Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Biomass as blast furnace injectant – Considering availability, pretreatment and deployment in the Swedish steel industry[☆]

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ARTICLE INFO

Article history:

Available online xxxx

Keywords:

Biomass

Coal

Blast furnace

Steelmaking

ABSTRACT

We have investigated and modeled the injection of biomass into blast furnaces (BF), in place of pulverized coal (PC) from fossil sources. This is the easiest way to reduce CO₂ emissions, beyond efficiency-improvements. The considered biomass is either pelletized, torrefied or pyrolyzed. It gives us three cases where we have calculated the maximum replacement ratio for each. It was found that charcoal from pyrolysis can fully replace PC, while torrefied material and pelletized wood can replace 22.8% and 20.0% respectively, by weight.

Our energy and mass balance model (MASMOD), with metallurgical sub-models for each zone, further indicates that (1) more Blast Furnace Gas (BFG) will be generated resulting in reduced fuel consumption in an integrated plant, (2) lower need of limestone can be expected, (3) lower amount of generated slag as well, and (4) reduced fuel consumption for heating the hot blast is anticipated. Overall, substantial energy savings are possible, which is one of the main findings in this paper.

Due to the high usage of PC in Sweden, large amounts of biomass is required if full substitution by charcoal is pursued (6.19 TWh/y). But according to our study, it is likely available in the long term for the blast furnace designated M3 (located in Luleå).

Finally, over a year with almost fully used production capacity (2008 used as reference), a 28.1% reduction in on-site emissions is possible by using charcoal. Torrefied material and wood pellets can reduce the emissions by 6.4% and 5.7% respectively. The complete replacement of PC in BF M3 can reduce 17.3% of the total emissions from the Swedish steel industry.

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1. Introduction

The scrap-based steelmaking is often highlighted as the future resource-efficient way of producing steel. The emissions-intensive ore-based route still dominates because of a simple fact, the recycled steel cannot yet supply the volume needed worldwide (only about 30% as of now [1]). Therefore, more virgin materials are needed in the loop of recycling and thus it is projected, considering the world population growth; that Blast Furnace (BF)

and Direct Reduced Iron (DRI) production will continue to dominate until at least 2050 [1].

Climate change, however, calls for a quicker response. Targets in the European Union (EU) call for a 20% cut in CO₂ emissions, a 20% improvement in energy efficiency and a 20% increase of renewable energy, by 2020. According to EU ambition, an 80% cut should be achieved until 2050, while the Swedish ambition is to cut 100% in net CO₂ emissions. This paper addresses the seemingly irreconcilable need for steel and cuts in emissions, by presenting research on how to reduce the footprint of blast furnaces. The idea is to replace pulverized coal (an auxiliary fuel), which is injected in large amounts in Swedish blast furnaces. The needed biomass is found in ample amounts in Sweden and available knowledge suggests that operating conditions will not be fundamentally affected [2–6].

[☆] This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

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Nomenclature

Expressions

Top gas temperature Outlet temperature at the top of a BF
 Hot stove Heat exchanger for preheating the blast or hot air
 Shaft efficiency $(\%CO_2 / (\%CO_2 + \%CO))_{TRZ} / (\%CO_2 / (\%CO_2 + \%CO))_{equilibrium}$

Abbreviations

BF Blast Furnace
 BFG Blast Furnace Gas or Top gas
 CFD Computational Fluid Dynamics
 COG Coke Oven Gas
 DRI Direct Reduced Iron
 EU European Union
 RAFT Raceway Adiabatic Flame Temperature (°C)
 HM Hot Metal or crude iron
 tHM ton of Hot Metal (t)
 HTC Hydrothermal Carbonization
 LCA Life Cycle Assessment
 LHV Lower Heating Value (MJ/kg)
 M2 Masugn 2, blast furnace in Oxelösund

M3 Masugn 3, blast furnace in Luleå
 M4 Masugn 4, blast furnace in Oxelösund
 PCI Pulverized Coal Injection
 SE Steam Explosion
 Eta CO Gas utilization efficiency $\%CO_2 / (\%CO_2 + \%CO)_{theoretical}$
 TRZ Thermal Reserve Zone

Roman letters

C Carbon content (%wt)
 H Hydrogen content (%wt)
 h hour
 N Nitrogen content (%wt)
 O Oxygen content (%wt)
 S Sulfur content (%wt)
 T Temperature (K)
 t ton (1000 kg)
 y year
 W Watt (J/s)

As such, this study aims to investigate the simplest application of biomass, to give a realistic replacement potential in the near future. Availability of biomass is another concern, which could prohibit the, more challenging, substitution of all fossil fuel in the steel industry. The considered pretreatments (carbonization, torrefaction and pelletization) are used from the outset as scenarios. For each pretreatment, the maximum replacement ratio is calculated, in addition to the effect on operating conditions (see Sections 3.1 and 4.1 for methodology and results respectively), then the needed biomass versus the available biomass is estimated (see Sections 3.2 and 4.2) and finally the corresponding maximum reduction in CO₂ emissions are estimated (see Sections 3.3 and 4.3).

This introduction is followed by a background, which covers motive and the previous work in this field. A methodology section describes how this study is carried out and Section 4 describes the results, followed by Section 5—the conclusions.

