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Steelmaking Integrated with a Polygeneration Plant for Improved Sustainability

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In this study, a process integration approach was used to investigate process economics and carbon dioxide emissions from a steelmaking plant. The suggested superstructure includes the main process units in steelmaking and a polygeneration system producing methanol, heat and electricity. In the steel plant, advanced blast furnace technologies such as top gas recycling and cold oxygen injection have been implemented. The effect of partially replacing of coke with alternative fuels with lower carbon barrier, such as oil, natural gas and biomass on liquid steel production cost and carbon dioxide emission from the integrated plant has been investigated. The results of the analysis demonstrate that an integration of steelmaking with a polygeneration system could increase the total energy efficiency and decrease the emissions of the system. The combinations of technologies and alternative fuels were found to reveal potential paths towards more sustainable steelmaking concepts.

1. Introduction

Steelmaking is a very energy intensive sector and as the sources of reduction potential and energy are mainly coal-based, it contributes to about 5 % of the global anthropogenic CO_2 emissions. It can be anticipated that the CO_2 emissions from the steel industry will increase further along with the growth of crude steel production, unless significant changes in the current process route, energy efficiency or some effective CO_2 emission reduction technologies can be implemented. It is therefore imperative to find novel process routes (Chakraborty et al., 2004) or new ways to fully utilize the carbon in the system and/or to replace part of it by renewable reductants.

To achieve a more sustainable steel production, there are approaches to reduce emissions in the short term such, as using more hydrogen-bearing reductants (e.g., natural gas, which reduces the coke consumption and increases furnace productivity) (Nogami et al., 2006) or increasing the energy efficiency of the unit processes. Long-term approaches include the substitution of fossil fuels with non-fossil sources of energy (e.g., biomass), integration of steelmaking with other chemical processes (such as polygeneration system and carbon capturing and sequestration plants) (Birat, 2009;Yagi and Akiyama, 2000), and conceptual design of novel steelmaking routes(Ariyama et al., 2005). In general, emission reduction strategies are complex due to several dependent and self-determining variables, such as production demand, availability of resources and technologies, energy efficiency, world economics, government and global policies, etc.

In the previous works, the blast furnace (BF) operation under top gas recycling with hot blast oxygen enrichment, cold oxygen injection and alternative auxiliary fuels in an integrated steelmaking plant has been considered.(Ghanbari et al., 2011; Ghanbari et al., 2012). In the present study, a comparison between steel cost and fossil-based carbon dioxide emission from the integrated plant with and without partial replacement of coke with other reductants in blast furnace has been made by minimizing liquid

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steel (ls) cost under realistic process and raw material supply constraints for blast furnace operation with top gas recycling and cold oxygen injection.

2. Process Description

The system studied in this work is shown in Fig. 1: It includes an integrated steelmaking plant with coke production, a sinter plant for producing the agglomerated iron ore, a blast furnace for reduction and melting, hot stoves for heating of the blast furnace combustion air (blast), and a basic oxygen furnace where the liquid iron is converted to steel (after some scrap addition). Secondary steelmaking units (ladle treatment and casting) as well as the rolling plant are left outside the present study. Furthermore, the system includes a combined heat and power (CHP) plant producing district heat and electricity. The above mentioned units are modelled in accordance with the conditions at a Finnish reference plant, which also specify the constraints to be imposed in the numerical treatment. (Helle et al., 2009;Helle et al., 2011) In addition to these conventional units, an air separation unit, a carbon capturing and sequestration unit, a biomass pyrolysis unit (optional) and a methanol synthesis plant are included in the system of this study.(Ghanbari et al., 2012)

