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Research paper

Economic assessment of options for biomass pretreatment and use in the blast furnace

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ABSTRACT

The steel industry still strongly relies on fossil sources of reductants and energy and a considerable part of the global carbon dioxide emissions therefore derives from this industrial sector. Plausible remedies to reduce the emissions are to minimize raw material use and to shift to using renewable energy sources. This paper investigates computationally the options of using biomass as an auxiliary reductant in the blast furnace, and the required pre-processing steps, focusing on energy use and process economics. In order to evaluate the economic feasibility, the problem is tackled as a process optimization task, minimizing the operation costs under different biomass preheating strategies. The paper provides a comparison between two preheating concepts, namely utilization of heat from hot stove flue gases or from combustion of blast furnace top gas. The use of hot stove flue gases reduces the annual operating costs of the preheating by about 0.5 M€ for a plant with a yearly steel production of 1.4 Mt.

1. Introduction

There is a common consensus in the scientific community that the CO_2 emissions are a major reason for the observed global warming. Pressure from society has therefore forced companies, entrepreneurs and communities to consider the carbon footprint of their activities. The steel industry has a large impact, with its annual CO_2 emissions comprising 6.8% (2010) of the total global CO_2 emissions [1] equaling a total of 20% of the CO_2 emissions deriving from the industry [2]. Therefore, reductions in the specific energy consumption, or a partial conversion to using renewable sources of energy and reductants, could help make this industrial production more sustainable.

Biomass is considered as a suitable substitute for fossil fuels due to its renewability and partial CO_2 neutrality [3]. A requirement, however, is that the biomass is harvested in a sensible way in order to avoid extensive environmental problems, such as erosion [4]. Additionally, the entire production chain should be considered both from an environmental and economic perspective when evaluating the feasibility of biomass use as a substitute fuel [5]. A common consensus seems to be that the biomass should be converted before use [2–4,6,7]. One way is by torrefaction, a mild form of pyrolysis [8,9], where the biomass is heated under a non-oxidizing atmosphere at modest temperatures ($\leq$300 °C). Products from this process can be divided into solid, liquid and gas [7,9]. This procedure improves fuel quality due to an increase in carbon content and heating value at the expense of solid yield [10]. At the same time the fuel becomes hydrophobic and easier to grind [9]. According to Phanphanich and Mani [11] torrefaction of wood at 300 °C lowers the energy demand for grinding to one tenth of what would be required with untreated wood. The composition of wood has also a significant effect on grindability. For instance, Tran et al. [9] found that the grinding time for torrefied stump wood was much longer than the corresponding times for torrefied samples of poplar and fuel chips and suggested that this was due to the higher lignin content of the stump wood. However, despite the benefits of increasing temperature it is not necessarily beneficial to progress in the fuel conversion if the product is to be used in iron making as an auxiliary reductant: The increase in heating value and carbon content may be compromised by yield loss, and the resulting decrease in hot metal productivity when a poor reductant is injected can be compensated for by oxygen enrichment of the blast furnace (BF) combustion air, *blast* [10,12].

Several suggestions have been made on biomass use in iron making. For instance Emmerich and Luengo [13] found babassu charcoal suitable for use in Brazilian iron making, due to its high mechanical strength, which is caused by its endocarp or hard inner woody layer with longitudinal fibres and high lignin content.

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Usually, however, the mechanical strength of charcoal is inadequate to be used directly as a burden material in the blast furnace [14], except in small furnaces no larger than 600 m^3 [2]. An option is to co-inject coal and charcoal [15], only charcoal [2,4,14] or less converted charcoal [6,10,12,16–18] into the furnace through the tuyeres. Pelletizing charcoal or mixing it with iron ore for burden feed has also been suggested [2]. Additionally, it should be possible to mix up to about 5% of charcoal with coal in coke production without degrading the coke quality [19]. Other benefits of using charcoal instead of fossil coal, besides that the fossil CO_2 emission are reduced, are lower ash-, sulphur- and phosphorus contents as well as a resulting reduction in the slag rate [2].

