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Potential Impacts on the Energy System at the Integrated Steelwork by Changing Injection Coal Types to the Blast Furnace

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Pulverized coal is often injected into the blast furnaces (BFs) at the integrated steelworks as reducing agent for the hot metal production. The BF process will behave different depending on the injection coal used. The objective of this study is to investigate how different types of coal will influence the BF, and the total energy system at an integrated steel plant. The major process units covered in the model are coking plant, BF, reheating furnace at the rolling mill and a power plant. They are all linked to each other via the main products as well as process gases (i.e. blast furnace gas (BFG) and coke oven gas (COG)) and oxygen network. At the studied plant, the mixed gas of BFG and COG is used within the coking batteries at the coking plant and hot stoves at the BF. The fuel used at the reheating furnace is COG and oil with high heating values. In total, 13 different types of coal and one biomass charcoal are included in the study. Possible impacts on energy and CO_2 emission from a holistic view have been analyzed for different types of coal and injection rates. The different strategies on pulverized coal injection to BF are presented and discussed.

1. Introduction

Pulverized coal injection (PCI) in the BF is mainly used for the economic benefits from replacing the expensive coke. PCI gives also other benefits, such as increased productivity, assists in maintaining furnace stability, improves the hot metal (HM) quality and reduces CO_2 emissions, Bennet et al. (2003). PCI rate has been increasing, and in some BF:s it exceeds of 200 kg / t HM. One important aspect of the PCI is the coke replacement ratio, which is decreasing with increasing volatile matter in the coal. Another important parameter for PCI is the combustion efficiency or coal burnout which has been studied by Mathieson et al. (2005) and later by Shen et al (2009). High combustion efficiency gives the possibility to have a higher PCI rate without getting much un-burnt PC. The combustion efficiency is increased through increased blast temperature and higher volatile matter content in the coal. In addition, hardgrove grindability index (HGI) is also an important factor which indicates the milling behaviour of the coal. Low volatile coals have generally higher HGI than high volatile coals which indicate on coal that is softer and easier to grind, ACARP (2012).

The Purpose in the present work is to evaluate different types of PCI coals for the BF:s, from a system perspective. A change in the coal quality changes the energy balance of the blast furnace, which will lead to a changed BFG and thus the energy balance for the integrated steelwork. Other changes due to the different coal type are production rate and element balance. 13 different coals, including 6 low volatile (LV), 5 high volatile (HV), one coking coal and one charcoal are studied. The charcoal analysis and price used are from Wang et al. (2012). All studied coals have low phosphorus and sulphur contents because of the negative influences they have on the HM. The coking coal is studied in case that there is lack of injection coals and the charcoal is studied to see how it can affected the steelwork from an environmentally friendly point of view. The main purpose of the study is to evaluate the LV and HV coals to find out the best conditions for BF injection.

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2. Method

The theoretical calculation is made by a static 1-dimensional blast furnace model, MASMOD, which is a spreadsheet-based model on the basis of comprehensive heat and mass balance covering the processes in an integrated steel plant. The used models in this study are coke plant, BF, hot stove, reheating furnace and power plant model. The BF model is used for a comprehensive heat and mass balance while the other models are used to have the entire heat and energy balance for the steelworks. The models are connected and balanced via iterative calculations. For example the BF model is linked to hot stoves model through the hot blast produced by the hot stoves and used by the BF. The BFG is generated from BF and used as a fuel in the hot stoves. The model has been described in detail by Hooey et al. (2010).

2.1 Input data

There are two BFs (BF2 and BF4) at the studied steelworks. For BF2, the input data used is from September – December 2011, and process data from March 2011 is used for BF4. The process data includes the essential data for the blast furnace and energy flow data for the whole plant. Table 1 shows information on the different coal types, which are analysed in different laboratories.

The main differences between the studied high and low volatile coals are:

- In the high volatile coals the volatile content is 34 - 39.6 % while the low volatile coals have relative low volatile content in the range of 12.7 – 23 %
- Most LV coals has higher gross heating value
- Most HV coals has higher sulphur content
- Most LV coals are easier to grind, when considering HGI.
- Most HV coals have higher oxygen and hydrogen contents
- Most HV coals are harder to handle due to the hardness, indicating more maintenance of the systems, for example the injection system.