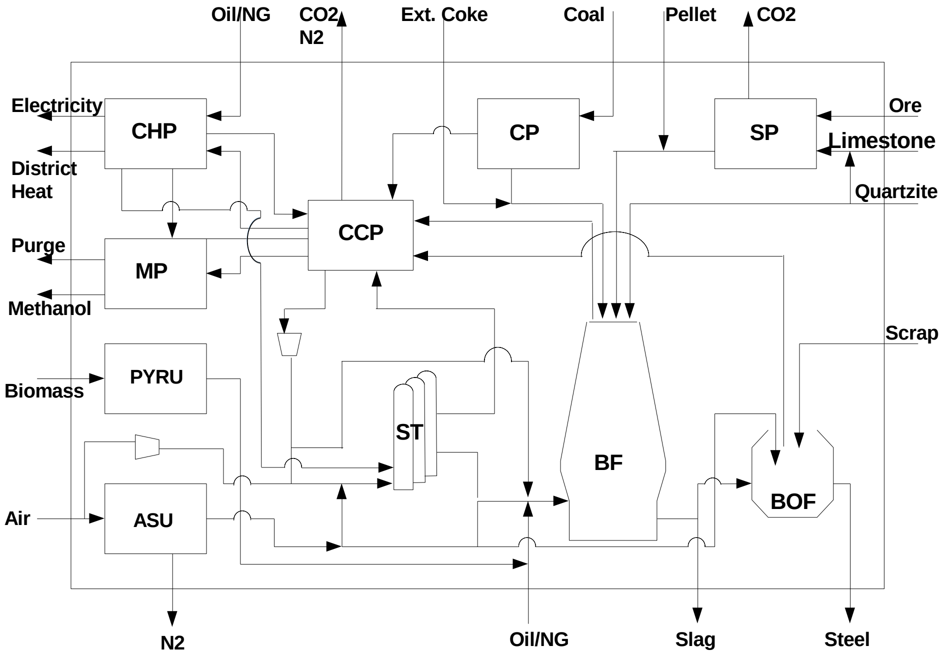

Figure 1 Integrated Steel Plant. CP: Coke Plant, SP: Sinter Plant, ST: Hot Stoves, CCP: CO_2 Capturing Plant, BF: Blast Furnace, BOF: Basic Oxygen Furnace, CHP: Combined Heat and Power Plant, PYRU: PYRolysis Unit, ASU: Air Separation Unit and MP: Methanol Plant.

3. Problem Formulation

The system has been optimized as a nonlinear constrained optimization problem, where the cost of liquid steel production is minimized with respect to a set of variables uniquely determining the state of the system under process constraints

$$\min \quad Cost\,(X)$$
$$f(X) = 0$$
$$g(X) \leq 0$$

where x holds seven input variables which completely determine the state of the system: blast furnace top gas recycling rate, oxygen enrichment, auxiliary reductant injection rate to the blast furnace, temperature of hot blast, pellet rate to the blast furnace, temperature of biomass pretreatment in pyrolysis and fuel rate in power plant. It assumed that the system uses the same fuel as an auxiliary reductant in the blast furnace and in the power plant for each case studied. The objective function expresses the cost of liquid steel production which is calculated using flow rates and unit costs and price for all raw materials and products, including carbon dioxide emission taxes and cost of stripping & storage. The nonlinear programming problem was solved numerically by sequential quadratic programming subject to equality constrains f and inequality constraints g, where the former are mass and energy balance equations for each process unit and the latter impose limits for some BF internal variables and for (some of) the material flows (cf. Table 1). (Ghanbari et al., 2012)

Table 1 Blast furnace input and some of the output variables and their constraints, as well as sinter and coke mass production rate constraints of the plant. The BF production rate limits (expressed in ton of hot metal, t_{hm}) were set to yield a steel production rate within [150,180] t_{ls}/h.

Variable	**Range**	**Variable**	**Range**
BF production rate	131-157 t_{hm}/h	**Bosh gas volume**	150-220 km^3n/h
Recycled top gas	0-220 km^3n/h	**Solid residence time**	6.0-9.5 h
Blast oxygen content	21-99 vol-%	**Slag rate**	≥ 0 kg/t_{hm}
Specific fuel rate in BF	0-120 kg/t_{hm}	**Top gas volume**	≥ 0 km^3n/h
Blast temperature	250-1200 °C	**Top gas CO content**	≥ 0 vol-%
Specific pellet rate	0-600 kg/t_{hm}	**Top gas CO_2 content**	≥ 0 vol-%
Pyrolysis temp	150-500 °C	**Top gas H_2 content**	≥ 0 vol-%
Specific coke rate	≥ 0 kg/t_{hm}	**Top gas N_2 content**	≥ 0 vol-%
Flame temperature	1800-2300 °C	**Top gas heating value**	≥ 0 MJ/m^3n
Top gas temperature	115-250 °C	**Sinter feed flow**	0-160 t/h
Own coke feed flow	0-55 t/h		

The CO_2 emissions are calculated on the basis of an overall carbon balance equation for the system, including all fossil carbon-bearing inputs (coal, oil, natural gas, external coke, limestone) and excluding the outflows of carbon with liquid steel, methanol, sold coke and stripped CO_2. Thus, the feed flow of biomass (BM) is excluded from the balance. The mass flow rate of external (bought) or exported (sold) coke is the absolute difference between the coke requirement in the blast furnace and sinter plant and the supply from the coke plant. The emissions associated with the production of external raw materials (e.g., pellets, external coke) were not considered, as the units were outside the balance boundaries of the system.

