Reduction of CO\textsubscript{2} Emissions from Integrated Steelmaking by Optimised Scrap Strategies: Application of Process Integration Models on the BF–BOF System

Christer RYMAN and Mikael LARSSON

Centre of Process Integration in Steelmaking, MEFOS-Metallurgical Research Institute AB, P.O. Box 812, SE-971 25 Luleå, Sweden.

(Received on April 28, 2006; accepted on October 4, 2006)

In integrated steelmaking there are a number of means to reduce CO\textsubscript{2} emissions. One approach is to increase the metallic Fe input to the production system. A common belief is that scrap works as a CO\textsubscript{2} diluent when introduced in iron ore based steelmaking. It is not necessarily so. Scrap is a key supplementary charge material in oxygen steelmaking converters, but scrap can also be utilised in ironmaking where it will decrease the use of reducing agents and with that also the specific CO\textsubscript{2} emissions. By the use of a process integration model which basically includes the primary processes of cokemaking, sintering, ironmaking and oxygen steelmaking the overall influence of scrap input on CO\textsubscript{2} emissions is demonstrated and commented. The influence of hot metal silicon content is elucidated by calculations with different material and process constraints. The results show that at moderate scrap rates, the reduction of CO\textsubscript{2} emissions is favoured by increased scrap additions to the oxygen converter. When the scrap additions to the converter balances the actual heat capacity of the bath, other means to achieve an increased scrap melting capacity can be taken into account. This include combinations of scrap addition to the blast furnace, increased silicon content in tapped hot metal, and/or addition of Ferro-silicon combined with further scrap additions to the oxygen converter. Different strategies for CO\textsubscript{2} emission reduction have to be suggested depending on if the objective is to minimise the site (direct) emissions or the global (indirect+direct) emissions.

KEY WORDS: CO\textsubscript{2} emissions; scrap; blast furnace; oxygen converter; optimisation; process integration.

1. Introduction

In today’s environmental creditable steel industry, it is essential that steelmakers keep track of their emission sources and formulate strategies to control the environmental performance for different process options. In the dominating iron- and steelmaking processes, coke and other carbon containing reducing agents are necessary prerequisites for the production of crude steel. As a result these processes release carbon dioxide (CO\textsubscript{2}) in quite substantial degrees. One way to reduce the CO\textsubscript{2} emissions is to increase the metallic Fe input to the production system. Metallic Fe, normally in the shape of scrap, is a key supplementary charge material in basic oxygen furnaces (BOF), but it can also be utilised in blast furnace (BF) ironmaking where it will decrease the use of reducing agents and with that also the specific CO\textsubscript{2} emissions. The impact of metallic charging to the BF and BOF, respectively, mainly with respect to energy use has been compiled in different publications.\textsuperscript{1,2} The objective of this present study is to consider the influence of scrap charging on CO\textsubscript{2} emissions for the ‘combined’ BF-BOF production system and to enlarge the discussion on the best course of action from the available alternatives, e.g. considering different scrap supply scenarios.

Analysing the potential for improving energy use and environmental performance in steelmaking often involves multifaceted interaction between several process sub systems. Improvements in a part of the system can propagate to other parts of the system and the total effect is not always a change for the better. A systematic approach can be of major help to avoid non-optimimal solutions and to analyse the interaction effects of different operational measures in the iron- and steelmaking processes. The methodology to couple specific process models to an overall analysis model can be described as process integration and has proved to be especially valuable for analysis of energy minimisation problems and related issues e.g. CO\textsubscript{2} emission minimisation.

2. System Definition

This paper focuses on the conventional processes for iron- and steelmaking from iron ore, which is the BF-BOF route. The final product from this system is liquid steel (LS). To make the system more complete, a number of supplementary processes with high impact on CO\textsubscript{2} emissions; coke production, sintering of iron ore and power production from waste gases, have also been taken into account. A schematic description of the system is shown in Fig. 1.

A given steel demand pulls the model. The demand is
met by the BOF model which is based on conventional heat and mass balances for the process. The ingoing Fe requirement is mainly met by liquid hot metal (HM) from the BF and the remainder by steel scrap, ferrous alloys or iron ore pellets. Coolants and flux additives, e.g. iron ore pellets, limestone and dolomite, can be added to fulfil a given CaO/SiO₂ ratio as well as the heat balance.

The blast furnace is a very complex process and thus complicated to fully model in this type of study. In earlier work, a method has been developed, to define an operating range by use of an off-line simulation model and optimisation between possible operation practices or combinations thereof. The model still includes heat balances for hot blast provision and power demands for auxiliary equipment.

