

System Analysis of Integrating Fast Pyrolysis to an Iron and Steel Plant

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Abstract:

The reducing of CO₂ allowance promotes steel industry to mitigate CO₂ emissions. Utilization of biomass e.g., as injectants in the blast furnace to replace pulverized coal (PC), has been proposed as one promising option to meet these requirements in the short-term. The aim of this work is to integrate a biomass fast pyrolysis to the iron and steel industry and to investigate the potential effects on the energy consumption and CO₂ emission. In this work, an iron and steel plant from Sweden was chosen as a case study. An optimization model was extended to cover the fast pyrolysis units in the system boundary. The fast pyrolysis plant produces different types of biomass products i.e., bio-char, bio-oil and bio-syngas. Different alternative to utilize biomass products within the system were included in the model. The investigation shows that the integration of a fast pyrolysis units has great potential on, not only reducing CO₂ emission, the potential energy savings.

Keywords:

Biomass, Fast Pyrolysis, Iron and Steel Plant, Process Integration.

1. Introduction

As the pressure on the steel industry is high to decrease its CO₂ emission, arising with the reduced CO₂ allowance, the focus has been turned to renewable fuels and its possibility to be used in the iron making processes e.g., as injectants to the blast furnace (BF) instead of pulverized coal injection (PCI). Using biomass and especially charcoal as injectants, is a not an entirely new idea to the field and is currently used in smaller BFs in Brazil with injection rates around 100-150 kg/t hot metal [1]. Earlier studies [2] also showed that replacing all or part of the PCI with pretreated biomass shows promising results for the energy utilization of the entire integrated steel plant. Now the questions that we ask ourselves in this study is if an on-site pyrolysis plant would contribute to an potential energy saving of the integrated system, and if there is a optimal way to use the biomass products generated from the fast pyrolysis process.

2. Modelling

The simulations over the BF system are achieved with static heat and material balance [3], which consists of three sub-models (BF, hot stoves and ingoing burden materials) all connected via iterative calculations. For this work, the key input to this model is the chemical analysis of the injected biomass, which generates stationary output (e.g., required biomass amount, generated slag and top gas) of the system. The main specific material consumption i.e., the outputs from the BF system, as well as the generated slag amount can be seen in Table 1. In the modelling work, the coke rate is kept the constant in order to have a stable operation. As earlier studies [2] shows bio-oil and bio-syngas have low replacement ratio of PCI, thus it is impossible to replace all PCI with

biomass in the BF in these cases. Charcoal on the other hand, have a 100% replacement ratio of PCI.

Table 1. Major specific material consumption and slag generation (kg/thm) in BF

	PCI	Charcoal	Bio-oil	Bio-syngas
Biomass	0	177.1	22.7	9.9
PCI	155.5	0	144.3	155.4
Coke	304.6	304.6	304.6	304.6
Limestone	41.0	31.0	40.5	41.0
Slag	149.6	137.7	148.6	149.6

Outputs from the static BF system model are used as inputs to an existing optimization model, formulated on the basis of mixed integer linear programming (MILP). The optimization model covers the entire integrated iron and steel plant, including some auxiliary process units, for instance, lime kiln, oxygen plant and a combined heat and power plant (CHP). In this work, the model is further extended to cover the fast pyrolysis unit. The equation editor used is called reMIND together with a commercial solver CPLEX [4], and the results are analyzed in Microsoft Excel. The principle of the optimization model is shown in Figure 1. This model has previously been used to optimize energy and material flows in terms of various objective functions, such as, energy, CO₂, cost, etc. [5-7]

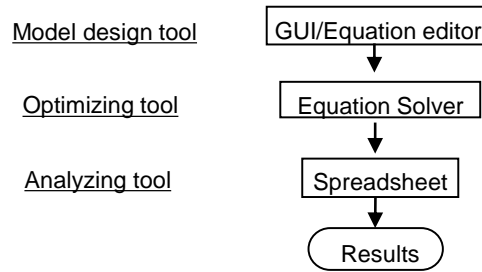


Figure 1. Flow chart of the optimization model.

