact categories which are climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resources depletion, and fossil depletion. In terms of the endpoint, the midpoint categories are further converted and aggregated into three endpoint damage impact indicators such as human health damage, ecosystem damage, and resource depletion. The Figure 11 indicates the relationship pathways between LCI data, midpoint and endpoint (Goedkoop et al., 2009).

In this study, the LCI data was compiled from several literatures which have performed simulations, cost estimates and research reports published by reliable organizations such as IEA, IPPC and IPCC with respect to the steel production with or without CCS processes. To

calculate the LCIA generated the LCI data, the characterization factors are taken from ReCiPe 2008 method for a part of process LCA and EXIOPOL for IO-based part (Goedkoop et al., 2009, Fantke and Wagner, 2009). As for the impact categories, the midpoint approach is performed to indicate the LCIA. The LCIA for process LCA part was carried out in the software Arda, which is in-house software built within the Industrial Ecology program of the Norwegian University of Science and Technology (NTNU). The LCIA of the IO based part was calculated by Matlab software.

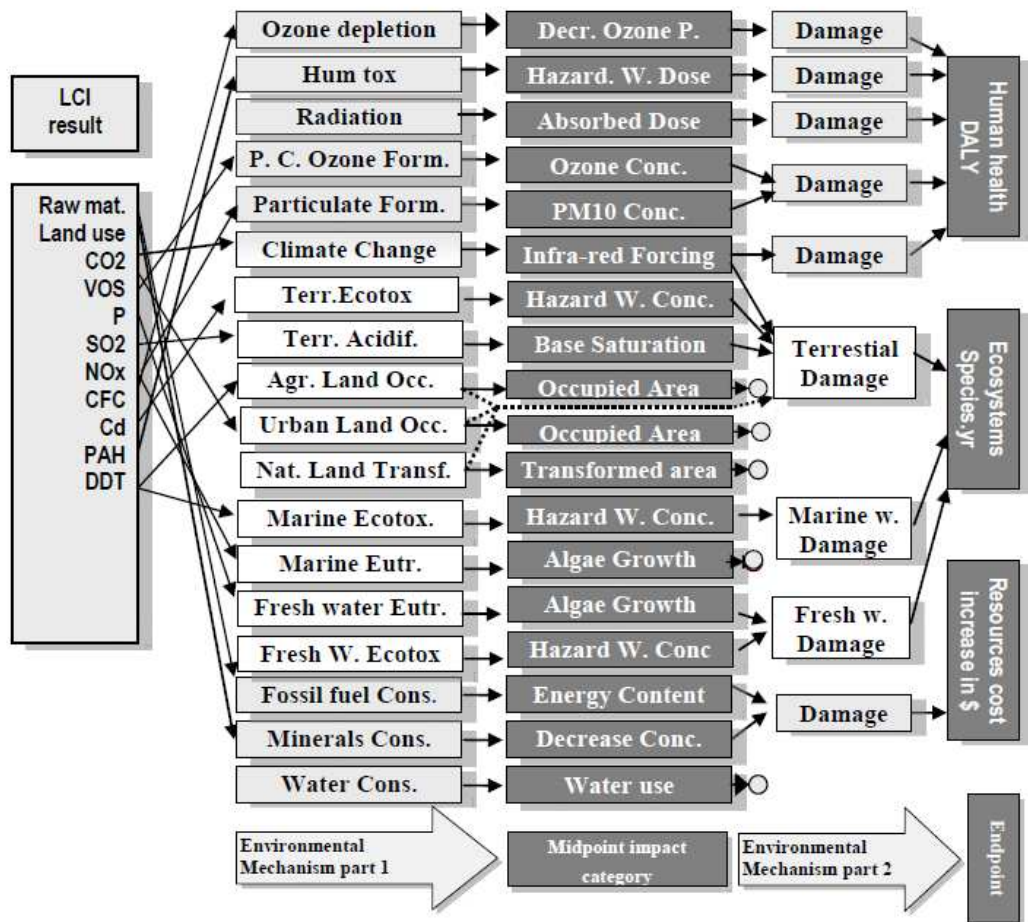


Figure 11. Midpoint and endpoint indicators in ReCiPe 2008 (Goedkoop et al., 2009)

4. System description

4.1 Goal and scope

The main goal of the study is to assess the environmental performance of CCS processes within iron making systems. Firstly, the systems with CCS are compared to iron making processes without CCS in terms of hybrid LCA. Secondly, through the study, the benchmark of CCS system is provided with each iron making technology that has no CO₂ capture system. The Functional unit is taken as 1kg pig iron from the ironmaking process regardless of with or without CCS system.

4.2 System description

The technologies of iron making that is existing or will become commercial status in short term period (10-15years) are selected among several technologies to be assessed (Kuramochi et al., 2012). The technologies of CO₂ capture are matched by technical properties, e.g., CO₂ partial pressure in emitted gas composition, of the ironmaking processes. Table 2 shows the 7 technologies and abbreviated name of them to present in the study.

Table 2. Technologies and theirs abbreviated name in the study.

Selected technology name	Abbreviated name
Blast furnace for world average	BF W.A.
Blast furnace for Best Available Technology	BF BAT
Top gas recycling blast furnace	TGRBF
COREX	COREX
BF BAT with CO ₂ capture by MEA solvent	BF BAT + MEA
TGRBF with CO ₂ capture by Pressure swing adsorption	TGRBF + PSA
COREX with CO ₂ capture by Selexol solvent	COREX + Selexol

Generally, the foreground systems for pig iron production without CCS consist of a reducing process such as BF and COREX, and pretreatment process for treating emissions of the system. As for the systems with CCS, they include CO₂ capture, transport and storage into a geological storage site as well. Other emissions arising from upstream like the production of sinter, pellets, coke, and coal and from downstream, e.g., waste treatment and disposal are also taken in to account in the assessment. When it comes to the CCS process in common, the captured CO₂ is compressed and supplied to the transport chain at 110bar and transported via 500km pipeline to the geological storage site via 1000m injection well. A pressure drop of 10bar per 100km occurs, therefore, a recompression station is needed

after 300km to maintain the pressure well above the critical pressure (74bar). Additional energy requirement is to inject CO₂ into storage at a pressure higher than reservoir fluid pressure (Singh et al., 2011a). In the study, the energy requirement for the recompression and injection of CO₂ captured from the iron making process is taken into account. Monitoring of the storage site and leakage of CO₂ is excluded in the study.

4.2.1 Blast furnace with and without CCS

In the study, the system foreground boundary of BF with and without CCS is shown in Figure 12. The yellow boundary describes the conventional BF system and the blue one presents the BF system with CCS.

In the conventional BF system, the input materials are sinter, pellet, coke, coal, natural gas, iron ore, limestone, water and air. The input materials are provided from outside boundary. Especially, coke is a reducing agent and coal mainly plays a role of an energy source to heat the blast furnace process. As for the emissions from the process, dust and sludge are generated from solid waste and air pollutants. The BFGs from the process must be treated to comply with the air pollutant regulation, thus, the pretreatment units are deployed after the BF process.

In the BF process, the blast furnace gas (BFG) is produced and it is provided into power production turbine to produce electricity and boilers for providing energy to other processes. Therefore, in the system, there are two products which are BFG and pig iron. To take the fact into account, an allocation method is carried out based on a literature (Hu et al., 2009) using heat values of input and output in the BF process. However, since the electricity production is outside of the boundary, only the partitioning of pig iron production is accounted for in the study.

As for the BF system with CCS which has MEA as a solvent, after pretreatment of the BFG, CO₂ rich gas goes to the CO₂ capture system. In the BF system with CCS, the chemical absorption technology is utilized to recovery CO₂. As mentioned in the technology overview chapter, the BF system can use the MEA as the solvent for recovering CO₂. According to the data of process modeling with respect to iron and steel production, 85% of CO₂ is assumed to be captured using MEA (Tobiesen et al., 2007). A solvent makeup of 1.5 kg MEA/t CO₂ is needed due to its loss via vapors and formation of degradation products (Arasto et al., 2012). The capture process additionally requires caustic soda to reclaim the amine from the heat stable salt and activated carbon to remove degradation production and decarbonized water. The air emissions of SO₂, NO₂, and particular matter (PM) also are removed in the capture process (Singh et al., 2011b). In the chemical absorption, heat is needed for regeneration of MEA. The steam consumption to regenerate the MEA is 3.37 MJ/kg CO₂

(Tobiesen et al., 2007). The energy requirements for the capture process are for solvent pumps, flue gas blower, cooling water pumps and CO₂ compression. The electricity demand of 0.308MJ/kg CO₂ is required in the capture system (Arasto et al., 2012). In terms of transport and storage of the CO₂ captured from BF system, the optimum economic pipeline of 250mm is estimated and the energy demand of the 2.67kWh/tCO₂ is needed for recompression and injection (Singh et al., 2011a).

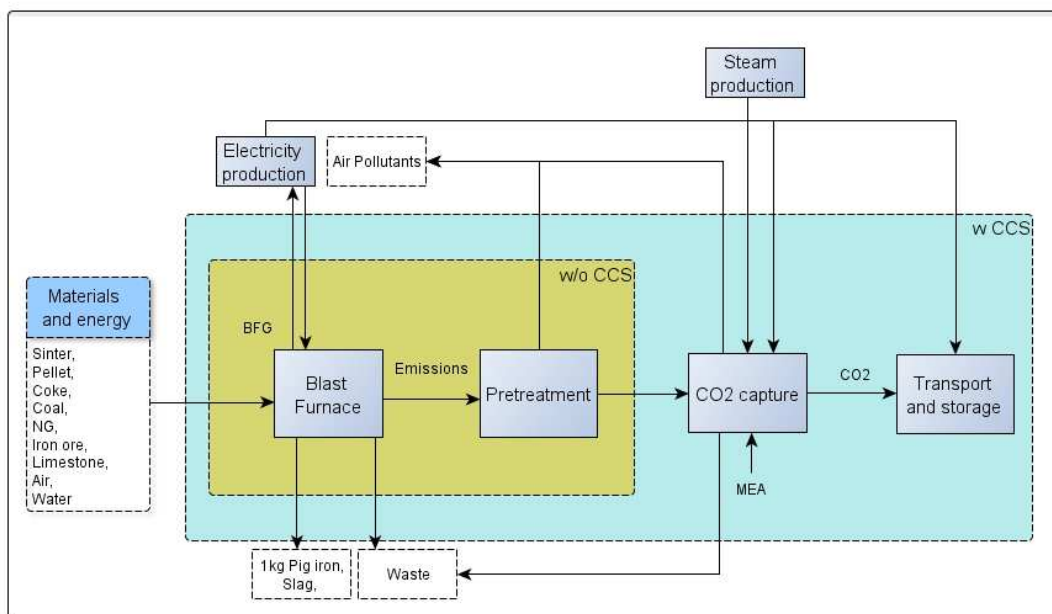


Figure 12. System boundary of Blast furnace with and without CCS.

4.2.2 Top gas recycling blast furnace with and without CCS

The foreground system boundary of TGRBF technology with and without CCS is presented in Figure 13. The input materials and emissions of the TGRBF process are identical with conventional BF technology. However, the TGRBF system uses the oxygen as an oxidizing agent. Additionally, while conventional BF system in the study utilizes the BFG for producing electricity, in the TGRBF system, the BFG is recycled into the BF process as a reducing agent. Therefore, the partitioning which is considered in the BF system is not taken account of. Other technical factors are same with the BF system except for the uses of oxygen and coke due to utilization of the BFG in the TGRBF. Besides, the TGRBF system is not considered with respect to the allocation by the two products.

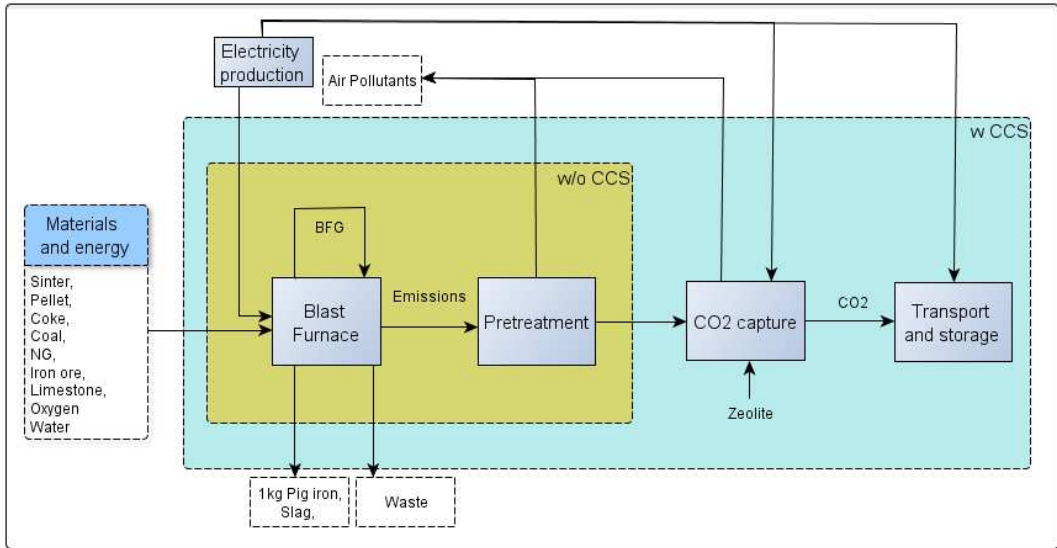


Figure 13. Foreground system boundary for TGRBF with and without CCS.

As the TGRBF system uses the oxygen as the oxidizing agent, the BFG composition is different with the conventional BF system. Considering the property, the selected CO₂ capture technology for the TGRBF system is physical swing adsorption. In the study, the Zeolite is used as adsorbent to recover CO₂ from the BF system. 85% of CO₂ is assumed as recovery efficiency in CO₂ capture system (Ho et al., 2008). The makeup amount of adsorbent, Zeolite, is 1.7kg Zeolite/t CO₂ and the makeup amount is estimated based on literature (Abanades et al., 2004). The spent Zeolite is disposal of into solid waste treatment. According to Ho et al., 2008 and Spigarelli and Kawatra, 2013, the PSA capture technology needs a pretreatment of SO_x, NO_x, and water vapor. That is because the impurities compete with CO₂ molecules for adsorption sites. Therefore, in the study, the removal efficiency of the impurities is taken account of in the pretreatment unit. Energy demand of the capture system is electricity of 0,42 MJ/kg CO₂ (Ritter, 2012) and for regeneration process, steam is not necessary unlike the MEA system. The optimum economic pipe diameter is calculated to be about 200mm and the energy demand of the 2.67kWh/tCO₂ is needed for recompression and injection (Singh et al., 2011a).

