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Evaluation of Steel Mills as Carbon Sinks

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Abstract – The iron and steel industry is one of the industries with the largest global contribution to CO_2 emissions. Possible mitigation options include use of biomass and carbon capture and storage. Combining these two mitigation options, this study evaluates the potential for BECCS at an integrated steel mill in Sweden. The injection of pulverized biocoal from torrefaction or pyrolysis into a blast furnace and CO_2 capture by amine absorption of the blast furnace gas leaving at the top of the furnace can reduce CO_2 site emissions by up to 61 %, when accounting for negative emissions (biogenic CO_2 being captured). The mitigation cost are estimated to 43 – 100 € per tonne CO_2 avoided, depending primarily on biomass prices and the share of biomass used in the process (the study assumes a cost effective capture rate of 84%). Besides a reduction in CO_2 emissions, the study highlights the potential for green by-products from injecting biogenic carbon into the blast furnace in the form of renewable electricity and CO_2 neutral steel. The study concludes that it is theoretically possible to reach carbon neutrality or even net-negative emissions in an integrated steel mill, but this would require considerable process changes and high demand of biomass. Nonetheless, the implementation of BECCS based on feasible biomass injection volumes in integrated steel mills is interesting as a near-term and possibly cost-effective option for CO_2 mitigation.

Keywords: Blast furnace, PCI, BECCS, Biomass, Steelmaking, Negative emissions

1 Introduction

The steel making industry relies heavily on coal for energy supply and reduction of the iron ore in the blast furnace and emits about 7% of the total global CO_2 emissions. Carbon capture and storage (CCS) technologies is a mitigation option which can achieve deep emission reductions from the steel industry. Furthermore, CCS in steel industry may be facilitated by relatively high CO_2 concentration in off-gases and the availability of excess heat that could power the capture process. Another possibility for decarbonization of the steel sector is the substitution of part of the coal with biomass. In a carbon constrained energy system, the steel sector may have more willingness to pay for woody biomass than other sectors such as heat and power, which have renewable alternatives to biomass. This work evaluates the potential of steel mills as a cost-effective option for achieving negative CO_2 emissions by introducing CCS and substituting part of the fossil carbon (coal) with biomass.

The current regulation around the methodology to determine the CO_2 emission benchmark for steel making processes based on sintered ore is however not straight forward and how to account for negative emissions, which are still unaccounted for in e.g. the EU ETS trading scheme, will further complicate this process. An object of major discussion is how to count for CO_2 from the waste gases from the blast furnace, the LD converter (BOF) and the coking plant, which are unavoidable byproducts from steelmaking. These gases are often used in heat and power generation sold on external markets. Today, in the EU-ETS, no free allowances are granted for waste gas exported for electricity production. Nevertheless, the CO_2 emissions from exported waste gases when producing heat are recognized for allocation of emission allowances. In Sweden for example, producers of metallurgical products do not pay energy or carbon taxes on electricity or fossil fuel for driving the metallurgical processes. Produced waste gases, explicitly blast furnace gas and coke oven gas, are also exempt from both energy and carbon dioxide taxation. Also, the power plant owner receiving the waste gases for combustion is exempted from carbon and energy taxation and has only to pay for auxiliary fuel such as firing oil. It is, thus, crucial to define a methodology that account for the carbon emission from steel making and surrounding processes in a manner that encourages and facilitates the implementation of CO_2 mitigation technologies and recognizes negative emissions.

Neither the replacement of fossil fuels in the steel making process nor the implementation of CCS is straight forward, as they would be highly integrated with the steel making process. This paper describes and discusses technologies for CO_2 separation and (biogenic) fossil-fuel replacement at different technology readiness level (TRL), with CO_2 absorption in amines from BFG and substitution of the pulverized coal in the blast furnace route being the technologies at highest TRL level. Thus, this work reviews and discusses the potential for net-negative CO_2 emissions by means of bioenergy carbon capture and storage (BECCS) in integrated steelworks. The mitigation potential for different levels of biomass introduction is related to cost for capture and storage. The cost for different CO_2 capture levels from the steel mill will depend on the number and type of CO_2 sources targeted and the level of heat recovery or heat generation required to power the capture process. The capture process applied is a post-combustion capture unit based on a 30-wt.% MEA solvent.

2 Background

2.1 Biomass in steel production

In 2016, the majority of the world's steel, 73.8 % [1], was produced as so called converter steel in basic oxygen furnaces (BOF). Almost all converter steel is produced in large integrated steel plants, where pre-treated iron ore reduction takes place in a blast furnace (BF) with subsequent refining of the hot metal (HM) in the BOF before the crude steel is processed into the desired alloy. Hot metal for converter steel can also be made from iron ore using smelting reduction (SR-BOF route). The global share of converter steel via SR-BOF was less than 1% in 2011 [1][2].

Nearly all remaining steel (other than converter steel), 25.7% [1], is produced in electric arc furnaces (EAF), predominantly using scrap steel as feed or direct reduced iron (DRI; or sponge iron). Roughly 16% of the steel produced in EAFs is derived from DRI [1,3]. Figure 1 shows these steel production routes and highlights potential biomass use in grey.