Table 1: Coal characteristics and ultimate coal analysis

Coal name	Ash (d.b.)	Vol (d.b.)	Gross MJ/kg	HGI	C	H	S
LV A (ref.)	8.4	20.4	32.4	68	82.4	4.0	0.24
LV B	7.6	21.0	33.2	60	82.1	4.3	0.27
LV C	8.1	15.5	33.1	65	82.3	3.7	0.56
LV D	12.0	23.0	31.1	83	76.9	4.0	0.35
LV E	9.5	12.7	32.4	62	83.4	3.6	0.38
LV F	9.1	21.0	31.7	60	81.3	3.9	0.28
HV 1	8.5	37.0	31.5	48	75.7	5.3	0.85
HV 2	7.5	35.5	32.3	51	78.1	5.0	0.85
HV 3	8.5	36.0	31.9	45	79.1	5.5	0.85
HV 4	8.4	34.0	30.7	67	75.3	4.9	0.45
HV 5	7.5	39.6	31.7	48	75.8	5.2	0.80
Charcoal	1.6	-	31.5	-	85.4	4.0	0.01
Coking coal	6.7	33.7	33.6	55	80.7	4.9	0.99

2.2 System boundaries

The system boundary includes the processes that are affected by the changed PCI, which is the BF:s and the processes that uses either BFG and/or COG. In addition, the desulphurisation process is covered through the changed need of reagent for sulphur removal. A change of BFG will have influence on COG in the hot stoves and the under firing in coking batteries, consequently it will effect on oil consumption in the reheating furnaces if there will be more available COG for oil replacement due to BFG's change. The amount of BFG to the power plant will also change. The SSAB Oxelösund steelworks with the energy flows are depicted in Figure 1.

Energy, cost and CO_2 evaluation

In this study the energy cost and CO_2 evaluation is made relative to the reference case. The energy evaluation includes the energy from reducing agents, oil and electricity production. The coke use is constant in all cases while the PCI rate is changing. The flaring of BFG, flaring of COG and the oil demand to the power plant is assumed as constant in all cases. The oil demand to the reheating furnace and electricity production is dependent on the BFG heating value and BFG amount available due to different demands of COG and BFG in the hot stove and under firing in coking batteries, which leads to a varying amount of BFG and COG left for the reheating furnace and the power plant. The CO_2 evaluation is made through the change of carbon in the BFG and change in the oil demand. CO_2 from charcoal is not accounted for as it is from a renewable carbon source.

