1. Introduction

Steel industry contributes by about 7% of the world’s anthropogenic CO₂ emissions despite the struggles during recent years to raise the efficiency of the steelmaking processes. A fundamental problem is that the main source of emissions in the chain, i.e., the blast furnace, has already been largely optimized: The most efficient furnaces are considered to operate only 5% above the theoretical minimum in terms of reductant consumption. Global concern about the possible effects of increasing greenhouse gas concentrations in the atmosphere has made it increasingly important to evaluate different methods to suppress emissions in steelmaking, but still keeping this industry sector profitable. Major opportunities are here seen in capturing and storing the arising CO₂ emissions and in a partial replacement of the fossil sources of energy and reduction potential (coal, oil and natural gas) by biomass. This paper studies the potential of partially replacing coke with injected biomass in the blast furnace. The solution to the problem is approached by first applying a thermodynamic blast furnace model to simulate the furnace under a large number of operational states within the feasible region. Special attention is paid to the potential of preprocessing the biomass into a form better suited as injectant in the blast furnace. This processing includes biomass drying and conversion by pyrolysis, which lowers the oxygen content and increases the heating value, but naturally also decreases the yield. The resulting linear blast furnace model is, together with simplified models of the coke plant, sinter plant, hot stoves, power plant and basic oxygen furnace, finally used to find the optimal setup under different price scenarios for the raw materials, products and emissions.

2. Modeling

2.1. System Studied

The study presented in this paper concerns the part of an integrated steel works up to the basic oxygen furnace (BOF), i.e., the production of raw steel, with the main focus on the operation of the blast furnace process, as depicted in Fig. 1. The cokemaking, sintermaking, and steelmaking facilities, the hot stoves and power plant as well as the BOF are merely modelled as simple unit processes providing the required raw materials and energy for the furnace and for converting the hot metal to raw steel and the arising process gases to power and heat. These models provide information about the inflows of raw materials as well as the outflows of “products” and emissions from the system, which form the basis of an economic analysis. By contrast, the blast furnace (BF) is modelled in more detail, and the (possible) pre-treatment of biomass is also considered. The following subsections briefly outline these models.

2.1.1. Models of Coke Plant, Sinter Plant and BOF

The coke plant is simply modelled to express a conversion of the feed coal into coke and coke oven gas (COG). In terms of mass and volume flow rates, respectively, we have

\[ \dot{m}_{\text{coke}} = \xi \dot{m}_{\text{coal}}, \quad V_{\text{COG}} = \xi_2 \dot{m}_{\text{coal}} \]  

where \( \dot{m}_i \) is the mass flow rate (in t/h) of component \( i \) and \( V_{\text{COG}} \) denotes the volume flow rate (in km³/n) of purified COG that is available for the power plant.

In the sinter plant model only three main components, i.e., iron ore, coke and limestone are considered. The mass flow of resulting sinter (excluding recycled flows) is expressed as

\[ \dot{m}_{\text{sint}} = \chi_1 \dot{m}_{\text{ore}} \]
while the feed of lime and coke are given by
\[ m_{\text{coke, int}} = \chi_2 m_{\text{sint}}, \quad m_{\text{lime, int}} = \chi_3 m_{\text{sint}} \]...........(3a, b)

where \( m_{i,j} \) denotes the mass flow of component \( i \) in/for \( j \).

Thus, the internal (subscript “int”) flow of coke, available for the blast furnace, is
\[ m_{\text{coke, int}} = m_{\text{coke}} - m_{\text{coke, sint}} \]........................(4)

Furthermore, the heat (flow) recovered in the sinter plant is taken into account, and is also assumed proportional to the mass flow of produced sinter, i.e.,
\[ Q_{\text{sint}} = \chi_4 m_{\text{sint}} \].................................(5)

The basic oxygen furnace (BOF) converts the hot metal (hm) produced in the blast furnace into raw steel (rs). Neglecting other additives than scrap, which for the sake of simplicity was assumed to be pure Fe, the mass flow of raw steel and the volume flow rates of oxygen (consumed in) and off-gases (produced in) the BOF can be written
\[ m_{\text{rs}} = \varphi_1 m_{\text{hm}} + m_{\text{scrap}}, \quad V_{\text{O}_2, \text{BOF}} = \varphi_2 m_{\text{hm}}, \quad V_{\text{BOF}} = \varphi_3 m_{\text{hm}} \]...........................(6a–c)

where \( \varphi_1 \) is obtained from the iron balance equation, and \( \varphi_2 \) and \( \varphi_3 \) from the carbon balance equation.

