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Energy Procedia 37 (2013) 7117 – 7124

Energy Procedia

GHGT-11

Costs and potential of carbon capture and storage at an integrated steel mill

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Abstract

In this study different possibilities and the feasibility of applying carbon capture at an integrated steel mill based on blast furnace process, in order to reduce carbon dioxide emissions were studied. Technologies considered for capturing of CO2 are post-combustion carbon capture (PCC) and oxygen blast furnace route (OBF). Post-combustion capture for the integrated steel mill was evaluated in an earlier study by Arasto et Al. and Tsupari et Al. [1, 2]. Implications of different capture amounts, different solvents for post-combustion capture and process integration levels to the greenhouse gas balance and operation economics are compared to the steel production base case with varying costs of CO2 emission allowances. Furthermore the effect of reducing the carbon intensity of steel production on the final steel production cost is evaluated.

Iron and steel industry is responsible of around 5% of the overall global CO2 emissions [3]. Steel production based on the blast furnace and basic oxygen furnace-based route is the main technology corresponding to the growth in global steel production [4] and this technology route is also the main source of CO2 emissions in the iron and steel industry.

The assessment of potential and cost for carbon capture and storage in the iron and steel industry is based on a case study on Ruukki Metals Oy's steel mill in Raahe. The mill is situated on the northeastern coast of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. It is also the largest CO_2 point source in Finland emitting approximately 4 Mton of CO_2 / year. Raahe steel mill produces district heat for use in the town nearby as well as for use onsite for heating of the premises. The power plant is connected to the national electricity grid, and thus it is possible to buy and sell electricity across system boundary.

In contrast to power plant applications of CCS, CO_2 emission sources at an integrated steel mill are scattered around the industrial site and the flue gases are led to several stacks. Due to this, the capture process evaluation is much more complex and requires system level optimization. Carbon capture processes and process integration options were modeled using Aspen Plus process modeling software and the results were used to estimate CO_2 emission reduction possibilities and carbon abatement costs at the integrated steel mill from an investor's point of view. Different heat integration options and heat utilization scenarios were investigated and optimized with a custom-built CC-Skynet™ economics toolkit. Heat available for solvent regeneration varies between these heat utilization scenarios and thus different capture amount are investigated depending on the heat available for solvent regeneration in different case

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Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.648

studies. Also different technologies related to oxygen blast furnace were considered, both for oxygen production and for top gas treatment. The application of oxygen blast furnace effects directly e.g. to the coke consumption of process and power production on site, and thus a new design considering new heat and process gas integration opportunities is essential.
With a whole chain approach, including CO_2 capture, processing, transport and storage, results show significant reduction potential at an integrated steel mill with carbon capture technologies. Ship transportation of CO_2 is considered due to the location of the installation. Results show also the cost structure and feasibility of the studied technologies. Cost breakeven points for carbon capture at an integrated steel mill, for the plant owner and costs for globally avoided emissions are calculated. The study also reveals some major technical restrictions of the application. Finally the pros and cons of the technologies are compared and the role and potential of CCS as a carbon abatement tool in the European steel industry is considered.

Keywords: Iron and steel industry; CCS; feasibility; post combustion capture; oxygen blast furnace

1. Introduction

It has been generally stated that climate change is one of the most serious environmental threats that humankind is facing and that greenhouse gas emissions (GHG's) should be reduced in every field of activities. Iron and steel industry is a significant sector contributing to about 10 % of worldwide CO_2 emissions from fossil fuel use [3] corresponding about 5 % of overall global GHG emissions.

Rautaruukki Ltd.'s Raahe steel mill is situated on the cost of the Gulf of Bothnia. It is the largest integrated steel mill in the Nordic countries producing hot rolled steel plates and coils. It is also the largest CO2 point source in Finland. In 2008, before economic down term and blast furnace revisions, CO2 emissions from the mill were 4.5 Mton / year [5].

A steel production route using blast furnace and basic oxygen furnace is the most widely used production method. A powerful reducing agent is needed, because iron ore is used as raw material for the process. Typical reducing agent is coke, resulting in high carbon intensity of the process. Most of the emissions result from combustion of blast furnace gas that is a side product of blast furnace process containing a lot of energy. Numerous improvements in complicated BF+BOF based steel mills are possible, but the reductions in CO_2 emissions are typically small in comparison to overall CO_2 emissions from the mills. By carbon capture and storage (CCS), CO_2 emissions could be reduced in large extent.

