

Chapter 5

Optimal Resource Allocation in Steel Making Using Torrefied Biomass as Auxiliary Reductant

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Abstract Steelmaking is an energy intensive industrial sector and being largely coal-based it gives rise to 5–6 % of the global CO₂ emissions. Energy use for producing 1 ton of crude steel has been reduced by 50 % since 1975, but the annual production rate of crude steel has been increasing more strongly. Since 2002, the production rate has increased by almost 80 % amounting to 1,510 Mt in 2012, and this trend seems to continue in the future. Therefore, making the iron production itself more efficient is not enough to reduce carbon dioxide emissions. A possible remedy is to replace part of the fossil reductants by renewables and to optimize the entire production chain from ores to steel, allowing more beneficial resource allocation in the processes involved. The present study focuses on the use of biomass as auxiliary reductant in the blast furnace, also paying attention to the effect of the introduction on the material and energy flows of the whole steel plant using a simulation model. Substituting part of the fossil coke or injected hydrocarbon by biomass may result in reduced fossil carbon dioxide emissions, as long as the biomass is harvested, transported and pre-processed in a sustainable way. As the biomass may need upgrading before it is used, a torrefaction model is included in the steel plant model. Results are presented from studies where the entire system is optimized with respect to costs, considering a penalty for CO₂ emissions.

5.1 Introduction

Whether or not global warming is occurring, the concern for it has further increased public awareness of anthropogenic activities with negative impacts. Previously it was e.g. acid rains, pesticides and ozone depletion, now it is, among

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others, carbon dioxide (CO₂) emissions. Substituting some of the fossil fuels used with “sustainable biomass” can lower the fossil CO₂ emissions. The amount by which the emissions are lowered however depends strongly on harvesting methods, transport related issues as well as on processing of the biomass. Therefore, long-term impact on the environment should be considered before a certain biomass is used as a substitute fuel. In this study, the use of a variety of biomasses as auxiliary reductants in steel production is considered. For this purpose, a mathematical model is used to optimize raw material streams and process parameters in the steel plant in order to minimize production cost of raw steel, also considering costs of emissions. Before the biomass is injected in the blast furnace it is taken to be torrefied and grinded to make it suitable as an auxiliary reductant in the process.

Torrefaction of biomass includes heating in a furnace under a non-oxidizing atmosphere and at modest temperatures, i.e. ≤ 300 °C. This form of mild pyrolysis [1] can be divided into three temperature zones: light (220 °C), mild (250 °C) and severe torrefaction (280 °C) [2]. Depending on the degree of torrefaction, biomass used and residence time different ratios of condensable, non-condensable and higher quality solids are acquired. In general, a higher torrefaction temperature improves fuel quality due to increase in heating value. At the same time, however, the solids suffer from yield loss [3]. The loss of mass at light torrefaction is mainly caused by degradation of hemicellulose, whilst both hemicellulose and cellulose accounts for it at mild to severe torrefaction [2]. Lignin does not yet degrade significantly at these temperatures. Biomass and grinding data used in this study are taken from the literature, where available. Here the main focus will be on analysing the suitability of the solid fraction deriving from the different biomasses. Future work will concentrate on the energy yields of the condensable and non-condensable fractions.

5.2 Steel Plant Model

The mathematical description of the plant consists of models of the blast furnace (BF) as well as of the basic oxygen furnace (BOF), coke oven (CP), grinding unit (GU), hot stoves (HS), power plant (PP), sinter plant (SP) and a torrefaction unit (TU). These units are described below. For an indicative schematic of the system studied, please refer to [4].

A semi-linearized surrogate BF model was created using eight input values, expressing 13 outputs (Table 5.1). The input values were varied within admissible regions for a large number of experimental runs with the original, more sophisticated model [5], where only the feasible solutions were retained [3, 5]. In earlier work, this approach was made to study resource allocation in steelmaking using one type of biomass as an auxiliary reductant [4, 6]. In the present study, the model was adapted to account for different types of biomass used by redeveloping the surrogate model on a large number of (feasible) points generated by the original model.