2.1.2. Biomass Pre-processing

Wood chips, forest slash or logging residues are potential non-fossil sources of energy and reduction potential in the ironmaking process.\(^8\) However, as pointed out by other investigators\(^5\) and also demonstrated by the present authors in earlier simulation analysis,\(^7\) injection of dry wood chips results in a low coke replacement ratio. A key issue is that the high oxygen content of the biomass, combined with the low heating value, results in low flame temperature and decreased productivity. A possible remedy is to pre-process the biomass into a form that is better suited for injection into the blast furnace\(^5,6\): A (partial) pyrolysis of the biomass prior to injection would lower its oxygen content, but naturally also decreases the yield (\( \eta \)) due to loss of valuable components, such as carbon and hydrogen. The asterisks (*) in Fig. 2 illustrate a typical dependence of yield and composition on the pyrolysis temperature.\(^9\) In order to express the variables for arbitrary pyrolysis temperatures, piecewise cubic hermite interpolating functions were adapted to the values within the temperature interval \( T_{\text{pyro}}=(150^\circ \text{C}, 800^\circ \text{C}) \), resulting in the curves depicted in the figure. Furthermore, the effective heating value of the biomass (\( H_{\text{bio}} \)) was estimated from reported values and approximated as function of the pyrolysis temperature (cf. Fig. 2). For the sake of simplicity, by-products of the pyrolysis units (e.g., tar, gases) were neglected, but so was also the energy needed to maintain the elevated pyrolysis temperatures.

Fig. 1. Schematic of the system studied, enclosed by the balance boundary (thick dashed line). CP: coke oven, SP: sinter plant, ST: hot stoves, PU: biomass pyrolysis unit, BF: blast furnace, BOF: basic oxygen furnace, and PP: power plant.

Fig. 2. Temperature dependence of key variables (yield, carbon, oxygen, and hydrogen content and heating value, \( H \)) in biomass pyrolysis.
2.1.3. Blast Furnace Model

The thermodynamic first-principles blast furnace model applied \(^{10-12}\) is based on the fundamental concepts introduced by Rist et al., \(^{13}\) using a division of the process into two main control volumes, with thermal and chemical equilibrium approached on the boundary—the reserve zone—between these. Given blast parameters and specific injection rates of auxiliary reductants, the model calculates the energy input through the tuyeres as well as the raceway adiabatic flame temperature and bosh gas volume. With this information, material and energy balance equations for the lower main control volume (elaboration zone) yield the hot metal production rate and the coke rate, as well as the amount and composition the gas at the thermal/chemical reserve zone, where the temperature and fractional approach to equilibrium are user-specified parameters. Since the upper boundary conditions of the lower zone are identical with the lower boundary conditions of the upper zone, the equations for the upper control volume (preparation zone) next yield the amount, temperature and composition of the top gas. With the help of the model, it is relatively straightforward to evaluate the use of different injected reducing agents, such as biomass, if the composition and heating value are known.

2.1.4. Hot Stoves

The blast furnace combustion air, the blast, is raised to a high pressure (slightly exceeding the blast pressure) in compressors followed by heating in the stoves (Fig. 3). In modelling the compression, the blast was approximated as an ideal gas, first calculating the power requirements for isentropic compression from ambient conditions \((T_0, p_0)\) to the blast pressure \((p_{bl})\). Using an efficiency factor of the compression, the true power requirement, \(P_{bl}\), and the gas temperature after compression, \(T_{2}^{i}\), can be determined. This gas is next mixed with the added oxygen, and the temperature of the mixture, \(T_{i}\), is solved for from an energy balance equation. The hot stoves, in turn, were assumed to operate as a single continuous counter-current heat exchanger in steady state, neglecting the regenerative nature of the operation of the stoves. The heat transferred is thus given by

\[
\dot{Q}_{st} = G_{st} \Delta T_{ln} \text{ ... ...} \text{(7)}
\]

where \(G_{st}\) is the heat conductance of the stoves and \(\Delta T_{ln}\) is the logarithmic mean temperature difference from the “hot” to the “cold” side.