4.2.3 COREX with and without CCS

Figure 14 shows a foreground system boundary of COREX both with and without CCS. In the COREX process, dissimilarly with the BF process, the coal can be used as both a reducing agent and an energy source. Oxygen is an oxidizing agent and pellet is a sole iron material, thus, when the COREX system is utilized to produce pig iron, the processes of sinter

production and coke production are reduced in the related upstream. The COREX gas has high heating value compared to the BFG and the COREX gas also goes to electricity production. Therefore, in the COREX system, the allocation of the partitioning into the electricity production is taken into account.

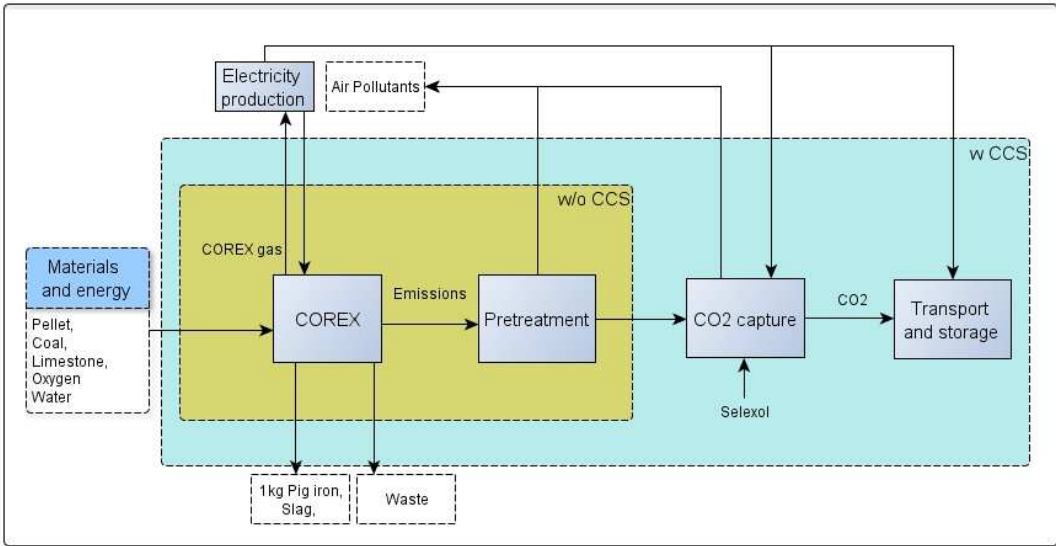


Figure 14. Foreground system boundary for COREX with and without CCS.

Based on the literature, the COREX system is matched with physical absorption technology which utilizes Selexol as a solvent for CO₂ recovery. The Selexol system has the CO₂ Capture efficiency of 90% (Lampert and Ziebig, 2007) and the solvent consumption is 7kg Selexol/t CO₂. No literature is found in terms of solvent loss to air and degradation problems. Moreover, it is assumed that all spent solvent ends up as solid waste and is incinerated. The particular matters of 50% can be reduced by the Selexol capture process (Singh et al., 2012). The energy demand for the CO₂ capture process is 0,59MJ/kg CO₂ and the amount is derived from literature which has done studies related iron and steel production with CCS (Gielen, 2003). For the transport and storage for the COREX with CCS, the optimum economic pipe diameter is estimated to be around 150mm and the energy requirement is 2.67kWh/tCO₂.

4.3 Inventory analysis

Table 3 and Table 4 show LCI data for input materials and energy sources, and emissions for the functional unit of 1kg pig iron for each technology. The input data for the world average and best available technology of BF are based on reports of World Steel Dynamics, 2011 (WSD, 2011) and IPCC, 2012 (IPCC, 2012), respectively. The data for the TGRBF comes from

BF BAT; however, as for inputs of coke and oxygen by technical differences, these two are estimated based on a literature (Kuramochi et al., 2012). When it comes to the COREX, the values are derived from Kuramochi et al., 2012 and Costa et al., 2001. As shown in table 4, most of emission data are estimated based on IPCC, 2012 through considering mass balance by input data. The emissions by the degradation of solvent and sorbent in capture processes are calculated from literatures which have performed the evaluation of process modeling for CO₂ capture (Singh, 2011, Ho et al., 2008).

In the study, the Background systems related with the foreground systems are lined with Ecoinvent v2.0 database in term of the physical units (Ecoinvent, 2007). Infrastructure for processes reducing iron oxides such as BF and COREX and capture units is accounted in capital investment attributed to various sectors in EXIOPOL database (Lutter et al., 2010). In the study, the capital cost is allocated into the EXIOPOL database using plant components of capital cost ratios (Minh, 1980). Other emissions arising from upstream, e.g., the materials and energy production, solvent and sorbent, and the emissions from downstream, e.g., waste treatment and disposal are also included in the assessment.

Table 3. Input data for 1kg ironmaking in each case technology.

Input data (kg/1kg pig iron)	BF W.A. a)	BF BAT b)	TGRBF ^{c)}	COREX d)	BF BAT + MEA ^{b)}	TGRBF +PSA ^{c)}	COREX +Seleoxl ^{d)}
Air	-	0,01	-	-	0,01	-	-
Steam coal	0,15	0,16	0,16	0,95	0,16	0,16	0,95
Lump ore	0,18	0,18	0,18		0,18	0,18	
Limestone	0,03	0,03	0,03	0,05	0,03	0,03	0,05
Lime	-	-	-	0,11	-	-	0,11
Natural gas (m ³)	0,11	0,11	0,11	-	0,11	0,11	-
Electricity (MJ)	0,14	0,27	0,27	0,27 ^{e)}	0,27	0,27	0,27 ^{e)}
Water	0,003	0,003	0,003	-	0,003	0,003	-
Coke	0,50	0,36	0,24 ^{c)}	-	0,36	0,24	-
Sinter	1,09	1,09	1,09	-	1,09	1,09	-
Pellet	0,36	0,36	0,36	1,50	0,36	0,36	1,50
Oxygen	0,12	0,12	0,51 ^{c)}	0,76	0,12	0,51	0,76

a)(WSD, 2011), b)(IPPC, 2012), c)The values are from IPCC, 2012, but the oxygen and coke is estimated based on (Kuramochi et al., 2012), d) (Kuramochi et al., 2012), e) (Costa et al., 2001)

Table 4. Direct emission data for 1kg pig iron production in terms of technologies with and without CCS.

Emissions (to air) ^{a)} (mg/1kg pig iron)	BF W.A.	BF BAT	TGRBF	COREX	BF BAT + MEA	TGRBF +PSA	COREX +Seleox I
CO ₂ (kg/1kg pig iron)	0,673	0,533	0,519	0,504	0,080	0,078	0,050
CO (kg/1kg pig iron)	0,527	0,418	0,117	0,481	0,835	0,117	0,481
H ₂ (kg/1kg pig iron)	-	0,003	0,002	0,012	0,007	0,002	0,012
SO ₂	214,2	171,7	149,8	15,5	0,9	7,5	15,5
NO _x	93,7	75,1	65,5	0,5	56,3	0	0,5
PM	116,2	93,2	81,3	1,7	46,6	81,3	0,8
H ₂ S	86,6	69,3	-	-	69,3	-	-
NH ₃ ^{b)}	-	-	-	-	15,8	-	-
Acetaldehyde ^{b)}	-	-	-	-	7,57E-05	-	-
Formaldehyde ^{b)}	-	-	-	-	1,19E-04	-	-
MEA ^{b)}	-	-	-	-	0,0284	-	-
Solid degradation products (s) ^{b)}	-	-	-	-	1449,8	750,5 ^{c)}	3,2
Activated carbon(s) ^{b)}	-	-	-	-	27,2	-	-

^{a)} (IPPC, 2012), ^{b)} (Singh, 2011), ^{c)} (Ho et al., 2008)

Table 5 indicates performance parameters in line with CCS performance, and lifetime and capital costs for the selected technologies. The performance data for the CO₂ capture process is based on the Tobiesen et al., 2007, Arasto et al., 2012, Singh, 2011, Lampert and Ziebig, 2007, Gielen, 2003 and Ho et al., 2008 that have carried out process modeling with regard to ironmaking process and studied environmental assessment related to CCS performance. Annual sequestered amounts of CO₂ are estimated through the production scale of iron produced and emitted CO₂ by each technology. The data for plant lifetime comes from Daniels, 2002 which has carried out a research for sustainable steel production technologies.

In particular, LCI data for pipeline is derivate from Ecoinvent v 2.0 (offshore natural gas pipeline in North Sea with a diameter of 1000m and 25mm thickness). If the data is used directly, material requirements will be overestimated. Therefore, through considering capacity of pipeline needed for each technology by captured CO₂, the optimum economic diameters of pipeline are estimated for 500km length. For injection well, LCI data is taken as offshore drilling well from Ecoinvent v 2.0 for 1000m depth (Singh, 2011).

Table 5. Performance parameters for different technologies for 1kg pig iron production with and with CCS.

Parameters ^{m)}		BF W.A.	BF BAT	TGRBF	COREX	BF BAT + MEA	TGRBF +PSA	COREX +Seleox I
CO ₂ removal efficiency ^{a)}	%	-	-	-	-	85	85	90 ^{b)}
Steam consumption for regeneration ^{a)}	MJ/kg CO ₂	-	-	-	-	3,37	-	-
Energy for capture ^{c)}	MJ/kg CO ₂	-	-	-	-	0,31	0,42	0,59
Energy for transport and storage ^{d)}	MJ/t CO ₂	-	-	-	-	0,74	0,74	0,74
CO ₂ sequestrated ^{e)}	Mt/yr	-	-	-	-	1,55	1,24	0,89
Pipeline diameter ^{f)}	Mm					250	200	150
Capital cost ^{g)}	M€	610	610	610	230	697	698	244
Annual iron production ^{h)}	Mt/yr	2,8	2,8	2,8	1	2,8	2,8	1
Plant life time ⁱ⁾	Yr	25	25	25	20	25	25	20
Co-capture ^{j)}		-	-	-	-	NOx, SOx, PM	-	PM
SO ₂ removal efficiency	%	-	-	-	-	99,5 ^{j)}	95 ^{k)}	-
NOx removal efficiency	%	-	-	-	-	25 ^{j)}	100 ^{k)}	-
PM removal efficiency ^{j)}	%	-	-	-	-	50		50
Solvent and sorbent consumption ^{l)}	kg/t CO ₂	-	-	-	-	1,5	1,7	0,007
Activated carbon ^{l)}	kg/t CO ₂	-	-	-	-	0,06	-	-
Decarbonized water ^{l)}	kg/t CO ₂	-	-	-	-	800	-	-
NaOH ^{l)}	kg/t CO ₂	-	-	-	-	0,13	-	-

^{a)} (Tobiesen et al., 2007),

^{b)} (Lampert and Ziebik, 2007),

^{c)} The value for BF BAT + MEA is from (Arasto et al., 2012). For TGRBF+PSA , the value is form (Ritter, 2012) and for COREX + Selexol, the value is taken from (Gielen, 2003).

^{d)} The values are estimated based on (Singh, 2011).

^{e)} All values are calculated by considering emitted CO₂ and production scale of each technology.

^{f)} Based on (Ecoinvent, 2007), the optimum economic diameters are estimated.

^{g)} (Kuramochi et al., 2012), (Ho et al., 2008)

ⁱ⁾ (Daniels, 2002)

^{j)} (Singh, 2011)

^{k)} For TGRBF + PSA, the SO₂ and NOx are removed in pretreatment instead of capture process and the values comes from (Ho et al., 2008).

^{l)} As for MEA and Zeolite in PSA, the values of makeup amount are calculated from (Abanades et al., 2004) and for Selexol, the value is from (Singh, 2011).

^{m)} 8500 full load hours per year for all technologies

5. Results

5.1 Life Cycle Impact Assessment (LCIA)

The main objective of the study investigates environmental impacts from CCS performance in iron and steel production. It is possible that the CCS systems reduce CO₂ emissions, controlling co-captured SO₂, NO_x, and PM in certain technologies. However, other direct and indirect emissions are generated from value chains for raw materials supplies to the waste treatment and disposal (Singh, 2011). Moreover, even different technologies for producing pig iron can present the different ranges for environmental impacts. Accordingly, in the chapter, diverse environmental impact factors are indicated depended on chosen technologies with and without CCS.

5.1.1 Global warming potential (GWP)

Figure 15 shows GWP from all iron making systems, with a breakdown into direct impact from the process of pig iron production and indirect emission from value chains. The GWP is caused mainly by emissions of CO₂ and CH₄, greenhouse gases, in conjunction with pig iron production. The CO₂ removal efficiencies of 85% for BF process with MEA solvent and TGRBF with PSA system and 90% for COREX with Selexol solvent are employed. The CCS systems can capture the direct emission of CO₂ in processes of pig iron production. However, it implies that it is not possible to reduce the GWP by indirect emission of CO₂ from other value chains.

Most technologies without CCS show that direct and indirect impacts for the pig iron production are evenly allocated for the GWP. In a case of TGRBF, the GWP caused by indirect impact presents 63% of total impact. While the systems without CCS shows that direct and indirect emissions similarly affect the GWP, the systems with CCS shows that the GWP is mainly caused by indirect emissions. That is because the direct emission of CO₂ from pig iron production is removed in CO₂ capture process in each technology. The impacts from the indirect emissions to the GWP are higher than 90% of total GWP for systems with CCS, BF BAT+MEA, TGRBF+PSA, and COREX+Selexol.