Objective function

The general description of the objective function in the MILP optimization model can be expressed as (1),

$$\min z(x, y) = \sum c_j x_j + b_j y_j, \quad j = 1, \dots, n \quad (1)$$

Subject to,

$$A_1 x \leq b_1$$

$$A_2 x + B y \leq b_2$$

$$x \in R^n, y \in \{1,0\} \text{ or integer}$$

Where, z is the linear objective function, which in this study describes the energy consumption of the system; x represents the studied variables; y represents the binary variables; c_j is the coefficient for the j th variable in the objective function; b_j is the coefficient for the j th binary variable in the objective function. A graphic description of the energy objective with listed variables is presented in Figure 2.

Two scenarios were constructed to either consider the by-products (not used in BF, CHP or internally in the fast pyrolysis) as useable energy source (producing electricity or heat) or as energy neutral (storage, export or selling of the products). All gas produced in the iron and steel process

i.e., coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG), are either going to flaring, CHP or internal users. The excess gas, in the figure noted as “gas savings”, is energy of the gas saved after optimization of the internal gas utilization. The amount of saved gas is thus potential excess energy that can be used for either district heating or electricity. This is counted as a positive term in the objective function and thus, if existing, it will lead to reduced energy consumption.

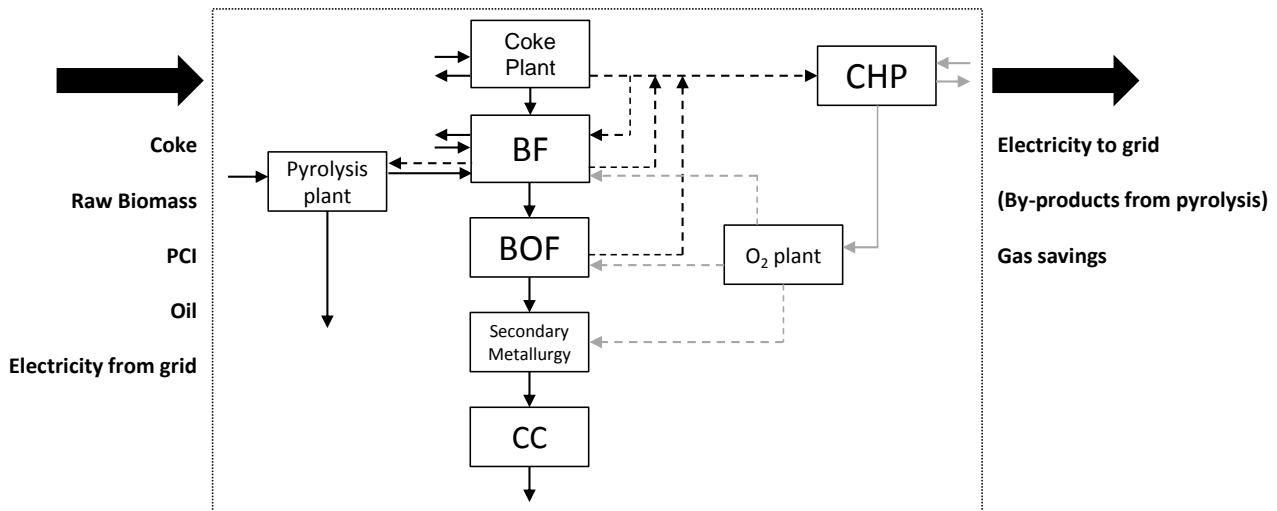


Figure 2. Energy objective and system boundary. Not all internal and external streams in the system are shown in the figure. Dotted lines are gas (black = flue gas, grey = oxygen), black solid lines are material, and grey solid lines are electricity streams.

Fast Pyrolysis

Changing parameters such as vapor residence time and temperature of the pyrolysis process will impact on the product yield, i.e., the composition of charcoal, bio-oil and biogas. Essentially, low process temperatures and long vapor residence time will favor production of charcoal. High process temperature with long vapor residence time will increase the production of gas, meanwhile fast pyrolysis i.e., moderate temperatures and short residence time, is often applied in situations when high content of bio-oil is wanted. All water that formed during the pyrolysis reaction will end up in the liquid phase i.e., bio-oil, and the solid and gas phase is technically dry. As for the ash content will end up in the solid phase i.e., charcoal.