The coke and sinter production model aim at fulfilling the requirements of coke and sinter respectively. Coke oven gas is also delivered to the sinter plant and BF where it is utilised for heating purposes. To close the energy loops within the system, excess gases from the coke plant, BF and BOF are recovered for power production.

3. Objective Function

The optimisation model used in this work is based on the mixed integer linear programming (MILP) method. This kind of model has been designed and used for the optimisation of various industrial energy systems. In the iron and steel industry, it has been used as a tool for energy and CO₂ emission optimisation for integrated steelmaking systems. The actual model used in this study has been described earlier by Larsson and Dahl. It has since then been further developed in the sense that the HM composition now can carry one or more quality variables, instead of being fixed, thus allowing improved analysis of the process dynamics between the BF and BOF.

Generally, the objective function for this kind of optimisation problem can be written as

\[
\min z = \sum_{j=1}^{n} c_j x_j, \quad x_j \in R \quad \text{...............(1)}
\]

where, \( z \) is the objective function for the minimisation problem. In this case it is the CO₂ emission which is set for the purpose of the optimisation; \( x \) are the studied variables (\( x_j \) means the \( j \)th variable); \( c \) are the coefficients for the objective function. For example, it could be emission factors for the variables.

Two objectives have been defined, ‘direct’ CO₂ emissions and ‘indirect’ CO₂ emissions. The direct emissions are actual emissions within the system that originate from the use of carbon and other CO₂-containing raw materials (e.g. limestone). The indirect CO₂ also take into account emissions, appearing from actual upstream production and transportation of raw materials. Both these objectives are relevant to consider since the direct emission (site emission) have its practical application when discussing local impacts, environmental permits etc. while the accumulated value of direct and indirect emissions add up to the total environmental effect (global emission) of a given action.

The coefficients used in this study are given in Table 1.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Unit</th>
<th>CO₂ direct (metric ton)</th>
<th>CO₂ indirect (metric ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal</td>
<td>(t)</td>
<td>2.948</td>
<td>0.051</td>
</tr>
<tr>
<td>Anthracite</td>
<td>(t)</td>
<td>3.260</td>
<td>0.051</td>
</tr>
<tr>
<td>PCI coal</td>
<td>(t)</td>
<td>2.948</td>
<td>0.051</td>
</tr>
<tr>
<td>Iron ore fines</td>
<td>(t)</td>
<td>-</td>
<td>0.447</td>
</tr>
<tr>
<td>Iron ore pellets</td>
<td>(t)</td>
<td>-</td>
<td>0.175</td>
</tr>
<tr>
<td>Scrap</td>
<td>(t)</td>
<td>0.015</td>
<td>0.019</td>
</tr>
<tr>
<td>Ferrosilicon</td>
<td>(t)</td>
<td>0.002</td>
<td>3.9</td>
</tr>
<tr>
<td>Limestone</td>
<td>(t)</td>
<td>0.440</td>
<td>0.018</td>
</tr>
<tr>
<td>Burnt dolomite</td>
<td>(t)</td>
<td>-</td>
<td>1.346</td>
</tr>
<tr>
<td>Burnt lime</td>
<td>(t)</td>
<td>-</td>
<td>1.346</td>
</tr>
<tr>
<td>Other fluxes</td>
<td>(t)</td>
<td>-</td>
<td>0.018</td>
</tr>
<tr>
<td>Oxygen</td>
<td>(km³/h)</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Power</td>
<td>(MWh)</td>
<td>-</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Factors for direct emissions are based on carbon contents of the raw materials. For the indirect emissions it has been assumed that the steel production site is coastal based in EU, with iron ore supplies from Brazil, coal supplies from Australia, and other flux materials mined within a 250 km radius from the site. The coefficients for scrap and power are from a study by Aichinger et al., and the emission factor for ferrosilicon production in Norway has been suggested by Monsen et al. Also burnt lime, iron ore pellets and oxygen carry indirect CO₂ from their own manufacturing processes. Emission deductions are also made for the deliveries of LS from the system and for some carbon rich by-products. In calculations when indirect emissions have been considered, the excess energy containing gases which have
not been used internally in the processes, are assumed to be used for power production on site. The energy efficiency for generation of electric power is set to 28% ($Q_{\text{power}}/Q_{\text{gas}}$). In an enlarged system which covers also rolling operations, oxygen and lime production etc. the gas utilisation would be different. In such a system other emission sources would be added and the power generation scope would be lessened. In this study, this is compensated by the emission factors for the mentioned products from auxiliary processes.

The credit coefficients for products leaving the system are given in Table 2.