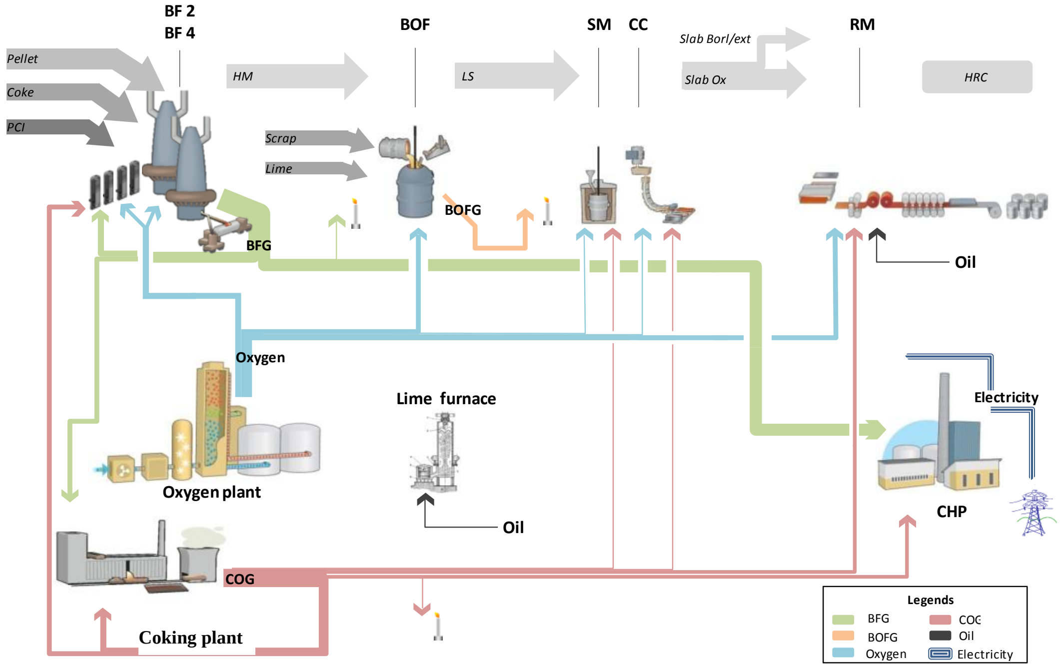

Figure 1: SSAB Oxelösund steelworks energy and oxygen flows; Abbreviation: BF-blast furnace; BOF-basic oxygen furnace; SM-secondary metallurgy; CC-continuous casting; RM-reheating furnace; HM-hot metal; LS-liquid steel; HRC-hot rolled coil; CHP-combined heat and power plant; BFG-blast furnace gas; BOFG-basic oxygen furnace gas; COG-coke oven gas

The cost evaluation includes the changed material cost in the BF, change in oil demand and changed electricity production. The cost of CO_2 is not considered in this work. Price of high volatile coal is assumed to be 30 % lower than low volatile coal. This is a rough estimation since the price varies due to other reasons also, such as fix carbon, ash, sulphur, phosphorous etc. The coking coal price comes from an assumption that the price of a LV-coal is 75 % of a coking coal.

2.3 Model calibration

The reference cases for BF2 and BF4 are chosen from stable periods of operation to give representative operating cases. The reference calculation for BF2 is based on process data from September - December 2011 and the reference calculation for BF4 is based on process data from March 2011. Table 2-4 shows chosen process data used as input data, calculated calibration parameters and model validation data for the reference calculation. The reference case is calculated through keeping the given process data constant and varying the calibration data to get as near as possible to the model validation data The model validation data, in Table 4, show that both the material and the energy balance are in good agreement with the process data when using the calibration data in Table 3.

Table 2: Given process data

	Unit	BF2	BF4
HM production	t/h	90.1	101.2
Blast amount	kNm^3 /h	90.4	108.5
T top gas	˚C	67.0	97.0
Eta CO	%	53.6	53.2
Top gas H_2	%	2.9	2.0
Coke	kg / t HM	360.7	404.4
PCI	kg / t HM	114.2	80.5

Table 3: Calibration data used in the model

	Unit	Calc. BF2	Calc. BF4
Slag amount*	kg / t HM	152.3	156.5
T reserve zone	˚C	890	890
BFG Energy*	GJ / t HM	4.43	4.46
Eta H_2	%	32.00	42.00
Heat losses	MJ / t HM	830	629
RAFT[1],*	˚C	2,192.0	2,082.3
Shaft efficiency	%	96.30	98.30

*calculated data;
[1]RAFT-raceway adiabatic flame temperature

Table 4: Model validation data

	Unit	Calc. BF2	Proc. BF2	Calc. BF4	Proc. BF4
Energy	-	-	-	-	-
BFG LHV	MJ / Nm3	2.91	2.89	2.87	2.78
H_2	%	2.71	2.71	1.94	1.99
CO	%	20.75	20.59	21.10	20.34
Slag	-	-	-	-	-
B2	-	0.95	0.91	0.88	0.91
CaO	%	31.4	30.5	30.4	30.6
SiO2	%	33.0	33.5	34.8	33.8

The given process data is used for the model calibration. Top gas temperature, eta CO(%CO_2 / (%CO_2 + %CO)), top gas H_2 and PCI amount will vary in the calculations. The thermal reserve zone temperature, eta H_2(%H_2O/(%H_2 + %H_2O)), heat losses and shaft efficiency is used as calibration data and is constant in all calculated cases. From Table 4 the calculated B2 is used in all calculations.

2.4 Calculations

13 types of injection coals are included in the calculations. The BF calculations are done through taking the Reserve zone temperature, Heat losses and Shaft efficiency (SE) from the model calibration and assuming them to be furnace specific parameters indicating that they will stay constant when changing PCI. The blast amount and the parameters above mentioned must be specified to get the desired results. Slag basicity (B2) is adjusted to be the same as in the reference case, through adjusting amounts of limestone and quartzite additions.