Only considering the systems without CCS, other literatures (Kuramochi et al., 2012, XU and Cang, 2010) have mentioned that TGRBF technology is more beneficial for GWP than BF technology. The reason of the difference with the study is caused by different system boundary and partitioning of BFG in the pig iron production. In this study, the power production is outside system boundary but in Kuramochi et al., 2012, it is contained in the system boundary for BF system. According to Wiley et al., 2011, the interlined energy network using BFG is the highest CO₂ emission source compared other processes such as BF, coke oven, sinter and etc., (Wiley et al., 2011). Therefore, if the energy production system

like electricity generation or heat boiler to provide the energy into other processes is taken into account, it might be possible that the BF system become the largest impact technology for the GWP, however, the this study only focuses on 1kg pig iron production excluding power production system within ironmaking technologies .

Moreover, environmental impacts from the oxygen requirement are concerned in the TGRBF system. The pure oxygen supply is a unit which needs high energy intensity to produce it, therefore, the impact of the oxygen- blown system is one of reasons why the TGRBF shows the highest GWP in the impact of the indirect emission. In terms of the COREX system, in spite of a requirement of the largest amount of oxygen, as the high partitioning of electricity generation into outside system boundary, the GWP of COREX indicates the lowest one among the 7 technologies. The advantages of the COREX system are reducing processes for coke and sinter production and high energy value of COREX gas in comparison with BFG; therefore, according to assumption in the study, almost 48% of total heat value used in COREX process goes to energy generation. The ratio is the value for the partitioning part.

Regarding to environmental performance for CCS deployment, the BF BAT+MEA system shows 26% reduction of the GWP for original BF BAT system. As for the TGRBF system, through employing the PSA process, the GWP can be reduced by 31% in comparison with the TGRBF without CCS. When the CCS system is applied to COREX system using physical absorption with Selexol solvent, the reducing the GWP is the most improved compared to other systems and it presents 48% reduction of the original COREX system.

As mentioned above, the CCS system can capture only direct CO₂ emission from the pig iron production. Thus, even though the CO₂ efficiency presents 85-90% in the CO₂ capture processes, in iron and steel industry which has high environmental impacts for GWP from indirect emissions, the results for total CO₂ removal efficiency describe 26-48% avoidance of the GWP. Besides, as performing CCS system, additional impacts are generated by demands of the infrastructure, solvent and adsorbent, other input materials, energy and waste treatment and disposal. Especially, the BF BAT+MEA, a chemical absorption technology, requires high thermal energy for solvent regeneration in comparison with other capture technologies such as PSA and physical absorption with Selexol. Thus, the energy requirement highly contributes to less avoidance of the GWP in the BF+MEA.

Comparing the 7 technologies for pig iron production with and without CCS, the COREX+Selexol system shows the lowest GWP and the TGRBF indicates the highest GWP. As the results, COREX technology with CCS shows the most advantage compared to others for the GWP and the largest reducing the GWP.

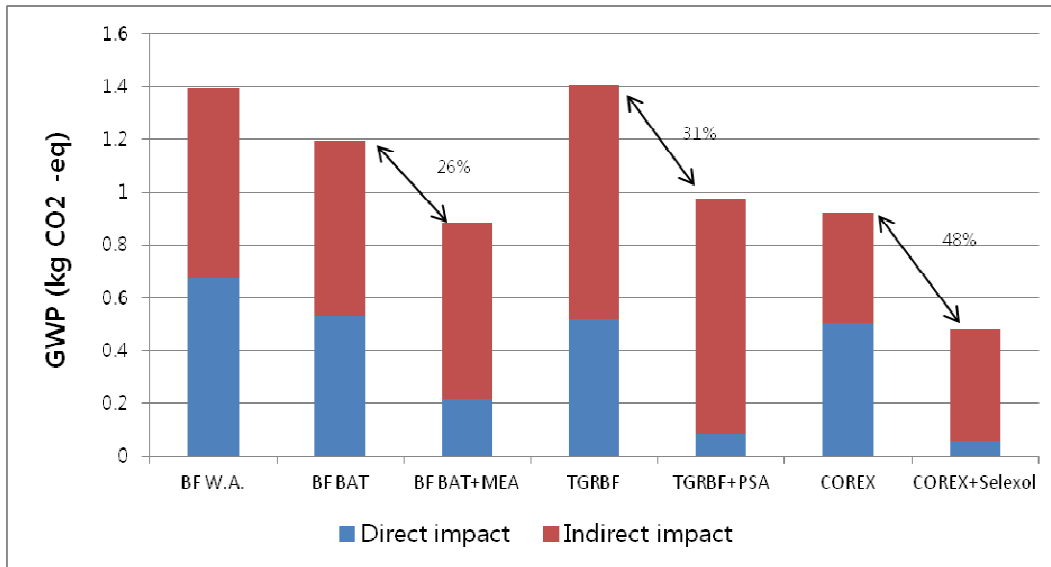


Figure 15. Global warming potential for 1kg pig iron production from different technologies.

5.1.2 Midpoint impact potential

In the chapter, environmental impacts are assessed by different fourteen midpoint indicators: agricultural land occupation potential (ALOP), global warming potential (GWP), fossil depletion potential (FDP), fossil depletion potential (FETP), human toxicity potential (HTP), ionizing radiation potential (IRP), marine ecotoxicity potential (METP), marine ecotoxicity potential (MEP), mineral depletion potential (MDP), particulate matter formation potential (PMFP), photochemical oxidant formation potential (POFP), terrestrial acidification potential (TAP), urban land occupation potential (ULOP), water depletion potential (WDP). Table 6 presents absolute values for midpoint factors with respect with different technologies of pig iron production with and without CCS. To be clearer, Figure16 displays relative impacts through normalized values by the BF BAT technology. In the chapter, main description focuses on comparison between technologies with and without CCS.

Table 6. Midpoint impact score for 1kg ironmaking in different technologies

Midpoint impact factors	Units	BF W.A.	BF BAT	BF BAT +MEA	TGRBF	TGRBF +PSA	COREX	COREX +Selexol I
ALOP	m2a	4,97E-02	4,04E-02	4,11E-02	3,83E-02	3,89E-02	3,46E-02	3,53E-02
GWP	kg CO ₂ -Eq	1,40E+00	1,20E+00	8,80E-01	1,41E+00	9,78E-01	9,25E-01	4,82E-01
FDP	kg oil-Eq	6,14E-01	5,09E-01	5,62E-01	5,32E-01	5,35E-01	4,29E-01	4,31E-01
FETP	kg 1,4-DCB-Eq	1,24E-02	1,03E-02	1,06E-02	1,20E-02	1,21E-02	1,00E-02	1,01E-02
HTP	kg 1,4-DCB-Eq	6,36E-01	5,43E-01	5,52E-01	6,38E-01	6,43E-01	4,46E-01	4,49E-01
IRP	kg U235-Eq	1,32E-01	1,25E-01	1,39E-01	2,67E-01	2,79E-01	1,81E-01	1,96E-01
METP	kg 1,4-DCB-Eq	2,99E-02	2,79E-02	3,07E-02	3,34E-02	3,67E-02	2,41E-02	2,51E-02
MEP	kg N-Eq	1,22E-03	1,04E-03	1,07E-03	1,21E-03	1,21E-03	8,38E-04	8,44E-04
MDP	kg Fe-Eq	1,08E+00	1,08E+00	1,08E+00	1,31E+00	1,31E+00	6,42E-01	6,43E-01
PMFP	kg PM10-Eq	5,55E-03	5,32E-03	5,33E-03	6,38E-03	6,38E-03	2,82E-03	2,83E-03
POFP	kg NMVOC	2,90E-02	2,34E-02	2,35E-02	1,08E-02	1,08E-02	2,38E-02	2,38E-02
TAP	kg SO ₂ -Eq	5,30E-03	4,88E-03	4,97E-03	6,05E-03	6,01E-03	2,44E-03	2,47E-03
ULOP	m2a	1,32E-02	1,10E-02	1,11E-02	1,08E-02	1,09E-02	8,84E-03	8,91E-03
WDP	m3	3,68E-03	3,14E-03	3,64E-03	4,33E-03	4,43E-03	3,05E-03	3,17E-03

The result reveals that the environmental impacts have trade-offs depending on the technologies of pig iron production. Comparing the systems with CCS to systems without CCS, impact factors of the BF+MEA and COREX+Selexol, with CCS, indicate higher impact scores than those of the BF BAT and COREX without CCS, respectively, except for GWP. For the TGRBF system, the tradeoff is shown by different trends with systems of BF associated with some of impacts. In the case of TGRBF without CCS, GWP and TAP is lower than the case for TGRBF+PSA, system with CCS and other impact factors show higher or almost similar impact potential.

In the BF BAT+MEA, various impacts show increases of 10% for FDP, 3% for FETP, 2% for HTP, 11% for IRP, 10% for METP, 3% of MEP, 2% for TAP, and 16% for WDP compared to the BF BAT system. The FDP and TAP increases are attributed to energy requirements for regeneration in the capture process and transport and storage stage. The reason is that to produce the energy, it is necessary to supply fossil fuels, a contributor for FDP, and during the production of energy, SO_x and NO_x, contributors for TAP, are mainly emitted. Even though BF BAF+MEA can remove 99.5% of SO₂ and 25% of NO_x as co-captured emissions during capture of CO₂, the chemical absorption with MEA requires the high amount of energy compared other system. The Ammonia emitted in capture process is a contributor related to increase TAP. In addition, the WDP increase is primarily caused by demand of the decarbonized water in the capture process of the chemical absorption. MEA degradation,

and its disposal slightly contribute to the increases of toxicity impacts such as FETP, HTP and METP. Various toxicity potentials and IRP also are affected by heat production required in the capture system. Overall, the BF BAT+MEA system demands high energy in regeneration of MEA in capture process and thereby, almost environmental impacts have increased compared to the BF BAT, the system without CCS except for GWP.

The TGRBF+PSA system indicates increased impacts of 4% for IRP, 10% for METP and 2% for WDP in comparison with the TGRBF. The causes of the increases come largely from additional supply of electricity for processes of CCS. In terms of METP, the additional demand of infrastructures by CO₂ capture also contributes on the increase. Several toxicity impacts such as FETP and HTP show slightly increases. However, unlikely with MEA, the increases is not caused by toxicity of adsorbent but related to supply of energy, e.g., electricity. As for the TAP in TGRBF+PSA, pretreatment processes before the capture remove 95% of SO₂ and 100% of NO_x considering the assumption of the study. However, the removed SO₂ and NO_x with CCS, the amount is very little, therefore, for whole amount emitted from whole life cycle, the decreased impact is only 1% of TAP. That is why the TAP is slightly less than the system without CCS. In the TGRBF and TGRBF+PSA, the remarkable difference between with and without CCS is not presented, however, the electricity supply for the additional processes by CCS deployment is a main contributor in line with the increased impact potentials.

For COREX with and without CCS, all of the toxicity impacts such as FETP (1%), HTP (1%), and METP (1%) increases in the COREX+Selexol system compared to without CCS. In the study, the database for disposal of the solid waste by solvent from CO₂ capture process can be used in solvent mixture and the waste is treated by incineration system. Thus, as the result of solid waste disposal, the toxicity impact potentials increase. Similarly with the TGRBF+PSA, additional energy requirement by the COREX+Selexol contributes increased impacts of IRP and WDP.

In the study, IRP and WDP increase by electricity production is dominantly attributed to nuclear power generation. That is because the used electricity system is the electricity mixture in Norway from several technologies of power production and supply source of electricity has diverse routes. Even though in Norway, hydropower system is main power supply system, the nuclear power system can be considered from other supply chain from other Nordic countries.

As for the ALOP, the BF+MEA system has the highest score among chosen technologies. In particular, the systems with CCS such as TGRBF+PSA and COREX+Selexol show higher impact potential scores than those of the systems without CCS. The ALOP is caused by the coal supply in the iron and steel industry for coke and coal. The TGRBF needs less direct coke

and coal compared to the other technologies. In the COREX system, the coal requirement can be largely allocated to produce the energy in the power plant and boilers because of the high heat value of COREX gas. Thus, the two systems can have low ALOP in comparison with BF technology. Although the BFG is considered in terms of partitioning for energy productions, the partitioning for energy is less than COREX gas. In terms of the systems with CCS, comparing to the systems without CCS, they required more energy to capture, transport and store the CO₂. To produce more energy by the CCS system, it shows higher impacts in comparison with the systems without CCS.

To sum up, the increased environmental impacts by CCS deployment are caused by mainly two reasons energy requirement for additional processes and solvent disposal. Depending on the technologies of pig iron production, the CCS systems are different since there are technical differences such as CO₂ partial pressure in emitted flue gas, inputs and outputs. Only in view of CCS performance for environmental impacts the BF BAT+MEA system shows remarkable increase the FDP, IRP, METP and WDP in comparison with others with CCS. Except for the IRP and POFP, the COREX and COREX+Selexol shows the lower environmental impact scores compared to those of other technologies. In the designed systems of 85% for BF BAT+MEA and TGRBF+PSA and 90% for COREX+Selexol system of CO₂ capture efficiency, all of three technologies of ironmaking has net benefit only for GWP as decreased impacts, 26% by BF+MEA, 31% by TGRBF+PSA and 48% by COREX+Selexol, respectively. In the TGRBF+PSA, slightly decrease shows for TAP.