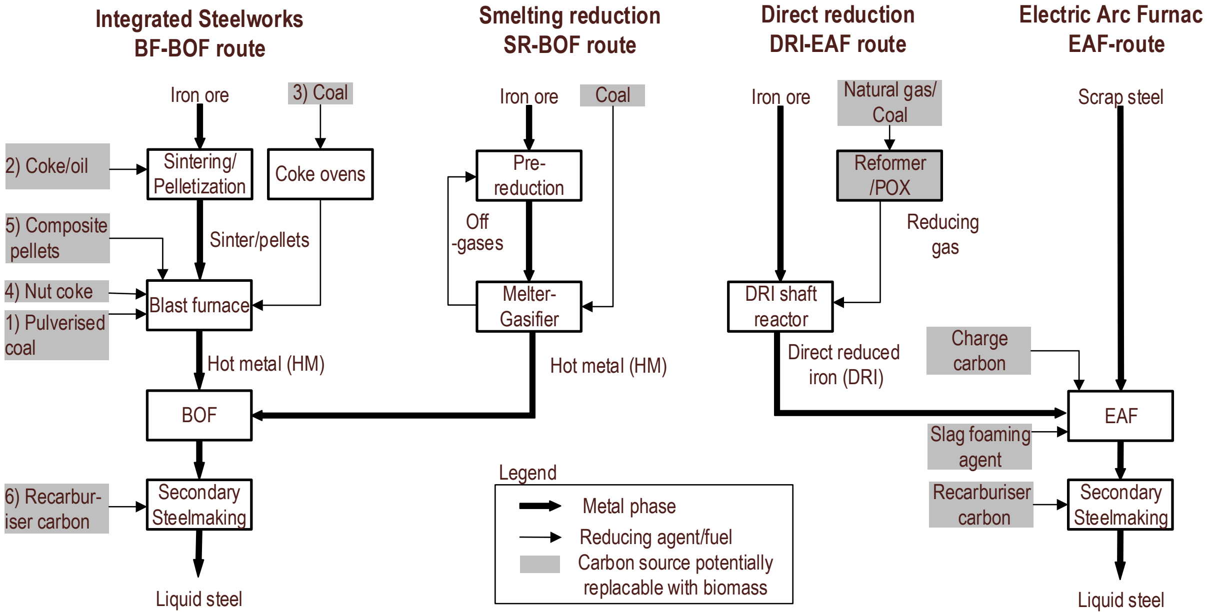

Figure 1 : Common routes for steel production and with the potential inlets for biomass indicated in grey. Adapted from [4][5] *; Numbers 1-6 highlight principle pathways for biomass introduction on the BF-BOF route*

For the BF-BOF route, the energy for melting the ore and the chemical reduction potential is mainly supplied by coke, which is introduced at the top of the BF in layers alternating with layers of iron ore burden. To increase efficiency, it is common practice for steel makers to replace part of the coke with coal (or other hydrocarbons such as oil, natural gas), which is introduced through the tuyeres into the lower part of the blast furnace - so called pulverized coal injection (PCI). Nevertheless, roughly 65 – 75 % of the carbon entering the blast furnace enters as coke. Figure 1 shows that biomass can be introduced into the BF-BOF route in six principle ways [4]:

1) Replacing parts or all of the coal for PCI with a pulverized biocoal;

2) replacing coke/oil with biofuel for sintering/pelletizing of iron ore;

3) partly replacing top-fed coke into the BF with biocoke by 2-10%;

4) party or fully replacing nut coke with biocoke, which is mixed into the iron ore burden;

5) introducing 5-10 % of iron feed as carbon/ore composite pellets with the carbon originating from biochar [6].

6) replacing coal-based char with biochar introduced into the ladle for recarburising the liquid steel (downstream of BOF).

These technologies for fossil-fuel replacement have reached different stages of development, with substitution of pulverized coal with biocoal (1) being the most feasible and promising with an emission reduction potential of up to 25 % of CO_2 emissions [6]. Compared to typical reductant addition rates of 570 – 700 kg/t HM, between 38 – 55 % of the carbon could be replaced by biogenic carbon if all these six replacement techniques would be applied [4][6], assuming biomass is available.

The smelting reduction route (SR-BOF route), see Figure 1, does not require iron ore pre-treatment and on-site coke production – instead, the iron ore is pre-reduced with off-gases from a melter-gasifier, where the final reduction and melting takes place by adding coal. Replacement between 20-100% of this coal with typical addition rate of 610 kg/t HM could be feasible.

Steel produced in an EAF requires comparatively little carbon since the iron/scrap steel feed is already reduced. As shown in Figure 1, Carbon mainly is added in form of charge carbon to create a sufficiently reducing atmosphere to prevent the oxidation of the metal phase. Carbon is also added as slag foaming agent and in the secondary steelmaking for recarburization. Altogether, only 18 kg carbon per tonne steel are typically added which potentially could be fully replaced by biomass [4].

For the DRI-EAF route in Figure 1, the steam reformed natural gas could be replaced by a biogas produced from gasification of biomass [7]. The high oxygen content of biomass would result in a CO_2 rich biogas which requires CO_2 separation before the biogas can be used for reducing iron ore.

To summarize, biomass can potentially be introduced in all four production routes shown in Figure 1. This concept study focuses on the integrated route (BF-BOF) which is motivated by the large potential of biomass for replacing PCI and the significance of integrated steel plants as dominating production route. The following section gives a short review on biomass upgrading technologies for biocoal injection replacing PCI.

2.2 Biomass upgrading for biocoal injection into blast furnaces

Woody biomass must be upgraded for utilization in blast furnaces to reach chemical and physical characteristics similar to pulverized coal. In principle, several upgrading technologies can be used including torrefaction, pyrolysis and gasification, each one giving different upgraded products. For substitution of pulverized coal, torrefaction and pyrolysis are the most suitable, since their main output is a solid carbon-rich and crushable product. Torrefaction is operated at lower temperature than pyrolysis (300 °C vs 500 °C) giving a higher yield of solid product, with a lower carbon content [8] (Table 2), and by-products in gas and liquid phase (tar). In pyrolysis, the devolatilization process is more extensive leading to a lower solid (charcoal) yield but much higher carbon content (Table 2) similar to coal with a significantly larger yield of liquids (bio-oil). In gasification, the temperature is increased above 800 °C with products only in gaseous and liquid phase, although reaching a higher conversion of the biomass. To date, substitution of pulverized coal is the main route for introduction of biomass in a blast furnace, but liquid (heavy oil) and gaseous (natural gas) reducing agent are also used as in BF, hence gasification could be could be applied.

For substitution of PCI, the quality of the upgraded biomass is paramount for utilization in the BF. Parameters vary for each BF, but in general a carbon content above $60\%_w$ is required, moreover the ash content has an influence on the slag formation and the oxygen content should be within specific ranges [9].

The byproducts formed both in pyrolysis and torrefaction are combusted to supply the heat to the upgrading reactor and for drying of the biomass. The energy in the by-product is proportional to the degree (temperature and residence time) of the upgrading process. Pyrolysis is overall exothermic with more energy in the by-products than necessary for the process and for drying. Torrefaction is often operated under autothermal conditions for other applications. However, to reach above $60\%_w$ of carbon in the biocoal for BF injection, the process must be driven into exothermal operation and some excess heat will be available for consumers on site. Therefore, a synergy between biomass utilization in BF and CCS technologies beyond the capture of biogenic carbon could be achieved, as the excess heat from upgrading could be used in the amine reboilers.