Table 5.1 Input and output variables for BF model (where units m^3n and t_{hm} refer to normal cubic meter and ton of hot metal, respectively)

Input variable	Range	Output variable	Range
X ₁ : Blast volume	0–140 $\text{km}^3\text{n/h}$	Y ₁ : Production rate	120–160 t_{hm}/h
X ₂ : Oxygen volume	0–40 $\text{km}^3\text{n/h}$	Y ₂ : Coke rate	≥ 0 kg/t_{hm}
X ₃ : Oil rate	0–120 kg/t_{hm}	Y ₃ : Flame temperature	2,000–2,300 °C
X ₄ : Blast temperature	850–1,100 °C	Y ₄ : Top gas temperature	100–250 °C
X ₅ : Pellet rate	0–1,200 kg/t_{hm}	Y ₅ : Bosh gas volume	170–200 $\text{km}^3\text{n}/\text{h}$
X ₆ : Limestone rate	0–100 kg/t_{hm}	Y ₆ : Residence time of solids	6.0–9.0 h
X ₇ : Oxygen flow with biomass	≥ 0 kg/t_{hm}	Y ₇ : Slag basicity, $X_{\text{CaO}}/X_{\text{SiO}_2}$	1.00–1.20
X ₈ : Energy flow with biomass	≥ 0 MJ/t_{hm}	Y ₈ : Slag rate	≥ 0 kg/t_{hm}
		Y ₉ : Top gas volume	≥ 0 $\text{km}^3\text{n}/\text{h}$
		Y ₁₀ : Top gas CO content	≥ 0 %
		Y ₁₁ : Top gas CO ₂ content	≥ 0 %
		Y ₁₂ : Top gas H ₂ content	≥ 0 %
		Y ₁₃ : Heating value of top gas	≥ 0 $\text{MJ}/\text{m}^3\text{n}$

Blast furnace top gas requirement for reaching a desired blast temperature at a given blast volume is determined by the hot stoves model, which considers the stove set as a single continuous counter-current heat exchanger. The total oxygen demand is dictated by the oxygen enrichment of the blast and by the oxygen needed for steel conversion in the BOFs. Remaining BF top gases, coke oven gases and half of the BOF gas are used for steam production in the power plant. Low pressure steam from turbines is used in a condenser, providing heat for district heating. Electricity produced, but not used by the grinding unit and for compression of the cold blast, is taken to be sold to the grid. The models of the coke plant, sinter plant and BOF are simple linear models based on the overall behaviour of these units in a Finnish steel plant used as reference for this work. The power demand for grinding the pre-treated biomass is based on data from literature. Here it was available for only two of the biomasses studied, namely pine-wood chips (Bio1) and logging residue (Bio2). An approximately ten-fold reduction in power demand could be seen when the biomass was torrefied at 300 °C in comparison to oven dried mass. The grinded biomass is injected into the BF. It should be noted that injecting untreated biomass into the BF would lower the production rate and flame temperature, so some pre-treatment is needed. However, a high torrefaction temperature results in unnecessary loss of yield [4]. For the sake of simplicity, the torrefaction unit is here considered to be self-sufficient; i.e. heat deriving from combusting product gases and liquids is assumed adequate for drying and torrefying the incoming biomass. A more accurate modelling of the heat demand of the torrefaction unit will be developed in future work.

5.3 Objective Function and Simulation Setup

The objective function comprises of raw material costs, penalty fee for fossil CO₂ emissions as well as credits for electricity and district heating sold.

$$F = \left(\sum \dot{m}_i c_i + \psi \dot{m}_{CO_2} c_{CO_2} - P_{el} - \dot{Q}_{dh} c_{dh} \right) / \dot{m}_{ls} \quad (5.1)$$

where \dot{m} is the mass flow rate, c is a cost factor, ψ expresses the mass ratio of fossil versus total CO₂, P is electrical power produced (reduced by the power demand of blast compression and grinding), \dot{Q}_{dh} is the district heat and subscript ls stands for liquid steel. Raw materials indicated by i are biomass, coal, coke (external), limestone, oil, ore, oxygen, pellets and scrap iron. Due to nonlinear terms in the surrogate BF model [4], the resulting optimization problem was solved by mixed integer linear programming problem (MILP) using the CPLEX software [7].

A set of five different possible biomasses (Bio1–5) were used in this study: pine wood chips (PC) and logging residue (LR) [8], loblolly pine (LP) [9], bagasse (B) [10] and reference wood (RW) [11]. Data for these are reported in Table 5.2. The grinding energy demand of Bio1 and Bio2 is given in Table 5.3.