Composition and product yield of the fast pyrolysis is from work done by KTH [8] (see case S/B=0) with conventional N₂ pyrolysis, see Table 2, and the biomass used is a mixture of pine and spruce saw dust provided by SCA. For simplifications, the fast pyrolysis plant is modelled to consist of a dryer, grinding unit and a fluid bed reactor, to facilitate the pyrolysis reaction. The reaction and grinding are assumed to have a constant energy demand, while the dryer removes all moisture content (assumed to be 50%) of the total ingoing raw biomass. The amount of raw biomass used in this study is estimated on the basis of a 20% replacement of PCI with bio-charcoal.

Table 2. Yield and composition of products generated from fast pyrolysis [5].

Parameter	Unit	Yield of biomass products			
		Charcoal	Bio-oil		Bio-syngas ¹
			Organic	Water	
Yield (dry feed) ²	wt %	20.56	37.45	19.47	22.52
Yield	wt % db.	25.53	45.50	-	27.96
C	wt % db.	80.1	57.64		40.02
H	wt % db.	3	6.66		3.01
N	wt % db.	0.9	0		0
O	wt % db.	14.43	35.7		56.97
S	wt % db.	0	0		0
P	wt % db.	0.02	0		0
Ash (A)	wt % db.	1.57	-		-
Moisture (M) (dry feed)	wt %	-	34.21	-	-
Heating value (LHV) ³	MJ/kg	29.21	14.02		10.53

¹ The detail analysis of bio-syngas: H₂ (0.43 wt %); CO (45.62 wt %); CO₂ (42.51 wt %); CH₄ (7.80 wt %); C_xH_y (3.62 wt %)

² Experiment show a mass balance closure of 93.66% [5].

³ Calculated from (2) and (3)

The low heating value (LHV) was calculated by using (2) correlation,

$$LHV = HHV - 0.212H - 0.0245M - 0.008O, \quad (2)$$

where H is % hydrogen; M is % moisture; O is % oxygen. The high heating value (HHV) [9] is derived from (3),

$$HHV = 0.3491C + 1.1783H + 1.005S - 0.1034O - 0.0151N - 0.0211A, \quad (3)$$

where C is % carbon; S is % sulphur; N is % nitrogen; A is % ash. All of above-mentioned compositions, with the exception of moisture content, are expressed as dry weight basis.

3. Results and Discussion

Figure 3 shows the modelling results for two different scenarios, i.e., -1 means that the by-products are used internally e.g., production of electricity and district heat, and thus lowering total energy consumption; meanwhile, 0 means the by-products do not affect the objective function, which can be interpreted that the by-products are sold, stored or exported, in which the energy value in the products has not been credits.

The energy consumption will be higher when only using bio-charcoal or bio-syngas compared to the current operation with PCI. However, the replacement ratio is highest in the case of bio-charcoal, which in turn gives the highest total CO₂ reduction, which can be seen in Table 3 and Table 4. For the case of bio-oil injection, the results are different depending if the by-products are used to produce electricity or heat, or just left for other uses without considering any energy credits. In the best case scenario, when the by-products from the pyrolysis are used for valuable energy production, it is sufficient to only inject bio-oil to the BF. However, if the surplus by-products would not be used in that manner, the bio-oil injection would be infeasible from an energy point of view. In this case, a mixture of 16% bio-oil and 84 % bio-charcoal would give the lowest energy consumption. Coinciding with this mixture is the highest total CO₂ reduction, which can be seen as a benefit from an environmental point of view. Nevertheless, the energy consumption is higher with only injecting bio-oil to the BF compared to using all the by-products generated internally.