The type of biomass used has a substantial influence on both the operation of the upgrading process and the economics. As mentioned, the steel industry could be more willing to pay for biogenic carbon than other sectors, however, the price ranges for untreated biomass vary over a wide range, from around 8.5 to 22 €/MWh for forest residues [10] down to nearly 0 €/MWh for waste wood and demolition wood. The higher price for residue of forest industry in the form of wood pellets, wood chips or saw dust with little impurities and a low ash content, is likely due to the high demand of these fuels in heat and electricity sectors. Wood waste and demolition wood from industry and construction have a very low price and are often available in industrialized areas. The main draw back with this type of biomass are contaminations due to adhesives, paint, and impregnation. These impurities can lead to heavy environmental issues, if released with gaseous or liquid phases [11] and combusted, although they do not pose a problem if they stay in the biocoal or charcoal and are fed to the BF. The choice of the feedstock-upgrading technology is plant dependent and both torrefaction and pyrolysis should be considered for forest residues. Nevertheless, only torrefaction is an option for waste wood, since the release of contaminants to liquid and gaseous by-products is significantly lower than for pyrolysis.

2.3 Carbon capture in steel industry

Similar to other base industries such as cement and petroleum, CCS allows for deep emission cuts from the steel manufacturing processes. Most studies focus on BF-BOF route and apply mature post combustion capture (PCC) technologies, predominantly amine absorption, but also membranes and vacuum pressure-swing-adsorption (VPSA) have been discussed. Reported emission reduction with PCC range between 20 – 80 % [12] [13,14], depending on technology and CO_2 source. A larger reduction is considered economically less feasible since an integrated steel plant has several flue gas stacks (power plant, hot stoves, coke ovens, lime kilns and others) as shown in the process scheme of the Luleå site in Figure 2. Capture cost increase for smaller and more remote stacks [12].

Many studies have evaluated CO_2 capture from blast furnace gas (BFG), since most carbon is injected into the BF [15] and BFG is used predominantly to fuel the hot stoves and the power plant, where the majority of the CO_2 leaves to atmosphere. Also, removal of CO_2 from BFG increases its heating value and leads to a re-allocation of BFG in the waste-gas distribution on site, overall leading to enhanced energy efficiency of the steel plant system [16].

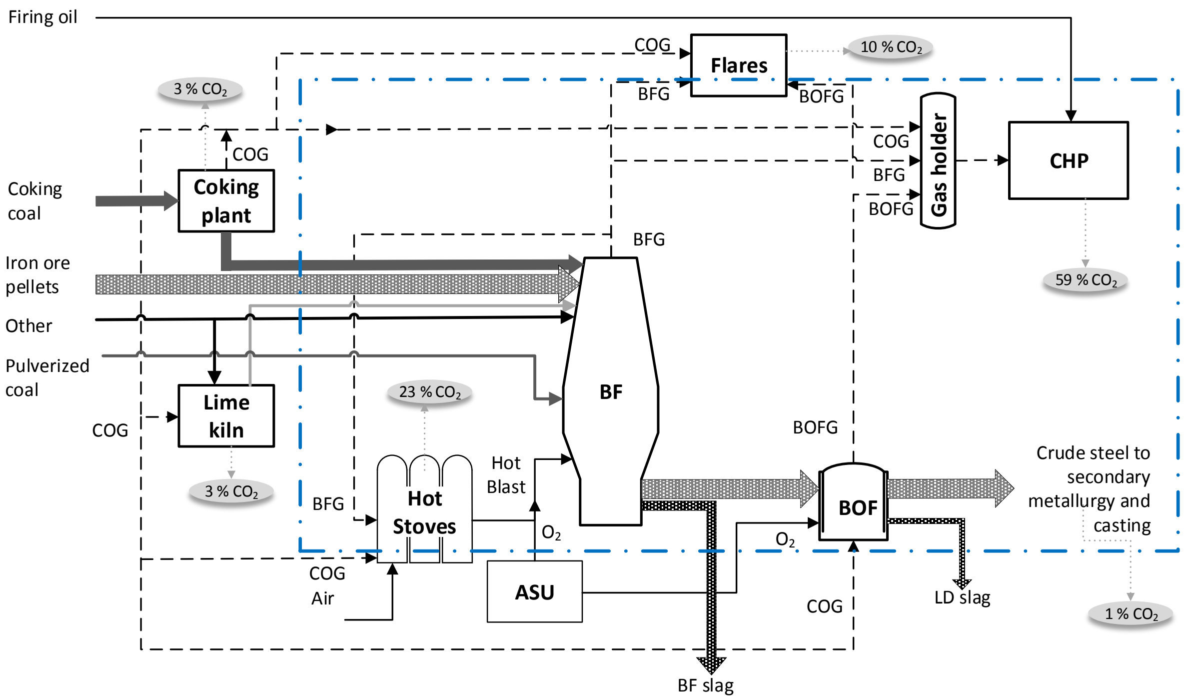

Figure 2 :Process scheme of integrated steel mill in Luleå, Sweden, with CO_2 point sources. Adapted from [16]. *The blue line indicates the system boundary for the carbon balance in this work..*

3 Method

The study is based on rudimentary carbon balances around the blast furnace and effected downstream units, CHP plant, BOF, Hot Stoves, and flaring stacks for BFG and BOF gas (BOFG) at the integrated steel mill in Luleå, Sweden, as outlined in Figure 2. This implies that emissions from other stacks on site (coking plant, lime kiln, various flaring stacks, desulphurization unit) are not included into the system boundary, as shown in Figure 2, and are assumed to remain unchanged. The methodology for the carbon balance is presented in the following section. In a subsequent section, the capture of CO_2 from BFG gas is explained. Finally, the framework for estimating mitigation cost is presented.

3.1 Carbon Balance

The carbon balance of the system is established based on the data presented in Table 1. The base year for the carbon balance is Year 2006, when site emissions were 1574 kg CO_2 per tonne hot metal [17]. The following assumptions are made:

- The BF gas phase composition does not change with biomass injection.

- Carbon introduced via tuyere injection (PC or biofuel) leaves BF with top gas and pig iron in equal shares, i.e. share of PCI carbon in input is set to be the same share in the iron phase carbon and BF top gas carbon.
- Re-allocation of steel mill gases, i.e. changes in gas distribution (COG, BFG) due to the biofuel injection are not considered. This is a conservative assumption, Wang et al. [18] have shown that biofuel injection implies a net excess of energy. Instead, the same fraction of BFG enters hot stoves and CHP in all cases; excess of BFG caused by biofuel injection goes to flaring.

