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OPTIMIZATION OF STEELMAKING USING FASTMET DRI IN THE BLAST FURNACE[1]

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Abstract

Steelmaking contributes by more than 5% to the world's anthropogenic CO_2 emissions, so new ways to reduce the emissions in this industrial sector must be found. For a transition to more sustainable production concepts, also economic factors must be considered. In this paper we study the potential of using direct reduced iron (DRI) from the Fastmet process, using rotary hearth furnace (RHF) technology, as a partial substitute of pellets in a blast furnace (BF). Simplified mathematical models of the different operations in a steel plant, including RHF, are combined with a more detailed model of the BF and the entire system is optimized by non-linear programming with respect to costs. The objective of the presented study is to analyze the prerequisites for an economical operation of an integrated steel plant equipped with an RHF, under different raw material prices and varying costs of CO_2 emission allowances. The blast furnace operation parameters are also analyzed for different amounts of DRI charged. The results illustrate the conditions under which it would be beneficiary in a steel plant to integrate the RHF and BF technologies.

Key words: Blast furnace; DRI; RHF; Optimization; CO_2.

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1 INTRODUCTION

Global crude steel production has fully recovered after two years of declining caused by the economic recession. World crude steel production reached 1527 million metric tons for the year of 2011 which is a new record for global crude steel production. According to World Steel Association, in the first half of 2012, the worldwide demand for steel has remained on the improving trend line. Further growth is forecast and crude steel output is expected to exceed 1.6 billion tons in 2012.(1,2)

Figure 1 shows the development of the crude steel produced through different steel production routes from 2000 to 2010.(2,3) In the year 2010, 69.8% of the steel was produced through the main primary production route Blast Furnace (BF) - Basic Oxygen Furnace (BOF), while Electric Arc Furnace (EAF) steel production accounted for 29.0% of the total amount. The use of Open Hearth (OH) technology is steadily declining and it accounted for only 1.2% of the total crude steel production.

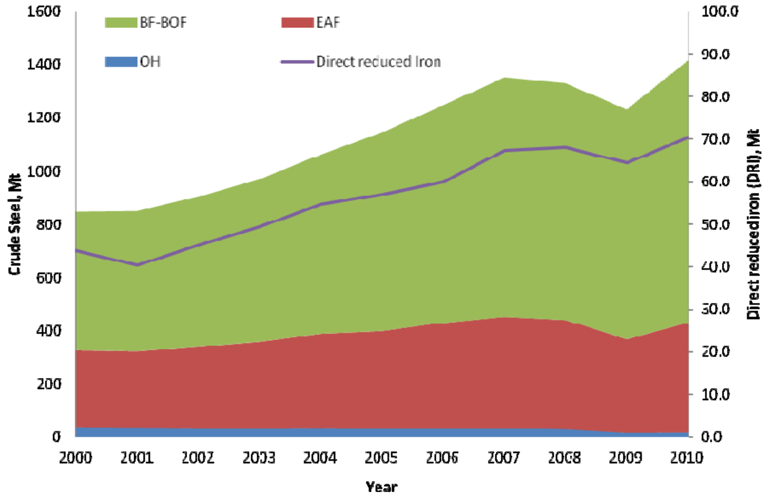

Figure 1. World crude steel production by process as well as production of direct reduced iron (DRI) since 2000.(2,3)

The growth and expansion of steel production have resulted in new challenges for the producers; the availability and costs of raw materials and energy sources as well as restriction of CO_2 emissions. Steel production is a highly energy intensive industrial process: The iron and steel sector is the second-largest industrial user of energy after the chemical and petrochemical sector.(4) In 2010 the energy intensity of steelmaking was 20.1 GJ/ton steel casted. Most of the total energy used in ore-based steel production is used in the blast furnace (Figure 2).

Steel production also gives rise to greenhouse gases that contribute to global warming. The greenhouse gas of most relevance to the world steel industry is carbon dioxide (CO_2). According to the International Energy Agency the iron and steel sector is the largest industrial source of CO_2 emissions. CO_2 emissions account for 99% of all steel industry greenhouse gas (GHG) emissions. The iron and steel industry accounts for approximately 5% of the total world CO_2 emissions.(4,5)

In 2010 the amount of CO_2 emissions in steel production was 1.8 tons of CO_2 per ton of steel casted. The CO_2 emission distribution of an integrated steel plant is illustrated in Figure 3. If the power plant is not taken into account the blast furnace together with coke plant and sinter plant are the major sources of the CO_2 emissions.

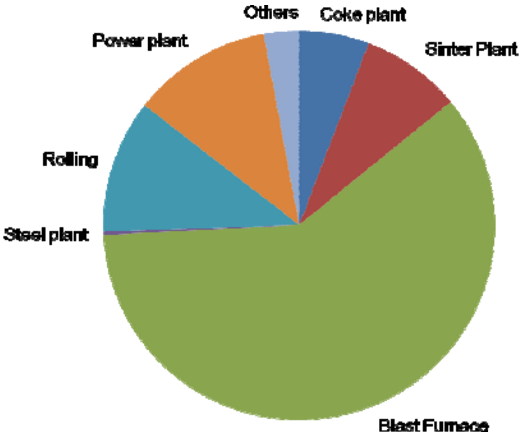

Figure 2. Distribution of energy consumption in integrated steel works.