\[
\Delta T_{ln} = (\Delta T_{1} - \Delta T_{2})/\ln(\Delta T_{1}/\Delta T_{2}) \text{ ... ... (8)}
\]

with \(\Delta T_{1} = T_{g1} - T_{i} \), and \(\Delta T_{2} = T_{g2} - T_{l} \) referring to the temperature differences at the two ends of the hot stoves, where subscript \(g\) refers to the combustion gas (cf. Fig. 3). The gas inlet temperature \(T_{g2}\) depends on the top gas composition and the air excess ratio \((\lambda)\), while the outgoing temperatures \(T_{g1}, T_{l}\) and the heat flow \(\dot{Q}_{st}\) are solved for from the energy balance equations on the blast and gas “sides” and the transport Eq. (7). In this equation, the heat conductivity of the hot stoves, \(G_{st}\), was tuned to yield an over-all performance of the model in agreement with observed values for the plant used as reference in the study, quantified in terms of hot blast and off-gas temperatures.

The share of top gas, \(\beta\), needed for the combustion in the stoves (cf. Fig. 3) is determined so as to reach the desired blast temperature, \(T_{bl}\), of the air/oxygen mixture, considering the present composition of the blast furnace top gas.

2.1.5. Power Plant

The power \((P_{pp})\) and heat \((\dot{Q}_{pp})\) produced in the power plant were calculated by assuming a mixture of the remaining blast furnace top gas, the coke oven gas and part \((\kappa)\) of the BOF gas to be burned with a given air excess, releasing heat at high temperature for producing steam for a turbine, assuming efficiency factors in the turbine and in the generator. The low pressure steam is finally condensed, releasing heat for district heat production. The net power production of the whole system (cf. Fig. 1), \(P\), is finally obtained by subtracting the power required for compression of the blast, i.e., \(P = P_{pp} - P_{sm}\), neglecting the power requirements for raw material transportation, cooling water pumping, etc. The power and heat from the power plant simply were expressed as

\[
P_{pp} = \alpha \gamma \dot{E}_{pp}; \quad \dot{Q}_{pp} = (1 - \alpha) \gamma \dot{E}_{pp};
\]

\[
\dot{E}_{pp} = F_{COG} H_{COG} + (1 - \beta) \dot{V}_{BF} H_{BF} + \kappa \dot{V}_{BOF} H_{BOF} \text{ ... ... (9a-c)}
\]

where \(\alpha\) is the distribution factor of energy between power and heat, \(\gamma\) is the overall efficiency of the power plant, and \(H_i\) \((i = \text{BF, COG or BOF})\) is the effective heating value of each gas, respectively, and \(\kappa\) expresses the share of BOF gas recovered to the power plant.

2.2. External Raw Materials

In addition to the flows reported above, the system studied also consumes oxygen in the blast furnace, as well as pellets and (possibly) external (subscript “ext”) coke in the blast furnace. The coke flow for the blast furnace is given by

\[
m_{c, BF} = m_{c, int} + m_{c, ext} \text{ ... ... (10)}
\]

All these raw materials are produced outside the balance boundary, so they are given a fixed price paying no attention to the emissions of CO\(_2\) that arise in their production.

2.3. Linearization of the Blast Furnace Model

The thermodynamic blast furnace model was run under a large number (>300 000) of input combinations, with input
variables uniformly distributed (with 3–6 different values of each) within their admissible regions (Table 1). The feed rate of unprocessed biomass was varied between \( m_{\text{bio}} = 0 \) t/h and \( m_{\text{bio}} = 15 \) t/h, yielding different flows of processed biomass depending on the pyrolysis temperature applied; the latter was varied between 150°C (only drying, no pyrolysis) and 800°C (maximum pyrolysis). An upper limit of \( m_{\text{bio}} = 120 \) kg/t hm (where \( m_{\text{bio}} = \frac{\eta_{\text{bio}}}{m_{\text{bio}}/m_{\text{bio}}} \)) was imposed for the specific injection rate of the biomass.