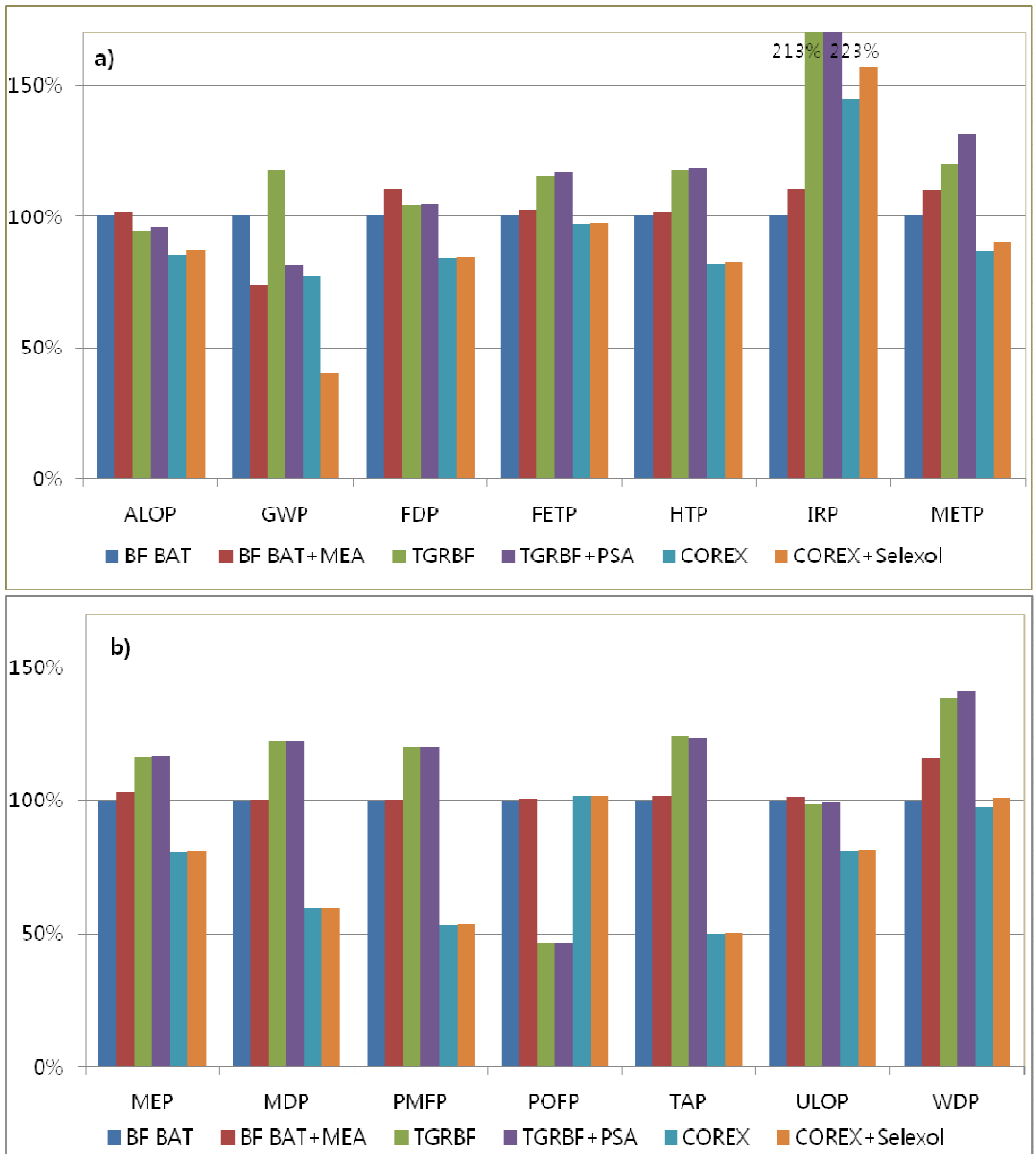


Figure 16. Relative impacts for 1kg pig iron from different technologies

5.1.3 Contribution analysis

Contribution analysis is implemented in order to discover which processes affect the environmental impacts through breakdown of the system. The technologies for ironmaking consist of main foreground processes such as pig iron production and capture process, and upstream processes such as sinter, pellet, hard coal, coke and oxygen production. In the study, each technology is broken down into main pig iron production with and without capture process, materials from sinter, pellet, iron ore, coke, coal, other suppliers and electricity. Additionally, solvent or sorbent production, compression, transport and storage stages are added, in case the system includes a CCS system. Furthermore, infrastructure of pig iron production and capture process are included for the analysis. In the study, pig iron production refers to processes reducing iron oxide such as blast furnace and COREX with and without CCS system.

Figure 17 presents the contribution of processes for GWP from each technology. Pig iron production, which is a reducing process of iron oxide, is the highest contributor for the GWP in BF W.A. and BF BAT. The tendencies of contribution analysis are almost similar as 48% for BF W.A. and 45% for BF BAT, respectively. Considering a CCS system, the BF+MEA system indicates that the contribution of pig iron production with capture technology decreases by 24%. In cases of three BF technologies with and without CCS, the related processes for pig iron production (24-48%), sinter (35-22%), and coke plant (18-13%) are main contributors for the GWP.

In the TGRBF system, pig iron (37%), sinter production (27%) and oxygen supply (15%) are main contributors for the GWP. As for the TGRBF+PSA, the contribution of pig iron production is only 9% of total GWP. The remarkable difference is that the contribution of oxygen supply shows an increase as 15% for the TGRBF and 21% for the TGRBF+PSA in comparison with BF technology. Oxygen supply is a process which requires high electricity to produce pure oxygen and thereby, the different oxidizing agent contributes to the contribution of the overall GWP.

Trend of the contribution is considerably different between systems of COREX with and without CCS. While the COREX without CCS has pig iron production (54%) as the highest contributor, in the COREX+Selexol system, the coal (30%) and oxygen (33%) are dominant contributors for the GWP. As the contribution of pig iron production in the COREX+Selexol system is reduced, other materials such as pellet, coal, and oxygen are presented as high contributors in terms of relative contribution. The coal is a higher contributor in both of the COREX systems with and without CCS; however, the contribution of sinter production, which is a remarkably high contributor in other systems, is removed by the no requirement.

Although the infrastructure is not high contributor in all of the systems for the GWP, a little difference between systems with and without CCS are found in the results. The cases of system with CCS have the higher contribution of infrastructure than that of systems without CCS. In particular, as for the BF technology, while when only process LCA is applied, the contribution of infrastructure is 0.05% of total GWP, in the LCA based on IOA, the result is changed to 0,34% of total GWP. As a results, the hybrid LCA can be taken into account with respect to the truncated impacts at the process LCA.

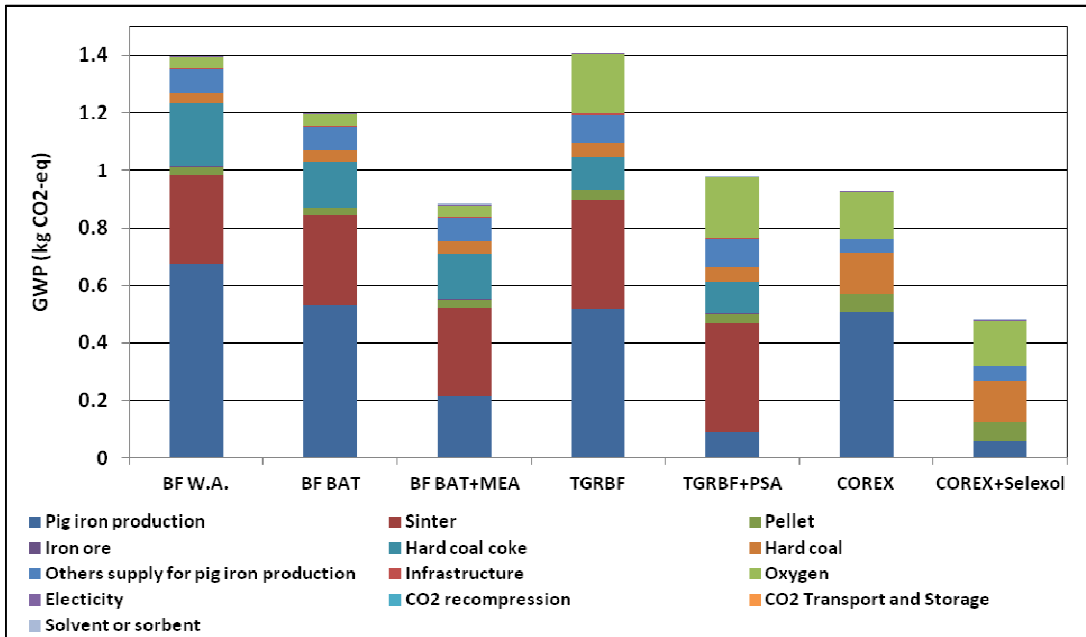


Figure 17. Contribution analysis of GWP.

When it comes to contribution analysis for FDP, the result is shown in Figure 18. Regardless of employment of CCS system, the coke is the highest contributor in three technologies with BF system. However, the BF+MEA system show that the pig iron production contributes to 9% of total FDP. As mentioned above, the chemical absorption process requires high amount of heat to regenerate MEA. Therefore, the additional heat requirement contributes to change of contribution analysis. TGRBF technologies both with and without CCS have sinter (15%), coke (37%) and coal (21%) as high contributors. Coke requirement from the BF technology can be reduced in the TGRBF technology; therefore, while the coke part is reduced, oxygen part increases in the total contribution. In terms of COREX technology, the coal is required higher than in other technology. As shown in the results, the coal is a dominate contributor as 76% of total FDP and the difference by the CCS system is negligible. In conclusion, the FDP is mainly caused by reducing agents such as coal and coke supplies.

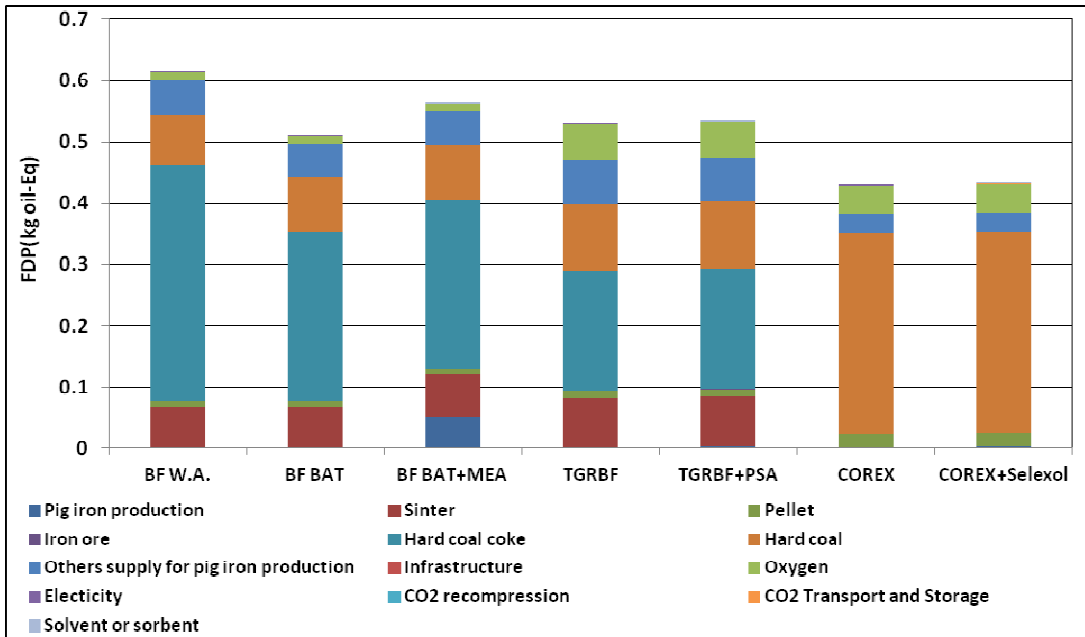


Figure 18. Contribution analysis of FDP.

Figure 19 presents results of contribution analysis for FETP. The coke is the highest contributor as 53-63% for BF technologies, and 33% for TGRBF technologies with and without CCS. About 65% of the FETP is attributed to the coal consumption in the COREX technologies with and without CCS. Oxygen requirement is the second highest contributor in TGRBF and COREX technologies. There is notable difference with and without CCS expect for BF and BF+MEA technologies. The contribution is that the disposal of solvent from the capture process affects the FETP as 2.6% for the BF+MEA. Consequently, the FETP is largely resulted from extraction of coal from mining.

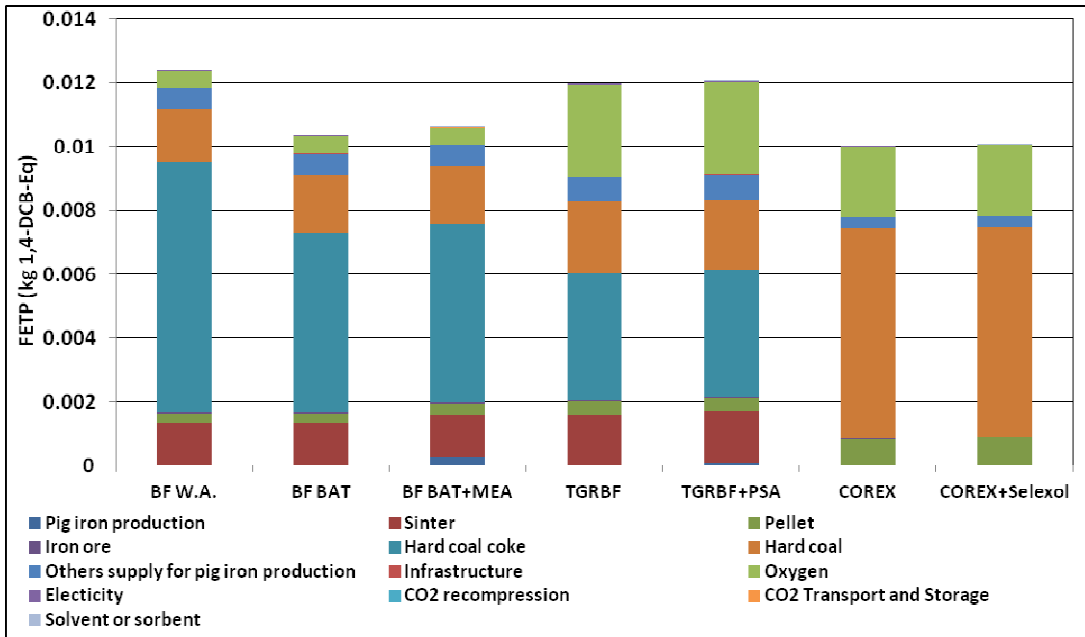


Figure 19. Contribution analysis of FETP.

Results of contribution analysis with respect to HTP are illustrated in Figure 20. The tendency of proportions from the contributors is almost similar with FETP. The HTP also is caused by the extraction of the coal from mining and coal requirement for energy production.