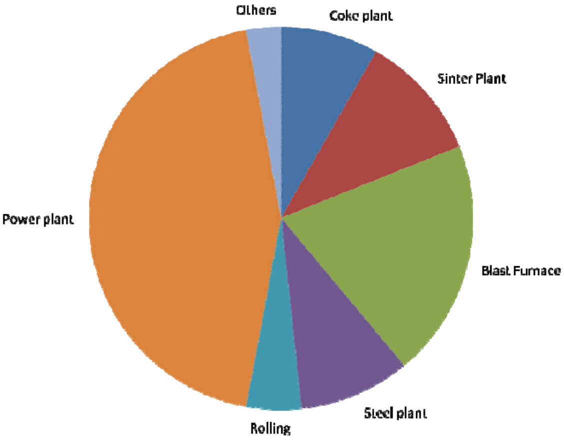

Figure 3. Distribution of CO_2 emissions in integrated steel works.

The steel industry is currently under a continuous social pressure to improve efficiency and decrease energy consumption and gas emissions. Energy efficiency has been a target for improvement within the steel industry long before climate change emerged as a global issue. As a result, over the past three decades steel companies have halved the energy consumed per ton of steel produced. However, due to this dramatic improvement in energy efficiency, it is estimated that there is now only room for marginal further improvement on the basis of existing technology. For instance, the blast furnace is already working close to its theoretical limits what comes to carbon utilization and thus it is extremely difficult to further lower the energy consumption and CO_2 emissions by improving the process efficiency. This means that without new production routes major advances in these fields cannot be achieved. In the longer term it will be necessary to identify and introduce breakthrough technologies that are viable. The alternative ironmaking processes are therefore expected to play an increasingly significant role in the iron and steel industry, especially since it is unlikely that any new blast furnaces will be built in developed countries due to high capital costs and environmental regulations.

One of the alternative technologies is direct reduction. World Direct Reduced Iron (DRI) production has grown almost continuously since 1970 (Figure 1). Although the vast majority of DRI is used in EAF, direct reduced iron can also be charged to BOF as a scrap substitute and to BF in order to increase the furnace productivity. In this article the influence of the usage of DRI in blast furnace on the Reducing Agent Ratio (RAR), CO_2 emissions and production cost will be studied.

2 USAGE OF DRI IN BLAST FURNACE

DRI has many positive attributes that promote its usage in steelmaking. DRI is a feed material with controlled and consistent size. DRI can also be continuously metered when discharged. It can be stored in bins and transported easily for continuous charging into any melt furnace.

When the burden used in a blast furnace consists of 100% iron oxide, approximately 45% of the total energy used in the blast furnace is consumed in reduction reactions.(1) Reducing the amount of charged oxides would therefore result in a decrease in the specific coke rate as well as an increase of productivity. This is the reason why replacing part of the total burden with direct reduced iron is justified. The effect of charging DRI on coke consumption and productivity in many blast furnaces all over the world is shown in Figure 4.

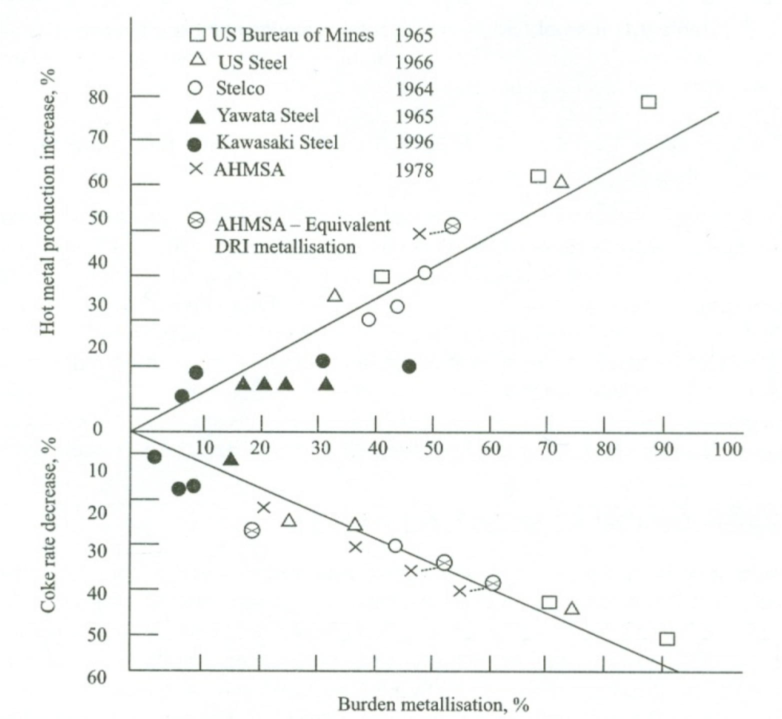

Figure 4. Effect of charging DRI on coke consumption and productivity.(6)

The actual benefits of charging partially reduced burdens to blast furnaces depend on the type of raw materials that are replaced, the chemical and physical characteristics of DRI, the operating conditions of the furnace and several other related factors.(7)

3 REDUCING AGENTS

As mentioned previously, one of the main reasons to use DRI in blast furnaces is to lower the amount of reducing agents, e.g., coke needed. Simultaneously with the coke rate decrease the CO_2 emissions from the blast furnace also decrease. Another option to achieve lower emission rates and reduced RAR of the whole process chain is to use a high reactivity reductant, such as wood charcoal. Wood charcoal can be charged in the blast furnace to replace coke and also in coal based DRI processes like in RHF to replace coal. The effect of metallization degree on productivity of RHF for wood charcoal and coal reductants is presented in Figure 5. It can be seen that at