2. Background

Efforts to reduce CO₂ emissions in Sweden have been re-focused, from generating renewable power and district heating, to supplying renewable fuels for industry and transportation. The steelmaking sector in Sweden is a large contributor to emissions, which calls for a concentrated effort, but it is by far not the simplest case where renewables may be introduced. The reason is a lock-in effect, which stems from long investments in fossil-based technology, but also energy saving measures. Integrating the steel production (e.g. using Coke Oven Gas (COG) as fuel-supply in other parts of the plant) results in better energy efficiency, but at the same time moves the industry further away from renewable alternatives. The main contributor is the blast furnace, which uses coal and generally dominates in terms of emissions and energy consumption [7].

Using biomass is one method to combat the emissions. In fact, biomass from the boreal forest has historically been used for steelmaking and contributed in the 18th century to propel Sweden to the top steelmaking nations worldwide. The later use of coal was almost universally adopted during the industrial revolution. Coke (coal treated in a coking process) overtook biomass as a reduction agent in iron making from: 1760 in Britain [8], 1835 in Belgium [8],

1853 in France [8] and at the beginning of the 20th century in Sweden [9]. The superior properties of Coke as bed material, enabled the large and efficient types of blast furnaces used today. The Swedish blast furnaces are listed in Table 1, which are many times larger than the older type. The general understanding is that large blast furnaces cannot function properly with raw or pretreated biomass as bed material. The main constraint is the low compression-strength of biomass at high temperatures, which impairs the passage of gases through the shaft.

Over the years, injection of pulverized coal (PC) has been introduced worldwide in the majority of all blast furnaces [2]—foremost as a cost saving measure. A previous study by some of the authors; Orre et al. [12], investigates the economic impact of introducing a range of injectants, where injections clearly lower the production cost versus an all-coke operating mode. Though, this practice might now pave the way of using significant portions of biofuel. Of the different streams of fossil fuel to the blast furnace, replacing the injection is understood as the easiest way to introduce biomass [2–6]. Thus, in Sweden, the carbon footprint of blast furnaces is possible to reduce significantly and since Sweden has abundant forest resources, favorable conditions exist for companies to pioneer this method.

With recent developments, the blast furnaces in Sweden can now operate with a comparably low total reductant rate, mainly due to large furnace volume and a large portion of high-quality pellets. The low coke rate of 320 kg/tHM (for BF M3 in Table 1) is usually not achieved unless a very high PC rate is used (200–230 kg/tHM according to Babich et al. [13]). As seen in Table 1, the PC rate for BF M3 is 135 kg/tHM, which is at the lower end of the European average (130–150 kg/tHM according to Lacroix et al. [14]). Thus, the CO₂ emissions are by comparison already low and the possibility of adding varying amounts of biofuels and changing the ratio of coke and coal, gives significant flexibility to balance economics and emissions. Norgate and Langberg [3] investigate the optimal balance, which is directly affected by emission caps and carbon tax. As the caps decreases and taxes increase, flexibility is key to competitive steelmaking. Note that the 2008 numbers for coal and coke rate, which are slightly different, is used in the simulation (155 and 305 kg/tHM respectively), total reductant rate is nearly unchanged however.

Table 1

Blast furnaces in Sweden (2014) [10], with estimated numbers for coal and coke consumption (2008) [11].

BF	Location	Coal/coke rate, kg/tHM (2014)	Working volume, m ³	Capacity, MthM/year	Production, MthM (2008)	Consumption, Mton (2008)	
						Coal	Coke
M3	Luleå	135/320	2540	2.55	2.24	0.31	0.73
M2	Oxelösund	110/370	1100	0.80	1.33 ^a	0.15 ^a	0.50 ^a
M4	Oxelösund	95/365	1339	1.10			

^a M2 + M4.

Other routes of introducing biomass to the blast furnace have been identified, research on mixing coal and biomass in the coking plant have been done by MacPhee et al. [15]. Biomass may also be used to replace coke partially, as bed material, though permeability quickly becomes a problem as the ratio is increased. Hanrot et al. [16] estimates that 20 kg/tHM coke can be replaced by charcoal, as this amount is gasified before reaching the thermal reserve zone where permeability is more critical. This is actually positive as the TRZ temperature decreases—by charcoal having higher gasification reactivity [17]—resulting in lower coke consumption. Additionally, the sinter pellets production may be considered a step in steelmaking, Butkovská et al. [18] and Mašlejová [19] investigates biomass use in production of sinter. Norgate and co-workers [3,4] as well as Suopajarvi and co-workers [5,6] consider all these options, where in each case at least partial substitution seems possible. However, of the direct input streams to the blast furnace, the PC is the only one easy to replace by 0–100 wt% pretreated biomass [16], while at the same time avoiding excessive investments and not jeopardizing the fundamental mechanisms of the blast furnace.

Availability of biomass is naturally another concern. Full substitution, in the Swedish steel industry, requires an amount on the level of national significance. For further reference Johansson [20] evaluates the feasibility of fuel substitution (also in downstream production steps) on a broader level, including organizational, behavioral and regulatory considerations.

In this work the future competing uses of biomass is considered and compared to the predicted availability, which is an important consideration. For instance, production of transportation fuels is a competing high added-value use of biomass; by 2030, the Swedish fleet of vehicles should be fossil-independent, which is a target set by the Swedish government. The existing forestry and agricultural industry cannot meet the demand from existing biomass users, in addition to new demand from transportation and industry. However, unconventional sources (such as stubs, needles, branches and tops) could be used in the future with developments in harvesting methods. Also, as demand for biomass increases, unprofitable regions might be further developed and market as a whole might grow—which is the reason most studies forecast an increase in biomass availability in the coming decades.