CCS is generally recognized as one of the key climate change mitigation options in several scenarios and the technology can be utilized also in the case of steel industry. Various carbon dioxide capture and storage technologies have been suggested to be applied for iron and steel industry [6]. Post combustion carbon capture and oxygen blast furnace are compares in this paper in order to highlight different properties and cost structure of the technologies.

2. Background

In this study, different possibilities for reducing CO_2 emissions at Raahe steel mill by applying post combustion carbon capture and oxygen blast furnace were investigated. Steel production in Raahe is based on blast furnace route. As emissions from the site are scattered around the site, only the most significant CO_2 emission sources were considered to be feasible option for capture of CO_2. The different capture amounts from different emission sources, different carbon dioxide capture technologies and integration levels were assessed in order to find out the effects on the greenhouse gas balance and economics of steel production with varying costs of CO_2 emission allowances. With post combustion carbon dioxide capture CO_2 is captured from two largest emission sources on site that are blast furnace and hot stoves. These processes represent around 60% of the site emissions. With oxygen blast furnace the power plant is removed, and CO_2 captured from the oxygen blast furnace process.

3. Carbon capture with post combustion carbon capture technology and oxygen blast furnace

3.1. Boundary description

Boundaries for the technical and economical evaluations are illustrated in the Figure 1. Boundaries not including the entire steel mill site can be assumed, since only the processes capture processes effects on are taken into account inside these boundaries. The capture processes effect on the other processes and outside site borders only with heat and electricity connection, and this enables the simple comparison of different carbon dioxide capture technologies.

In the reference situation of this study, hot stoves are fuelled with blast furnace gas, whilst power plant utilizes a mixture of cases containing blast furnace gas, coke oven gas and converter gas. All these gases originate from fossil sources, mainly coal in this case.

Heat integration is the most important connection of process units, when considering the application of post combustion capture processes on site. The enormous need for the steam utilized for the regeneration of solvent is the major factor affecting the system. In the case of oxygen blast furnace, more fundamental alterations to the process are needed. However, as there is a lot of potential for waste heat recovery on site, also different waste heat recovery investments are considered in order to supply the heat demand of steelmaking processes, district heating network and carbon capture processes, and most importantly to partly compensate for the energy requirements of the capture processes. In general, if more waste heat is recovered, power plant can produce more electricity instead of supplying utility steam.

As heat is available on several different temperature levels, the heat streams were considered on four different exergy levels, from high pressure process steam to heat that can be utilized for preheating the district heat return streams.

The steel production of the steel mill and the utility steam consumption stays constant when applying carbon capture. The amount of heat supplied to district heating network to heat up the plant area and the city nearby remains constant. The amount of electricity bought from the grid varies depending on the power plant production, in order to balance the power use at the plant. CO_2 leaves from the system boundary either in the flue gases from power plant and hot stoves or is shipped to a permanent underground storage.

As there is no capacity for permanent storage CO_2 in Finland, the CO_2 has to be transported and stored outside Finland. The storage phase in this study is evaluated according to Teir et Al. [7] and the CO_2 transportation including costs related are assumed based on the methodology presented by Kujanpää et Al. [8].

Different heat integration options and heat utilization scenarios were investigated with the Aspen Plus process modeling software with the integration processes modeled. The optimization of heat utilization scenarios, different capture processes and integration opportunities was conducted with custom-built CC-Skynet™ economics toolkit. Heat available for solvent regeneration and steel production processes varied between technologies and heat utilization scenarios. The different capture amounts were investigated depending on the heat available for solvent regeneration in different post combustion case studied as with the application oxygen blast furnace only full capture rate was considered to be realistic.