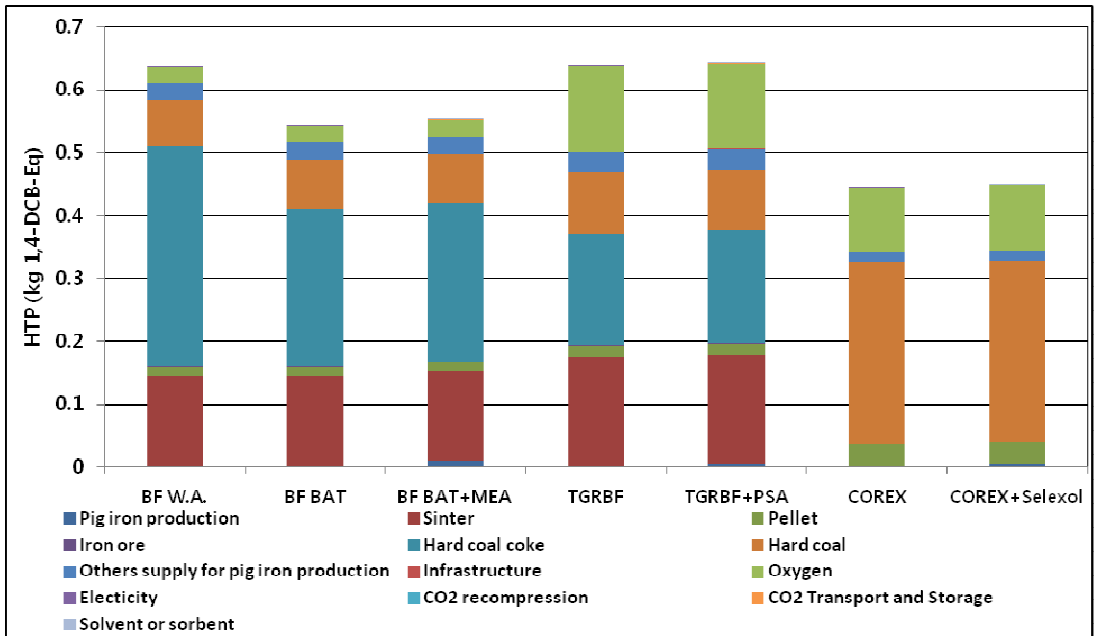


Figure 20. Contribution analysis of HTP.

Considering IRP, while impact categories are evenly contributed from sinter, other supplies and oxygen in BF technologies with and without CCS, the oxygen is prominent contributor the COREX and TGRBF. According to structural path analysis in the study, the impact from oxygen production is associated with electricity supply chains. In particular, the systems with CCS show the contributor increased of pig iron production with CO₂ capture due to increased requirement of energy for operating the process. It is supplied from the nuclear power plant by mixture Nordic electricity; the contribution is higher than that by other electricity supply chains. In conclusion, the energy demand is the largest resource for the IRP. These results are reflected in Figure 21.

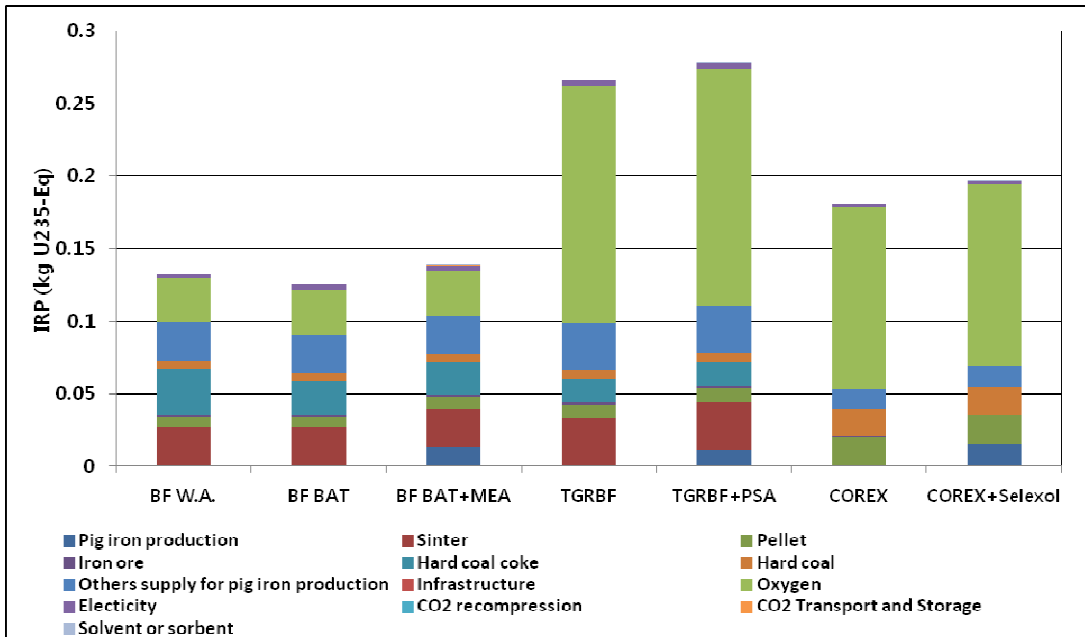


Figure 21. Contribution analysis of IRP

As shown in Figure 22, the infrastructure part is about 60% in BF and TGRBF and 44% in COREX of total METP both with and without CCS. Comparing with other toxicity potentials such as HTP and FETP, the contribution from infrastructure is significantly higher. Additional needs of infrastructure by CO₂ capture units show contribution of increases in the system with CCS.

On the other hands, Nickel is the largest contributors for the METP as about more than 50% during life cycle in iron and steel industry. According to the EXIOPOL, the characterization factors of Nickel show about 107 times for HTP and 6000 times for FETP in the METP. When EXIOPOL, which have been used in the study, is compared with characterization factors of Nickel from ReCiPe 2008, the scores are significantly higher. Besides coke for technologies with BF and TGRBF and Coal for technologies with COREX also can be high contributions in the METP. As a result, the too high characterization factors for the infrastructure from EXIOPOL have to be checked whether it overestimate environmental impacts for the METP or not. According to Corsten et al., 2013, for marine aquatic ecotoxicity, there is ongoing debate on the characterization factors used in LCA methodology (Corsten et al., 2013). Therefore, the point that the significantly high characterization factor can attributed to High contribution of infrastructure can be one of reasons why the results is like this.

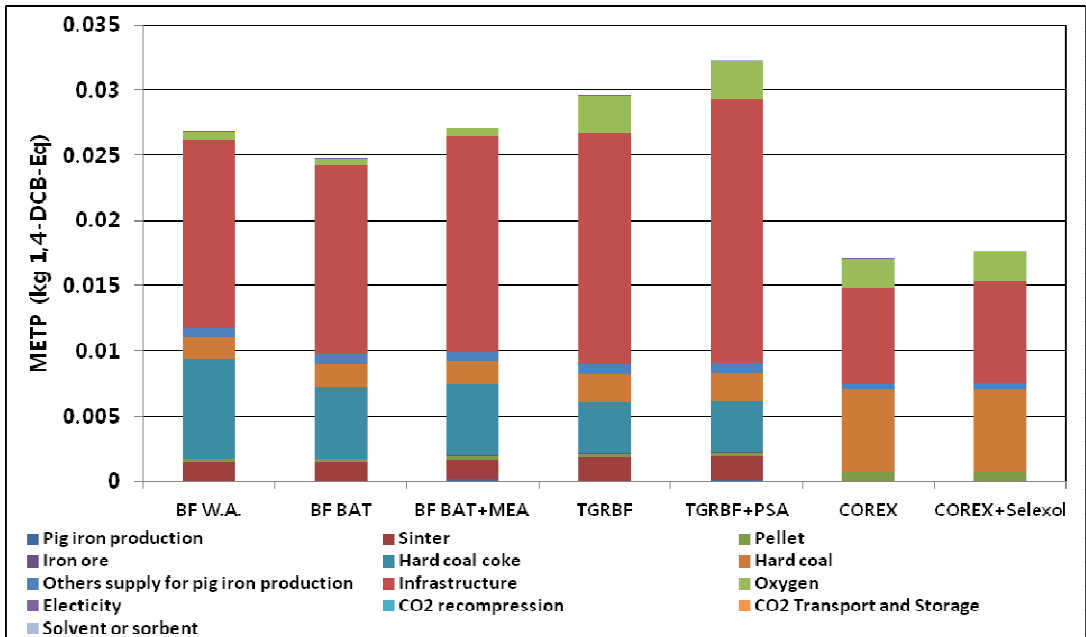


Figure 22. Contribution analysis of METP

MDP is illustrated in Figure 23. The main contributors are sinter and pellet requirements. Although there are differences depended on technologies, the MEP is caused by demands of iron materials. Notable difference is not shown between systems with and without CCS.

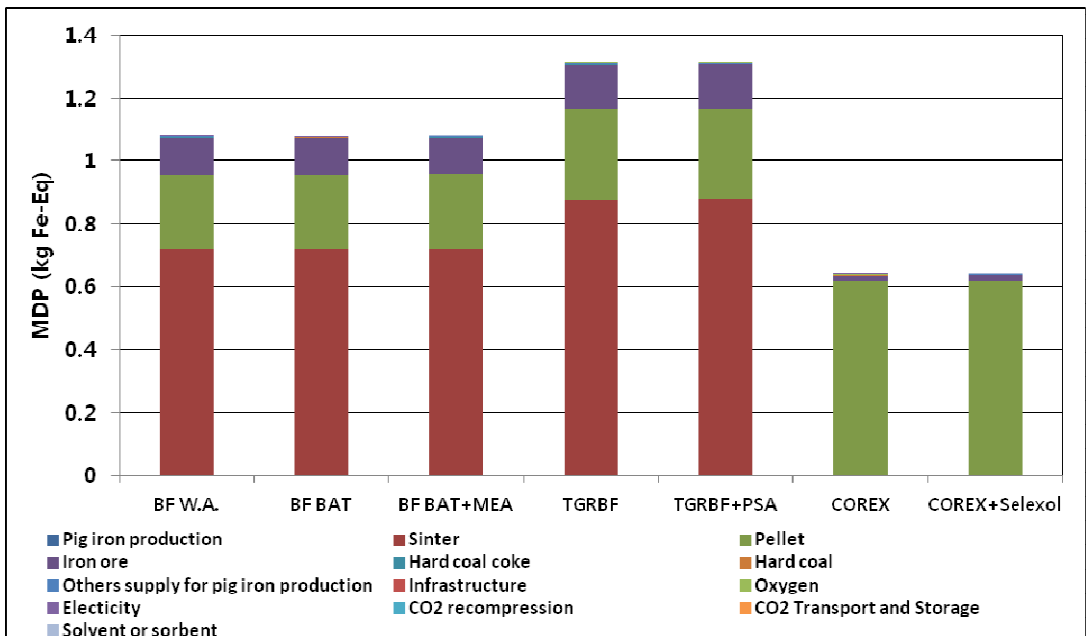


Figure 23. Contribution analysis of MDP

When it comes to PMFP, sinter is the highest contributor in BF and TGRBF technology both with and without CCS as about 60% of total PMFP. In COREX technology due to no sinter requirement, the pellet is the highest contributor as 77% of total PMFP. Overall, the PMFP is related to the sinter and pellet requirements rather than direct emission from pig iron production. According to the Burchart-Korol 2013, sinter plant is the largest contributor to dust and gas emissions in the Polantian iron and steel industry (Burchart-Korol, 2013). Even though it is not possible to compare the COREX technology, the result is similar with this study about BF technology.

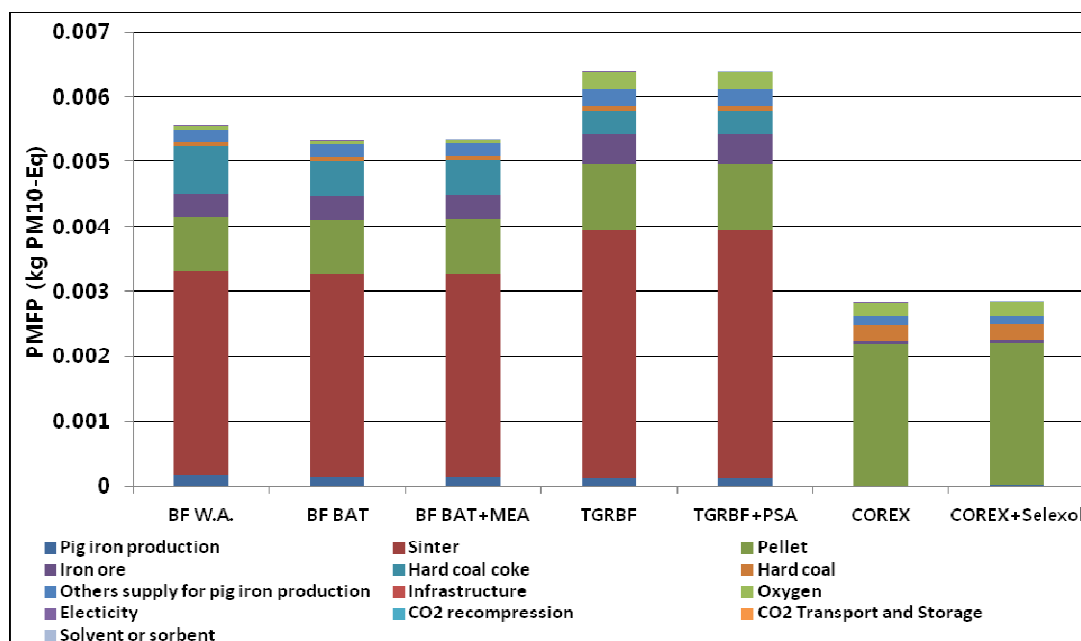


Figure 24. Contribution analysis of PMFP

As for POFP, carbon monoxide is the most dominant contributor in ironmaking technology. As shown in Figure 25, the POFP is resulted from the direct CO emission in the pig iron production. However, the sinter plant required in BF and TGRBF technologies with and without CCS influences the POFP as the second highest contributor. In comparison with other impact categories, the POFP show that the TGRBF with and without CCS is the lowest because the TGRBF can reuse the CO gas generated from the flue gas as the reducing agent in the BF process and thus, it can reduce the relatively large direct CO emission compared with other technologies. The technical property can reduce the direct CO emission in the BFG, and be reflected in the results. The results show that the effects of the CCS performance are negligible.