If a biofuel would be used in a blast furnace, the infrastructure and pretreatment process must be constructed. The uncertainty and hence the lack of predictions, makes it difficult to evaluate the biomass potential beyond 2030. Still, this time frame is not very far-reaching since the introduction of biomass in the blast furnaces will take time. This is one aspect further investigated in this paper. Finally, the CO₂ reductions that may be achieved based on the maximum injection rate of each biofuel is estimated, with considerations for needed biomass. Modeling the injection of biofuels is naturally the first step, before pilot scale experiments and industrial trials.

Other modeling and experimental efforts of investigating Pulverized Coal Injections have been done to see the behavior on a particle level, with aid of, for example Computational Fluid Dynamics (CFD) [21,22] or drop-tube furnaces [23,24]. These types

of investigations are useful to study a specific effect in a small zone of the furnace. However, constructing a detailed model of the whole blast furnace is very challenging, considering the numerous physical and chemical phenomena. Another type of model is suggested in works such as Suopajarvi and Fabritius [25], Grip et al. [26], or Sakamoto et al. [7] with the purpose to simulate an integrated steel plant. It is important to evaluate the effects of biofuels on the whole plant, though the most critical considerations for steel company is to ensure that the blast furnace can continue running uninterrupted and maintaining the same performance.

The type of model used in this paper, is appropriate for studying the steady state of a whole blast furnace on a simplified level. The different zones are then, connected by mass and heat exchange and specific metallurgical considerations govern each zone, for example the reactions of hot metal, slag, iron ore pellets, coke, injectants and additives.

3. Methodology

The maximum replacement rate for each pretreatment method is first estimated, with subsequent changes in operating conditions, and then translated to a required amount of biomass and a possible net reduction in CO₂ emissions. The issues left out in this work are economic aspects and the sustainability of harvesting such large amounts of biomass. This methodology section describes how each step is carried out. Table 2 shows the assumed properties of the PCI and the biomass products. The considered ones are charcoal, torrefied biomass and pellets (raw but dry and densified biomass)—all from woody biomass, mainly pine and spruce. Note that the moisture content is estimated after storage in a dry environment, which would be realistic in a real plant. But, as with most of these parameters, it would be possible to control them by altering the process conditions and adding more steps; such as reducing ash content by acid washing. The biomass considered in this paper would likely not need any such treatment as the contaminants are low in concentration. However, if a high ash content feedstock would be considered, a screening or leaching step could be introduced.

Table 2

Ultimate analysis of PCI and investigated biomass products [11].

Parameter	Unit	PCI	Biomass products [11]		
			Charcoal	Torrefied material	Wood pellets
C	wt% ^a	85.0	84.7	58.0	50.5
H	wt% ^a	3.9	3.35	5.30	6.2
N	wt% ^a	2.1	0.13	0.48	0.1
O	wt% ^a	2.1	10.6	34.0	42.6
S	wt% ^a	0.4	0.02	0.03	0.01
Ash	wt% ^a	7.8	1.9	3.2	0.5
Moisture	wt%	1.0	4.5	7.7	9.4
LHV	MJ/kg	33.5	31.6	21.6	19.2

^a Dry basis.

Fig. 1. Blast furnace model used in this paper, showing the different sub-models, zone-specific reactions as well as inlet and outlet streams.

3.1. Simulation and maximum replacement potential

A schematic diagram of the model is shown in Fig. 1. This type of model has not previously been used to study the injection of bio-fuels, which will affect not only the carbon footprint, but also slag generation rate, limestone consumption, chemistry and a number of other factors.

With the outset from pretreatment, the simulation is carried out on a case-by-case basis. A 1-D static, heat and mass balance model (MASMOD) is used, introduced previously by Hoey et al. [27]. Fig. 1 shows the layout of the model, together with the blast furnace and the various input and output streams. The overall scheme links together three sub-models, the blast furnace model, the hot stove model and the burden model. An overall solution is obtained iteratively. The model has previously undergone some platform changes, as of now it is used in a Microsoft Excel environment.

The burden model, balances the required basicity and reduction degree in the blast furnace model, by charging enough materials, including coke, pellets, sinter and additives (limestone and quartz). The blast furnace model (including the lower, upper and thermal reserve zone) calculates a number of reactions given in Fig. 1. The blast furnace model is linked to the hot stove model through the hot blast required. The hot stove is a heat exchanger that preheats the air, i.e. the hot blast to the blast furnace. The energy balance equation in the hot stove model calculates the fuel required to ensure a sufficient heat supply. Commonly, the air combustion technique is applied in the hot stove with Blast Furnace Gas (BFG), which is often mixed with Coke Oven Gas (COG) in order to get a sufficient heating value. For the blast furnace, the amount of injectants required (for both coal and biofuel) is calculated to achieve a constant Raceway Adiabatic Flame Temperature (RAFT). In principle two main parameters limit the application, a maximum oxygen enrichment of the hot blast and a minimum allowed top gas temperature. As the nature of the volatile matter in biomass is different from coal, the extra energy that may be required is considered by introducing a so called “cracking energy” in the calculation of each injectant. More complex and numerous inter-molecular bonds are present and the total amount of volatiles is higher; consequently more energy appears to be needed to achieve the combustion (analogous to how high volatile matter coal behaves when injected).