Table 1 : Input data for mass balance around BF and downstream units. Base year : 2006

Parameter	Unit	Value	Source
Pig iron produced (hot metal)	kton	2256.2	SSAB report 2006 [17]
Coke	kton	740.6	[17]
PCI	kton	318	[17]
BF-slag	kton	365	[17]
Limestone	kton	68.3	[17]
Pellets	kton	3071.3	[17]
Firing Oil (E01) to CHP	m^3	495.6	[17]
Blast oxygen content	vol.%	23.9	Wang et al. [18]
Plant load	$\%_{year}$	98	“
Pig iron carbon content	wt.%	4.75	Wikström et al. [19]
Blast furnace gas (BFG)	Mm^3	2987	SSAB report 2006 [17]
BFG CO_2 concentration	vol.$\%_{db}$	25	Sundqvist et al. [16]
BFG CO concentration	vol.$\%_{db}$	21	“
Mixed gas to CHP	Mm^3	2270	SSAB report 2006 [17]
of which BFG	%	89.3	“
of which BOFG	%	9.0	“
of which COG	%	1.7	“

Two biofuels are evaluated – a charcoal obtained from (slow) pyrolysis and a solid biofuel upgraded via torrefaction. The reductants of this study are presented in Table 2. Considering energy density, raceway adiabatic flame temperature, ash content, and the biofuel composition, more mass of biomass has to be injected in relation to a reference PCI [18]. This replacement factor f, see Eq.(1), reaches 1.07 for charcoal from pyrolysis and 1.16 for torrefied biomass (specific biomasses according to Table 2). The limitations to the biofuel substitution are made up of a maximum oxygen enrichment in the hot blast of 25.4 vol.% and a minimum top gas temperature of 100 °C [18]. The maximum share of biomass in the injectant ($\phi_{\max}$), see biomass substitution ϕ in Eq. (2), reaches 100 % and 33.6 % for charcoal and torrefied biomass, respectively.

$$f = \frac{\dot{m}_{\mathrm{bio}}}{\dot{m}_{\mathrm{PCI,ref}}} \tag{1}$$

$$\phi = \frac{\dot{m}_{\mathrm{bio}}}{\dot{m}_{\mathrm{bio}} + \dot{m}_{\mathrm{PC}}} \tag{2}$$

Table 2 : Fuel properties of blast furnace injectants and burden coke.

Reductant type/feedstock		**coke** metallurgic coking coal	**PCI-coal** Non-coking coal	**charcoal** pyrolysed softwood	**torrefied biomass** forest residue
C	wt.%$_{\mathrm{db}}$	88.3	85.0	84.7	58.0
H	wt.%$_{\mathrm{db}}$	n.a.	03.9	3.35	5.3
N	wt.%$_{\mathrm{db}}$	n.a.	2.1	0.13	0.48
O	wt.%$_{\mathrm{db}}$	n.a.	2.1	10.6	34.0
S	wt.%$_{\mathrm{db}}$	0.58	0.4	0.02	0.03
Ash	wt.%$_{\mathrm{db}}$	10.9	7.8	1.9	3.2
moisture	wt.%	3.5	1.0	4.5	7.7
LHV	MJ/kg	n.a.	33.5	31.6	21.6
Source		[20]	[18][21]	[18][21]	[18][21]

3.2 Post-combustion capture with MEA

Carbon capture is implemented as an amine absorption process using a 30 wt.% monoethanolamine (MEA) aqueous solvent. The technical performance of capturing BFG at the Luleå site with this solvent has been evaluated by Sundqvist et al. [16] who conclude that BFG is the most efficient point source on site in terms of specific energy demand for the reboiler. Their assessment of exploitable waste heat accumulates to approx. 150 MW when generating 3 bar steam for solvent regeneration. This corresponds to waste heat recovery due to a change to 100% turbine backpressure operation mode, utilization of excess gases in steam boiler instead of flaring, flue gas waste heat recovery from hot stoves,. This heat can capture roughly 84% of the CO_2 in the BFG. Applying further heat recovery methods like dry coke quenching and dry slag granulation could drive the capture of more than 92% of the CO_2 in the BFG [16].

3.3 Avoided emissions calculation

This work is limited to reducing CO_2 emissions in the blast furnace. The work assumes that introduced biomass is carbon neutral (LUC and emissions for growth, harvest and transport are unconsidered) and that captured biogenic emissions are recognized. To allocate the emissions between the parts of the process, fossil and biogenic carbon introduced is separated in the carbon balance and their ratio is maintained for all carbon containing flows downstream of the BF. The proportional allocation is a simple way to evaluate combined bio-coal injection and capture. This methodology is applied in Equation (3), that determines the amount of CO_2 avoided, is adapted from [22]. The carbon intensity of electricity used (from the electricity system) is not considered in the analysis.

$$\begin{aligned} CO_2 \text{ avoided} &= \text{Emissions}_{\text{Ref. PCI}} - \text{Emissions}_{\text{Bio+CCS,NEGATIVE}} \\ &= \text{Emissions}_{\text{Ref. PCI}} - (\text{Total Emissions} - \text{Biogenic Emission} - \text{Captured biogenic } CO_2)_{\text{Bio+CCS}} \end{aligned} \tag{3}$$

3.4 Green products

A share of the products from the steel site could be accredited as green or renewable products when introducing biomass and capturing CO_2. We assume that a share of CO2-neutral crude steel (CS) is produced equal to the site emission reduction calculated by Eq. (3). The total amount of produced crude steel in 2006 is reported to 2.206 Mt CS.

In this work, the products created by biomass injection are renewable electricity and district heating, produced in the power plant from partly biogenic BFG and BOFG. We assume that the share of biogenic energy in these gases equals the share of biogenic carbon entering the blast furnace. This is motivated with CO and H_2 being the only combustible species and both can originate from biomass or emerge from biogenic carbon (water-gas shift reaction). According to the power plant operator Lulekraft [23], around 600 GWh electricity and 770 GWh hot water are produced annually. Together, BFG and BOFG comprise 90% of the energy delivered to the power plant.