### 4. Problem Constraints

After the objective function is established, some necessary boundary conditions are defined to govern the process in order to make sure that the results are reasonable and may be identified in the current model. The boundary conditions can be expressed by Eq. (2) which is used to describe variations in the system.

$$x_i \leq b_i, \quad i = 1, \ldots, n \tag{2}$$

where, $b_i$ describes the boundary for the $i$th variable $x$. The $x_i$ variables could be the corresponding flow variables, and the boundaries, $b_i$, are the corresponding restrictions.

To facilitate the analysis of this particular study the following three terms are defined:

- **Iron Oxide Ratio (IOR)**
  $$\text{IOR} = \frac{Fe_{\text{oxide}} \text{ (to BF)}}{Fe_{\text{tot}} \text{ (to BF)}} = \frac{Fe_{\text{oxide}} \text{ (to BF)} - Fe_{\text{melted}} \text{ (to BF)}}{Fe_{\text{oxide}} \text{ (to BF)}} \tag{3}$$

- **Hot Metal Ratio (HMR)**
  $$\text{HMR} = \frac{x_{\text{HM}} \text{ (to BOF)}}{x_{\text{HM}} \text{ (to BOF)} + x_{\text{scrap}} \text{ (to BOF)}} \tag{4}$$

- **Total Scrap Ratio (TSR)**
  $$\text{TSR} = \frac{x_{\text{scrap}} \text{ (to BF)} + x_{\text{scrap}} \text{ (to BOF)}}{x_{\text{LS}} \text{ (from BOF)}} \tag{5}$$

The constraints for the most important nodes in the analysed system are summarised in Table 3. An arbitrary production level of 500 t/h is chosen for the calculations in the model.

The main emphasis of this paper is the scrap utilisation. Reasonable upper boundaries for the level of scrap use in the BF and BOF have been set to 30% of the ferrous burden charge to each process, equivalent to IOR 70% and HMR 70%. This means that the operation of this system is within established borders but yet a very high accumulated scrap utilisation (more than 50% TSR) is conceivable. The ratio between iron ore pellets and sinter in the BF burden has been kept fixed to limit the variable variation external to the BF and BOF models. The HM carbon and silicon contents, and the HM temperature are the main factors which determine the quantity of scrap which can be melted in the BOF process. The most important factor which influences the scrap melting capacity has proved to be the hot metal silicon content. When the HM silicon content increases 0.1% the scrap melting capacity of the BOF increases in the order of 1%. In principle, there are two options to increase the incoming silicon content to the oxygen converter:

- Change in BF operation practice to reduce more SiO2,
- Addition of Ferro-silicon in the BOF.

From a CO2 point of view, both options are double acting measures since they increase the scrap melting capacity of the BOF at the cost of increased fossil reductant use (e.g. coke) either in the BF or in an upstream Ferro-silicon plant. It is important to consider this when analysing the CO2 emission minimisation problem.

### 5. Result and Discussion

#### 5.1. Optimisation by the MILP Method

The aim with this part of the study is to analyse the prospects to reduce the CO2 emissions at different scrap supply scenarios. With the given definition and constraints, the system have been optimised for minimisation of the CO2 emission at six fixed TSR: s=0, 10, 20, 30, 40 and 50% and once with the TSR as an adjustable variable. Table 4 shows the results from optimisation of the combined direct and indirect objective function. The CO2 emissions range from 1.360 t/t LS at 44.9% TSR to 2.019 t/t LS at zero TSR. In the operating range from 0 to 20% TSR, the primary outcome of the optimisation is a BF practice resulting in low silicon content in the HM leading to low specific coke consumption and low slag volumes in the BOF. The model range for HM silicon content is 0.2 to 1.6%. In the model calculation this corresponds to a specific coke consumption of 311 and 334 kg/t HM respectively when combined with a fixed coal injection rate of 160 kg/t HM. At the lower silicon boundary the BOF has a calculated scrap melting capacity up to 20% TSR, which is equivalent to 81.2% HMR in the studied system. At lower scrap levels the cooling need in the BOF has to be met by charging of other coolants i.e. iron ore pellets. The optimised solutions for 20, 30 and 40% TSR include a mutual HMR of 81.2%. In general terms this seems to works as a threshold value where scrap charging in the BOF is brought...
to a standstill, and further scrap utilisation is directed towards the BF process. At 50% TSR where the BF iron oxide ratio (IOR) has reached the lower boundary of 70%, defined earlier, the marginal scrap is once again directed towards the BOF. This is facilitated by increased silicon content of the HM from the BF. It is notable that despite the fact that TSR is allowed to exceed 50% the minimum CO₂ objective is found at about 45% TSR.