The reference blast furnace used in the simulation is BF M3 in Table 1, designated Masugn 3 by the owner SSAB. The maximum replacement potential is based on (1) the top gas temperature and (2) the oxygen content of the biofuel, which is offset by an oxygen enrichment of the blast—to keep the Raceway Adiabatic Flame Temperature (RAFT) constant. The oxygen enrichment is restricted to a maximum of 25.4% for practical reasons and the top gas temperature must be above 100 °C to avoid condensation; these two factors are the main limiting factors for biofuel use. The conditions in Table 3 are furthermore used as a Basecase with 100% coal. The coke rate is kept constant to ensure a stable operation; other parameters that either varies or is held constant, is given in Table 3. Note that the coal and coke rate are slightly different in Table 3 (2008), compared to Table 1 (2014), the total reductant rate is nearly unchanged however. The 2008 numbers for coal and coke rate is used, as this represents an uneventful year with high productivity; the reference period is April 28–June 4 with a production rate of 275.7 tHM/h.

The simulation is carried out by increasing gradually the feed rate of biofuels and observing changes in operating conditions. A maximum replacement potential is determined when either of above given conditions are met. At the same time, other factors developed during the simulation, which are reported in the results

Table 3

Key parameters of blast furnace 3 operation for the reference period.

Parameter	Unit	Base case (100% Coal)	Cases of biomass use (0–100%)
<i>Feed rate</i>			
Coke	kg/tHM	305	Kept constant
PCI	kg/tHM	155	Varies
Biofuel	kg/tHM	0	Controlling variable
Limestone	kg/tHM	41	Varies
<i>Controlled parameters</i>			
O ₂ in the blast	%	23.9	<25.4
RAFT	°C	2151	Kept constant
Blast temp.	°C	1106	Kept constant
Top gas temp.	°C	133	>100
<i>Operating conditions</i>			
Eta CO	%	55.5	Varies
Shaft efficiency	%	98.5	Kept constant
Slag formation	kg/tHM	149.6	Varies

section. Any possible energy saving in the blast furnace is estimated according to the inputs and outputs of the system given in Fig. 2. The inputs and outputs given in Fig. 2 are the ones that will change in comparison with base case of 100% coal.

3.2. Required vs available biomass in Sweden

The required amount of raw biomass for each pretreatment, requires the conversion efficiency on both energy and weight basis, which is reported in Table 4. The conversion technologies considered in this paper are (1) pelletization (produces a dry and densified product which is clearly defined and widely available), (2) torrefaction and (3) pyrolysis, which all can use various kinds of forest residue. The other conversion technologies in Table 4 yield, for Hydrothermal Carbonization (HTC) and Steam Explosion (SE), a product similar to torrefied biomass. HTC is normally used for biomass with already high moisture content, such as sewage sludge. SE is similar to torrefaction, however, by use of high-pressure steam, the biomass structure is altered to be more susceptible to pelletization. LignoBoost produces, from the lignin fraction generated in the pulping process, a pelletized product similar to coal. Note that shaping of biomass into pellets has no effect within the context of the model. Instead pelletization is specified as the product meets clearly defined standards (low moisture content, ash content, etc.) and is widely available.

The raw biomass availability is an actively investigated issue in Sweden, as the industrial interest for biomass is considerable. To evaluate the biomass availability for use in blast furnaces, a long term view is appropriate. Table 5 shows a summary of supply-potential studies in Sweden that also predicts the development until 2050. The minimum prediction and maximum prediction are given for each decennium with the number of studies indicated in brackets. In the case, most notably 2050, where a value is given by just one prediction, the specific study is indicated. As seen, most studies are limited to 2030 due to the uncertainty; this is reflected by a drop of the average value of supply potential. It seems the longer predictions are conservative in terms of estimates and the expansion of potential predicted by many, levels-off after 2030.

Svebio [28] estimated the potential for all types of biomass, including peat and waste. The long term potential of biomass can be as high as 394 TWh per year, of which agricultural biomass can play a significant role.

The blast furnace will primarily use forest biomass, though we base our calculations on total biomass availability. This is relevant since elasticity should be expected—meaning that companies with low-value products will switch to other fuels (or raw materials) with lower value. For example, boilers are expected to use more waste in the future, leaving more forest biomass for the blast furnaces. Transportation fuels can be produced—via gasification or catalytic fast pyrolysis for example—from other biomass sources as well and do not require forest biomass specifically.

In Table 6 a base scenario from Energimyndigheten (Andersson et al. [31]) is given, which assumes that the iron and steel industry continue using fossil fuels—thus we avoid double counting—and the rest of the industry remains the same and only develops according to existing regulations.

Table 6 also includes two scenarios from Hansson and Grahn [32] concerning the increased use of biomass for transportation, which is an ambition set by the Swedish government. The competing uses of biomass are an important factor for the economic viability. Scenario 1 assumes a completion of all initiated projects. Scenario 2 assumes an expansion beyond the current plans with more actors entering the market.

3.3. Reduction in CO₂ emissions

The specific tonnage reduced, is based on the physical amount of CO₂, otherwise emitted by the coal. According to the European Commission, substitution of coal by biomass in the industry should be regarded as a 100% reduction in CO₂ emissions. This means that biomass is completely carbon neutral. Although disputed, this is the leading assumption in this paper. For further reference, Suopajarvi et al. [6] and Burchart-Korol [33], investigates it in detail by LCA and stresses that all aspects (transports, land-use, etc.) should be considered given the option to use biomass or continue using fossil fuels. However, the carbon footprint indicator in

Fig. 2. The inputs and outputs of the considered system for estimating the change in energy use. The streams are those that will change in comparison with the base case of 100% coal use. A detailed hot stove schematic is also shown to provide additional information on how energy saving is calculated in the results section.

Table 4

Details of available solid conversion technologies shown in for biomass in Sweden [11].