Varying the model inputs independently in the simulation runs also gives rise to infeasible furnace states, e.g., with top gas temperatures well below 100°C or flame temperatures approaching the hot metal temperature, so the resulting data set was "filtered" by removing infeasible solutions. This left about 13 000 feasible solutions to be used for developing the linearized model. The linear process model is derived from the inverse of the functions depicted as curves in Fig. 2.

This left about 13 000 feasible solutions to be used for developing the linearized model. The linear process model is derived from the inverse of the functions depicted as curves in Fig. 2. The linear model

\[
y_i = K_{i,0} + K_{i,1} \frac{p_{\text{at}}}{\text{km}^3/\text{n}} + K_{i,2} \frac{p_{\text{at, BF}}}{\text{km}^3/\text{n}} + K_{i,3} \frac{m_{\text{oil}}}{\text{kg}/\text{t hm}} + K_{i,4} \frac{T_{\text{bio}}}{\text{C}} + K_{i,5} \frac{m_{\text{pel}}}{\text{kg}/\text{t hm}} + K_{i,6} \frac{m_{\text{lime, BF}}}{\text{kg}/\text{t hm}} + K_{i,7} \frac{O_{\text{bio}}}{\text{kg}/\text{t hm}} + K_{i,8} \frac{E_{\text{bio}}}{\text{MJ}/\text{t hm}} \]
\]

predicts thirteen central BF quantities, \( y \), listed in Table 2. Note that the specific mass of ore was not included as an input in Eq. (12) since the specific pellet rate implicitly fixes the sinter rate through the Fe balance equation.

2.4. Emissions of CO₂ from the System

With the models outlined in the subsections above, the total CO₂ emissions from the system can be expressed as a function of the difference between the carbon input and output, where the latter only includes the carbon in the raw steel after the BOF. This gives for the total mass outflow rate of carbon dioxide

\[
m_{\text{CO}_2} = \frac{44}{12} (m_{\text{coal}} X_{\text{C,coal}} + m_{\text{lime}} X_{\text{C,lime}} + m_{\text{oil}} X_{\text{C,oil}} + m_{\text{c,ext}} X_{\text{C,ext}} + m_{\text{bio}} X_{\text{C,bio}}) \]  
(13)

where the total inflow of limestone is given by

\[
m_{\text{lime}} = m_{\text{lime,sim}} + m_{\text{lime,BF}} \]  
(14)

and \( X_{C,i} \) expresses the mass fraction of carbon in component \( i \). Note that this includes the emissions from the power plant, which is fed by the gasses from processes in the system, but neither from the oxygen plant nor pellet plant, which are external units.

3. Objective Function

The task of finding the optimal state of operation of the system was tackled by minimizing the specific costs of raw steel production with respect to the eight inputs variables of the BF model. The use of scrap in the BOF was not optimized but instead fixed at 25% of the hot metal flow. The economic objective function \( F \), expressed in specific terms (i.e., per tonne raw steel), is given by

\[
F = \frac{m_{\text{ore}}}{\text{t}} \frac{c_{\text{ore}}}{\text{t}} + \frac{m_{\text{pel}}}{\text{t}} \frac{c_{\text{pel}}}{\text{t}} + \frac{m_{\text{coal}}}{\text{t}} \frac{c_{\text{coal}}}{\text{t}} + \frac{m_{\text{c,ext}}}{\text{t}} \frac{c_{\text{c,ext}}}{\text{t}} + \frac{m_{\text{bio}}}{\text{t}} \frac{c_{\text{bio}}}{\text{t}} + \frac{m_{\text{lime}}}{\text{t}} \frac{c_{\text{lime}}}{\text{t}} + \frac{m_{\text{scrap}}}{\text{t}} \frac{c_{\text{scrap}}}{\text{t}} + \frac{p_{\text{O}_2}}{\text{km}^3/\text{n}} \frac{c_{\text{O}_2}}{\text{t}} + \frac{m_{\text{CO}_2}}{\text{t}} \frac{c_{\text{CO}_2}}{\text{t}} - \frac{P}{\text{MW}} \frac{c_{\text{el}}}{\text{t}}
\]
where the total inflow of pure oxygen and the outflow of district heat are