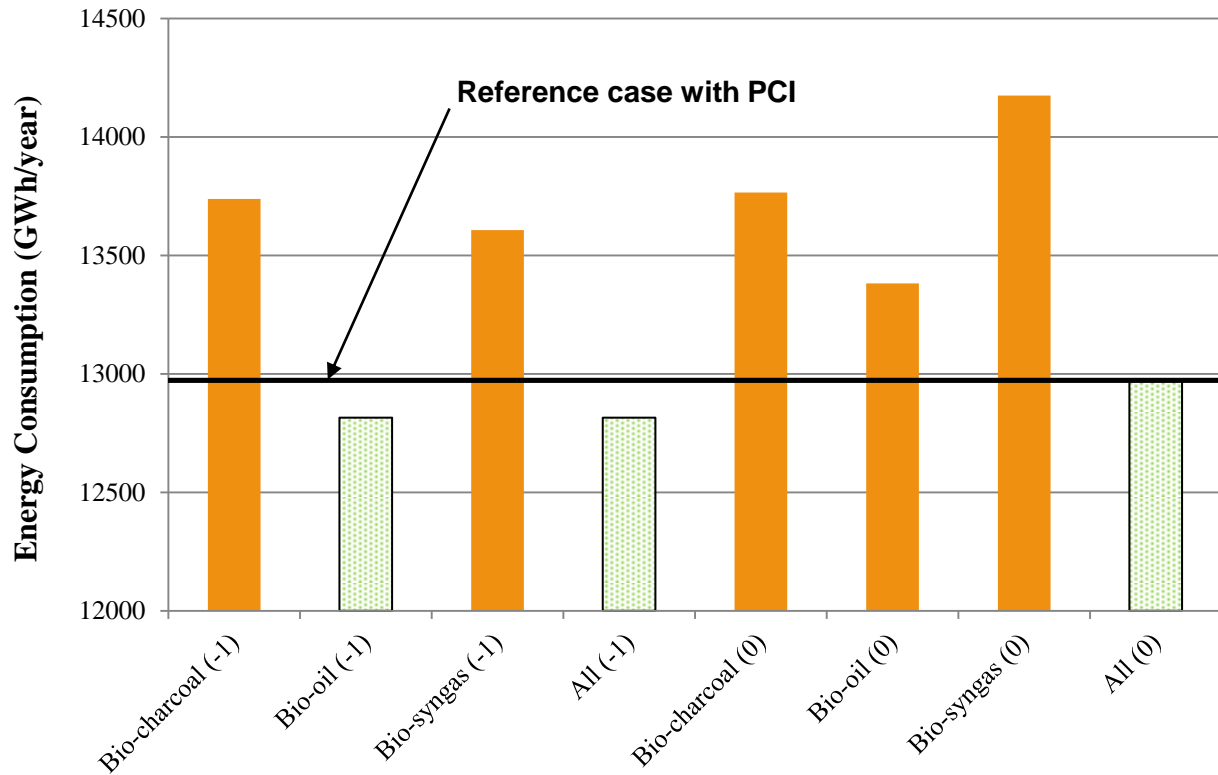


Figure 3. Comparison of different individual pyrolysis products and the optimal mixture of products for injection to BF, with (-1) and without (0) counting the energy bearing by-products. Bars below the solid line indicate an energy consumption that is equal or less than that of only using PCI.

Table 3. Summarized results of integration of a pyrolysis plant where the by-products is used (-1).

	Unit	PCI	Bio-Charcoal	Bio-Oil	Bio-Syngas	Optimal Mix ¹
Energy requirement	GWh/h	1.480	1.567	1.462	1.552	1.462
CO₂ Emissions	ton/h	456.2	437.0	447.9	456.9	447.9
PCI Reduction	%	-	15.6	7.2	0.1	7.2
CO₂ Reduction²	%	-	4.2	1.8	-0.2	1.8

¹ Optimal mixture composition: Bio-Oil

² CO₂ emission reduction is for the entire steel plant

Table 4. Summarized results of integration of a pyrolysis plant where the by-products are not used (0).