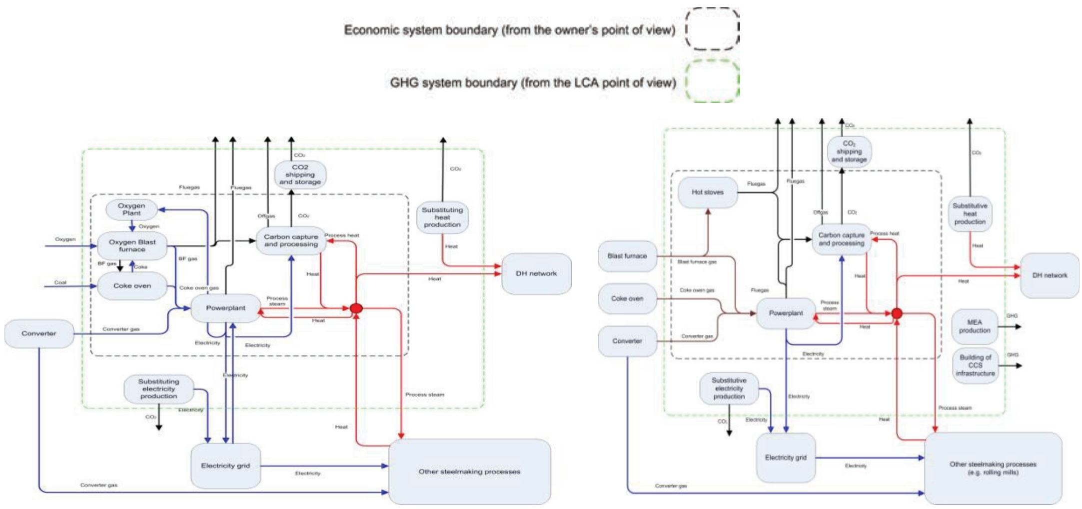

Fig. 1. System boundaries, plant level integration and mass and energy flows with the application of post combustion carbon dioxide capture and carbon dioxide capture with an oxygen blast furnace

3.2. Post combustion carbon capture

Post combustion carbon capture was considered as the capture technology for this study according to Arasto et Al. and Tsupari et Al. [1, 2]. The main arguments for the application of this technology are the readiness of the technology in the scale needed and the fact that the current steelmaking processes are least effected with this technology. There are no significant differences regarding CO_2 content, composition or impurities between typical flue gas of the power plant on site and the hot stoves. Therefore a single capture unit processing both flue gas streams was considered. The total CO_2 flow from both flue gas streams to the capture unit is 103kg/s. 90% capture rate of the flue gas treated was targeted for in all carbon capture cases.

Capture is modeled with three different solvent scrubbing technologies

- 30% MEA. This was chosen as a baseline reference solvent to enable comparison of result to other studies performed. This was also considered as an early implementation option, if the capture was to be implemented in the near future.
- the Siemens amino acid salt was considered to represent an advanced solvent, with a lower regeneration energy and advanced properties if compared to the baseline MEA [9]
- Hypothetical solvent, able to be regenerated at a significantly lower temperature than baseline MEA. This is assumed to be the result of solvent development work if solvents would be developed with the target of lowering the regeneration temperature, even with the expense of development in regeneration energy. This was investigated in order to evaluate the potential of solvent development for the purposes when low exergy waste heat is available for low cost. The solvent properties are estimated based on Zahng et Al. [10]

3.3. Carbon capture with oxygen blast furnace

The replacement of a conventional blast furnace with an oxygen blast furnace affects only a part of processes at an integrated steel mill. The system boundary is selected to only include all process units affected by the change [Fig. 1]. In principle the process resembles a lot like a conventional blast furnace process. The difference is that an oxygen blast furnace is fired with pure oxygen instead of oxygen enriched air. The top gas recycling blast furnace relies on separation of the off gases so that the useful components can be recycled back into the furnace and used as a reducing agent. This would reduce the amount of coke needed in the furnace. In addition, the concept of injecting oxygen into the furnace instead of preheated air removes unwanted nitrogen from the gas, facilitating carbon dioxide capture and storage. To enable sufficient temperature profile, gas flow and to increase the utilization rate of the coal a part of the blast furnace top gas is recycled back to the furnace. A small part of the top gas is utilized to heat up the recycled top gas to be injected back to the blast furnace. Because of the utilization of pure oxygen the top gas of the blast furnaces does not contain any or very little nitrogen. The CO_2 of the top gas is separated and the hydrogen and carbon monoxide recycled back to the blast furnace to act as reductants and improve the energy balance. The separated CO_2 is purified, compressed and sent to a permanent storage.

The introduction of oxygen blast furnace to the mill requires additional process units such as additional capacity in oxygen production. An additional air separation (ASU) unit is needed, to provide oxygen for the increased oxygen demand. In addition to the ASU a CO_2 removal process to separate carbon dioxide from the top gas is needed. Vacuum pressure swing adsorption was chosen as the removal process in this study and compared to the capture from top gas with MEA scrubbing process. VPSA is a technology used to separate some gas species from a mixture of gases under pressure according to the species' molecular characteristics and affinity for an adsorbent material. It operates at near-ambient temperatures and so differs from cryogenic distillation techniques of gas separation. In addition to the adsorption vessels operated cyclically, VPSA system comprises of a compressor and a vacuum pump.