3.5 Cost estimation

An estimation of the CO_2 avoidance cost, defined as a sum of annualized CO_2 capture cost, CO_2 transport and storage cost, and purchase cost for biomass upgraded off-site, is performed. Cost data is taken from literature and adapted to the year 2016 by Eurostats Harmonised Indices of Consumer Prices (HICP) [24].The estimated cost of CO_2 capture from BFG via MEA absorption varies between 50 – 90 €/ t captured CO_2 in case of capturing 85 - 90% from BFG with heat generated (partly) by newly installed fossil fired boilers [15] [25] [26]. MEA capture from BFG driven by waste heat only, has been cost estimated in an “nth-of-a-kind” approach to 26 – 33 € per ton CO_2 captured by Skagestad et al. [27]. Their estimation includes CAPEX and OPEX for the capture plant with CO_2 compression to 110 bar and the piping for gas and steam transport to the capture plant. The work presented here adopts these results from Skagestad et al., and assumes capture cost of 26.5 € (2016)/t CO_2 that allow a capture rate of 84 % from the BFG.

In addition to capture cost, transportation and storage cost are taken from Kjärstad et al. [28] and adapted to 16 € (2016) /t CO_2 . Kjärstad et al. conclude that transport by ship is the cost efficient transport alternative to pipelines for CO_2 sources in Bothnia Bay [28]. The mentioned cost represents the transport to the capture site Faludden south of Gotland.

Reported prices for biomass vary strongly. Cost of charcoal (pyrolysis) ranges between 200 – 500 €/t [29][21]. The cost for torrefied biomass range between approx. 35 – 60 €/MWh [30] which translates to approximately 200 – 360 €/t (assuming heating value from Table 2). Imported torrefied biomass from North America could have lower prices of 140 €/t [10]. As reference, untreated woody biomass has a price, which typically range between 20 and 120 €/t (8.5 – 22 €/MWh, depending on heating value). These biomass prices are gathered from several sources and a definite cost year is not available. Price development due to currency changes/inflation is thus assumed negligible compared to the large price range. In this work, the price for treated biomass is varied in the range between 0 – 500 € (2016)/t for charcoal and between 0 – 360 € (2016)/t for torrefied biomass.

4 Results

4.1 Effect of BECCS on carbon balance and green products

Figure 3 shows the carbon balance of the BF with reference PCI. Carbon is needed both for reduction of the iron-ore and heat supply for the integrated route of steelmaking. The majority (87%) of carbon introduced in the BF leaves as top gas. Most of the carbon remaining in the molten iron phase is removed in the BOF before the steel obtains its final carbon content in a recarburization step (not shown).

Figure 4 shows the carbon balance after full replacement of PC ($\phi = 1$) with charcoal (from biomass pyrolysis) and implementation of a BFG CO_2 capture unit. This level of biomass injection corresponds to around 30% of biogenic carbon in the process (and thus according to the chosen methodology to 30% of bio carbon in the pig iron and the BFG). The biogenic CO and CO_2 in the BFG have value in subsequent units. In the capture unit, with a capture efficiency of 84 %, 0.38 kg captured biogenic carbon per kg injected biogenic carbon can be accounted as negative emissions. The biogenic carbon monoxide and hydrogen can generate renewable electricity and heat in the CHP plant when oxidized to CO_2 and water. Some of the biogenic carbon in the pig iron enters the CHP as CO after being released as BOFG from the converter. Altogether 164 GWh renewable electricity and 211 GWh renewable hot water for district heating can be produced, which translates to 0.60 kWh and 0.77 kWh per kg injected bio-carbon, respectively. Also, 26 %of the crude steel production can be accounted as steel with zero-carbon footprint due to bio-carbon injection alone. This equals 2.1 kg CS per kg injected bio-carbon. Thus, each biogenic carbon atom entering the depicted blast furnace system creates value two times – in the iron reduction and as negative emission (capture of biogenic CO_2), or in the iron reduction and in energy generation (exothermic oxidation of biogenic CO and H_2). Furthermore, each captured and stored *fossil* carbon atom also contributes to CO_2-neutral steel with additional 35 % percentage points. Together, bio-carbon and carbon capture derived CO_2-

neutral steel amounts to 1.35 Mt/year, which may hold a potential value to certain end consumers and can be an asset to steelmakers on initial niche-markets for carbon-free steel.

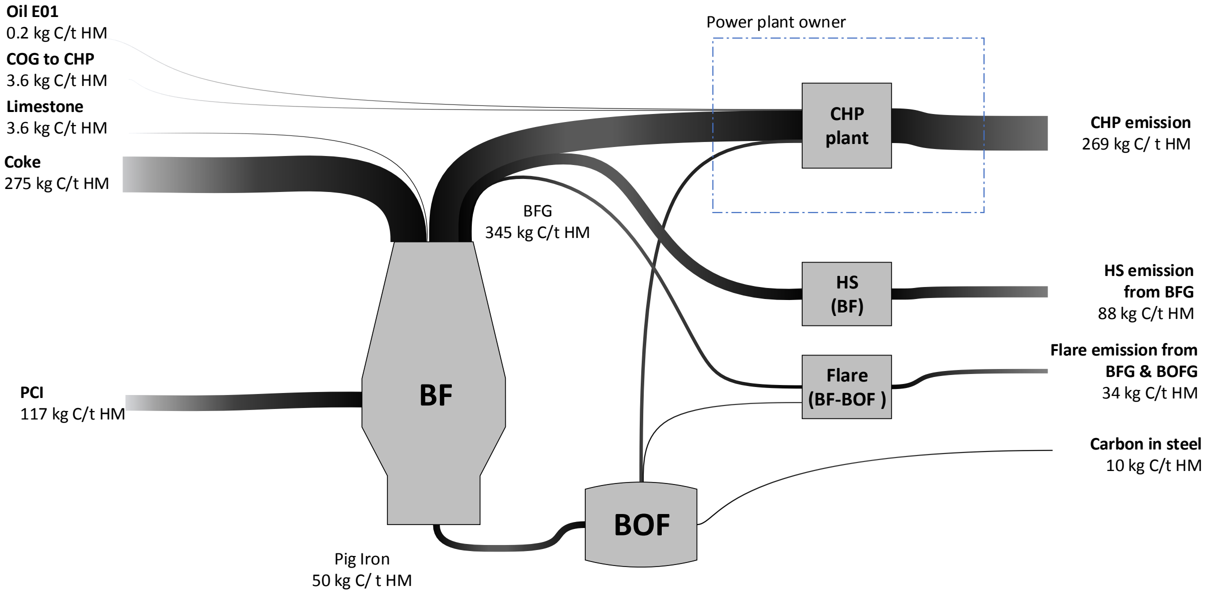

Figure 3 : Carbon balance around blast furnace and downstream units for integrated steel works with reference PCI