Parameter, unit	Solid conversion process					
	Pelletization	Pyrolysis	Torrefaction	Steam Explosion	HTC	LignoBoost
Temp, °C	70	400–500	200–300	160–260	180–220	70
Pressure, MPa	High	–	–	0.7–5	2.3–2.5	High
Product	Wood pellets	Charcoal	Torrefied material	SE biomass	HTC biomass	Pellets
Yield, wt%	~100	35	70	70	70	~100
Yield, energy%	~100	56	90	79	80	~100
Source	Several	Skogens kol	Torkapparater	SEKAB	KTH	Several
Production	2.3 Mton/y	6000 ton/y	1 ton/h	–	–	2.3 Mton/y
Status	Industrial use	Small scale	Pilot	Pilot	Lab	Commercial
Price, €/MWh	33	55	39.5–67.7	–	29.2	33

Table 5Reported availability studies of *forest biomass* (collected from Wetterlund et al. [29], with Ref. [30] being corrected) and *total biomass* including peat and waste, from Svebio [28].

Ref.	Biomass	Interval (number of studies), TWh/year					
		2000	2010	2020	2030	2040	2050
[29]	Primary forest	16–113.5 (23)	25.8–111.0 (14)	16.0–126.0 (16)	16.0–71.2 (7)	(0)	18–52 (3)
	Secondary residue	12–44 (13)	20–59.6 (6)	16.8–63.7 (9)	40.0–68.1 (2)	(0)	60 (1) [30]
	Stump	0.3–8.0 (5)	10.0–57.5 (4)	10.0 (1)	(0)	(0)	(0)
	Total forest biomass	80–159.6 (3)	111.0–173.8 (3)	107.0–181.7 (7)	143–195.2 (2)	(0)	157 (1) [30]
[28]	Total biomass	(0)	(0)	248 (1)	(0)	(0)	394 [*] (1)

^{*} Long term.**Table 6**

Estimated use of biomass, excluding Peat and Waste.

Ref.	Sector (Scenario)	Estimated use based on regulation, TWh/year		
		2007	2020	2030
[31]	Industry	55.1	64.3	69
	Transportation	3.5	6.2	6.4
	Residential and service	13.9	13.9	16.4
	Electricity	12	19.5	20.5
	Heating	36.5	44	43.7
	Total	121	150.4	155
[32]	Transportation ^a (Scenario 1)	3.5	26	30
	Transportation ^a (Scenario 2)	3.5	28	50

^a Assuming a conversion efficiency of 50% on energy basis.

Burchart-Korol [33] shows that for wood chips, this factor is unmistakably in favor of using biomass. Other factors like land occupation are in favor of using coal and regarding toxicity to humans, both choices are about the same. Another factor is of course the sustainability of harvesting a high level of residue with a fast rotation rate, which is investigated in other works—see for example Egnell and Börjeson [34].

4. Results

4.1. Maximum replacement potential

The low energy density of biofuels is caused by a higher oxygen content, which in turn forces an additional oxygen enrichment of the blast. In this way, the RAFT is kept constant in order to ensure stable operating conditions. Likewise, a number of other parameters are kept constant, which is shown in Table 3 (note that this list of parameters is not exhaustive).

By increasing the feed rate in the simulations, several changes in the operating conditions can be observed. A replacement limit is reached for wood pellets and torrefied material, since the O₂ enrichment cannot exceed 25.4%; see Fig. 3(a). Charcoal can

replace coal fully, although an O₂ content of 24.6% is needed, compared to 23.9 in case of 100% coal. On the other hand, low sulfur and gangue content as well as a high volatile content, results in a potentially lower limestone consumption; see Fig. 3(c). This in turn reduces the slag generation rate, which is an important impact of biofuel use. As seen in that graph, it is most pronounced in the case of Charcoal.

At the maximum level of replacement, the total amount of required energy and mass input increases, for all biofuels—see Fig. 3(b). This is mainly, but not exclusively due to the lower energy density. In principal, a larger amount of combustion products should reach a fixed temperature, hence more energy is needed. But as mentioned in the methodology section a “cracking energy” is also needed, requiring additional input energy.

Despite the high energy-need for injections. Substantial energy savings are likely possible, considering the system of an integrated plant (Fig. 2). For each biofuel, a calculated energy saving is shown in Fig. 3(d), which is one of the main findings in this paper. The reason is explained by the following paragraphs.

With the oxygen enrichment into the hot blast, the required hot blast volume becomes lower, consequently the energy consumption in the hot stove will decrease, especially for COG. In addition, more BFG will be generated, which will lead to a potential energy saving in the integrated plant where BFG is used as a fuel. A corresponding decrease in the top gas temperature is shown in Fig. 3(c). The sensible heat in the top gas cannot be recovered as the temperature is too low. But as the latent heat increases when biofuels are used, more can be exported outside the boundaries of Fig. 2. Thus an energy saving—by top gas replacing other fuels in the steel plant—is predicted, see Fig. 3(d). Due to the above reasons, for a high hot metal production rate, the estimated energy saving can be as large as 168.9 GWh per year when using wood pellets. The main reason is that wood pellets have higher oxygen content (see Table 2).

Fig. 4 shows how the energy saving is added up which corresponds to the inputs and outputs of the energy system defined in Fig. 2. More blast furnace gas is generated and less coke oven gas is needed, considering the boundaries of Fig. 2. At the same time extra injectants and electricity for oxygen enrichment is needed,

Fig. 3. Replacement potential for the different biomass products, as well as the impact on a number of parameters; (a) the gradual injection of biofuels with limits due to the maximum oxygen enrichment, (b) injection rate of coal (grey) and biofuel (green) at maximum replacement, (c) resulting limestone use, slag generation rate and top gas temperature, (d) potential energy saving due to top gas generation rate according to the input and output streams within the boundaries shown in Fig. 2.