\[ \dot{V}_{O_2} = \dot{V}_{O_2, BF} + \dot{V}_{O_2, BOF} \] \hspace{1cm} (16)

\[ Q_{\text{sh}} = Q_{pp} + Q_{\text{dist}} \] \hspace{1cm} (17)

and \( c_i \) express specific or volumetric cost terms. Note the negative signs of the last two “credit” terms in Eq. (15) for the produced electricity and heat. No credit was here given for the production of slag. As for the cost of emissions, a factor \( \psi \) was introduced expressing the share of \( \text{CO}_2 \) emissions originating from fossil sources, calculated from the carbon inputs as

\[ \psi = \frac{m_{\text{coal}} X_{\text{coal}} + m_{\text{coke, ext}} X_{\text{coke}} + m_{\text{sint}} X_{\text{sint}} + m_{\text{bio}} X_{\text{bio}}}{m_{\text{coal}} + m_{\text{coke, ext}} + m_{\text{sint}} + m_{\text{bio}}} \] \hspace{1cm} (18)

Also note that no operation costs were included for the unit processes in the system.

The optimization task was solved as a nonlinear programming problem, constraining the search by the box constraints of the input and output variables (Tables 1 and 2) as well as by upper limits on some of the raw materials (e.g., internal coke, sinter and biomass, cf. Table 1).

4. Results

The optimization study presented in this section is based on the price structure of raw materials given in Table 3, applied to a steel plant with one 1 100 m\(^3\) blast furnace. The production rate of interest was varied between 140 and 185 t rs/h, where the latter value is very close to the upper feasibility limit of the system; for higher productivities it was impossible to find a feasible point for the BF within the variable bounds (Tables 1 and 2). In order to study the effect of future energy and emission scenarios, different values for the price of biomass and emissions were used. The model parameters of Eqs. (1)–(3), (5), (6) and (9) were \( \xi_1 = 0.695, \xi_2 = 319.7 \text{ m}^3 \text{ n} / \text{ t}, \chi_1 = 1.042, \chi_2 = 0.0460, \chi_3 = 0.0714, \chi_4 = 85.12 \text{ MJ} / \text{ t}, \varphi_1 = 0.8953, \varphi_2 = 45.62 \text{ m}^3 \text{ n} / \text{ t}, \varphi_3 = 41.48 \text{ m}^3 \text{ n} / \text{ t}, \kappa = 0.5, \gamma = 0.83 \text{ and } \alpha = 0.2, \) and the effective heating values of coke oven and basic oxygen gas used were 16.8 MJ/m\(^3\) and 11.4 MJ/m\(^3\), respectively.

4.1. Optimal Solutions under Different Production Rates

An analysis of the optimization results for production rates in the range 140–185 t rs/h revealed that there were local minima in the price of raw steel that corresponded to different degrees of pre-treatment of the biomass. These solutions were found at the minimum pyrolysis temperature (150°C, i.e., no pyrolysis) as well as at some intermediate temperatures (approx. 250°C and 425°C). However, the global optimum always corresponded to injection of biomass pre-treated at intermediate temperatures or to operation without biomass. Thus, the high carbon content and heating value achieved at maximum pyrolysis (here 800°C) do not compensate for the yield loss (cf. Fig. 2) enough to make this a solution. Another general finding was that the specific oil injection rate is maximum (\( m_{\text{oil}} = 122 \text{ kg} / \text{ t} \text{ hm} \)) in all solutions for which \( \dot{m}_{\text{coal}} > 150 \text{ t} / \text{ s} \).