Torrefaction time normally ranges from a few minutes to 1 or 2 h [1, 2]. Biomass 1 and 2 had a reported torrefaction time of 30 min, whilst the following two had a torrefaction time of 2.5 and 60 min, respectively. An increase in the residence time reduces the hydrogen and oxygen content, while the carbon content is increased. It can also cause secondary reactions between volatiles and solids [1], which make comparison of the biomasses more difficult. However, many authors concluded that the effect of residence time is of less importance than that of temperature [1, 2, 12]. Another problem, pointed out by Ohlinger et al. [1], is the drying method used on the biomass samples, where, e.g., a remoistened sample could lead to modified binding forces within the sample. Therefore, the reported performance of the biomasses should be treated with certain caution. The system simulated is a steel plant with one BF and with an overall production of 160 t_q/h. The coke plant can produce 55 t/h of coke and the BF is operated with a blast temperature of 1,100 °C. Four cases were simulated, as indicated in Table 5.4. In the four cases investigated, the biomass feed rate, oxygen availability and oil rate to the blast furnace (expressed in specific quantities per ton of hot metal) were varied. Raw material prices and energy prices, as well as the carbon dioxide emission cost are given in Table 5.5.

5.4 Results

Optimization results for the cases using the biomasses are presented below, where the optimal values at lower or upper bounds are reported in bold Italic and bold Roman fonts, respectively. Table 5.6 presents results for Case 1, with and without

Table 5.2 Data for biomass used in simulations (bold font: linearized values)

	T (°C)	Bio1-PC	Bio2-LR	Bio3-LP	Bio4-B	Bio5-RW
C (%-wt)	–	47.21	47.29	50.5	46.38	50.1
	225	49.47	50.15	53.73	51.85	60.15
	250	51.46	54.91	54.44	53.04	70.6
	275	54.91	53.24	55.38	59.32	72.25
	300	63.67	66.07	57.3	65.59	73.2
H (%-wt)	–	6.64	6.2	6.26	4.68	6
	225	6.07	6.1	6.03	4.92	5.78
	250	5.86	5.87	5.98	4.97	5.2
	275	6.2	5.39	5.92	4.64	5.02
	300	5.58	4.92	5.79	4.31	4.9
O (%-wt)	–	45.76	45.19	42.6	44.11	43.9
	225	44.03	42.74	39.51	36.08	32.39
	250	42.02	40.96	38.84	34.34	24.3
	275	38.17	40.12	37.92	26.23	22.8
	300	29.99	27.34	36	18.11	21.9
HHV (MJ/kg)	–	18.46	18.79	20	18.32	20.02
	225	19.48	19.79	21.94	20.46	24.35
	250	20.08	21.21	22.36	20.94	28.12
	275	21.82	22.03	22.92	22.14	28.63
	300	25.38	26.41	24	23.37	28.91
Yield	–	100	100	100	100	100
	225	89	88	88.14	67.96	78.79
	250	82	81	85.56	60.99	65.2
	275	73	70	82.23	48.99	56.93
	300	52	52	75.9	36.98	51.4

Table 5.3 Grinding energy for Bio1 and 2

	T °C	Bio1 PC	Bio2 LR
Grinding energy (kWh/t)	–	237.7	236.7
	225	102.6	113.8
	250	71.4	110.4
	275	52	78
	300	23.9	37.6

Table 5.4 Experimental plan

Cases	1	2	3	4
Biomass (t/h)	30	15	15	15
Oxygen (km ³ n/h)	20	20	10	20
Oil (kg/t hm)	120	120	120	60

grinding for Bio1 and Bio2. This allows for a comparison of the effect of the grinding power on the optimization. For indicative top gas composition, please refer to [4].

Table 5.5 Raw material prices

Biomass	60 €/t
Ore	80 €/t
Pellets	100 €/t
Coal	145 €/t
Coke	300 €/t
Oil	150 €/t
Limestone	30 €/t
Oxygen	50 €/km ³ n
Electricity sold	50 €/MWh
District heating sold	10 €/MWh
CO ₂ tax	20 €/t
Scrap	100 €/t
Electricity bought	100 €/MWh

As seen from Table 5.6, the maximum amount of biomass (120 kg of torrefied biomass/ t_{hm}) is injected for all materials, except for Bio4 (bagasse), which is not used at all. The reason for this is its high material loss during heating. Bio5 also suffers also from low yield. However, this is compensated by its higher heating value and thus, higher energy yield. Additionally, BF operation with Bio5 uses less blast than for the other biomasses, while the oxygen enrichment is at maximum, i.e., the blast oxygen is 32 %. All samples use maximum oil input (16.8 t/h) and are also forced to use pellets (56.5 t/h), since the sinter production limit (153.6 t/h) is reached. In addition, no coke is bought for cases 1–3 nor is any limestone used in the BF. For the biomass with reported grinding energy, consideration of this only affects the production price and not the optimal operation state, since the cost is marginal. As for the production price between the biomasses, the most beneficial one is Bio5, while the most expensive alternative is to use no biomass (which was the case where Bio4 was an option).