Fig. 4. Energy saving, added up from the change in needed coke oven gas, injectants and electricity for O₂ production versus produced blast furnace gas.

see Fig. 4. For wood pellets, a number of factors favorably combine, resulting in the highest energy saving.

4.2. Required vs available biomass in Sweden

The blast furnace will primarily use forest biomass, though we base our calculations on total biomass availability. This is relevant since elasticity should be expected—meaning that companies with low-value products will switch to other fuels or raw materials with lower value. For example, boilers are expected to use more waste in the future, leaving more forest biomass for the blast furnaces.

The uncertainty and hence the lack of predictions, makes it difficult—beyond 2030—to evaluate the available biomass for injection into blast furnaces. Still, this timeframe is not very far-reaching since the introduction of biomass will take time.

Though, most studies forecast a growing total availability of biomass, as increased use is expected to drive the development of remote locations and harvesting methods. On the other hand, if the use reaches too high levels, the economic viability will suffer. Considering the significant competition expected in the south of Sweden, as well as the required development of costly infrastructure, BF M3 is primarily suitable for a switch to biomass.

Fig. 5 shows the location of the blast furnaces and the used amount of coal; other primary biomass users are also shown as to give the regional circumstances. In the north of Sweden (where BF M3 in Table 1 is located), a larger unused potential is expected, and it is hence the logical place to start-out with biomass injection. As indicated in Fig. 5, an unused potential of forest biomass exists today, about 0.7 TWh/y for both Västerbotten (377 GWh/y) and Norrbotten (359 GWh/y).

On the right hand side of Fig. 5, the long-term predictions of potential secondary forest residue, total forest biomass and total biomass; are shown (reported in Table 5). In the midterm, until 2030, potentially available biomass is expected to grow; error bars indicate the maximum and minimum prediction if several studies are considered.

The biomass availability of Svebio [28] is shown in Fig. 6 divided into peat (tan), waste (yellow), agricultural residue (orange), black liquor (blue) and wood fuels (light green). Forecasts of the biomass-use, for a number of scenarios, are also shown in Fig. 6 (reported in Table 6). The scenarios (indicated as deep red, red and pink respectively) include a base scenario from Energimyndigheten (Andersson et al. [31], see Table 6) and an increase in biomass use for transportation (1 and 2 from Hansson and Grahn [32], see Table 6). The expanded use of biomass for transportation would demand large amounts of biofuel. In the

Fig. 5. The location of the blast furnaces, the competing user and the available as well as development in potentially available biomass. Error bars are for given the maximum and minimum prediction, in the case where several studies overlay.

Fig. 6. Potential CO₂ saving and the required biomass for maximum replacement of PCI for each biomass product in blast furnace M3. The required biomass are then compared to the available biomass by arrows. Availability [28] is divided into peat (tan), waste (yellow), agricultural residue (orange), black liquor (blue) and wood fuels (light green). Predicted use from Table 6 [31] (deep red) is shown, in addition to the scenarios from Table 6 [32] (red and pink) of extensive biomass-use of transportation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenario with the highest use for transportation, by 2030 the required biomass will exceed the available *forest biomass* (shown in Fig. 5 and as light green in Fig. 6; note that the highest prediction is not exceeded—only the average). While imports might cover the difference, the competition for *forest biomass* in particular will be severe by 2030—if transportation will become a major biomass-consumer.

Also shown in Fig. 6, is the required pulverized coal for BF M3 (considering 8760 h/y with 98% operating availability and a

production rate of 275.7 tHM/h) which amounts to 368 kton/y. Replacement by charcoal requires 7.2% more weight according to the simulations for BF M3, see Fig. 3 b); as such 394 kton is required, or 3.43 TWh. By using the energy and mass output yield of 56% and 35% respectively from Table 4; 6.19 TWh or 1.13 Mton of dry raw biomass will be needed for conversion to charcoal and full replacement of coal. The green area, in Fig. 6, shows this amount in relation to the expected total biomass use and availability, in the future. This is a significant portion of the used biomass

today, such amounts are not readily available in the market (compare, for example 6.19 TWh/y for the case of charcoal, with the available 0.7 TWh/y in the north of Sweden, see Fig. 5). But, as the biomass potential is expected to grow in the long term, enough is likely to be available—especially as Blast Furnace M3 is located in a less densely populated area.

4.3. Reduction in CO₂ emissions

Finally, for BF M3, the possible CO₂ reductions are given in Fig. 6. This is at the maximum replacement limit of each biofuel. By using charcoal, the largest reduction is possible, since 100% replacement is possible. At the same time the highest relative need of raw biomass is required.

For reference the plant in Luleå emitted an estimated 3.7 Mton CO₂ in 2008. The same year, Swedish steel industry emitted an estimated 6.6 Mton CO₂ [11]. By replacing the injection completely with charcoal, the on-site emissions can be reduced by 28.1%; torrefied material and wood pellets can reduce a maximum of 6.4% and 5.7% respectively. The reduction is also substantial on an industry-level; replacing the coal used in this furnace alone, would cut the emissions of the whole industry by 17.3%.