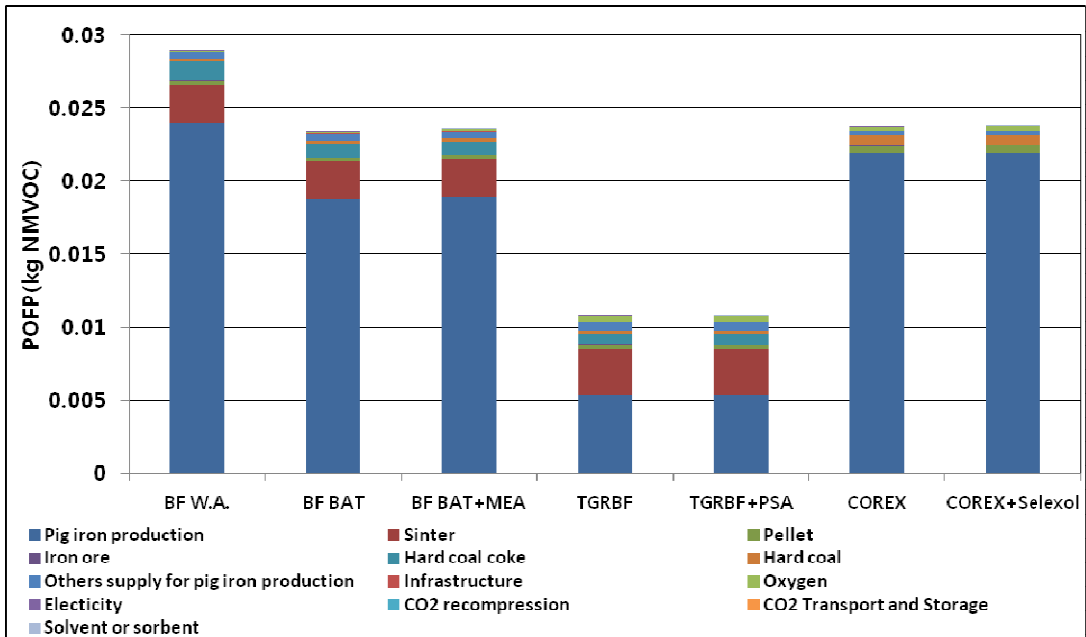


Figure 25. Contribution analysis of POFP.

In the iron and steel industry, TAP is caused by SO_x and NO_x emissions by more than 90% and effects from others such as NH₃ is relatively negligible. The four technologies of BF and TRGBF with and without CCS have the sinter as the largest contributor (about 60%). While the BF with CCS shows slightly higher impact in pig iron production than the BF without CCS, the TGRBF with CCS presents a slightly reduction of the impact in the pig iron production compared to the TGRBBF without CCS. In terms of COREX, pellet (25%), coal (31%) and oxygen (27%) are the large contributors instead of the sinter. It is because COREX system does not requires the sinter supply but demands higher amount of coal and oxygen than those in other systems, BF and TGRBF with and without CCS. The TAP is attributed on iron materials such as pellet and sinter, and reducing agents such as coke, coal depending on technologies.

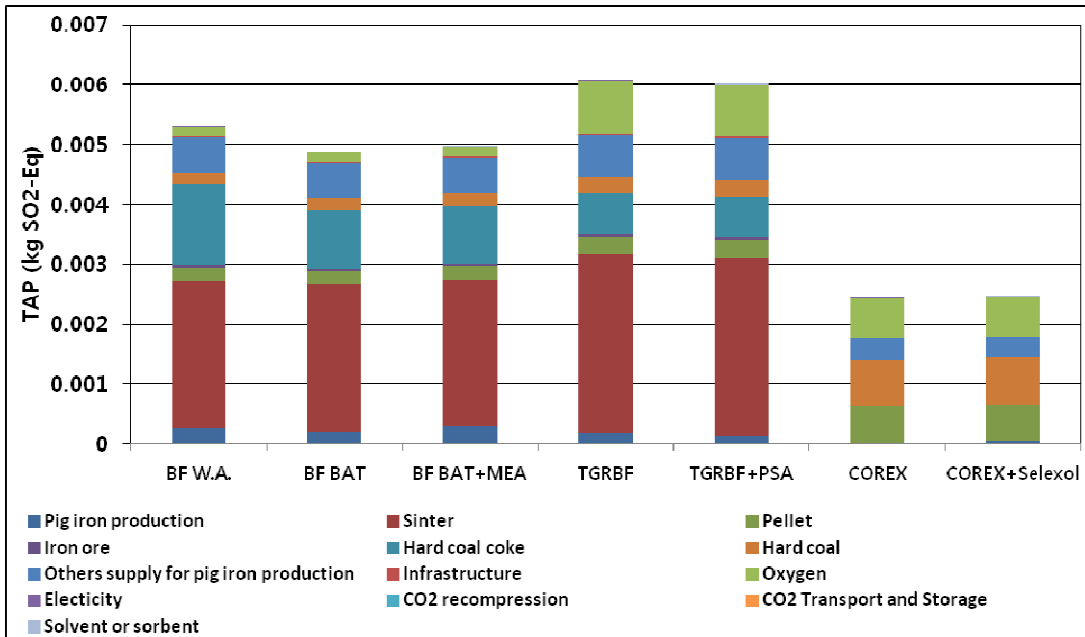


Figure 26. Contribution analysis of TAP

Overall, the contribution analysis reveals that the GWP has relatively significant difference between with and without CCS system. Transport and storage stages including recompression are not high contributors with respect to the chosen environmental impact categories. When it comes to the CO₂ capture process, the increased contributions into impact potentials show in FDP only for BF+MEA and IRP for three technologies, the BF+MEA, TGRBF+PSA, and COREX+Selexol. The two changed impact categories are related to the additional energy requirement in the capture process. The solvent disposal from the capture process in BF+MEA slightly contributes to changes of toxicity impacts such as FETP and HTP.

The direct CO₂ emission from the pig iron production contributes strongly to the GWP in cases of the systems without CCS. The sinter supply also contributes to GWP in terms of all of technologies expect for the COREX system with and without CCS. The coke and coal, reducing agents and energy sources, are major contributors to the FETP, HTP, FDP and MEP. The MDP, PMFP, and TAP are highly attributed to sinter and pellet requirement. Moreover, the technologies (BF and TGRBF) which use sinter with pellet in ironmaking process show that sinter is a higher contributor than pellet. In contrast to the other toxicity impacts, the infrastructure is the largest contributor to the METP. As for the IRP, oxygen supply remarkably contributes to the impact. Additionally, in the Appendix, results indicates the contribution analysis for MEP, FEP, and WDP (FA 1-3).

5.2 Sensitivity analysis

In the study, a sensitivity analysis is performed to disclose the impact of assumptions made and the variation of input data on the result of the comparison. It is based literature sources for the lowest requirement of inputs, i.e., the best-case and the highest requirement of inputs, i.e., worst-case systems including typical case systems with and without CCS (BF, BF+MEA, TGRBF, TGRBF+PSA, COREX, and COREX+Selexol). As the results of the contribution analysis, in iron and steel industry, the coke and coal, i.e., reducing agents and energy source, and sinter, i.e., a material of ironmaking processes, are the large contributors for most of environmental impact categories. Besides, oxygen is indicated as one of high contributors with respect to IRP, toxicity potentials, and TAP. In addition, when the CCS system is performed, the additional energies such as electricity or steam also can lead to main changes for contributions. Therefore, the sensitivity analysis has been performed through changes of the important input parameters and estimation of emissions by the changes of inputs. The error bars in Figure 27 present the variation derived from the ranges of the parameter values presented in TA 1-3.

Figure 27a) shows GWP of the best, typical and worst cases for 1kg pig iron by different technologies with and without CCS. For the BF technology, the results illustrate the 1.77 kg CO₂-eq for the worst case and 1.08 kg CO₂-eq for the best case. For the BF+MEA technology, the worst case is shown as 1.30kg CO₂-eq and the best case is presented by 0.75 kg CO₂-eq. In the cases of the BF technologies with and without CCS, the error ranges are 48% for worst cases and 10-15% for best case compared to typical cases.

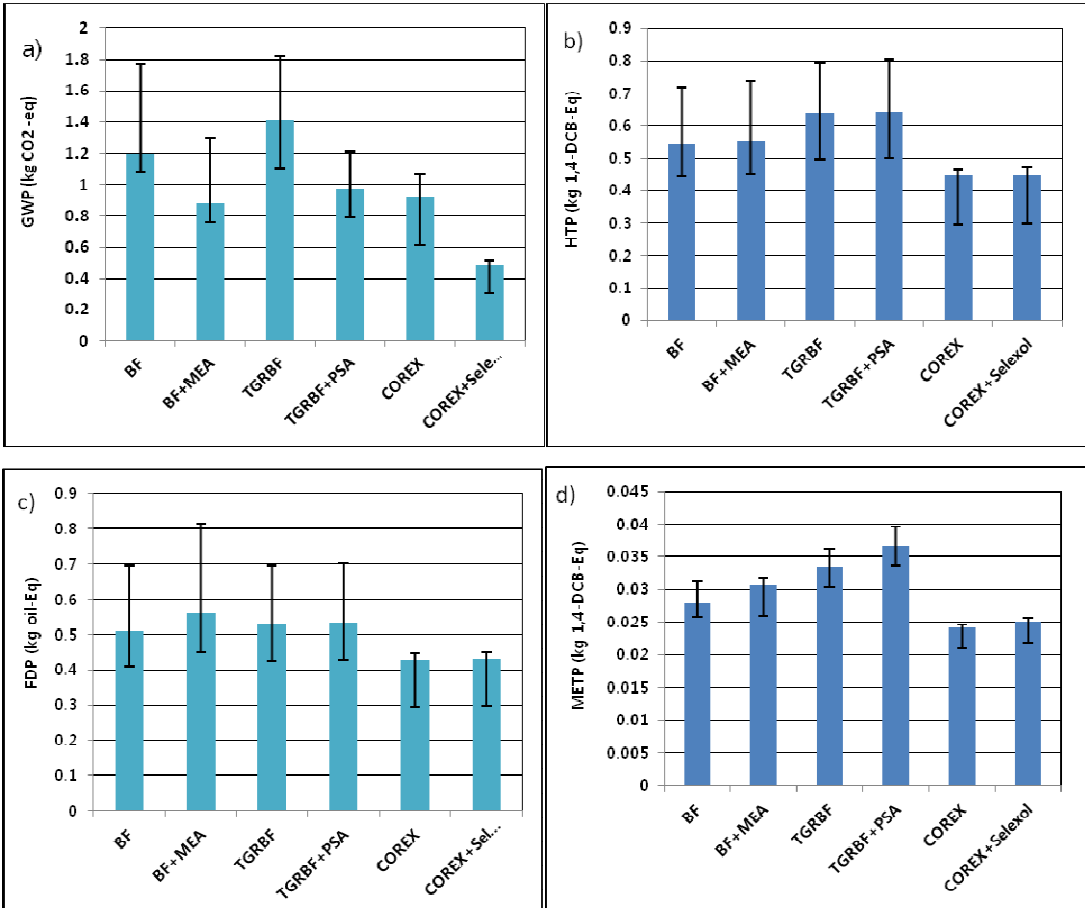
Considering the TGRBF without CCS, the error ranges show +30% (1.82 kg CO₂-eq) for the worst case and -22% (1.10 kg CO₂-eq) for the best case in comparison with the typical case. The variation ranges mean that the important input parameters such as sinter, coal, and coke contribute high GWP. Moreover, depending on quality and quantity of materials, the GWP range can be changed.

When it comes to COREX systems with and without CCS, the results show that variation ranges are presented less than those of other technologies. That is because the requirements of coke and sinter are reduced in the COREX technology and the fact might be reflected into the results.

Overall, if each of the worst cases and the best cases is compared with other worst cases and best cases, respectively, the tendency of the GWP scores is similar with the typical cases. According to Birat and Maizière-lès-Metz, 2010, the specific CO₂ emissions for steel production have been indicated from 1.26 to 2.0 kg CO₂ per kg crude steel based on several literatures with BF technology. Although the system boundary of the literatures cannot be

definitely equal with this study, it means that depending to the data source, the uncertainty can be generated.

Additionally, the other results for sensitivity analysis with respect to the other impact categories are reflected in Figure 27 from b) to j). When it comes to the other impact factors, the significant differences between best and worst cases are found. The COREX with and without CCS have narrower ranges of error than those of other technologies. As a result, the important input parameters such as reducing agents, materials based on iron, energy sources like electricity or steam, and oxygen can affect the environmental impact changes and thus as the change of parameters, the uncertainty can be considerably fluctuated.