The calculated scenario is designed to answer how the energy balance, PCI amount, material balance and cost will change with different types of coal. The coke rate is constant to get how much of PC is required to replace the reference coal. The blast rate (Nm^3 / h) is kept constant to see the effects on production rate.

The energy calculation is done through comparing the used specific energy, per ton HM, to the reference case in the integrated steel plant. Eq (1) shows how ΔE, the difference in the energy usage for one type PCI compared to the reference coal, LVA, is calculated.

$$\Delta E = E_{LVA} - E_n = E_{LVA\,in} - E_{LVA\,out} - (E_{n\,in} - E_{n\,out}) \tag{1}$$

where, E_n is the energy usage in the integrated steel plant with the type of PCI, n; $E_{n\ in}$ is the ingoing energy with the coal to the coking plant, external coke, PCI, electricity, oil, other fuels and district heating. ; $E_{n\,out}$ is electricity and district heating.

The change in the energy balance due to changes of PCI can be seen from the PCI demand, oil demand and the electricity production while the other energies are constant with all PCI types. This implies that Eq(2) give ΔE.

$$\Delta E = (E_{LVA\,PCI} + E_{LVA\,oil} - E_{LVA\,el\,prod}) - (E_{n\,PCI} + E_{n\,oil} - E_{n\,el\,prod}) \tag{2}$$

ΔCO_2 is the difference in the CO_2 emissions from PCI *n* compared to the reference PCI, LVA. The CO_2 emissions changes are mainly due to changed PCI come from the carbon in PCI, oil and limestone.

ΔCost is the difference in the costs from PCI *n* compared to the reference PCI, LVA. The differences in cost come from PCI, limestone, quartzite, desulfurization reagent, oil and electricity production.

3. Results

Figure 2 shows the relative energy saving, ΔE, for the studied integrated steel plant. The charcoal gives the lowest total energy usage and the coking coal gives the second lowest total energy usage. When the cheap high volatile coals are checked, it is HV5 which gives the lowest energy usage. LVB gives the lowest energy usage of the low volatile coals, but it is only slightly lower than the reference LVA.

Figure 3 shows the consumption of PCI, consumption of oil and electricity production in GJ per ton produced HM. The PCI consumption is higher for the high volatile coals than other coal types. Charcoal gives the lowest injection coal rate. The high volatile coal HV5 leads to the lowest oil consumption. HV3 gives the highest electricity production.

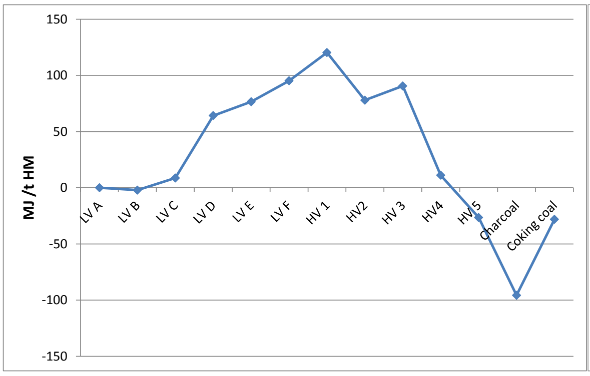

Figure 2: ΔE in MJ / t HM for all type of coal

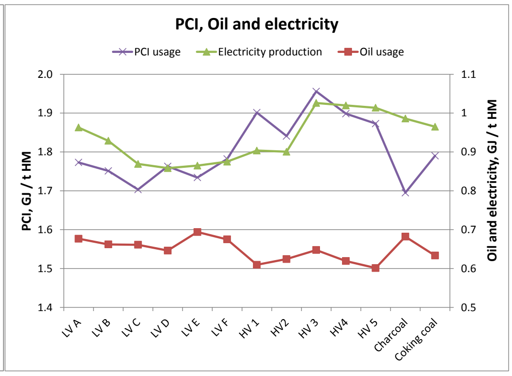

Figure 3: PCI consumption, oil consumption and electricity production in GJ / t HM

According to Figure 4, the charcoal gives the lowest CO_2 emissions because it is a renewable fuel and the CO_2 from the charcoal is not taken into account. The annual CO_2 emission reduction is up to 255 kt. When comparing the low volatile coals it is LVC which has the lowest CO_2 emissions of about 17.5 kt. Comparing the high volatile coals it is coal HV2 which gives the lowest emissions of about 5.5 kt.