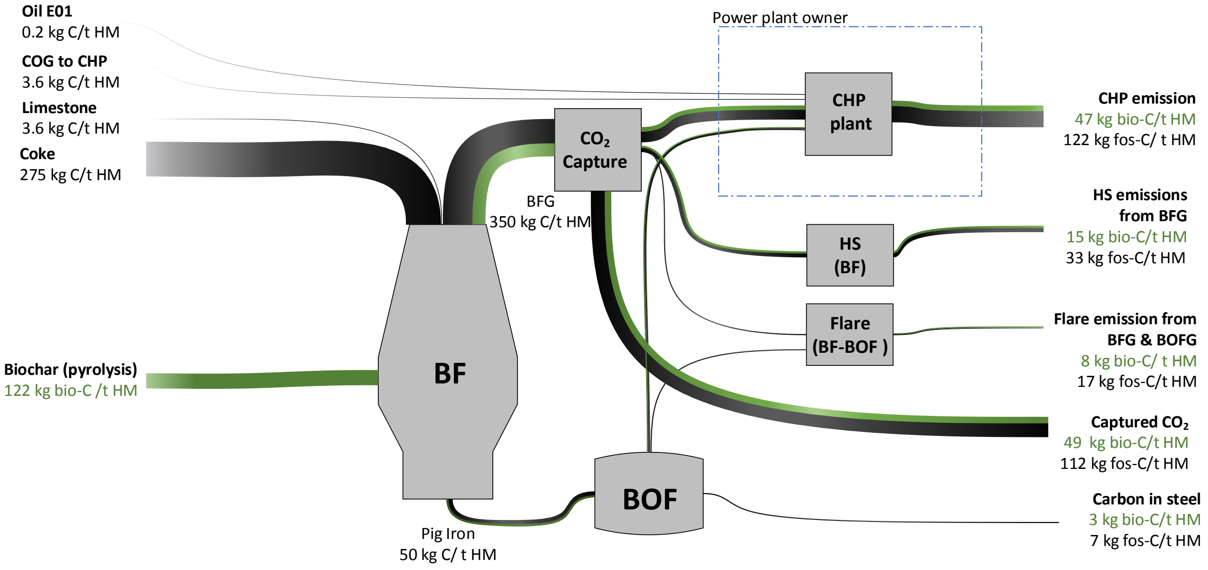

Figure 4 : Carbon balance around blast furnace and downstream units for integrated steel works with 100 % charcoal (pyrolysis) injection and 84% capture of BFG.

4.2 Avoided emissions and possibility for net-zero steel making

The potential of the two types of biomass, charcoal from pyrolysis and torrefied biomass, in avoiding CO_2 emissions from steel making are shown in Figure 5. Up to 6 % and 29 % of the reference fossil emissions of the BF system may be avoided with torrefied biomass and charcoal, respectively, when introducing the maximum share of biomass, see $\phi_{\max}$ in section 3.1. Torrefied biomass can only replace pulverized fossil coal to about one third which is why the line for avoided CO_2 in Figure 5 is shorter than for charcoal from pyrolysis. Also, the incline of the curve for torrefied biomass shown in Figure 5 is smaller than for charcoal due to a higher replacement factor f, see section 3.1, which means more carbon has to added overall when using torrefied biomass to reach the same performance in the BF as with charcoal from pyrolysis. Capturing a theoretic 100 % CO_2 of the BFG in combination with biomass introduction could yield up to 53 % and 77 % emissions reduction, respectively. The implementation of the cost-effective capture ratio of 84 % of the BFG (the amount that may be powered entirely by excess heat from the process) and maximum PC substitution with charcoal yields an emission reduction of 69 %. Related to the site emissions in 2006 (including CO_2 sources outside the BF system examined here), this corresponds to 61 % of the total site CO_2 emission. One could argue, that the effect of BECCS on emission reduction is considerable, since conventional CCS with 84 % capture from BFG would only reduce the total site emissions by 35 %. Additional mitigation through CCS would require capture from more stacks and at the expense of additional heat. The theoretic maximum capture of 100% would reduce total site carbon emission by 68%.

However, even with full implementation of the mitigation technologies with high technology readiness (PCI replacement and PCC from BFG) it is not possible to reach zero emissions on site level. The site net emissions are shown in Figure 6 and *Figure 7* for charcoal and torrefied biomass, respectively. Roughly twice the amount of charcoal and three times the amount of torrefied biomass would have to enter the BF in order for the site net emissions to become negative. These large amounts of fossil coke cannot be replaced by PCI. As mentioned in section 2.2, if all pathways for biomass introduction on BF-BOF route were employed to full extent, roughly 55% of the carbon used in an integrated steel mill could be replaced. Thus, any site-wide CO_2 capture exceeding the remaining 45 % carbon would lead to negative emissions. For the Luleå site with no on-site pelletization, CO_2 capture from BFG would have to be 99 % to reach net-zero.