The optimal raw steel price for different price levels of biomass (\( c_{\text{bio}} = 20–110 \text{ €} / \text{ t} \) with steps of 30 €/t) and emissions (\( c_{\text{CO}_2} = 0–60 \text{ €} / \text{ t} \) with steps of 20 €/t) is illustrated in Fig. 4 with solid lines, while the raw steel price for biomass-free operation is depicted by dashed lines. It is interesting to note that a minimum occurs in the raw steel price for operation without biomass. For a low biomass price and/or high emission costs a clear economic advantage is seen in biomass injection, but also more moderate alternatives seem economically feasible. For instance, with \( c_{\text{bio}} = 80 \text{ €} / \text{ t} \) and today’s price of \( \text{CO}_2 \) emissions (\( c_{\text{CO}_2} = 20 \text{ €} / \text{ t} \)), the price advantage of biomass injection varies between 2.3 €/t rs and 6.1 €/t rs, with the maximum advantage at a production rate of \( \dot{m}_{\text{rs}} = 180 \text{ t} / \text{ s} \), corresponding to an annual saving exceeding 9 M€. At high biomass price and low emission price, however, biomass injection brings about no economic advantage at low production rates, and only marginally better economy at high production rates. The dramatic rise in the price of steel above \( \dot{m}_{\text{rs}} = 182 \text{ t} / \text{ s} \) produced with injection of biomass is due to the fact that external coke must be used (cf. Subsec. 4.2).

Figure 5 depicts the specific injection levels of biomass corresponding to the optimal solutions presented in Fig. 4, illustrating a quite regular behavior for most cases, with a few exceptions. In general, the biomass feed rate is maximum, but drops dramatically as the maximum production rate is approached. However, the cases with high biomass price and low emission costs exhibit different patterns, partly due to regions where the optimal pyrolysis temperature is approximately 425°C, and some of the cases with high levels of both biomass and emissions lack the abrupt drop in injection rate at high productivity.

In order to comprehensively illustrate the different local optima and their relation to the best solution and to the economy of biomass-free operation, the following approach was made: The pyrolysis temperature was fixed at a number of levels corresponding to the values at the local minima encountered, and the remaining variables were optimized to find the states with minimum costs. Figure 6 illustrates the raw steel price at different production rates, biomass price

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**Table 3.** Costs in the objective function, Eq. (15).

| Term     | Value    |
|----------|----------|
| \( c_{\text{cm}} \) | 80 €/t   |
| \( c_{\text{cp}} \) | 100 €/t  |
| \( c_{\text{cont}} \) | 145 €/t  |
| \( c_{\text{coke, ext}} \) | 300 €/t  |
| \( c_{\text{oil}} \) | 150 €/t  |
| \( c_{\text{ns}} \) | 30 €/t   |
| \( c_{\text{bio}} \) | 50 €/km³/n |
| \( c_{\text{temp}} \) | 100 €/t  |
| \( c_{\text{ed}} \) | 50 €/MWh  |
| \( c_{\text{hs}} \) | 10 €/MWh  |
and emission costs for four different cases: 1) No biomass injection (dashed-dotted line), injection of biomass pretreated 2) at 150°C (dashed line), 3) at 250°C (solid line), and 4) at 425°C (dotted line). The figure illustrates that operation under case 3) yields the lowest cost, but also that the margin is small if the biomass price is high ($c_{\text{bio}}/\text{t}$) unless the emission costs are considerably higher than today. Another fact worth noting is that injection of biomass pyrolysed at 425°C (Case 4) yields an auxiliary reductant of sufficient quality for operation within the whole production range, which is seen in a rather stable raw steel price, but higher than in Case 2. Finally, it may be noted that the injection of unpyrolysed biomass is (usually) more economical than operation without biomass injection, but...
the advantage is usually marginal.

In summary, the results presented above illustrate that the most economic use of biomass requires pyrolysis of it at an intermediate temperature prior to injection into the blast furnace.

4.2. Optimal Solutions under Different Price of Biomass and Emissions

The results can also be analyzed from another point of view by keeping the production rate fixed and varying the biomass price and the price of emissions. Since biomass injection is most beneficial at high steel production rates, only the case with a production rate of 180 t rs/h (corresponding to 157.2 t hm/h in the blast furnace) is studied in this subsection.