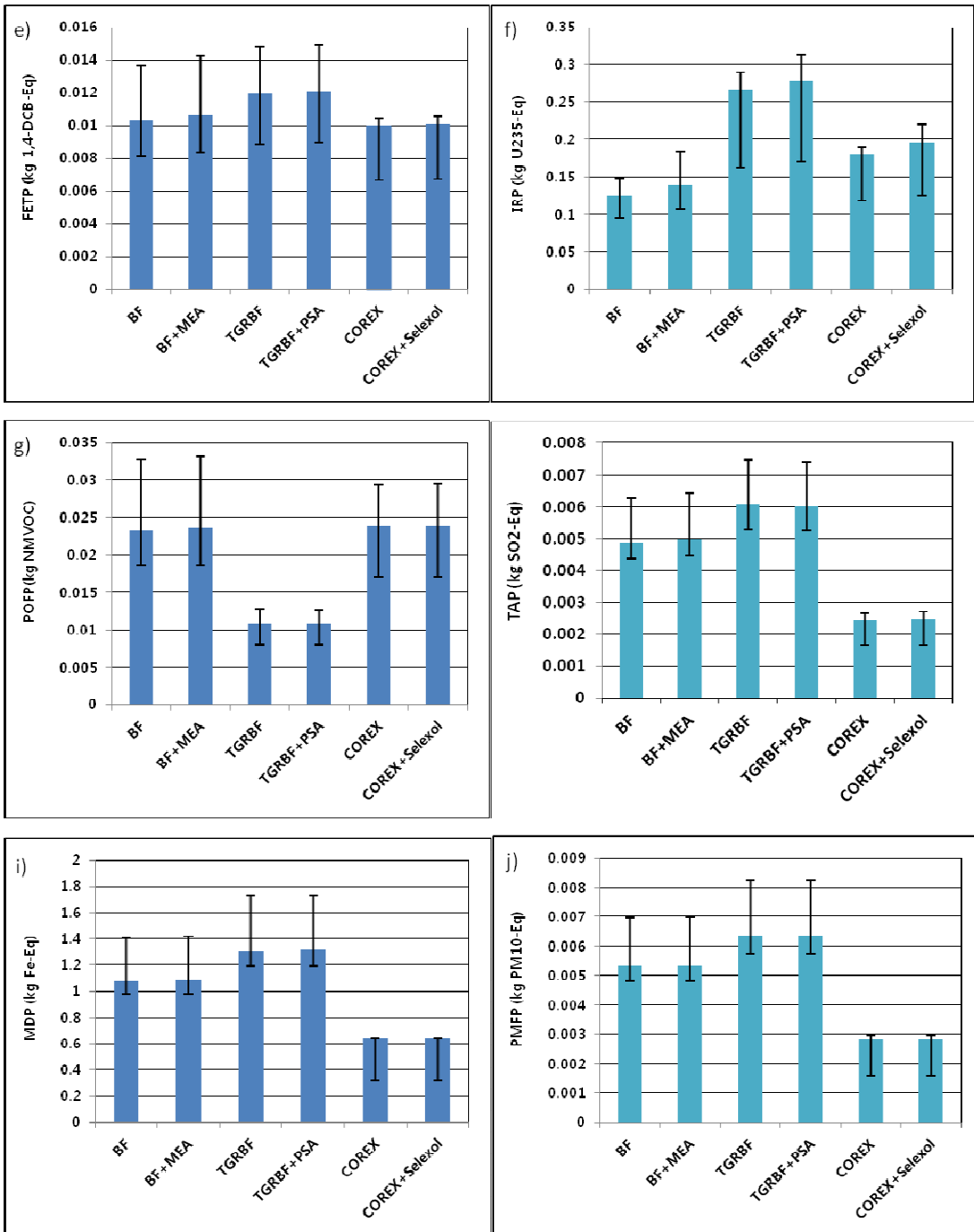


Figure 27. Sensitivity analysis of different technologies for 1kg pig iron production with and without CCS (a) GWP, b) HTP, c) FDP, d) METP, e) FETP, f) IRP, g) POFP, h) HTP, i) MDP, j) PMFP).

6. Discussion

6.1 Limitations of the study

Three key limitations have been identified in the study. The first issue concerns the quality of data collected from the literature. Most literatures used in the study have carried out simulation and modeling for iron and steel industry with and without CCS. However, in current state, there is no commercial steel production with CCS and even data from pilot plants is limited. Moreover, except for the BF BAT data based on IPPC, 2012, as for the other technologies, no all data is found on the emissions into environmental compartments and thus, it is necessary to estimate them using mass balance from inputs. Especially, data for PSA (pressure swing adsorption) process comes from the study for power plant with CCS. To reduce the limitation, in the study, more or less 45 literatures have are investigated and compared for chosen technologies. Consequently, as far as possible, the results are derived from the most reliable LCI data through review of relevant literatures.

Secondly, system boundary issue can be considered. As far as iron and steel industry is concerned, the study mainly focuses on the pig iron production instead of final products in such as alloyed steel, stainless steel or hot-rolled coil. Regarding the additional life cycle stage, it is possible that other environmental impact issues are generated. However, this study have researched the highest impact part, processes reducing iron oxides in the iron and steel industry, therefore, the result can be feasible. Power production in steel industry is excluded in the study; however, as mentioned before, the power generator contributes high environmental impacts (Wiley et al., 2011). However, the power productions might have differences depended on the technologies, thus, the study should be more studied.

As for CCS system, the leakage of CO₂ is assumed negligibly and monitoring of the transport and storage site is also not concerned in the study. According to Corsten et al., 2013, the leakages and monitoring of CO₂ have been arguable whether the parts should be included in the analysis. That is because the leakage of CO₂ could occur after long periods of time like hundreds or thousands of years and their environmental impact might be different related to continuous emissions during lifetime. In the point, the estimation of the impacts by the leakage or monitoring has limitations. To avoid the uncertainty, the study has excluded the effects.

The third issue concerns characterization factors in impact categories. In the study, additional characterization factors for human and environmental toxicity are not added. Some of literatures such as Singh et al., 2011b and Koornneef et al., 2008 have partially applied the characterization factor based on literatures of risk assessment for MEA. However, the majority of the LCA studies for CCS especially in power plant sectors have not

mentioned additional characterization factors aside from selected database such as CML, ReCiPe 2008. In addition, the studies for characterization factors of MEA also are limited (Corsten et al., 2013). Therefore, this study does not consider additional characterization factors expect for ReCiPe 2008 midpoint approach and EXOIPOI.

6.2 Discussion for the study

The goal of this study was to disclose environmental performance due to the implementation of the capture, transport and storage of CO₂, by comparing 7 technologies of pig iron production with and without CCS.

In the chapter, this study will be compared to other LCA studies. However, up to date, the LCA study of iron and steel sector with CCS is rare and limited. Therefore, the comparison is implemented using studies of power production sectors with CCS through reviewing the main trend by CCS deployment.

In the study, the results have shown the reduction of the GWP in the pig iron production with CCS system. The net reduction of the GWP is 26% in the BF+MEA, 31% in the TGRBF+PSA, and 48% in the COREX+Selexol when the CO₂ removal efficiencies of 85% for BF process with MEA solvent and TGRBF with PSA system, and 90% for COREX with Selexol solvent are employed. According to the LCA studies in power plant sectors with CCS, although the applied removal efficiency range is 85-95%, the net reduction of GWP is not reached to the applied removal efficiency similar with this study (Singh, 2011, Koornneef et al., 2008, Korre et al., 2010).

In the environmental impact analysis for power plant sectors with CCS, the indirect impacts from upstream and downstream also affect the GWP. Although the technically different properties exist between the power and iron and steel sectors, the impacts from the indirect emission contribute to the net change of the GWP because CO₂ capture processes can reduced only in the direct emission of CO₂. In addition, the loss in the efficiency is related to additional demands for fuel and other materials for the CCS deployment (Zapp et al., 2012).

Considering the technical distinction between power plant and iron and steel sectors, according to Singh, 2011, the direct emission of CO₂ at the power plant without capture contribute to more than 90% for coal power generation and 82% for natural gas power plant. However, as the results of this study show, the direct and indirect emission impacts contribute respectively around half percentage to the total GWP. The point can affects the less net changes of GWP reduction in the iron and steel sector than those of power plant sectors.

In general, the study shows an increase in other environmental impacts for the technologies with CCS, except for TAP in the TGRBF+PSA technology, while the GWP decrease in the systems with CCS. As also mentioned in Koornneef et al., 2008, trade-offs for environmental impacts are associated with energy requirements and the formation of waste in the capture process, and upstream environmental interventions, especially in the coal supply chain.

The results for CO₂ transport and storage stages have presented relatively small environmental impacts in terms of overall technologies in this study. According to Zapp et al., 2012, even though there is variation depended on technologies for power production, most of LCA studies for CCS system, the transport and storage stages indicate the smaller environmental impacts than the capture stage.

When regeneration of solvent of MEA is used in the capture process, this study has presented increases of typically toxicological impacts on humans and fresh water increase. The increased trend of toxicological impacts have been shown in the literatures for environmental impact analysis about power plant with CCS such as Koornneef et al., 2008, Singh, 2011, Zapp et al., 2012, and Corsten et al., 2013. Especially, Corsten et al., 2013 which has review LCA studies of CCS technologies in power generation described that the emission of MEA to the atmosphere have impacts on human toxicity and terrestrial ecotoxicity. Veltman et al., 2010 and Singh et al., 2011a and 2011b also mentioned that the MEA emission and degradation products affect several toxicological impacts. In the study, besides from direct degradation emissions, the solvent disposal unit effects contributes to increased impact of fresh water ecotoxicity and additional energy demand in the capture process affect the increase of human toxicity.

In particular, the iron and steel industry has high HTP and FETP in the upstream like coal, coke, and sinter production which demand the extraction of coal and iron ore. In the point, the upstream impacts show significant high contributions for the toxicological impacts compared to other processes regardless of existence of CCS system. In conclusion, the increase of the toxicity impacts is not remarkable in the BFBAT+MEA as shown 2.6% increase.

When it comes to other capture technologies using the other solvent or sorbent such as Selexol or Zeolite, the notable change for toxicological impacts is not indicated in this study. According to Corsten et al., 2013, compared to the MEA solvent, the effect of Selexol on human toxicity appears negligible.

Co-benefits that were expected with the addition of CCS are reduction of SO_x, NO_x and PM. However, although the BF+MEA technology has the benefit for reducing the emissions, the TAP increased in the results. In the results of Zapp et al., 2012, the additional requirements of energy and coal demand for CCS system generate SO₂ and NO_x emission, causing

additional acidification and eutrophication potentials when employing post-combustion technology associated with MEA solvent. In this study, the TGRBF+PSA technology show a benefit from the reduction of emissions for the TAP because the PSA technology, physical adsorption, requires less energy for sorbent regeneration compared to chemical absorption and thus the fact is reflected in the result.

Overall, the iron and steel industry has differences with power production sectors. The iron and steel industry needs not only coal supply as a reducing agent and energy source but also iron materials. Therefore, environmental impacts from indirect emissions can be higher than the power production sectors which primarily demand fuels. Aside from the main product like pig iron, coke and sinter plant show large environmental impacts with respect to GWP, FDP, FETP, HTP, MEP, FMFP, and TAP. According to Burchart-KoralDorata, 2013, the most significant environmental impact was related to coke consumption in the BF and iron ore consumption in the sinter plant for human health. In addition, significant source of GHG emissions included coke. The metal and mineral depletion was caused by iron consumption in the sintering process (Burchart-Koral, 2013). In this study, BF technologies with and without CCS, the related processes for pig iron production (24-48%), sinter (35-22%), coke plant (18-13%) are main contributors for the GWP. According to the Iosif et al, 2009, inventories of CO₂ emission for the steel production has high values in the sinter, coke plant and blast furnace, and thus the tendency is similar with the results of this study (Iosif et al., 2009).

In the study, the COREX technology with and without CCS showed the lowest environmental impacts expects for the IRP, and POFP, showing the highest decrease of the GWP in a case with CCS in comparison with other technologies for pig iron production. The results are shown due to reductions of sinter and coke processes.

7. Conclusion

Even though there have been recommendations to mitigate CO₂ emission for employing CCS into industrial sectors such as iron and steel, cement and other sectors of high CO₂ intensity, up to date, the systematic studies for environmental impact assessment for technologies with CCS have been less and limited for the industry sectors. Through results of the study, the environmental performance and potentials of CCS deployment in the iron and steel sectors has been presented. This study has shown that hybrid LCA method is a helpful tool to support the discussion about environmental effects with respect to CCS technologies depended on different ironmaking technologies.

The selected technologies for 1kg pig iron production were blast furnace (BF), top gas recycling blast furnace (TGRBF), and COREX which have shown technical distinctions such as input materials and emissions. Based on the property of each ironmaking technology, the employed CO₂ capture technologies were BF adding chemical absorption by MEA solvent, TGRBF using pressure swing adsorption with zeolite, and COREX with physical absorption using selexol solvent.

The net reduction of GWP is 26% in the BF+MEA, 31% in the TGRBF+PSA, and 48% in the COREX+Selexol when performing CCS technologies into pig iron production in life cycle boundary. In terms of BF+MEA, expect for the GWP, other environmental impacts showed increases. As for TGRBF+PSA, while GWP and TAP decreased compared to TGRBF without CCS, the other environmental impacts were increased. COREX+Selexol showed same trend with the BF+MEA. When it comes to the change range of the environmental impacts, the BF+MEA presented the higher increases on overall environmental impact categories except for GWP than other technologies with CCS. Regardless of CCS implementation, the COREX technology showed the highest benefits for most environmental impact factors aside from IRP and POFP.

In the study, the changes by the CCS performance in the chosen technologies were caused by additional energy requirement for capture process in all technology. Especially, in the BF+MEA, the HTP and FETP resulted from the solvent disposal of MEA and emissions of degradation in the capture unit. In term of IRP, the all technologies with CCS showed increases than technology without CCS because of the energy requirements in the capture unit. METP increases in all systems with CCS were contributed by the additional needs of infrastructure.

The benefit of additional pretreatment for SO_x, and NO_x which affect acidification potentials was presented in the TGRBF+PSA system. However, although in the BF+MEA

system has considered about co-capture of the emissions, trade-off was showed due to additional energy requirements for regeneration of solvent in capture unit.

In conclusion, the study has shown that COREX technologies with and without CCS is the highest benefits for all of environmental impacts including GWP, except for IRP and POFP. In addition, even if performing the CCS implementation, the increases of environmental impacts was the smallest among the technologies. The environmental benefits result from the reduction of sinter and coke plant which are processes of large environmental impacts and high potential of COREX gas to produce energy in the ironmaking in a case of system without CCS. It can be beneficial to select physical absorption for CO₂ capture using Selexol solvent which requires less energy and show less toxicological impacts in the system with CCS. Overall, additional energy requirements by CO₂ capture unit in all technologies have mainly contributed increases in terms of most environmental impacts compared to transport and storage, and other materials such as solvent and sorbent production.

7.1 Recommendation

In the chapter, tow parts of recommendations will be provided. One is technical points for iron and steel sector. The other is for future study based on this study.

Given performance of CCS technology in iron and steel industry, the additional energy requirement affects most environmental impacts. Therefore, improvement of energy efficiency is necessary. Moreover, because the MEA regeneration needs large energy, recommendation is that steam is generated from more environmental friendly technology like renewable energy. According to Corsten et al., 2013, MDEA showed lower toxicological impacts than MEA and other solvent also have developed toward less toxicity. Therefore, if performing the chemical absorption for CO₂ capture, less toxicological solvents can be used to reduce environmental impact.