In cases 2–3, where biomass availability is further restricted, no Bio4 is used, while the maximum amount of other biomasses (15 t/h) is utilized. In Case 2, Bio5 again requires maximum blast oxygen and the torrefaction temperature remains the same as in Case 1. Limiting the oxygen flow to 10 km³n/h (Case 3) reduces the blast oxygen content for Bio5. For Cases 2–3, the optimal torrefaction temperatures for the other biomasses (Bio1–Bio3) vary greatly compared to Case 1. Here the temperatures are much lower; Bio3 is used un-torrefied in the furnace, as is also the case for Bio1 and Bio2 when not grinded. A reason for this behaviour is the lowered amount biomass available, so a maximum or near-maximum yield is more beneficial for maximizing the objective function. As for production cost, Bio5 is no longer the most beneficial one, but instead un-grinded Bio2. In comparison, the grinded Bio2 is 1.1 (€/t_{is}) more expensive than Bio2 without grinding. Bio1 follows a similar trend. Production prices at the optimized states are shown in Fig. 5.1 (left) and biomass torrefaction temperatures for all cases in (right).

Halving the oil injection rate (Case 4) increases the production cost with all biomass alternatives, as the oil is the cheapest reductant. Surprisingly, the use of

Table 5.6 Simulation results from Case 1—Bio1 and 2 with and without Grinding (Gr.)

Case 1	Bio1 (Gr./No gr.)	Bio2 (Gr./no gr.)	Bio3	Bio4	Bio5 (ref)		
Biomass (t/h)	25	25	21	21	22	0	30
Coking coal (t/h)	60.9	60.9	59.7	59.7	65.8	77.6	61.1
Oxygen (km ³ /h)	7.3	7.3	4.9	4.9	7.6	7.5	15.7
Electricity sold (MW)	21.8	21.8	20.6	20.6	23.9	23.8	32.0
District heat sold (MW)	58.1	58.1	57.2	57.2	61.4	69.5	165.5
Fossil CO ₂ emissions (t/t _{is})	1.37	1.37	1.35	1.35	1.45	1.65	1.37
Blast volume (km ³ /h)	138.9	138.9	140.0	140.0	135.3	140.0	112.9
Pyrolysis temperature (°C)	283	283	250	250	292	272	276
Compressor power (MW)	7.4	7.4	7.6	7.6	7.2	7.4	5.9
Flame temperature (°C)	2,021	2,021	2,070	2,070	2,023	2,116	2,010
Bosh gas volume (km ³ /h)	200.0	200.0	196.7	196.7	200.0	197.7	185.0
Residence time (h)	8.8	8.8	8.9	8.9	8.5	7.6	8.9
Slag basicity (-)	1.08	1.08	1.08	1.08	1.06	1.04	1.07
Top gas temperature (°C)	246	246	243	243	231	195	209
Coke rate (kg/t hm)	250.6	250.6	244.2	244.2	274.9	333.4	251.2
Slag rate (kg/t hm)	209.2	209.2	208.7	208.7	211.0	215.2	204.8
CO ₂ emissions (€/t steel)	27.4	27.4	27.0	27.0	29.0	32.9	27.5
Liquid steel (€/t steel)	237.8	237.6	234.7	234.1	241.6	247.6	232.3
Injected biomass (kg/t hm)	120	120	120	120	120	0	120
Grinding energy (MWh)	0.7	N/A	1.9	N/A	N/A	N/A	N/A