Figure 7 illustrates the optimal feed rate of biomass (top row), the pyrolysis temperature, the specific biomass injection rate and the economic advantage of biomass injection (bottom row), where the last variable corresponds to the price difference in the raw steel production costs for operation without and with biomass. For all the cases studied, the optimal preprocessing temperature is $T_{\text{pyro}} = 250^\circ C$ whenever biomass is injected, giving a yield of $\eta = 65.2\%$ (cf. Fig. 2). For a low biomass price it is always optimal to use the maximum allowable feed flow of biomass (15 t/h), giving a specific injection rate of $15 \text{ t/h} \times 0.652/157.2 \text{ t/hm} = 0.62 \text{ kg/t hm}$. As the price of biomass is increased, a threshold value is encountered, where the optimal feed rate is reduced to $m_{\text{bio}}^{\text{opt}} = 10.5 \text{ t/h}$. This corresponds to the point of operation where the use of internal coke is increased to its maximum value (55 t/h), which thus implies the point where biomass injection becomes less economical than the usage of coke from the own coke plant. As the biomass price is increased 35–50 €/t beyond this point, the optimal injection rate suddenly drops to zero. This is the point where biomass injection becomes less economical than using external coke. These transitions obviously also depend on the price of emissions. The decrease in the declination rate of the economic advantage ($\Delta F$) observed at the first transition point is due to the lower biomass injection rate above this point.

A more detailed view of the process conditions is presented in Table 4, which reports some key variables at the optimal state of the system for some price levels of biomass, $c_{\text{bio}} = 100$ €/t, 150 €/t and 200 €/t, which correspond to the three levels of biomass injection seen in Fig. 7. The first of these applies maximum biomass feed (15 t/h) and maximum blast oxygen content (32%), and gives rise to a specific emission of 1.49 tons of fossil carbon dioxide per ton of raw steel. A biomass price increase to 150 €/t lowers the injection level by almost 20 kg/t hm and increases the coke rate by 12.4 kg/t hm. For the highest biomass price, no biomass is fed to the system and the specific fossil CO2 emissions increase to 1.61 t/t rs. The raw steel is now about 4.5 €/t more expensive than in the first case, due to the clearly higher coke rate and the higher costs of CO2 emissions.

Summarizing the findings concerning the transition points observed, where it becomes more economical to use coal or external coke than biomass, respectively, the following approximate expressions can be derived from the results:

$$c_{\text{bio}}^* = \begin{cases} 0.603c_{\text{coal}} + 1.632c_{\text{CO}_2} + 0.009m_{\text{cs}} & \text{if } m_{\text{cs}} < 170 \text{ t/h} \\ 1.464c_{\text{coal}} + 1.573c_{\text{CO}_2} - 0.696m_{\text{cs}} & \text{if } m_{\text{cs}} > 175 \text{ t/h} \end{cases}$$

(19)
Thus, at low productivity, the biomass price should not exceed 60% of the price of coking coal to be economical if the emissions are free, and at increased production rates the biomass price is allowed to be a few €/t higher. Equation (20), in turn, implies that the biomass price should be less than 45% of the price of external coke if the emissions are free. As for the effect of the emission price, the biomass price is allowed to increase by about 1.5 €/t for every 1 €/t increase in $c_{CO2}$.

5. Conclusions and Future Work

The use of biomass in steelmaking has been seen as a potential way of reducing harmful CO2 emissions from this industry sector. This paper has mathematically analyzed the economy of injecting dry biomass, in unprocessed or processed form, into the blast furnace, considering costs of raw materials, energy and CO2 emissions of the unit processes up to the basic oxygen furnace. The results clearly demonstrate that injection of biomass may be economical if its price is below a certain share of the coal (or coke) price, and this critical ratio increases with the emission price. The study also indicated that pre-processing of the biomass is necessary. This is due to the fact that a high productivity of the blast furnace cannot be reached with injection of an auxiliary reductant with high oxygen content and low heating value. The optimal degree of pre-treatment was found to correspond to a pyrolysis temperature of about 250°C, where this auxiliary reductant has achieved a...
higher carbon content and heating value without excessive yield loss. The present study did not optimize the whole integrated steel plant but only the units up to the basic oxygen furnace, and, e.g., the use of scrap in the BF and BOF was not optimized. It would be natural to include such decisions in the present model, and simultaneously also consider energy requirements of the oxygen plant and rolling mill. Aspects concerning the process technology and economy of the biomass pyrolysis unit, including the production of tar and off gases, as well as the drying, combustibility and grindability of the biomass should also be evaluated in more detail in the future.