Because the majority of the top gas is injected back to the blast furnace, there is no excess supply of blast furnace gas to be utilized in the power plant. Therefore the power and heat production is drastically diminished at the power plant. As the need for heating of the blast is also diminished and the hot stoves not utilized any more the emissions from this source does not exist anymore. There is a small CO_2 emission from the heating of the recycled top gas.

4. Results

4.1. Energy and emission balance of carbon capture

Emissions and cost of the steelmaking with carbon capture processes are compared to the situation without the carbon capture. Annual cash flows within the system boundary described in Figure 1 were evaluated. The balances of different CCS cases were compared with the reference case without CCS. The production levels of the steel mill in different cases are considered constant.

As described above the approach allowed investigation of different CO2 capture amounts and different technologies. The smallest captured CO2 amounts (0.3 Mt/a) were in the cases with only recovered heat used for post combustion capture processes. The largest captured CO2 amounts (2.9 Mt/a) in the cases were all available fuel power was used for regenerating solvent. With only the low pressure steam available utilized for solvent regeneration the capture amounts are in the range of 2Mt/a. Captured amount with oxygen blast furnace were 1,4Mt/a, however the avoided emissions in the mill are greater as also coke consumption decreases. District heat sold from the boundary was constant in every case, 300 GWh/a, which is based on the district heat demand in the surrounding city of the mill. The captured CO_2 amounts and CO2 emissions avoided in the mill are not the same, as overall CO_2 emissions avoided, since e.g. the assumptions on emission from replacing energy production effect significantly on the overall emissions avoided.

The capacity for electricity production on the power plant gets smaller as he amount of captured CO_2 gets higher with the post combustion capture because the steam is utilized for regeneration of solvent instead of utilized in the low pressure section of the steam turbine. In the reference case the annual electricity production is around 1200GWh/a. When low pressure steam is utilized for solvent regeneration electricity production decreases by 40% to 730GWh/a. When all fuel power is utilized to produce steam for regeneration, no electricity is produced at all. However this leads to the largest amounts of captured CO_2. When applying oxygen blast furnace, no electricity is produced either. When oxygen blast furnace is applied, the main effects on the energy balance of the plant are: the amount of coke is reduced, LPG consumption is increasing slightly and that there is no more on site electricity production.

When different solvent options are considered, low temperature solvent was the considered to be the best alternative. This is due to the ability to utilize low exergy heat that is widely available at site. A large share of this cannot be utilized with other solvents considered. The advanced solvent proved out to be almost as good as the low temperature solvent with only a little smaller capture amounts. In comparison to MEA with the advanced solvent roughly 8% more CO_2 could be captured with the same integrations and utilization scenarios.

4.2. Cost of carbon capture and storage

The result of the cost modeling is the cost of CO_2 capture including transport & storage, from investor's point of view. The cost structure is investigated varying EU-ETS price and electricity price. If the operation economics of different CCS cases are compared to the base case steel production with varying costs of electricity we can define break point prices of EU-ETS where CCS turns feasible over reference case making CCS investment reasonable [Fig. 2].

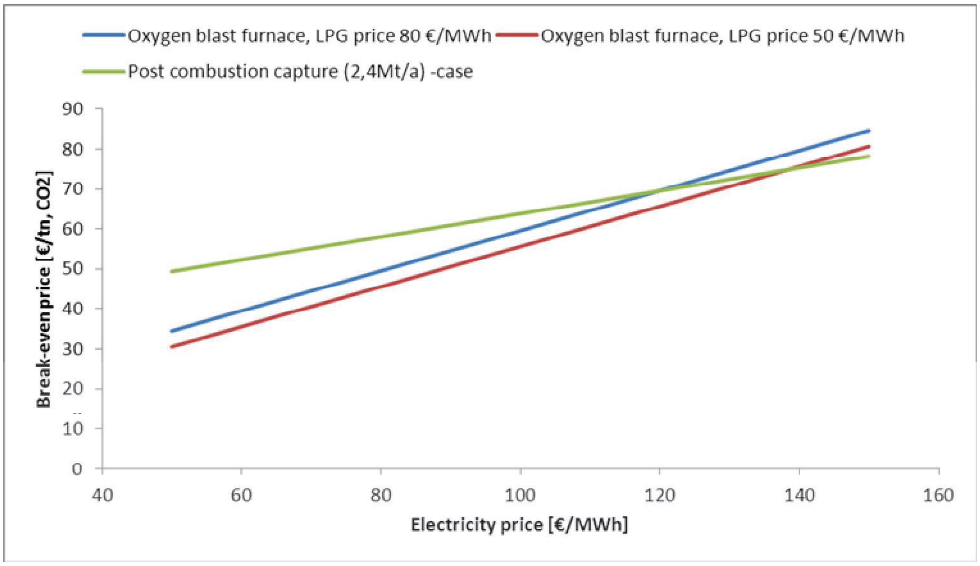

Fig. 2. The effect of electricity price to the break-even price when CO_2 capture becomes more feasible than buying CO_2 emission allowances, from the operator's point of view.