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the same metallization degree productivity is significantly higher for wood charcoal than for coal.(8)

In addition to high reactivity wood charcoal is also considered as renewable because the carbon cycle of wood is short, 5-10 years, compared to fossil coal's cycle of approximately 100 million years. According to Norgate and Langberg replacing a kilogram of non-renewable carbon with charcoal carbon creates 3,42kg CO_2 benefit in global warming potential.(9)

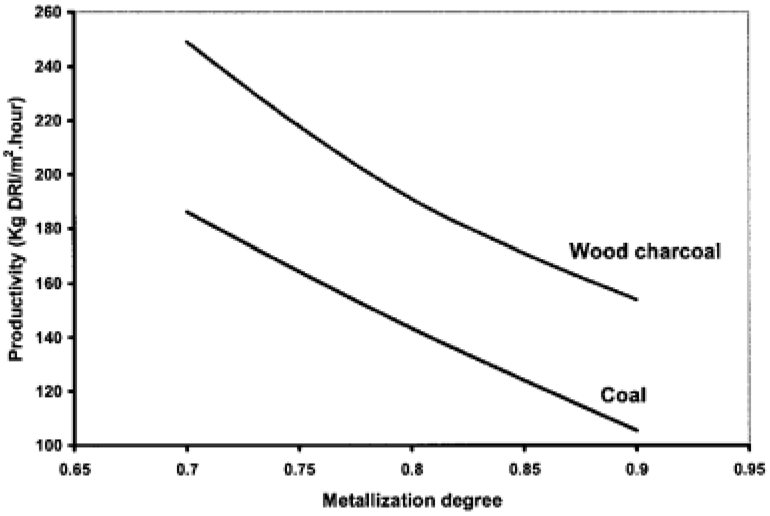

Figure 5. Effect of metallization degree on productivity of RHF for wood charcoal and coal reductants.(8)

4 PROCESS ALTERNATIVES

Figure 6 show the flow sheet of the two process alternatives compared in this study. The first process (Figure 6 left) is a conventional blast furnace route where pellets as well as coke are charged from the top to the blast furnace and oxygen enriched air and heavy oil are injected through the tuyeres. In the basic oxygen process hot metal and steel scrap are fed to a converter and the carbon content is reduced by blowing oxygen into the metal. After the converter secondary steelmaking processes are applied to the molten steel to make fine adjustments to the steel temperature, composition and cleanness. Molten steel is then casted into solid slabs, blooms or billets. The final stages are the forming operations such as hot or cold rolling, machining, coating and heat treatment. The main purpose of these operations is usually to achieve large shape changes such as from billet to steel wire and to give the steel component its final shape and properties.(10)

In the second process alternative, part of the pellet feed is substituted by direct reduced iron. The DRI process selected for this comparison is the coal-based Fastmet process. The option with the DRI plant is depicted on the right side of Figure 6 and contained within dashed lines.

Fastmet is a rotary hearth based process, where the feed pellets (composite agglomerates made from iron oxide fines and a carbon source such as coal) are charged into the hearth, one to two layers deep, and as they move on the hearth they are heated by burners firing above the hearth. Combustion of volatiles from the reductant and carbon monoxide from the iron reduction supplies the primary energy to the RHF for the reduction reactions. Fastmet DRI is continuously discharged from the RHF using a water-cooled screw. The Fastmet process is illustrated in Figure 7.

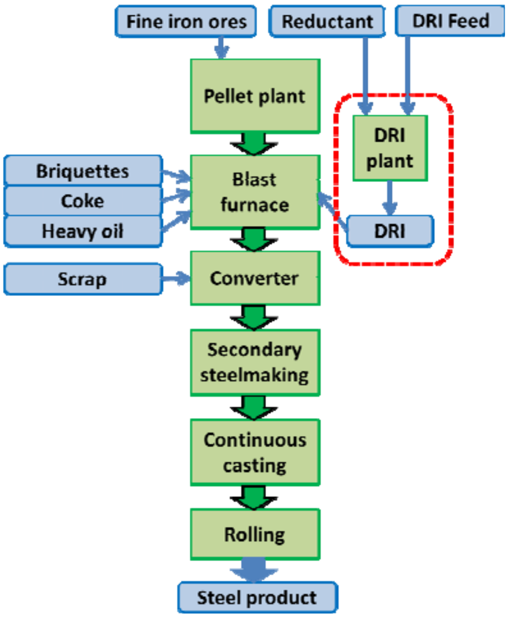

Figure 6. Integrated steel plant with DRI option.

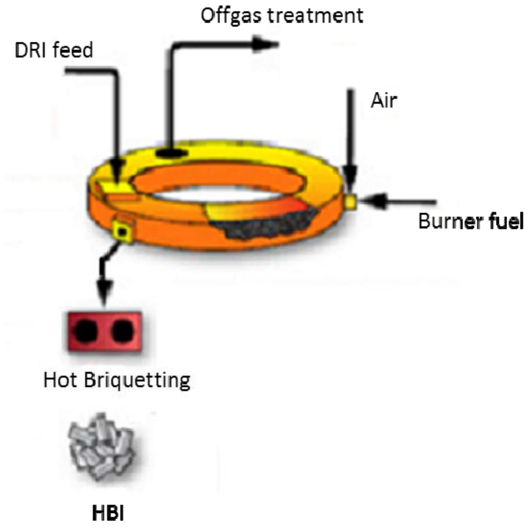

Figure 7. Flowsheet of the FASTMET process.