	Unit	PCI	Bio-Charcoal	Bio-Oil	Bio-Syngas	Optimal Mix ¹
Energy requirement	GWh/h	1.480	1.570	1.526	1.617	1.479
CO₂ Emissions	Ton/h	456.2	437.0	447.9	456.9	429.7
PCI Reduction	%	-	15.6	7.2	0.1	21.6
CO₂ Reduction²	%	-	4.2	1.8	-0.2	5.8

¹ Optimal mixture composition: 16% Bio-oil and 84% Bio-charcoal






² CO₂ emission reduction is for the entire steel plant

Due to the low bio-charcoal yield (20.56%) the fast pyrolysis process needs to have a high biomass capacity (amount of raw biomass in ton per hour) in order to replace a one fifth of the PCI. In this study, a 73.8 ton raw biomass per hour was estimated to be the input to the pyrolysis unit, which is clearly underestimated as the bio-charcoal generated is only a 15.6% replacement of PCI as shown

in Table 3 and Table 4. Nowadays, decentralized fast pyrolysis plants with a fluidized bed reactor can handle up to 12 ton/h [10] indicating four pyrolysis units with the similar capacity are required. However, it should be pointed out that pyrolysis plants in this commercial scale (12 ton/h) take up large space, making it difficult to build the process near existing steel plants, therefore the smart process design and knowledge from the existing plant site are necessary.

Fluidized bed reactors uses various types of natural sand i.e., SiO₂ (silica or quartz), Al₂O₃ (alumina), which is difficult to separate out from the bio-charcoal. These are certainly not inert in the BF and may cause at least increased need for limestone. Table 5 shows some commonly used fluidized bed materials from reference [11].

Table 5. Commonly used fluidized bed materials with mineral composition.

Parameter	Common fluidized materials				
	Silica/Quartz sand	Olivine	Dolomite	Sintered dolomite	γ -Alumina
					
Source	Natural	Natural	Natural	Natural	Synthetic
SiO ₂	84.0-86.0	39.0-42.0		1.0	<1.0
Al ₂ O ₃	8.0	<1.0	1.0	0.5	98.0
CaCO ₃ (*CaO)	<1.0	<1.0	58.0-59.0	58.5	-
MgCO ₃ (*MgO)	<1.0	48.0-50.0	41.0-42.0	39.5	-
Fe ₂ O ₃	8.3	8.0-10.0		0.5	<0.1
Typical formula	SiO ₂	(Mg,Fe) ₂ SiO ₄	CaMg(CO ₃) ₂	CaMg(CO ₃) ₂	Al ₂ O ₃
Suitable in FP	Yes	Uncertain	Uncertain	Uncertain	Yes
Suitable in BF	Not likely	Not likely	Yes	Yes	Not likely

Alternative bed materials [12], which are used in e.g., boiler, to prevent bed agglomeration are:

- Fe_xO_y (iron oxide)
- Calcined bauxite (mixture of Al₂O₃, Fe₂O₃, SiO₂, TiO₂, CaO)
- Limestone

The use of limestone or magnesium containing minerals would be positive for the BF as these would decrease the need for addition of flux, even though a lower liquid yield in the fast pyrolysis process is expected. At the same time a catalytic effect is possible, which alters not only the yield, but also the composition out from the pyrolysis and potentially resulting in a better quality product. As further research, the possibility to use recycled BF or BOF slag as fluid bed material should be investigated, since these slags contains similar compounds as commercial used fluid bed materials, and can in smaller quantities be recycled in the process system.

4. Conclusion

This study has investigated the potential effects to the whole iron and steel plant in terms of energy and CO₂ reduction when integrating a fast pyrolysis plant. With the assumed production capacity of the biomass pyrolysis unit, the results show a potential energy saving dependent on how the by-products from the pyrolysis are used. When by-products from the pyrolysis are used internally, for instance at the CHP plant to produce electricity and heat, the results show that it would be possible to save energy in the system by injecting bio-oil to the BF. However, if the by-products cannot be

used in such a manner due to some limitations at the site, the injection of just bio-oil would be infeasible from an energy point of view; the model would then recommend a mixture of bio-oil (16%) and bio-charcoal (84%) for BF injection. Hence, a great vigilance should be taken in how the by-products are used.

Acknowledgement

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