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Nomenclature

\( c \): Cost factor (€/t, €/km³ or C/MWh)
\( B \): Slag basicity (\( = \frac{X_{CaO}}{X_{SiO_2}} \))
\( E \): Energy (MJ/t hm), Eq. (15)
\( F \): Energy flow (MW)
\( G \): Economic objective function (€/t rs)
\( H \): Heat conductivity (MW/°C)
\( K \): Effective heating value (MJ/kg or MJ/nm³)
\( m \): Mass flow rate (t/h)
\( O \): Biomass oxygen (kg/t hm)
\( p \): Pressure (kPa)
\( P \): Electric power (MW)
\( E_0 \): Energy (MJ/t hm), Eq. (15)
\( T \): Time (s, h)
\( T \): Temperature (°C)
\( V \): Volume flow rate (km³/h)
\( x \): Input variable in linear BF model, Eq. (12)
\( y \): Output variable in linear BF model, Eq. (12)
\( x \): Mass ratio
\( \alpha \): Parameter in Eq. (9)
\( \beta \): Share of BF gas burned in the hot stoves (Fig. 3)
\( \chi \): Parameters in Eqs. (2), (3), (5)
\( \Delta \): Difference operator
\( \gamma \): Overall power production efficiency, Eq. (9a, b)
\( \eta \): Pyrolysis yield
\( \varphi \): Parameters in Eq. (6)
\( \kappa \): Share of BOF gas burned in power plant, Eq. (9c)
\( \lambda \): Air excess ratio in combustion (Fig. 3)
\( \xi \): Parameters in Eq. (1)
\( \psi \): Share of fossil carbon in carbon input, Eq. (18)
\( \tau \): Residence time of burden (h)

Greek

\( \alpha \): Parameter in Eq. (9)
\( \beta \): Share of BF gas burned in the hot stoves (Fig. 3)
\( \chi \): Parameters in Eqs. (2), (3), (5)
\( \Delta \): Difference operator
\( \gamma \): Overall power production efficiency, Eq. (9a, b)
\( \eta \): Pyrolysis yield
\( \varphi \): Parameters in Eq. (6)
\( \kappa \): Share of BOF gas burned in power plant, Eq. (9c)
\( \lambda \): Air excess ratio in combustion (Fig. 3)
\( \xi \): Parameters in Eq. (1)
\( \psi \): Share of fossil carbon in carbon input, Eq. (18)
\( \tau \): Residence time of burden (h)

Subscripts

\( \text{air} \): Air
\( \text{BF} \): Blast furnace
\( \text{bio} \): Biomass
\( \text{bg} \): Bosh gas
\( \text{bl} \): Blast

\( \text{BOF} \): Basic oxygen furnace
\( \text{C} \): Carbon
\( \text{coal} \): Coking coal
\( \text{CO} \): Carbon monoxide
\( \text{COG} \): Coke oven gas
\( \text{CO}_2 \): Carbon dioxide
\( \text{coke} \): Coke
\( \text{dh} \): District heat
\( \text{el} \): Electricity
\( \text{ext} \): External (coke)
\( \text{fl} \): (Raceway adiabatic) flame
\( g \): Combustion gas

\( \text{H}, \text{H}_2 \): Hydrogen
\( \text{heat} \): Heat
\( \text{hm} \): Hot metal
\( i \): General index
\( \text{int} \): Internal (coke)
\( j \): General index
\( \text{lime} \): Limestone
\( \ln \): Logarithmic mean value
\( \text{O}, \text{O}_2 \): Oxygen
\( \text{oil} \): (Heavy) oil
\( \text{ore} \): Ore
\( \text{pel} \): Pellet
\( \text{pp} \): Power plant
\( \text{pyro} \): Pyrolysis
\( \text{rs} \): Raw steel
\( \text{scrap} \): Scrap
\( \text{sint} \): Sinter
\( \text{slag} \): Slag
\( \text{st} \): Hot stoves

\( \text{stoich} \): Requirement for stoichiometric combustion conditions

Superscript

\( ** \): Values at transition

A dot above a symbol denotes a flow rate.

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