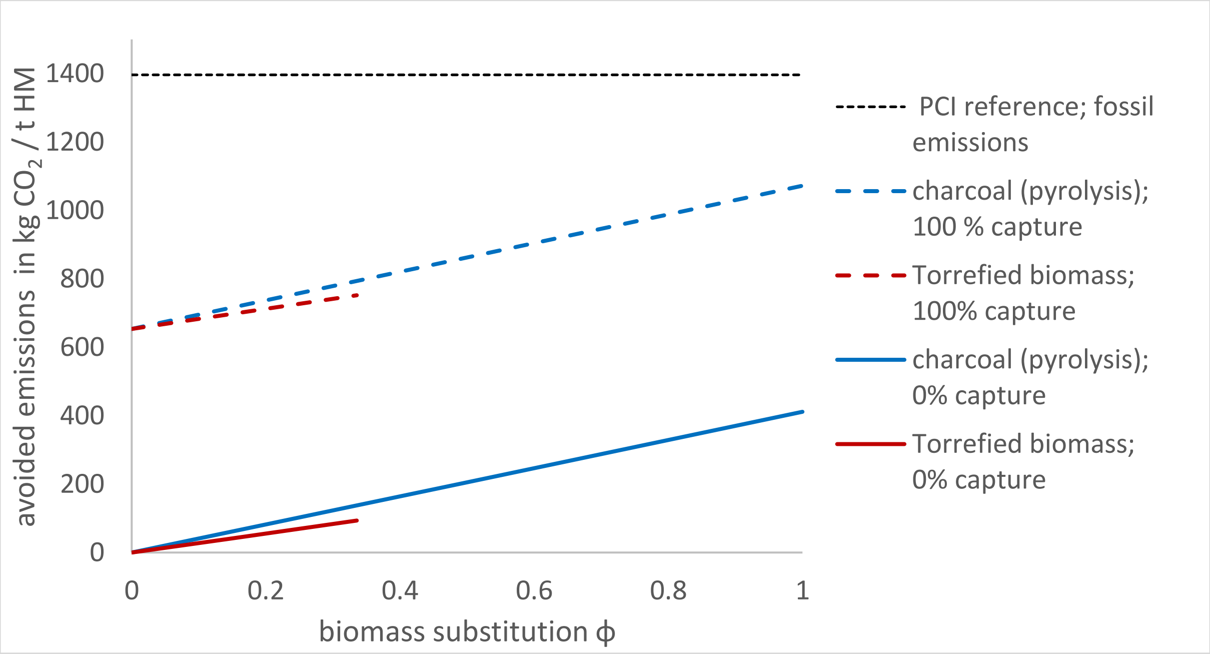

Figure 5 : Achieved emissions reduction with bio-energy CCS for an integrated steel mill in dependence of the biomass substitution in the BF tuyere injection.

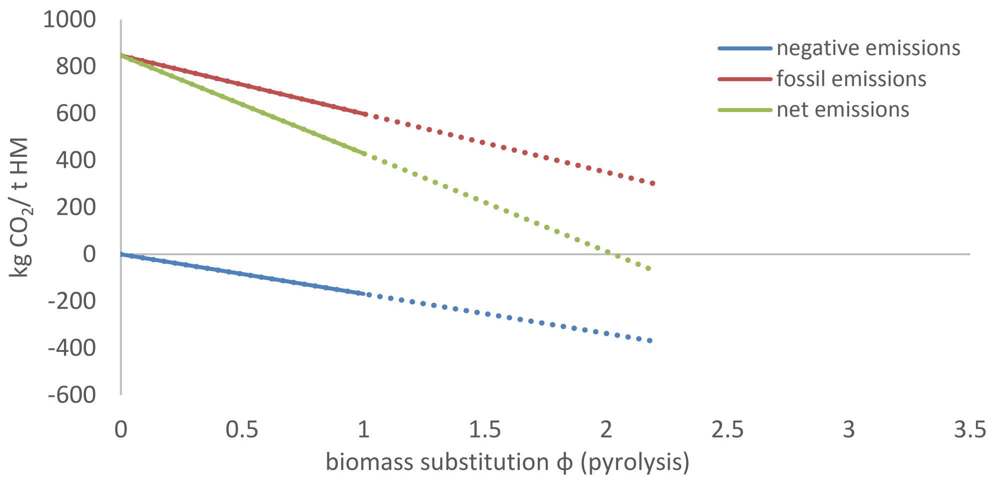

Figure 6 : Charcaol from pyrolysis - proximity to net-zero emission; 84% capture rate from BFG

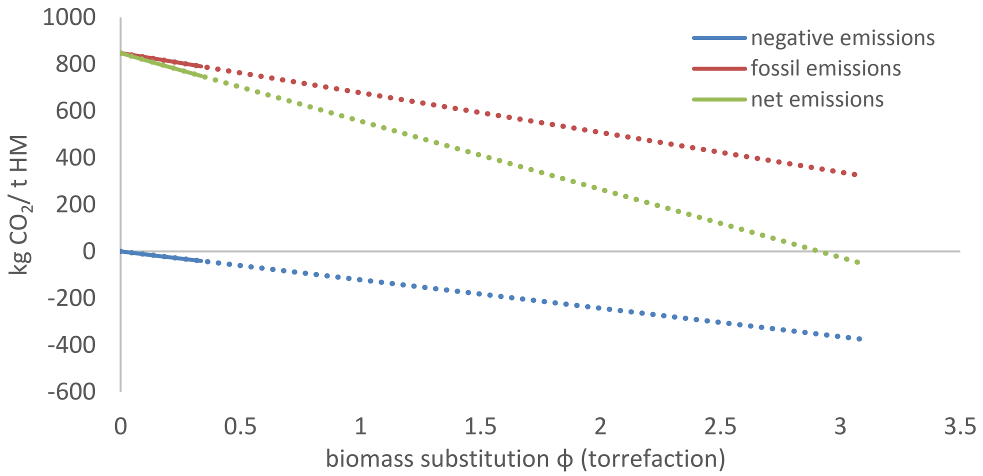

Figure 7 : *Torrefied biomass - proximity to net-zero emissions; 84% capture rate from BFG*

4.3 Mitigation cost

This section discusses the interplay between CO_2 mitigation cost through biomass introduction and CCS implementation. Figure 8 shows the mitigation cost in € per tonne CO_2 depending on the level of biomass substitution, ϕ. The torrefied biomass has lower mitigation cost than charcoal in both cases, since its cost are assumed lower. The effect is, however, small because of the inferior performance in creating additional emission reduction as shown in the section above. Compared to fossil CCS, both types of biomass increase the mitigation costs when replacing PCI. At full substitution, bio-energy CCS based on charcoal has mitigation costs of 100 €/t CO_2 – more than double than the calculated 43 €/t CO_2 of fossil CCS. The graph also shows a curve called "break-even", where the price of treated biomass balances the capture, transport and storage costs. The break-even price is 119 €/t charcoal and 76 €/t torrefied biomass. Biomass prices below the break-even price would lead to a reduction in mitigation cost compared to fossil CCS. In the extreme case that charcoal is for free, the mitigation cost would drop to 24 €/t CO_2 at biomass substitution of $\phi = 1$.