5. Conclusions

The result of the simulation indicates a full replacement potential for charcoal, a replacement potential of 22.8% for torrefied material and 20% for raw wood pellets. No alkali-related problems are predicted by the model. Instead a number operational benefits were found when using biomass; (1) more Blast Furnace Gas (BFG) will be generated resulting in reduced fuel consumption in an integrated plant, (2) lower need of limestone can be expected, (3) lower slag generation rate as well and (4) less energy is required for heating the hot blast since oxygen enrichment reduces the total volume of gas. An energy saving potential of 50.2, 115.7 and 168.9 GWh/year has been estimated for charcoal, torrefied material and wood pellets respectively. Though, further work is required to understand all impacts. Technical and economic constraints might still arise, linked to for example, logistic issues or quality aspects of the produced iron. During further work, experimental tests and industrial trials, in addition to models should be used.

There is a potential for increased use of biomass, though predictions indicate that strong competition can be expected, especially in the south of Sweden. However, as much as would be needed to replace PCI in BF M3 should be available in the short term (by 2020, 128 TWh/y) and long term (189 TWh/y), considering the developments of remote regions and harvesting methods. Other industries are all interested in using more biomass; the development in each industry will affect the economic feasibility of using biomass in the steel industry. Most notably, biomass for transportation fuels would affect the economic viability of using biomass in the steel industry. As presented in Fig. 6, the total biomass use, according to the base scenario is for the short term 150 TWh/y (by 2020) and long term 155 TWh/y (by 2030). Large scale conversion to transportation fuels results in a total biomass use of 172 TWh/y (2020) and 199 TWh/y (2030) respectively. Note that this is not limited to forest biomass.

Finally, favorable conditions exist for companies to pioneer this method in Sweden; in this paper considering the availability of biomass, technical limitations of the blast furnace operation and the payoff of greatly reducing emissions. Completely replacing the injected coal by charcoal in this furnace, will reduce the on-site emissions by 28.1% (torrefied material and wood pellets can reduce

a maximum of 6.4% and 5.7% respectively) or 17.3% of the emissions from the whole industry.

Acknowledgements

The authors thankfully acknowledge the Swedish Energy Agency (Energimyndigheten) for financial support of the research work (project number: 35819-1). For additional financial support, the following companies and institutions are acknowledged; SCA, Sveaskog, Swerea MEFOS and KTH. For support in other ways, the following project partners are also acknowledged; LKAB and SSAB. We are grateful to all above-named organizations for the opportunity to carry out this research.

References

- [1] The Steel Eco-Cycle, Scientific Report 2004–2012, D853. Jernkontoret Research; 2012. <http://www.jernkontoret.se/ladda_hem_och_bestall/publikationer/stalforskning/rapporter/D_853.pdf>.
- [2] Feliciano-Bruzual C. Charcoal injection in blast furnaces (Bio-PCI): CO₂ reduction potential and economic prospects. *J Mater Res Technol* 2014;3(3):233–43. <http://dx.doi.org/10.1016/j.jmrt.2014.06.001>.
- [3] Norgate T, Langberg D. Environmental and economic aspects of charcoal use in steelmaking. *ISIJ Int* 2009;49(4):587–95.
- [4] Norgate T, Haque N, Somerville M, Jahanshahi S. Biomass as a source of renewable carbon for iron and steelmaking. *ISIJ Int* 2012;52(8):1472–81.
- [5] Suopajarvi H, Fabritius T. Towards more sustainable ironmaking—an analysis of energy wood availability in Finland and the economics of charcoal production. *Sustainability* 2013;5(3):1188–207. <http://dx.doi.org/10.3390/su5031188>.
- [6] Suopajarvi H, Pongrácz E, Fabritius T. The potential of using biomass-based reducing agents in the blast furnace: a review of thermochemical conversion technologies and assessments related to sustainability. *Renew Sustain Energy Rev* 2013;25:511–28. <http://dx.doi.org/10.1016/j.rser.2013.05.005>.
- [7] Sakamoto Y, Tonooka Y, Yanagisawa Y. Estimation of energy consumption for each process in the Japanese steel industry: a process analysis. *Energy Convers Manage* 1999;40(11):1129–40. [http://dx.doi.org/10.1016/S0196-8904\(99\)00025-4](http://dx.doi.org/10.1016/S0196-8904(99)00025-4).
- [8] Fremdling R. Foreign trade-transfer-adaptation: the British iron making technology on the continent (Belgium and France). Groningen Growth and Development Centre. University of Groningen; 2002. 200255. <<http://ideas.repec.org/p/dgr/rugggd/200255.html>>.
- [9] Arpi G. The supply with charcoal of the Swedish iron industry from 1830 to 1950. *Geogr Ann* 1953;35(1):11–27. <http://www.jstor.org/stable/520263>.
- [10] Olsson E. Private communication. SSAB EMEA; 2014.
- [11] Wei W, Mellin P, Yang W, Wang C, Hultgren A, Salman H. Utilization of biomass for blast furnace in Sweden – report I: Biomass availability and upgrading technologies. KTH Royal Institute of Technology; 2013. <http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-138493>.
- [12] Orre J, Wang C, Larsson J, Olsson E. Potential impacts on the energy system at the integrated steelwork by changing injection coal types to the blast furnace. *Chem Eng Trans* 2013;35:973–8. <http://dx.doi.org/10.3303/cer1335162>.
- [13] Babich A, Gudenau HW, Senk D, Formoso A, Menendez JL, Kochura V. Experimental modelling and measurements in the raceway when injecting auxiliary substances. In: Proceedings of the international blast furnace lower zone symposium. Wollongong, Australia; 25–27 November 2002. p. 1–14. <http://meveus.ihk.rwth-aachen.de/moodle/file.php/1/homepage/papers/122_Wollongong_2002_Raceway.pdf>.
- [14] Lacroix P, Dauwels G, Dufresne P, Godijn R, Perini PG, Stricker KP, et al. High blast furnaces productivity operations with low coke rates in the European Union. *Metall Res Technol* 2001;3(98):259–68. <http://dx.doi.org/10.1051/metal:2001181>.
- [15] MacPhee JA, Gransden JF, Giroux L, Price JT. Possible CO₂ mitigation via addition of charcoal to coking coal blends. *Fuel Process Technol* 2009;90(1):16–20. <http://dx.doi.org/10.1016/j.fuproc.2008.07.007>.
- [16] Hanrot F, Sert D, Delinchant J, Pietruck R, Bürger T, Babich A, et al. CO₂ mitigation for steelmaking using charcoal and plastics wastes as reducing agents and secondary raw materials. In: Proceedings of the 1st Spanish national conference on advances in materials recycling and eco-energy. Madrid, Spain; 12–13 November 2009. <<http://hdl.handle.net/10261/18433>>.
- [17] Ng KW, MacPhee JA, Giroux L, Todoschuk T. Reactivity of bio-coke with CO₂. *Fuel Process Technol* 2011;92(4):801–4. <http://dx.doi.org/10.1016/j.fuproc.2010.08.005>.
- [18] Butkovská M, Fröhlichová M, Findorák R, Legemza J, Ivanišin D. Influence of charcoal on quality of agglomerate. In: Proceedings of acta metallurgica slovac, vol. 4; 2014. p. 9–16. doi: 10.12776/amsc.v4i0.258.
- [19] Mašlejová S. Utilization of biomass in ironmaking. In: Proceedings of the 22nd international conference on metallurgy and materials (Metal 2013); 2013. <<http://www.metal2014.com/files/proceedings/12/reports/1744.pdf>>.