5. Conclusions

As a technical option, it is possible to significantly lower greenhouse gas emissions from the steel industry with both, the post combustion carbon capture technologies and oxygen blast furnace covered in this study. The post combustion capture technology is considered to be technically realizable already in near future; nevertheless no commercial application for the scale exists yet. The oxygen blast furnace technology is seen to be more in the research phase. Cost breakeven point, when CCS turns more feasible than buying carbon credits in the reference case, for the plant owner is in the range of 46 - 90 €/t CO2, if electricity prices only between 80 - 100 €/MWh are considered. Cost for globally avoided emissions is in the range of 60 – 100 €/t CO_2 respectively. Despite the fact that the oxygen blast furnaces seems to be more economical solution, the overall profitability and the effects on the production costs of steel are more complicated. For example the sensitivity of oxygen blast furnace process for the electricity price is higher than in the reference case or with post combustion capture. This includes high risk as the ETS price penetration to the electricity market price is of significance.

Acknowledgements

This work was carried out in the Carbon Capture and Storage Program (CCSP) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes.

References

[1] Arasto, A., Tsupari, E. , Kärki, J., Pisilä, E., Sorsamäki, L., 2012. Post-Combustion Capture of CO2 at an Integrated Steel Mill –Part I: Technical Concept Analysis. International Journal of Greenhouse Gas Control January 2012. DOI: http://dx.doi.org/10.1016/j.ijggc.2012.08.018. In press

[2] Tsupari, E., Kärki, J., Arasto, A., Pisilä, E., 2012. Post-Combustion Capture of CO2 at an Integrated Steel Mill -Part II Economic Feasibility. International Journal of Greenhouse Gas Control January 2012. DOI: http://dx.doi.org/10.1016/j.ijggc.2012.08.017 In press

[3] IEA 2008, CO2 capture and storage, A key carbon abatement option. International Energy Agency. France

[4] Worldsteel, 2010. Steel statistical yearbook 2010. Worldsteel Association. Worldsteel Committee on Economic Studies – Brussels.

[5] EMV 2011. Emission allowance balance. Energy Market Authority of Finland. www.emvi.fi/files/paastooikeustase2010.pdf (available October 2011, in Finnish).

[6] Romano, Anantharaman, Arasto, Ahnd, Ferrari, Dijkstra, Boavida, 2012, Application of advanced technologies for CO2 capture from industrial sources, GHGT-11 Proceedings, Energy Procedia (2013)

[7] Teir, Sebastian; Arasto, Antti; Tsupari, Eemeli; Koljonen, Tiina; Kärki, Janne; Kujanpää, Lauri; Lehtilä, Antti; Nieminen, Matti; Aatos, Soile. 2011. Hiilidioksidin talteenoton ja varastoinnin (CCS:n) soveltaminen Suomen olosuhteissa. Espoo, VTT. 76 s. + liitt. 3 s. VTT Tiedotteita - Research Notes; 2576 ISBN 978-951-38-7697-5; 978-951-38-7698-2 http://www.vtt.fi/inf/pdf/tiedotteet/2011/T2576.pdf

[8] Kujanpää, Lauri; Rauramo, Joonas; Arasto, Antti. 2011. Cross-border CO2 infrastructure options for a CCS demonstration in Finland. Energy Procedia. Elsevier, vol. 4, ss. 2425-2431 DOI: 10.1016/j.egypro.2011.02.136

[9] Fortum 2010, Environmental Impact Assessment for carbon capture in Meri-Pori power plant. Available http://www.ely-keskus.fi/fi/ELYkeskukset/varsinaissuomenely/Ymparistonsuojelu/YVA/paattyneet/energiansiirto/Documents/forhiiliv/Forhiili_YVAselostus.pdf (in Finnish).

[10] Zhang J., Chen J., Misch R., Agar D., 2010. Carbon dioxide absorption in biphasic amine solvents with enhanced low temperature solvent regeneration., Chemical Engineering Transactions, 21, 169-174 DOI: 10.3303/CET1021029.