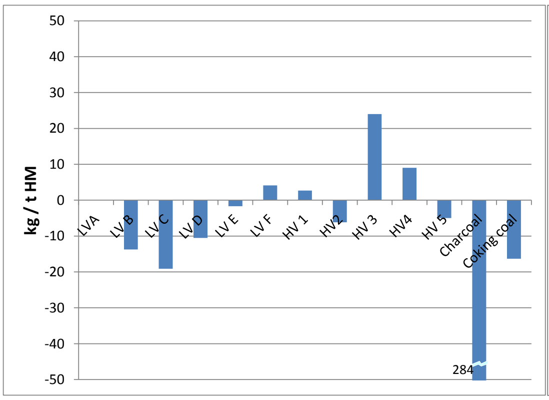

Figure 4: The change in CO_2 emissions compared to LVA

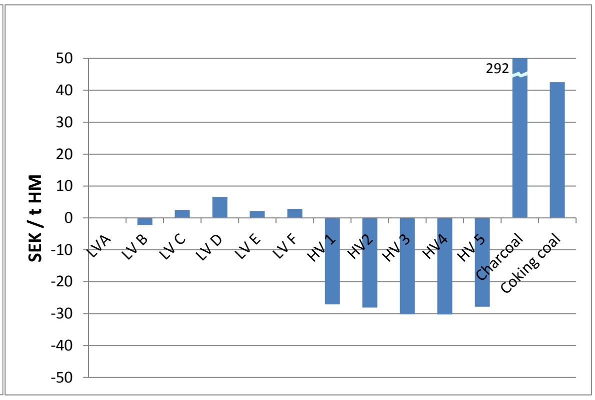

Figure 5: The change in cost compared to LVA

Figure 5 show that the high volatile coals have the lowest production costs due to the low PCI price. HV4 has the lowest production cost, by comparing with the reference case the cost saving potential is about 26 MSEK per year. As for the low volatile coals LVB has the lowest cost, by estimation the annual cost saving potential is up to 2 MSEK.

4. Discussion

In the cost evaluation it is seen that there are a worse economy using the low volatile coals. This is the fact when there is a possibility to grind as much coal as needed and the mechanical problems isn't taken into account. The low volatile coals gives also lower CO_2 emissions, which is seen in Figure 4, and a possibility to a higher production. In times when the focus isn't to produce as much as possible it seems like a good idea to operate the BF:s with high volatile coals due to the cost benefits. HV3, which is the most cost efficient coal to use, has the highest CO_2 emissions and gives high total energy consumption in the integrated steel plant. The coal HV3 gives the lowest production cost because it produces much gas with quite high heating value, which is seen in Figure 3 where it gives a high electricity production and fairly low oil demand. This will be different when taking into account the costs from CO_2 emissions. Charcoal decreases the carbon foot print. Another benefit from charcoal is the decreased CO_2 emission costs. The high volatile coals give a decrease in oil consumption due to the increase of BFG heating value, due to a more ineffective BF operation. A BFG with higher heating value is used more efficiently in the hot stoves and the coking plant which decreases the need for COG, and therefore more oil in the reheating furnace can be replaced.

5. Conclusions

The production cost is lower with high volatile coals compared to low volatile coals. This cost reduction is due to the lower price of high volatile coals. The specific PCI rate is higher for high volatile coals than for low, which leads to decreased productivity and increased CO_2 emissions compared to low volatile coals. Low volatile coals gives an effective BF operation but leads to higher oil demand at reheating furnace and lower electricity production at the power plant due to less energy in the BFG. The cost of using coking coal as injection coal is more costly than normal coals but it is cheaper than an all coke BF operation. Charcoal gives the lowest total energy demand and CO_2 emissions which make it a good option for going towards an environmentally friendly steel production.

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