The Nordic countries have vast forests. In Finland forests cover 75% [20] of the total land area and in Sweden this figure is 69% [21]. Residues from forestry, such as logging residues, stumps and small diameter wood, as well as stem wood with quality problems, are potential sources of biomass fuels. In 2006 the theoretical logging residual potential in Finland was estimated to be around 16.2 TWh, while in 2020 it is estimated to be in the range of 23.7–31.5 TWh [19]. Although there seems to be an installed capacity in Finnish heat and power plants to utilize 27 TWh of forest chips by 2020, Suopajärvi et al. [19] concluded that in accordance to techno-ecological potential estimations there would be an excess of forest chips available near the steel plants in Finland. However, it was estimated that raw material costs of delivered biomass would be 188 € t^{-1} charcoal and total production costs of charcoal in developed countries, accounting for the entire supply chain, would rise to 268–478 € t^{-1} charcoal. A conservative estimate would yield a charcoal price of 400 € t^{-1} in Finland. Considering the prices of coal and oil, the breakeven points with a penalty fee for fossil CO_2 emissions would be around 31 and 47 € t^{-1} when replacing injected oil and coal by charcoal, respectively [19]. This estimate is, however, based on the assumption of a low production yield, i.e. 6.7 tonne of raw material (at 50% water mass fraction) to produce 1 tonne of charcoal. Feliciano-Bruzual [2] reported similar charcoal prices, ranging from 210 to 450 € t^{-1} (using the exchange rate 1 US$ = 0.79 €). Here the highest prices were in Europe, where at the moment the charcoal production is very small. Mobini et al. [3] on the other hand looked into the possibility of integrating torrefaction into wood pellet production and also assessed the distribution supply chain. In the case study a 20 t h^{-1} conventional pellet plant was selected with a yield loss of 21.5% with pellet torrefaction. He found out that the supply chain CO_2 emissions and energy consumption from British Columbia in Canada to an international port in North Vancouver (840 km by rail) were 27 g kWh^{-1} and 12.7% of the total energy for regular pellets, while for torrefied pellets these were 24 g kWh^{-1} and 11.3%, respectively [3]. A steel plant that replaces 100 kg of pulverized coal injection (PCI) per tonne hot metal by 100 kg of charcoal per tonne hot metal experiences an increase in coke consumption of around 18 kg per tonne hot metal. Emission-wise this means a reduction of approximately 300 kg of CO_2 per tonne hot metal. For the example above the real reduction in fossil CO_2 emissions is about 5% less when supply chain emissions and energy consumptions are accounted for. This simple example illustrates how the true CO_2 emissions might look like when emissions arising in the transportation are accounted for. Reported total product costs for regular and torrefied pellets [3], when delivered to Rotterdam in Europe, were 119 € t^{-1} and 139 € t^{-1} (using the exchange rate 1 CAN$ = 0.7 €), respectively. In terms of energy the costs were 7.7 € GJ^{-1} for regular and 7 € GJ^{-1} for torrefied pellets, respectively. The investment costs for a 20 t h^{-1} pellet mill was estimated to be 14.0 M€ and costs for the torrefaction process were estimated to be 13.7 M€.

It may be motivated to consider an integration of the biomass drying and torrefaction units with a steel plant, since this could reduce or even remove the need of additional fuels otherwise needed for these processes given that there are residual sources of heat available at the steel plant. In earlier work [22–24] the present authors studied computationally the option of using biomass in ironmaking by optimizing raw material streams and process parameters of the steel plant with respect to operating costs. The work focused on an evaluation of how to optimally distribute resources between multiple furnaces under different operation and external constraints. Carbon dioxide emissions deriving from fossil fuels were subjected to a penalty fee, which was also included in the objective function, while the biomass was, for the sake of simplicity, assumed to be carbon neutral. It was concluded that a limited amount of pre-treated biomass could be injected into the BF as an auxiliary reductant without endangering the production process.

The present study will mainly focus on the energy consumption in drying of the incoming biomass, which is torrefied in a subsequent process step. Heat for drying is provided either by using flue gas from the hot stoves (regenerative heat exchangers for preheating the combustion air, blast, for the BF) or by combustion of BF top gas, or a combination of both. In Section 2 of the paper, the steel plant unit process models are briefly outlined, including the biomass torrefaction unit, followed by a description of the optimization problem that is stated. Section 3 describes the dryer design and the implications of using the different gases as heat sources for it. In the fourth section, the numerical experiments are presented, and in Section 5 the results of the optimization of the steel plant with respect to the economic objective are given. The implications of the optimized states on the CO_2 emissions of the plant are also discussed. Finally, Section 6 presents concluding remarks and proposes some directions of further investigations.

2. The system

The steel plant system with its unit processes is briefly outlined in the next subsection, including the biomass torrefaction and grinding units, and in subsection 2.2 the optimization problem is formulated.

2.1. Unit process models in the steel plant

The steel plant system considered here is composed of multiple units: coke plant (CP), sinter plant (SP), blast furnace (BF), hot stoves (HS), basic oxygen furnace (BOF), power plant (PP), biomass drying unit (DU), torrefaction unit (TU) and grinding unit (GU). The mathematical models of these are briefly described in the Appendix. The surrogate model of the blast furnace used in the work is largely based on the model presented by Helle et al. [10,25], where eight input values are used, expressing 13 outputs (see Table 1). The models of CP, SP and BOF are simple linear ones that are based on the overall behavior of these units in a Finnish steel plant used as reference. In spite of the fact that no sinter plant is used at the moment in Finland, such iron ore agglomeration units are frequently used elsewhere in steelmaking plants and it was here used to allow for comparison with earlier results by the authors [22–24]. The oxygen demand of the plant is determined by its requirement in the BOF and its use as enrichment of the blast. Both depend strongly on the steel production rate. The hot stove set is approximated as a single continuous counter-current heat exchanger and is fired by BF top gas. Electricity is produced in the power plant with turbines using high pressure steam, which is produced using the heat from combustion of the (remaining) BF top gas, coke oven gas and half of the BOF gas. The reason for not using all BOF gas is that this would require large gas holder capacity due to intermittent operation of the converters. The low pressure steam