5 MODELING

5.1 System Studied

In the present study, mathematical models of the different unit processes in an integrated steel plant are combined (Figure 8) to create a system model, which is optimized by minimizing the operation cost of rolled steel.

$$\begin{aligned}\frac{F}{€/\mathrm{t_{steel}}} = \Bigg(& \frac{\dot{m}_{\mathrm{pel}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{pel}}}{€/\mathrm{t}} + \frac{\dot{m}_{\mathrm{coal}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{coal}}}{€/\mathrm{t}} + \frac{\dot{m}_{\mathrm{coke,ext}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{coke,ext}}}{€/\mathrm{t}} + \frac{\dot{m}_{\mathrm{oil}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{oil}}}{€/\mathrm{t}} + \frac{\dot{V}_{\mathrm{O_2}}}{\mathrm{km^3n/h}} \cdot \frac{c_{\mathrm{O_2}}}{€/\mathrm{km^3n}} + \\ & \frac{\dot{m}_{\mathrm{lime}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{lime}}}{€/\mathrm{t}} + \frac{\dot{m}_{\mathrm{quartz}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{quartz}}}{€/\mathrm{t}} + \frac{\dot{m}_{\mathrm{scrap}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{scrap}}}{€/\mathrm{t}} + \frac{\dot{V}_{\mathrm{ng}}}{\mathrm{km^3n/h}} \cdot \frac{c_{\mathrm{ng}}}{€/\mathrm{km^3n}} + \frac{\dot{m}_{\mathrm{CO_2}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{CO_2}}}{€/\mathrm{t}} + \\ & \frac{\dot{m}_{\mathrm{DRIf}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{DRIf}}}{€/\mathrm{t}} - \frac{\dot{m}_{\mathrm{red}}}{\mathrm{t/h}} \cdot \frac{c_{\mathrm{red}}}{€/\mathrm{t}} - \frac{P}{\mathrm{MW}} \cdot \frac{c_{\mathrm{el}}}{€/\mathrm{MWh}} - \frac{\dot{Q}_{\mathrm{heat}}}{\mathrm{MW}} \cdot \frac{c_{\mathrm{heat}}}{€/\mathrm{MWh}} \Bigg) \Bigg/ \frac{\dot{m}_{\mathrm{steel}}}{\mathrm{t_{steel}/h}} \end{aligned} \qquad (1)$$

Table 1. The fixed cost factors used in MATLAB optimization

Pellets c_{pel} €/t	Coking coal c_{coal} €/t	External Coke $c_{coke,ext}$ €/t	Oil c_{oil} €/t	Limestone c_{lime} €/t	Quartzite c_{quartz} €/t
120	145	300	150	30	30

Oxygen c_{O2} €/km^{3}n	Natural gas c_{ng} €/km^{3}n	Bought scrap c_{scrap} €/t	Reductant c_{red} €/t	Electricity c_{el} €/MWh	Sold heat c_{heat} €/MWh
50	200	100	100	50	10

The optimization was done with Matlab with respect to the inputs of the blast furnace model (Table 2) at different production rates, CO_2 emission allowance costs and DRI feed costs. The fixed cost factors of Eq. (1) are presented in Table 1. The prices of coal and charcoal were set equal and also the higher productivity of RHF (Figure 5) with charcoal was ignored. Thus, if the RHF would operate with 50% less reductant when charcoal is used the charcoal price would be 100% higher than the coal price.

Three separate cases were studied: Case 1 was the normal blast furnace operation with 100% pellet burden and 100 kg/thm briquettes charged to the furnace to utilize the fines arising in the different process steps. In cases 2 and 3 DRI was used in the blast furnace together with pellets and the fines were used as a feed material the RHF. In case 2 coal was used in the RHF and in case 3 charcoal. The coke plant operation is adjusted so that all the coke produced is used in the process.