- [20] Johansson MT. Improved energy efficiency and fuel substitution in the iron and steel industry. Linköping University; 2014. <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-105849>.
- [21] Du SW, Chen WH, Lucas J. Performances of pulverized coal injection in blowpipe and tuyere at various operational conditions. *Energy Convers Manage* 2007;48(7):2069–76. <http://dx.doi.org/10.1016/j.enconman.2007.01.013>.
- [22] Maier C, Jordan C, Feilmayr C, Thaler C, Harasek M. Multi-scale modeling of hydrocarbon injection into the blast furnace raceway. In: Proceedings of the 10th international conference on CFD in oil & gas, metallurgical and process industries (CFD2014); 2014. <http://www.sintef.no/project/CDF2014/docs/Official_Proceedings_CFD2014%20redusert%20filstr.pdf>.
- [23] Chen WH, Du SW, Yang TH. Volatile release and particle formation characteristics of injected pulverized coal in blast furnaces. *Energy Convers Manage* 2007;48(7):2025–33. <http://dx.doi.org/10.1016/j.enconman.2007.01.001>.
- [24] Chen WH, Du SW, Tsai CH, Wang ZY. Torrefied biomasses in a drop tube furnace to evaluate their utility in blast furnaces. *Bioresour Technol* 2012;111:433–8. <http://dx.doi.org/10.1016/j.biortech.2012.01.163>.
- [25] Suopajarvi H, Fabritius T. Effects of biomass use in integrated steel plant – gate-to-gate life cycle inventory method. *ISIJ Int* 2012;52(5):779–87.
- [26] Grip CE, Larsson M, Harvey S, Nilsson L. Process integration. Tests and application of different tools on an integrated steelmaking site. *Appl Therm Eng* 2013;53(2):366–72. <http://dx.doi.org/10.1016/j.applthermaleng.2012.03.040>.
- [27] Hooye P, Bodén A, Wang C, Grip CE, Jansson B. Design and application of a spreadsheet-based model of the blast furnace factory. *ISIJ Int* 2010;50(7):924–30.
- [28] Svebio. Potentialen för bioenergi – tillgång – användning. Svebio; 2008. <<http://www.svebio.se/sites/default/files/Potentialen%20f%C3%B6r%20bioenergi.pdf>>.
- [29] Wetterlund E, Pettersson K, Mossberg J, Torén J, Hoffstedt C, von Schenck A, et al. Optimal localisation of next generation biofuel production in Sweden. The Swedish Knowledge Centre for Renewable Fuels (f3); 2013. http://f3centre.se/sites/default/files/f3_report_2013-8_optimal_localisation_130517_0.pdf.
- [30] Kommissionen mot oljeberoende. På väg mot ett oljefritt Sverige. Stadsrådsberedningen; 2006. <<http://www.regeringen.se/sb/d/108/a/66280>>.
- [31] Andersson D, Anners C, Nilsson L, Svensson E, Kadic Z, Sahlin M, et al. Långsiktsprogno 2012. Energimyndighet report; 2013. <<https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=2698>>.
- [32] Hansson J, Grahm M. Utsikt för förnybara drivmedel i Sverige. IVL Svenska Miljöinstitutet; 2013. <http://spbi.se/wp-content/uploads/2013/03/IVL_B2083_2013_final.pdf>.
- [33] Burchart-Korol D. Sustainability and eco-efficiency assessment of biomass use in steelmaking. In: Proceedings of the 22nd international conference on metallurgy and materials (Metal 2013); 2013. <<http://www.metal2014.com/files/proceedings/12/reports/1447.pdf>>.
- [34] Egnell G, Börjeson P. Theoretical versus market available supply of biomass for energy from long-rotation forestry and agriculture – Swedish experiences. IEA bioenergy report; 2012. <http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_TR2012-02.pdf>.