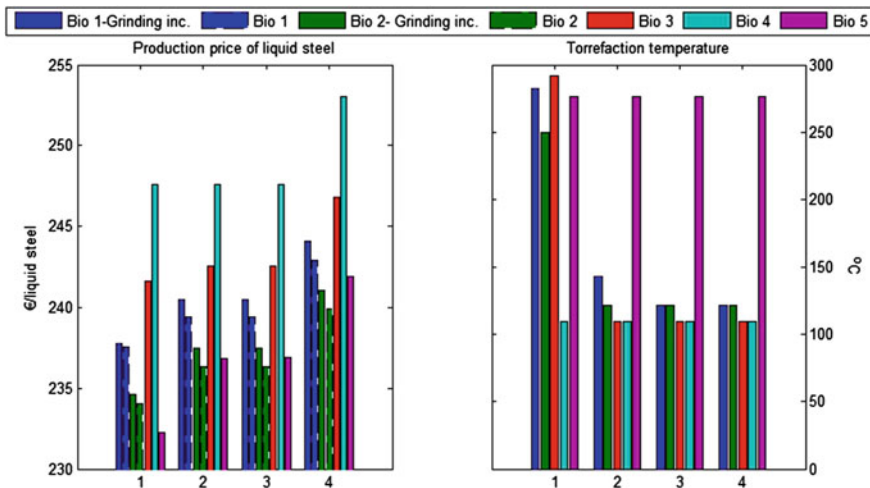


Fig. 5.1 Liquid steel production costs depending on biomass used (*left*). Biomass torrefaction temperature; Bio1 and 2 with grinding (*right*)

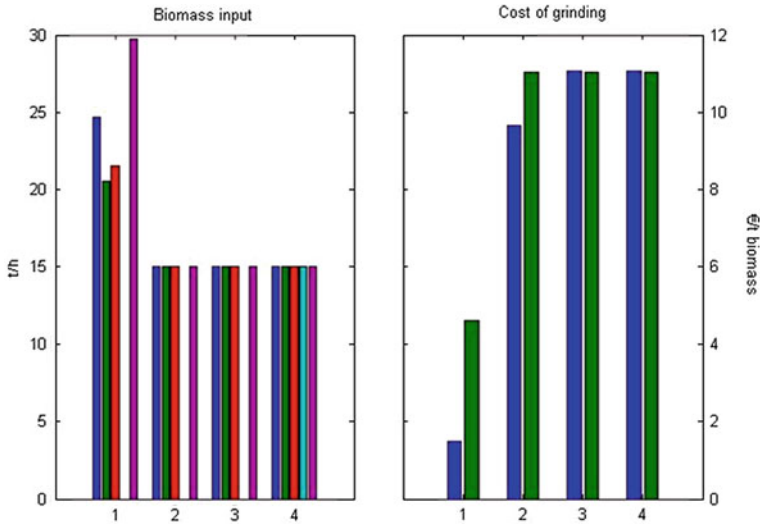


Fig. 5.2 Biomass input (*left*). Grinding costs (*right*)

bagasse (Bio4) becomes beneficial for this case. It is, like for Bio3, used untorrefied. Along with the reduction of the oil rate, external coke is needed with Bio3–Bio5, because of the restriction on own coke availability (55 t/h). This, in turn, makes it more beneficial to replace a small part of the sinter with pellets and the lower bound for slag basicity is reached (Bio3–Bio5) but no limestone addition is needed. Here Bio2 gives the lowest production costs, even when the grinding cost is included. Biomass use and grinding effect as well as costs are presented in Fig. 5.2.

5.5 Conclusion

The potential of using biomass as an injected fuel in the blast furnace of a steelmaking plant has been studied by simulation and optimization. Five different biomasses were evaluated, using four cases with constrained resources at the steel plant. The effect of torrefaction on yield and heating value determines the suitability of a biomass to be used in a blast furnace, where feasibility was expressed in economic terms, considering costs of raw materials, energy and the taxation on CO₂ emissions. The study showed that it is difficult to draw definite conclusions on the biomass which would be the most beneficial one, since the optimal choice changes with the process conditions. For instance, the use of bagasse was not economical until the oil content was severely restricted. The optimization also showed that in some cases it was better to conduct a strong torrefaction, while in other cases the use of un-torrefied biomass was optimal. Using information about

the grinding energy, available for pine chips and logging residue (Bio1 and Bio2), increased the production price in the Cases 2–4 with about 1.1 €/ton of liquid steel. Therefore, the effect of grinding should be considered, in particular since the injection of non-grinded biomass would be very challenging in practice. A crucial factor is the condensable and non-condensable fractions in the torrefaction process and their energy yields. Consideration of these is likely to affect the optimal raw material streams and production price. Additionally, they affect the dimensioning of the torrefaction unit, which, in turn, has its own limitations. These problems are to be addressed in future work.

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