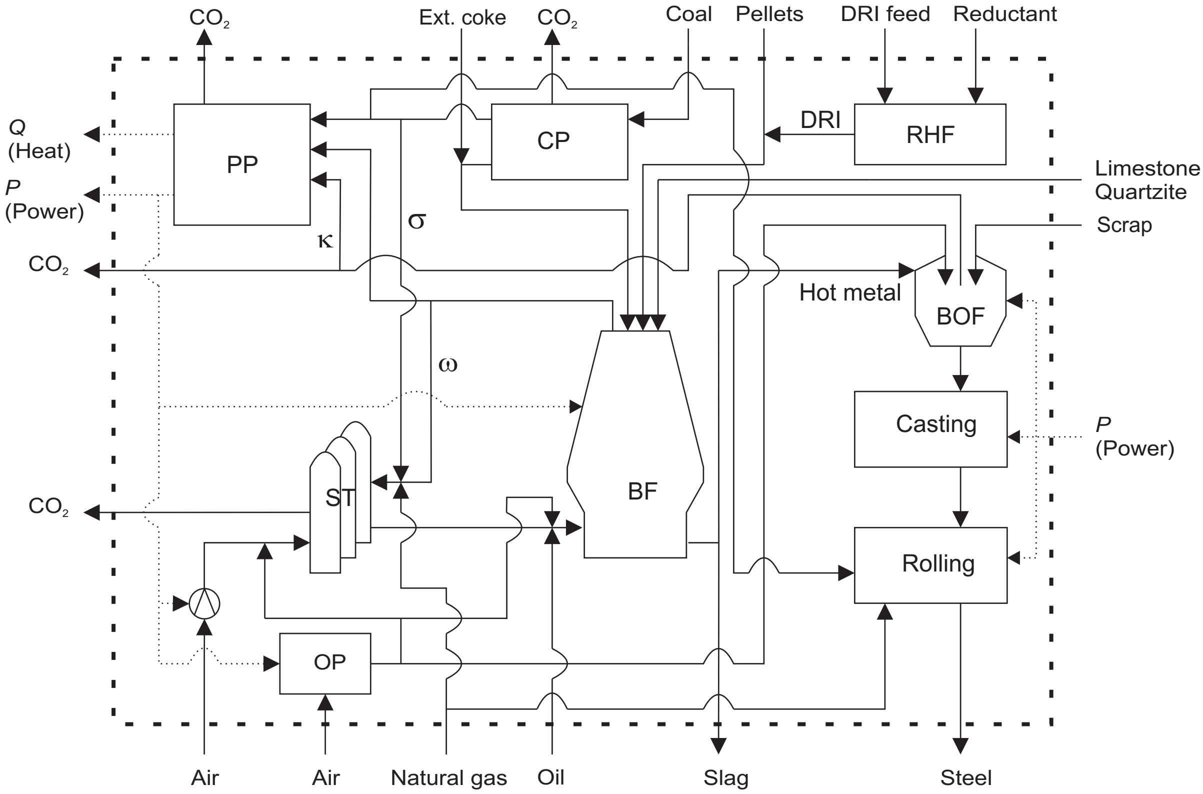

Figure 8. System with its units: CP: coke-making plant, ST: hot stoves, OP: Oxygen plant, BF: blast furnace, RHF: Rotary hearth furnace, BOF: basic oxygen furnace and PP: power plant.

5.2 Process Models

The heart of the mathematical description is the blast furnace model, which is described in detail by Helle, Helle and Saxén.(11) It is based on the division of the process into two control volumes, upper preparation zone and lower elaboration zone, separated by reserve zone where the temperatures of solids and gas are known and the gas composition can be calculated. Table 2 lists some of the blast furnace variables together with the constraints used in the optimization.

The other unit processes were modeled with simple equations describing the outputs as linear functions of the inputs. Fastmet was modeled so that for each ton of DRI produced, 1.31 ton of DRI feed is required. Scrap is charged to the BOF and the liquid steel mass is estimated to be 14.5% higher than the hot metal (hm) mass from the BF. The losses in casting are estimated to be 5% of the liquid steel and in rolling 4% of the rolled slabs. These coefficients together with the hot metal production reported in Table 2 yield a production range of 130 to 170 tons of rolled steel per hour.

Table 2. Constraints for blast furnace model. Input variables in the optimization are denoted with an asterisk (*)

Variable	Symbol	Range
Production rate*	$\dot{m}_{\mathrm{hm}}$	127.1-166.2 t_{hm}/h
Specific DRI rate*	$\dot{m}_{\mathrm{DRI}}$	0-400 kg/thm
Blast oxygen*	$Y_{\mathrm{O_2,bl}}$	21-99 vol-%
Specific oil rate*	m_{oil}	0-120 kg/thm
Blast temperature*	T_{bl}	250-1200 °C
Blast volume	$\dot{V}_{\mathrm{bl}}$	≥ 0 km^{3}n/h
Specific coke rate	m_{coke}	≥ 0 kg/ t_{hm}
Flame temperature	T_{fl}	1850-2300 °C
Top gas temperature	T_{BF}	115-250 °C
Bosh gas volume	$\dot{V}_{\mathrm{bg}}$	150-250 km^{3}n/h
Solid residence time	τ	6.0-9.5 h
Slag rate	m_{slag}	≥175 kg/ t_{hm}

6 RESULTS AND DISCUSSION

6.1 Minimum Cost of Steelmaking

Figure 9 depicts the minimum cost of rolled steel as a function of the steel production rate. The figure shows that the use of DRI produced with Fastmet is more economical when the production rate is high and the cost of DRI feed stays low.