No constraints were imposed on the quantities of electricity and district heat sold. The fixed cost factors used in this study are c_{ore} = 80 €/t, c_{pellet} = 120 €/t, c_{coal} = 145 €/t, c_{coke} = 300 €/t, $c_{quartzite}$ = 30 €/t, $c_{limestone}$ = 30 €/t, c_{scrap} = 100 €/t, $c_{methanol}$ = 250 €/t, $c_{electricity}$ = 50 €/MWh, $c_{district\ heat}$ = 10 €/MWh and c_{fuel} = c_{oil} / c_{NG} / c_{BM} =150/200/50 €/t. As for the costs of emissions (c_{CO2}), these were varied in the states to be presented. It should be stressed that the operating cost of CO_2 stripping are included in the power and heat costs of the capturing unit.

4. Results and Discussion

The system is studied for a constant steel production rate of 170 ton liquid steel per hour with carbon dioxide emission and storage costs of [0-150] €/t_{CO2}. To find the best possible results, each optimization problem was run with 10 different random starting points and the best results were reported. Table 2 shows some of the optimal values for the system at a steel production rate of 170 t_{ls}/h and cost of emission and storage of 25 €/t_{CO2}. Case studies include three different fuels (biomass, oil and natural gas) and two operational selections which are operations of blast furnace (BF) with and

Table 2 Optimal process variables for the system with a steel production rate of 170 t_{ls}/h and costs of emissions and storage of 25 [€/t_{CO2}].

Variable	Biomass		Oil		Natural Gas	
	BF Inj.	-	BF Inj.	-	BF Inj.	-
Blast volume (km^{3}n/h)	28.0	24.6	29.0	24.6	26.5	26.9
Blast oxygen (vol %)	99.0	99.0	99.0	99.0	99.0	99.0
BFG volume (km^{3}n/h)	166.2	210.7	166.1	210.7	177.1	186.5
BF TGR rate (km^{3}n/h)	147.0	208.6	143.2	208.3	170.9	182.0
Sinter feed rate (t/h)	160.0	160.0	160.0	160.0	160.0	160.0
Coal feed rate (t/h)	79.1	79.1	79.1	79.1	79.1	79.1
Specific coke rate (kg/t_{hm})	220.4	309.6	220.9	309.6	281.7	321.0
Specific aux. fuel rate (kg/t_{hm})	118.7	0.0	101.5	0.0	24.8	0.0
Specific pellet rate (kg/t_{hm})	457.6	457.6	457.6	457.6	457.6	457.6
Flame temperature (ºC)	1954	1800	1800	1800	1800	1882
Blast temperature (ºC)	1200	1200	1200	1200	1200	1078
Pyrolysis temperature(ºC)	500	500	-	-	-	-
Bosh gas volume (km^{3}n/h)	160.0	198.1	174.0	198.1	179.5	175.8
Top gas temperature (ºC)	115.0	201.6	146.4	201.6	133.4	115.7
Burden residence time (h)	9.5	7.5	9.5	7.5	8.0	7.3
Slag rate (kg/t_{hm})	205.3	210.0	199.7	210.0	208.6	210.6
COG volume (km^{3}n/h)	17.6	17.6	17.6	17.6	17.6	17.6
BOFG volume (km^{3}n/h)	6.5	6.5	6.5	6.5	6.5	6.5
Aux. fuel excluding BF (t/h)	12.0	10.7	8.8	7.9	6.4	6.29
Bought/sold coke (t/h)	0.0	0.0	0.0	0.0	9.4	0.0
Sold methanol (t/h)	19.0	17.9	20.9	17.9	18.5	18.0
Specific emission (t_{CO2}/t_{ls})	0.48	0.39	0.98	0.53	0.6	0.47
Specific steel cost (€/t_{ls})	195.4	215.0	215.7	222.5	219.3	224.4

without injecting the same fuel as auxiliary reducing agent partially replacing coke. By injecting the auxiliary fuel, the specific coke rate, steel production cost, slag rate, top gas recycling rate and specific emission decreases and methanol production, residence time and blast furnace top gases increases. Figure 2 show the specific emission and liquid steel production cost for constant steel production rate of 170 [t_{ls}/h] and storage cost of 25 [€/t_{CO2}] with respect to different emission price for all case studies. A linear behaviour has been observed in increases of the steel cost by increasing the emission prices.