As shown the results, COREX has benefits for environmental impacts through reducing the several processes such as sinter and coke plants which show high impact potentials. Therefore, the iron and steel industry has been improved in technology through reducing processes which can affect environmental impacts, especially for GWP. Aside from the COREX technology, Finex also have been introduced as an advanced technology which can reduces processes related to coke, sinter and pellet plant. Smelting-reduction processes such as COREX and Finex have demonstrated larger benefits for the cost-efficient and environmental points than conventional BF technology (XU and Cang, 2010). According to Burchart-Korol, 2013, for preventing pollutant in iron and steel industry, substitution of raw materials can be employed toward reducing environmental impacts. In addition, not only

CO₂ capture processes but also the other suppliers such as oxygen, sinter and pellet production require the environmental friendly energy source.

Based on the study, considering the future study's direction, the first suggestion is changes for assumed the system boundary for each technology. In the study, the electricity turbine was outside studied system boundary. However, some of literature mentioned that the electricity production also can be high GWP potential (Wiley et al., 2011). Therefore, in the future study, the issue for the conventional BF and COREX system will contribute changes of environmental impacts and in addition, the fact should be identified.

According to IEA, 2011 report, advanced technologies such as Finex, and HIsarna processes for the potentials of CCS in the iron and steel sector were suggested on the future roadmap. In addition, Kuramochi et al., 2012 also assessed the advance technology in an economic aspect. Therefore, above the commercial phases, it is necessary that the advanced technologies with CCS are assessed in terms of environmental performance.

Several reports such as ULCOS and IEA have provided roadmaps and scenarios for reaching the CO₂ mitigation. However, the evaluation of the scenarios has not been studied in terms of environmental aspects especially for iron and steel sector. In the study of Singh, 2011, the scenarios were evaluated in view of environment, therefore, future study for the assessment is recommended.

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Appendix

TA 1. Parameters for worst and best cases of BF technology with and without CCS for sensitivity analysis

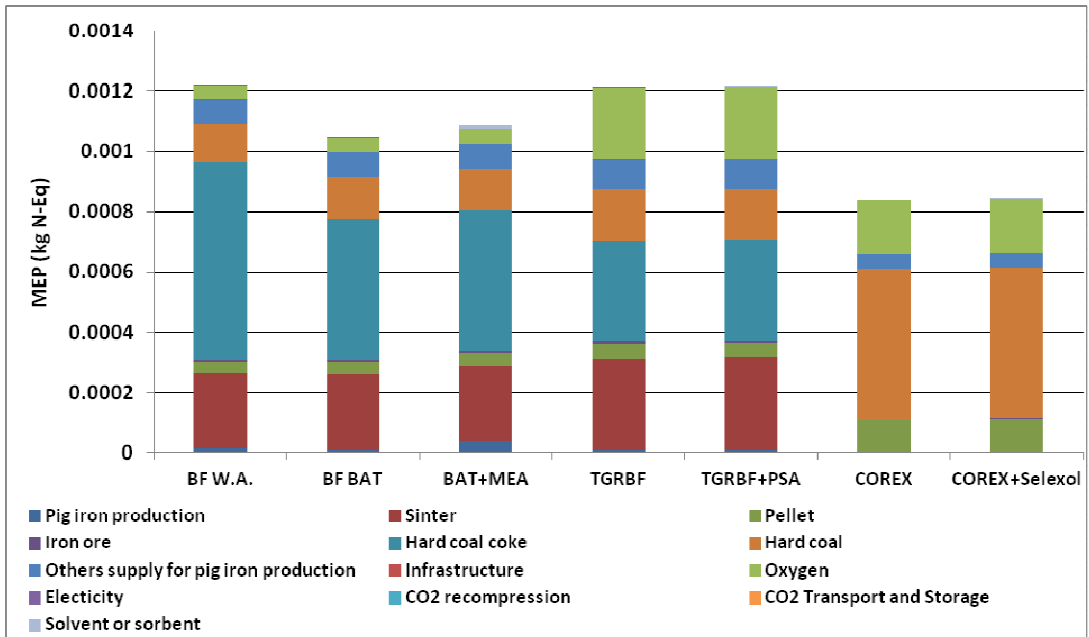
Inputs (kg/FU)	BF worst	Source	BF best	Source	BF+MEA worst	BF+MEA best
Steam coal	0,216	(Hu et al., 2009)	0,084	(Costa et al., 2001)	Same data with BF worst	Same data with BF best
Lump ore	0,239	(Hu et al., 2009)	0,150	(Costa et al., 2001)		
Limestone	0,150	(Costa et al., 2001)	0,026	(IPPC, 2012)		
Natural gas (MJ)	1,200	(Costa et al., 2001)	0,114	(IPPC, 2012)		
Electricity (MJ)	0,306	(Costa et al., 2001)	0,010	(Daniels, 2002)		
Water	0,588	(Hu et al., 2009)	0,003	(IPPC, 2012)		
Coke	0,500	(WSD, 2011)	0,300	(Hu et al., 2009)		
Sinter	1,410	(Daniels, 2002)	1,088	(IPPC, 2012)		
Pellet	0,490	(Kuramochi et al., 2012)	0,239	(Hu et al., 2009)		
Oxygen	0,116	(IPPC, 2012)	0,050	(Costa et al., 2001)		
Steam for regeneration of solvent (MJ)					4.40 (Kuramochi et al., 2012)	2.58 (Arasto et al., 2012)
Electricity for capture process (MJ)					0.54 (Kuramochi et al., 2012)	0.31 (Arasto et al., 2012)
Emissions (kg/FU)						
CO ₂ (air)	0,925		0,495		-0,786	-0,421
CO(air)	0,588		0,315		0,588	0,315
H ₂ (air)	0,003		0,003		0,003	0,003
SO ₂ (air)	2,36E-04		1,27E-04		-2,35E-04	-1,26E-04
NOx(air)	1,03E-04		5,55E-05		-2,59E-05	-1,39E-05
PM(air)	1,28E-04		6,88E-05		-6,41E-05	-3,44E-05

TA 2. Parameters for worst and best cases of TGRBF technology with and without CCS for sensitivity analysis

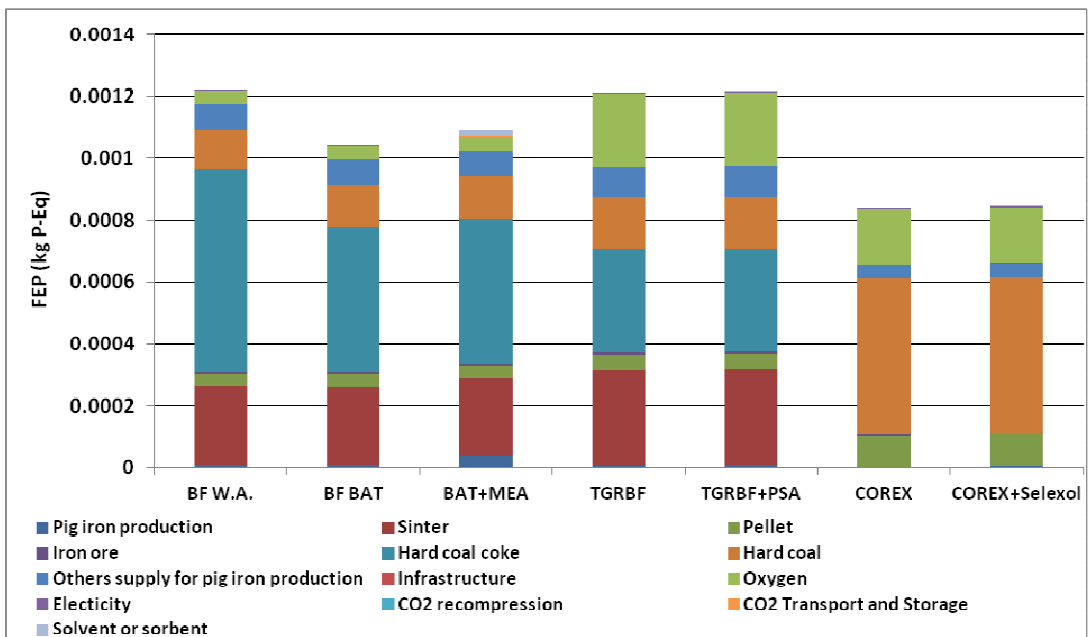
Inputs (kg/FU)	TGRBF worst	Source	BF BAT best	Source	TGRBF+PSA worst	TGRBF+PSA best
Steam coal	0,216	(Hu et al., 2009)	0,084	(Costa et al., 2001)	Same data with TGRBF worst	Same data with TGRBF best
Lump ore	0,239	(Hu et al., 2009)	0,150	(Costa et al., 2001)		
Limestone	0,150	(Costa et al., 2001)	0,026	(IPPC, 2012)		
Natural gas (MJ)	1,200	(Costa et al., 2001)	0,114	(IPPC, 2012)		
Electricity (MJ)	0,306	(Costa et al., 2001)	0,010	(Daniels, 2002)		
Water	0,588	(Hu et al., 2009)	0,003	(IPPC, 2012)		
Coke	0,328	(WSD, 2011), (Kuramochi et al., 2012)	0,197	(Hu et al., 2009), (Kuramochi et al., 2012)		
Sinter	1,410	(Daniels, 2002)	1,088	(IPPC, 2012)		
Pellet	0,490	(Kuramochi et al., 2012)	0,239	(Hu et al., 2009)		
Oxygen	0,507	(IPPC, 2012), (Kuramochi et al., 2012)	0,219	(Costa et al., 2001), (Kuramochi et al., 2012)		
Electricity for capture process (MJ)					0.61 (Khoo et al., 2011)	0.42 (Ritter, 2012)
Emissions (kg/FU)						
CO ₂ (air)	0,735		0,378		-0,625	-0,321
CO(air)	0,126		0,065		0,126	0,065
H ₂ (air)	0,002		0,002		0,002	0,002
SO ₂ (air)	2,04E-04		1,50E-04		-1,94E-04	-1,42E-04
NO _x (air)	8,91E-05		6,55E-05		-8,91E-05	-6,55E-05
PM(air)	1,11E-04		8,13E-05		1,11E-04	8,13E-05

TA 3. Parameters for worst and best cases of COREX technology with and without CCS for sensitivity analysis

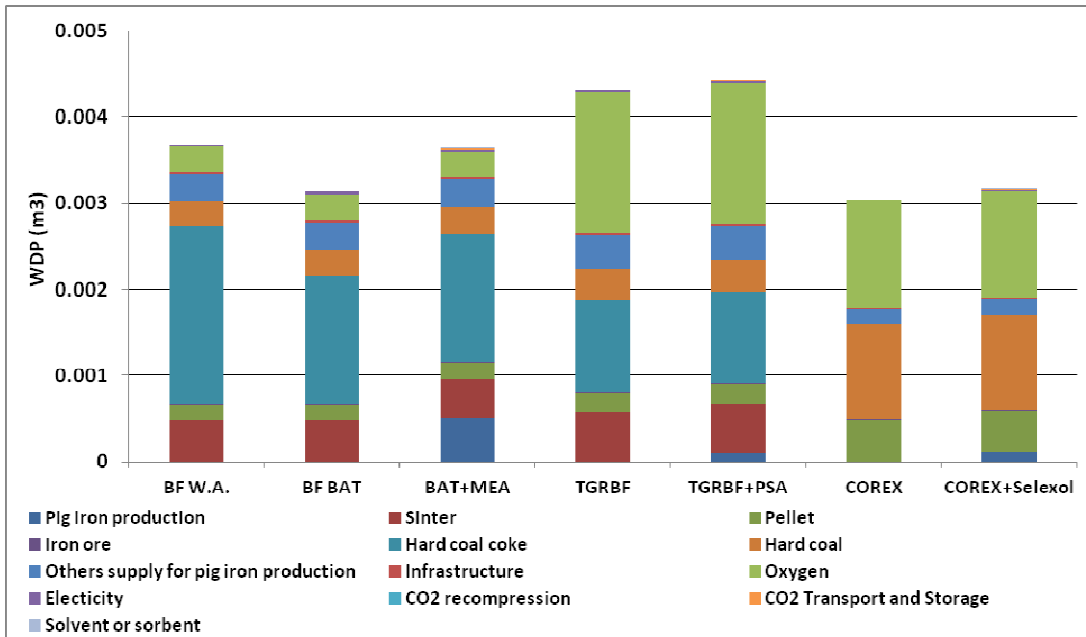
Inputs (kg/FU)	COREX worst	Source	COREX best	Source	COREX +Selexol worst	COREX +Selexol best
Steam coal	0,990	(Hu et al., 2009)	0,645	(Barman et al., 2011)	Same data with COREX worst	Same data with COREX best
Fine ore	0,150	(Hu et al., 2009)	0,150	(Hu et al., 2009)		
Lump ore	0,600	(Hu et al., 2009)	0,050	(Daniels, 2002)		
Limestone	0,325	(Costa et al., 2001)	0,050	(Kuramochi et al., 2012)		
Natural gas (MJ)	0,010	(Costa et al., 2001)	0,010	(Costa et al., 2001)		
Electricity (MJ)	0,324	(Hu et al., 2009)	0,270	(Costa et al., 2001)		
Water	1,300	(Hu et al., 2009)	1,300	(Hu et al., 2009)		
Coke	0,120	(Barman et al., 2011)		(Hu et al., 2009)		
Pellet	1,500	(Kuramochi et al., 2012)	0,750	(Hu et al., 2009)		
Oxygen	0,800	(Costa et al., 2001)	0,482	(Barman et al., 2011)		
Energy for capture process (MJ)					0.97 (Kuramochi et al., 2012)	0.34 (Lampert and Ziebik, 2007)
Emissions(kg/FU)						
CO ₂ (air)	0,629		0,344		-0,566	-0,309
CO(air)	0,601		0,328		0,601	0,328
H ₂ (air)	0,012		0,012		0,012	0,012
SO ₂ (air)	1,53E-04		1,55E-05		1,53E-04	1,55E-05
NOx(air)	7,14E-06		5,09E-07		7,14E-06	5,09E-07
PM(air)	8,16E-06		1,66E-06		-4,08E-06	-8,31E-07



FA 1. Contribution analysis of MEP (Marine eutrophication potential).



FA 2. Contribution analysis of FEP (Freshwater eutrophication potential).



FA 3. Contribution analysis of WDP (Water depletion potential).