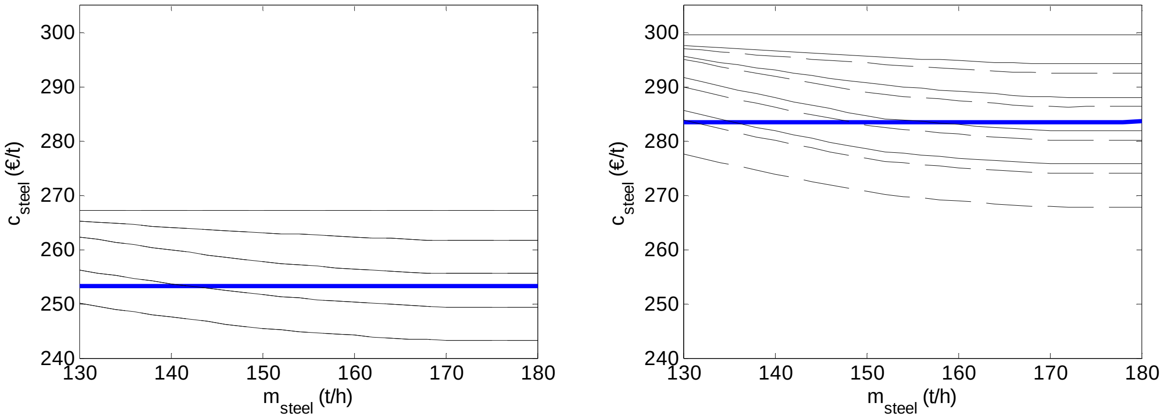

Figure 9. Cost of rolled steel. Thick line = Case 1, normal BF operation, no DRI. Thin lines (solid = Case 2 with coal in RHF, dashed = Case 3 with charcoal in RHF) depict the minimum cost with different prices for the DRI feed. c_{DRIf}/c_{pel} = [0.6 0.7 0.8 0.9 1.0] in ascending order. Left panel c_{CO2} = 0 €/t and right panel c_{CO2} = 20 €/t.

Increasing emission costs decrease the potential of DRI usage since the emissions increase when Fastmet DRI is used. The effect of using charcoal in the RHF can be seen in the right panel (dashed lines), and the cost of steel decreases due to lower emissions. Since the price of coal and charcoal used in the RHF were identical, also the results are identical when no penalty for CO_2 emissions is added, hence no dashed lines in the left panel of Figure 9.

Figure 10 illustrates the optimal DRI rate (left) and RAR (right) as a function of the production rate and the relative cost of DRI feed. When the relative cost of DRI feed is low, the DRI rate reaches the maximum level. When the relative cost increases the optimal DRI rate increases as a function of the production rate from 130 kg/t_{hm} at 130 t_{steel}/h to 400 kg/t_{hm} at production rates above 170 t_{steel}/h. When the cost of DRI feed reaches the pellet cost the optimal DRI rate decreases to the selected minimum of 60 kg/h. The behavior of the RAR is opposite that of the DRI rate as can be seen in the right part of Figure 10. This clearly shows the positive influence of DRI use: the region of low DRI rate, in Figure 10 (left) can be seen as the high plateau where the RAR is 421 kg/t_{hm}, whereas when the DRI-rate is 400 kg/t_{hm} the RAR is between 315 and 346 kg/t_{hm}.

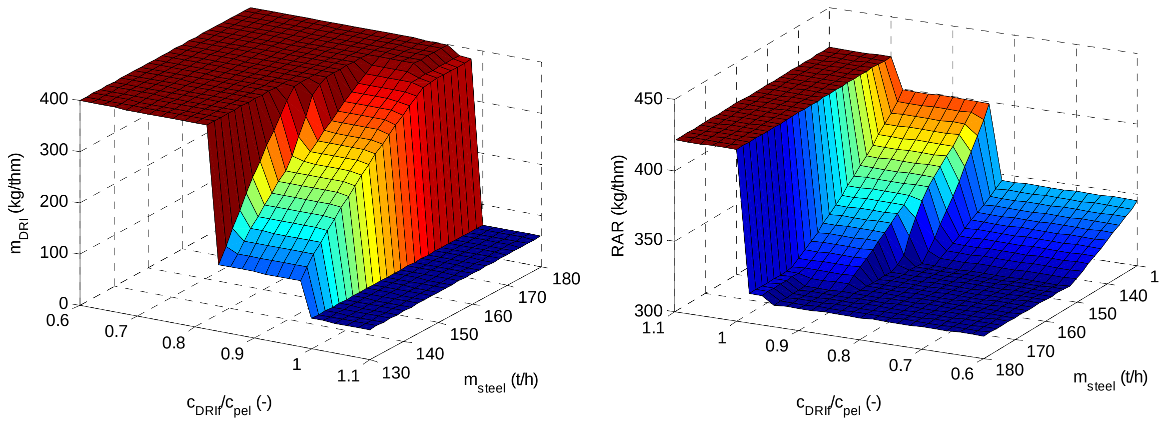

Figure 10. Left: Optimal DRI rate. Right: Optimal RAR as a function of the production rate and relative cost of DRI feed for Case 2 with $c_{CO2} = 0$.