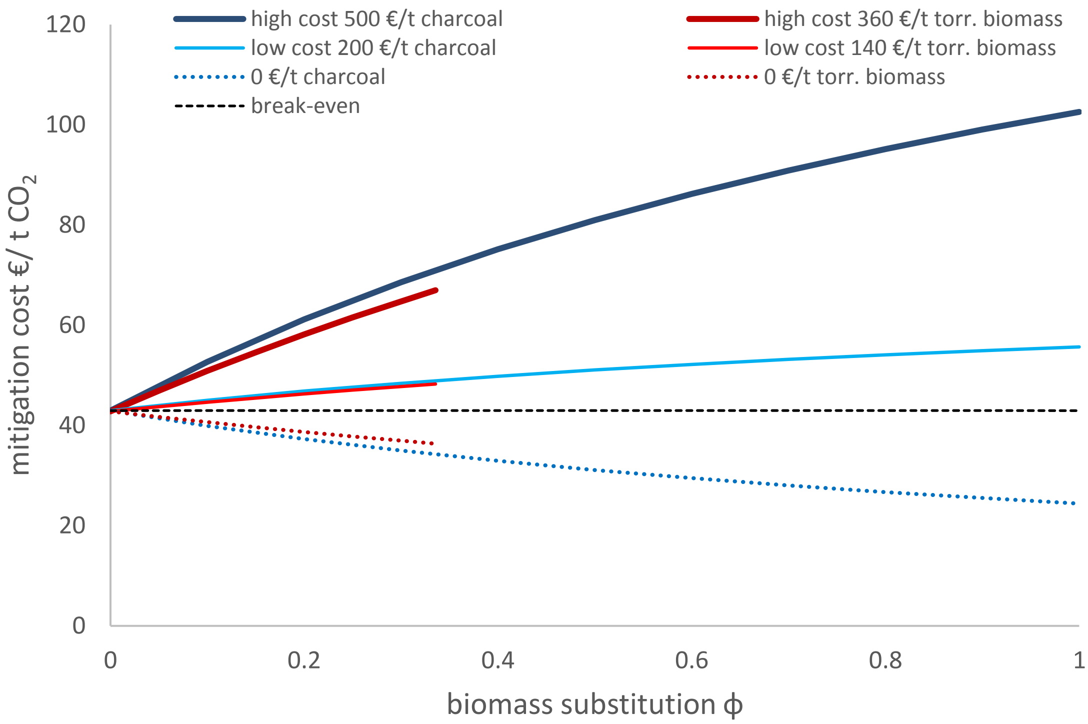

Figure 8 : Cost of CO_2 mitigation for BECCS at an integrated steelmill; 84% capture rate from BFG

5 Discussion

The estimated emission reduction potential of 61 % may appear promising and charcoal from pyrolysis the better choice for biomass injection into the blast furnace. However, as a drop-in solution using existing blast furnaces the PCI substitution rate may be limited to 10–15 % considering that:

1) The operation of the PCI may be limited by practicalities not considered in literature studies. No large scale plant has yet operated biomass tuyere injection and a stepwise increase in biomass share with time is expected not to interfere with the operation. The impact of biomass ash species on the slag phase and metallurgical properties on large scale is not evaluated (to the authors' knowledge) and is a major operational concern.
2) The vast amount of biomass required may overshoot what is available to the site and may limit the level of substitution. For the charcoal considered, full substitution would require roughly 1 million ton dry raw biomass (yield of 35 wt.%) per year. According to Wang et al. [18], this amounts to 2.5 % of the total available biomass (peat, waste, agricultural residue, black liquor and wood fuels) in Sweden projected for 2020. This can be compared to the estimated total biomass use (all sectors) of 70 % of available biomass in 2020 with the heat and power sector alone using 18 % of the available biomass in 2020 [18]. However, as discussed, the steel industry may be willing to pay more for biomass than for example CHP plants that are in competition with solar and

wind generation. Furthermore, in steelmaking the biogenic carbon may be used to produce CO_2 neutral steel as well as heat and power.

3) The biomass treatment technologies do not exist in the required scale. The largest plants for biomass upgrading to the desired quality existing today can produce about 100 000 t/a and, thus, there is a need for considerable scale up of this technology. In light of a lower substitution rate, the mitigation cost in Figure 8 become less sensitive to the biomass price and type and lie between 43 - 56 €/ t CO_2.

Besides these concerns on the scale of biomass substitution, the concept shows that a share of the emissions can be mitigated at relatively low cost. Further mitigation and an economic boost for biomass introduction could be CCU in form of bio-fuel production from CO in the blast furnace gas. Thereby another renewable product is generated from introduced carbon which can substitute fossil fuels externally – of course at the expense of renewable electricity production.

Possibilities for future work include the extension to an integrated modelling approach, similar to the work by Wiklund et al. [10], in order to assess possible heat integration between biomass pre-treatment on site and the CCS system. Depending on the moisture content, there might be an excess of torrefaction or pyrolysis gases that is not needed for biomass heating. The combustion of these may deliver additional heat for capture at low cost. Also, the reboiler condensate could potentially be used to pre-heat biomass and release more heat to the reboiler at 130 °C. Furthermore, crediting reduced limestone consumption and slag production as well as considering energy savings due to biomass introduction and subsequent gas re-allocation in the integrated steel mill system may reveal further synergies and limitations. The economic impact on avoidance cost due to green electricity is not considered here and may reveal relevant savings. Finally, to what extent the steel industry will apply CCS and biogenic feedstock will obviously depend on when and to what extent there will be a market for zero-carbon steel.

6 Conclusions

This work assesses the potential for the steel mill blast furnace, as a major carbon user, to work as a source for net-negative CO_2 emission in a relatively near future through the implementation of carbon capture and storage and increased use of biomass. The blast furnace is special in that it uses the carbon for two purposes – both as a reducing agent and as an energy source – and it is, thus, possible to get out more carbon neutral product per amount of carbon avoided than in other applications. Although the amount of carbon avoided is of course the same. The blast furnace constitutes a near term option or CO_2 mitigation by means of biomass substitution of pulverized coal injection (PCI) and absorption through amine technologies (PCC).

The result of this work shows that potential for CO_2 reduction from full implementation of PCI and 84% PCC from BFG may reach up to 61%. At this level of implementation 2.1 kg of CO_2 neutral crude steel (26% of total) and 0.60 and 0.77 kWh of CO_2 neutral electricity and heat may be produced per kg of biogenic carbon added. In addition, 0.38 kg of biogenic carbon per kg of biogenic carbon may be captured, amounting to 168 kg negative CO_2 per tonne hot metal. Furthermore, additional 35 % of CO_2 neutral crude steel can be ascribed to fossil carbon capture.

In absolute numbers, a total of 1.35 Mt CO_2 neutral steel can be produced and 375 GWh renewable energy at full implementation of the presented BECCS concept at mitigation cost of 100 € per tonne CO_2. For a low-cost implementation with biomass substitution rates limited to 10 % and a capture rate of 84 %, these absolute numbers are reduced to 0.82 Mt CO_2 neutral steel and 37.5 GWh and renewable energy at a cost of ca. 53 € per tonne CO_2.

In summary, the blast furnace is interesting as a near-term and cost-effective option for CO_2 mitigation. However, considerable changes to the existing process have to be made to be able to reach full site carbon neutrality or net-negative emissions.

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