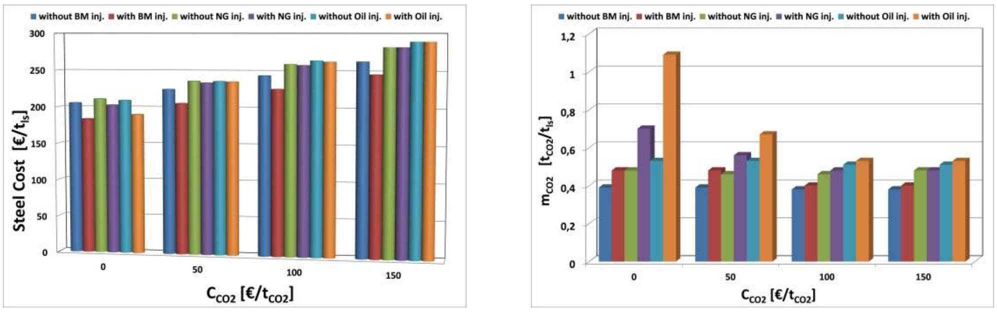

Figure 2 Steel production cost [€/t_{CO2}] and specific carbon dioxide emissions [t_{CO2}/t_{ls}] for a constant steel production rate of 170 [t_{ls}/h] and a CO_2 storage cost of 25 [€/t_{CO2}] at different CO_2 emission costs.

In all cases, injecting auxiliary fuels to the blast furnace lowers the steel production cost, but this positive effect decreases at increasing emission prices: At the highest emission cost, there is no economic benefit of oil or natural gas injection. In all scenarios, injecting auxiliary fuels to the blast furnace increases the specific emission rate mainly due to lower optimal top gas recycling rate. This effect gets less prominent at increasing emission costs. The lowest specific emission is obtained for the system using biomass and without BF injection.

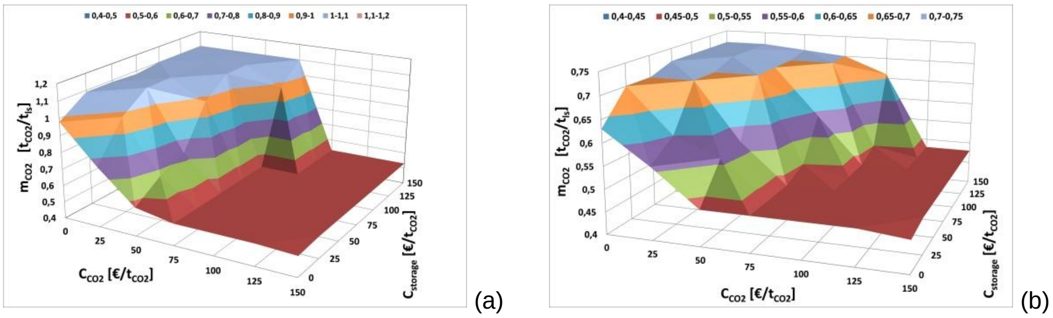

Figure 3 Specific carbon dioxide emission [t_{CO2}/t_{ls}] at a constant steel production rate of 170 [t_{ls}/h] as a function of CO_2 emission and storage costs.(a) System using oil, and (b) natural gas as fuel with BF injection.

Figure 3 shows the specific emission at a steel production rate of 170 [t_{ls}/h] at different costs of emission and storage for the system using oil and natural gas as fuel with injection in the blast furnace. In the different scenarios, the specific emissions vary in the range 0.53-1.1 [t_{CO2}/t_{ls}] for system with oil, and within 0.48-0.72 [t_{CO2}/t_{ls}] for the system with natural gas. At high emission costs, the optimal state of the system is, naturally, the one with minimal emissions and for oil the CO_2 storage cost is seen to have a minor effect on this transition. On the other hand, for natural gas (Fig. 3b) the transition to the lowest emissions occurs when the emission costs are roughly equivalent to the storage costs.

5. Conclusions

The optimal operation state of a future steelmaking plant with blast furnace top gas recycling and cold oxygen injection as well as carbon capture and storage, integrated with a polygeneration system, has been studied mathematically by minimizing the cost of steel production. Coke was partially replaced by different auxiliary fuels, i.e. Biomass, oil or natural gas. The results show that injecting fuels in the blast furnace decreases the optimal steel production cost but increases the specific emissions from the system. Different scenarios of carbon dioxide emission and storage costs were investigated and the effects on the specific emissions of the system were determined. The auxiliary fuels were found to have different effects on the optimal state of the system, in particular with respect to emissions and production costs. Therefore, it is important to consider the tradeoff between environmental and economic aspects to achieve a sustainable operational level of steelmaking.

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