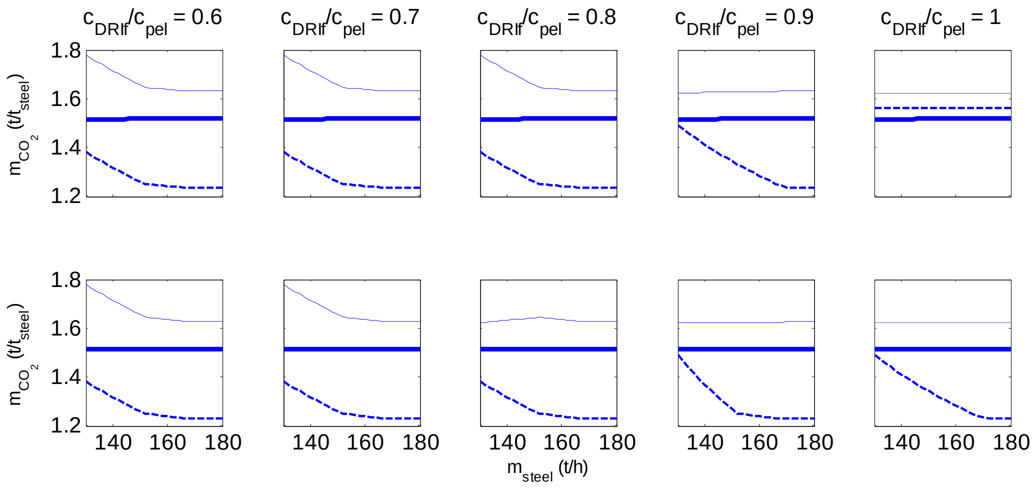

Figure 11. CO_2 emissions. Thick line = Case 1. Thin lines operation with DRI (solid = Case 2, dashed = Case 3). Upper panels: $c_{CO2} = 0$, lower panels $c_{CO2} = 20$.

Figure 11 illustrates the specific CO_2 emission from the system studied and it clearly shows the negative influence of using FASTMET DRI produced with regular coal in the BF (thin solid lines vs. thick solid lines in the upper panels of Figure 11). Figure 10 (right) showed the decrease in the RAR when the DRI rate increases, but the main problem is that the need for coal in the FASTMET exceeds the amount of saved coke in the BF. The production of 1 ton DRI with FASTMET requires 382 kg coal. If 400 kg/t_{hm} DRI is used, 153 kg coal is needed to produce the DRI. On the other hand,

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only 106 kg coke is saved in the BF. However, when the DRI is produced with charcoal the specific CO_2 emissions are lower than in the basic case almost throughout the examined region.

Figure 12 clarifies the influence of the increased CO_2 emission cost on the DRI rate. When coal is used in the RHF, the optimal DRI rate decreases when the emission cost increases (upper panels). However, when charcoal is used in the RHF, the optimal DRI rate increases with increasing emission cost.

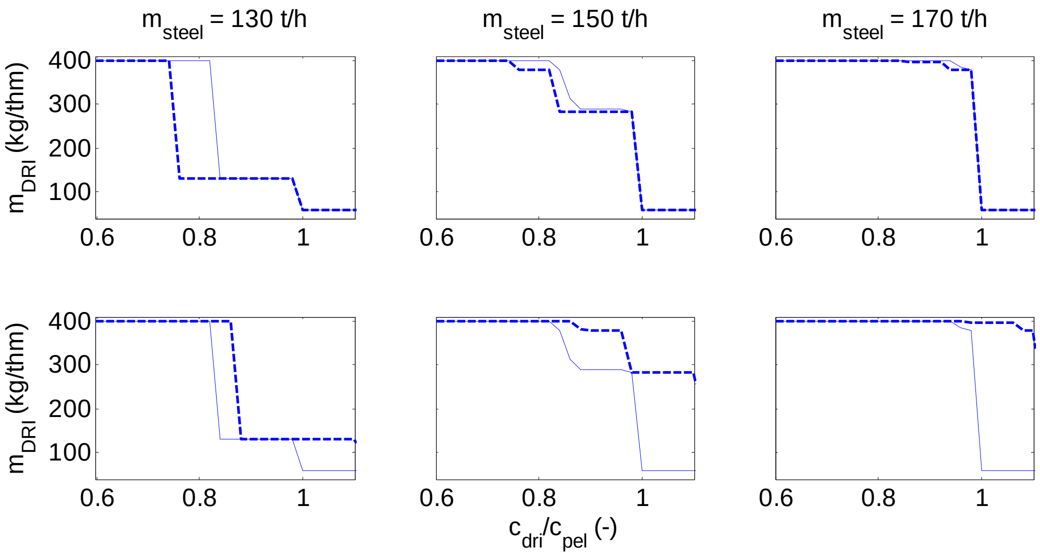

Figure 12. DRI rate. Upper panels: Case 2, coal used in RHF. Lower panels: Case 3, charcoal used in RHF. Solid lines c_{CO2} = 0 €/t and dashed lines c_{CO2} = 20 €/t.

6.2 Influence of DRI on Blast Furnace Operation

Table 3 shows the process conditions for blast furnace operation with briquettes and with different DRI rates. The blast furnace operation was optimized to minimize the specific coke rate, with same model constraints as reported in Table 1. It can be seen that if the production is low, an addition of > 200 kg/thm DRI increases the residence time of the burden to the upper limit and massive additions of limestone and quartize are used to decrease the residence time in the furnace. At the high production rate the same problem does not appear. Also the decrease in coke rate is clearer at high production, since no coke is needed to melt the extra limestone and quartzite. It is clear that the use of DRI improves the performance of the blast furnace. For example, when the production rate is 130 t_{hm}/h the required blast volume decreases from 117 km^3n/h to 106 km^3n/h when the DRI rate is increased from 0 to 100 kg/t_{hm}.

Table 3. DRI in Blast furnace

Production: thm/h	130	130	130	130	130	130	180	180	180	180	180	180
Pellet: kg/thm	1333,8	1405,8	1275,2	1144,3	1013,3	882,4	1333,8	-	1275,2	1144,6	1013,9	883,3
DRI: kg/thm	0	0	100	200	300	400	0	0	100	200	300	400
Briquette: kg/thm	100	0	0	0	0	0	100	0	0	0	0	0
Coke: kg/thm	297	331	289	268	265	263	297	-	289	257	226	194
Oil: kg/thm	120	120	120	120	120	116,7	120	-	120	120	120	120
Limestone: kg/thm	16,47	56,75	55,49	90,40	136,89	174,35	16,47	-	55,49	53,79	52,09	50,38
Quartzite: kg/thm	8,70	19,32	20,78	41,33	67,87	89,70	8,70	-	20,78	21,46	22,14	22,83
Blast volume: m3n/h	109324	116954	105664	105157	113624	121559	151372	-	146303	138207	130111	122015
Blast temperature: °C	1200	1074	1200	1114	836	602	1200	-	1200	1200	1200	1200
Blast oxygen: %	28	28	28	28	28	27,8	28	-	28	28	28	28
Blast air volume: m3n/h	99513	106459	96181	95720	103427	110955	137787	-	133174	125804	118434	111065
Blast oxygen, stoves: m3n/h	9811	10496	9483	9437	10197	10605	13585	-	13130	12403	11677	10950
Flame temperature: °C	2238	2178	2222	2157	1991	1850	2238	-	2222	2193	2161	2126
Bosh gas volume: km3n/h	160519	170442	155759	155101	166111	175663	222258	-	215667	205138	194611	184083
Solid residence time: h	8,87	8,17	9,05	9,50	9,50	9,50	6,41	-	6,54	7,14	7,88	8,81
P compressor: MW	5,58	5,97	5,39	5,37	5,80	6,22	7,73	-	7,47	7,05	6,64	6,23
Flame temperature, stoves: °C	1331	1320	1330	1336	1339	1338	1331	-	1330	1342	1354	1369
Steel slag: kg/thm	50	50	50	50	50	50	50	50	50	50	50	50
Slag: kg/thm	175	175	175	216,76	272,80	318,99	175	-	175	175	175	175
Slag basicity: -	1,09	1,09	1,09	1,07	1,05	1,04	1,09	-	1,09	1,10	1,10	1,10
Top gas volume: km3n/h	174	185	168	165	173	179	240	-	233	219	204	190
Top gas temperature: °C	125	115	126	115	115	115	125	-	126	144	152	151
Top gas CO: %	23	23	23	23	23	23	23	-	23	23	23	23
Top gas CO2: %	25	25	25	24	23	21	25	-	25	24	23	22
Top gas H2: %	7	7	7	7	7	7	7	-	7	8	8	9
Top gas N2: %	46	45	45	46	48	49	46	-	45	45	46	46
TG needed in stoves: m3n/h	51138	47766	49381	44135	33509	23647	72152	-	69589	64372	59323	54427

7 CONCLUSIONS

When DRI is used in the blast furnace the overall economy of the process is improved if the used DRI raw material is cheap enough compared to the pellets, which the DRI will replace. The main problem is the energy usage of the Fastmet, which leads to increased emissions, i.e., more coal is used by the RHF than is saved is the blast furnace by the use of DRI. However, if the DRI is produced with charcoal as the reductant in the RHF, the emissions can decrease significantly. The results also show the complexity of the system studied and how the optimal DRI rate changes as a function of the production rate, the cost of the DRI feed and the cost of the emission allowances.

When only the blast furnace is optimized to reach minimum coke rate the coke rate decreases when DRI is added. High DRI rates become more useful when the blast furnace is operated at high production rates.

LIST OF SYMBOLS

F	Economic objective function (€/t_{steel})
c	Cost factor (€/t, €/km^{3}n or €/MWh)
$\dot{m}$	Mass flow rate (t/h)
P	Electric power (MW)
$\dot{V}$	Volume flow rate (km^{3}n/h)
$\dot{Q}$	Heat flow (MW)

REFERENCES

1 Management Engineering & Production Services (MEPS), Steel News –24.01.2012, http://www.meps.co.uk/steelnews.htm [Cited 14/02/12]
2 Data from World Steel Association [Cited 14/02/12] Available at: http://www.worldsteel.org
3 World Direct Reduction Statistics 2010, Midrex
4 *Energy Technology Perspectives 2010, Scenarios and Strategies to 2050*, OECD/IEA, http://www.iea.org/techno/etp/index.asp [Cited 02/03/12]
5 ETSAP 2010, Iron and Steel Technology Brief 102, International Energy Association Energy Technology Systems Analysis Programme
6 Chatterjee, A. *Sponge Iron Production by Direct Reduction of Iron Oxide*, PHI Learning Private Limited, New Delhi, 2010, ISBN-978-81-203-3644-5
7 Astier, J.E. International Conference on Alternative Routes to Iron & Steel under Indian Conditions, Jamshedpur, India, February 1996, p. 11
8 Fruehan, R.J. *Bessemer Lecture, New Steelmaking Processes: drivers, requirements and potential impact*, Ironmaking and Steelmaking, Vol.32 (2005), No.1, p.3-8
9 Norgate, T. and Langberg, D. *Environmental and Economic aspect of Charcoal Use in Steelmaking*, ISIJ International, Vol.49 (2009), No.4, P.587-595
10 Data from Steel University [Cited 09/12/11] Available at: http://www.steeluniversity.org
11 Helle, H., Helle M., Saxén, H., 2011. *Nonlinear optimization of steel production using traditional and novel blast furnace operation strategies*, Chemical Engineering Science 66, 6470-6481.