Table 5 shows the results for the minimum CO₂ objective when considering direct emissions only. The CO₂ emissions range from 1.113 t/t LS at 54.7% TSR to 1.895 t/t LS at zero TSR. At 0, 10 and 20% TSR, the solutions of the min-
imisation problems are identical to the solutions in the previous table, however with a decreased objective value of approximately 0.1 t CO₂/t LS, since the indirect emissions are not included. The main difference, compared with the solutions of Table 4, is that scrap will not be allocated to the BF at a HMR equal to 81.2%. Instead the HMR reaches its predefined lower boundary somewhere between TSR 30 and 40%, and first as a result of that, scrap seems to be directed to the BF process. At 30, 40 and 50% TSR the scrap melting capacity in the BOF has been enhanced by additions of Ferro-silicon. This is also reflected in increased use of fluxes and high specific slag volumes. The optimised solution is found at the defined maximum scrap charging levels in the two processes.

5.2. Influence of Different Scrap Ratios

The interpretation of Tables 4 and 5 is that it is possible to find an optimum distribution between scrap charging in the BF and the BOF for each TSR, which gives the lowest possible CO₂ emission for the system. The results also indicates that at higher TSR:s there is a rivalry between the two options to elevate the silicon input. At some circumstances it is favourable to raise the silicon content in the BF and at other occasions to add Ferro-silicon to the converter. Another issue which is raised from Table 4 is the question about optimal HMR and the range of variation in the objective value if the scrap is allocated between the BF and BOF in other ratios than the optimised solution.

To demonstrate the variation in the objective value at different TSR:s, calculations have been made according to Figs. 2 and 3. The objective value is then plotted against HMR at constant TSR values. In principle, a feasibility region for the different solutions is defined by the lower and upper boundaries for HMR on the x-axis, which are 70 and 100%, and in the lower-right and in the upper-left area by the lower and upper boundaries for IOR, which are also 70 and 100%. The optimised solutions for CO₂ minimisation corresponding to the previous paragraph have been marked with circles. From the earlier discussion it was pointed out that there is a balance point at 81.2% HMR where the objective function is minimised for TSR:s in the range 20 to 40% when considering both direct and indirect emissions in the analysed system. This has been marked with an arrow in Fig. 2. From a process point of view this marks the maximum amount of scrap which can be melted by means of HM with the silicon content at the lower boundary, in our example [%Si] equals 0.2. To reach lower HMR it becomes necessary to provide more chemical energy, e.g. by increasing the amount of silicon entering the BOF vessel. To distinguish between the effects of raised silicon in the BF and the introduction of Ferro-silicon to the system these variables have been constrained one at a time which divides the TSR line into two lines. The dashed line indicates that Ferro-silicon is constrained to zero and that the only way to increase the chemical energy input to the BOF is to increase the SiO₂ reduction in the BF. The dotted line indicates that HM silicon from the BF is restricted to 0.2% and that chemical energy in the state of Ferro-silicon is used to increase the scrap melting capacity of the system. In Fig. 2 the two lines are almost overlapping. In Fig. 3, on the other hand, the same analysis shows that it is significantly more favourable to make use of the Ferro-silicon additions to lower the CO₂ emissions. According to this analysis the main divergence between the results when considering direct and indirect emissions versus direct emission is the estimated value of the two methods to increase the BOF melting capacity. When only direct emissions are considered Ferro-silicon has an almost negligible emission factor whereas when the manufacturing process is accounted the emissions from the reduction of SiO₂ in the iron BF compared to reduction of SiO₂ in an electric submerged arc furnace are almost equal.
5.3. CO₂ Minimisation Strategies at TSR Less Than 20%

At low to moderate scrap ratios the definite interpretation is that scrap is best used in the BOF. There is no meaning to reduce IOR below 100% by scrap additions to the BF. At these scrap rates the heat balance in the BOF will show a surplus of heat, therefore there is always a need to add coolants to the process. As long as scrap is available it should be used instead of other coolants. This is independent of the choice of objective function in this study. If indirect emissions are accounted the emission level is somewhat higher. For each percent HMR decrease, the specific CO₂ emission will decease with 2.2–3.2 kg CO₂/t LS. TSR-levels between 10 and 20% are regarded as the normal operating range at most integrated steel plants. From a CO₂ emission perspective the best practice is to find the balance point where the scrap load to the BOF is maximised in relation to the actual heat capacity of the bath. With the case data of this study the total specific emissions at the balanced HMR is 1.692 t CO₂/t LS of which 1.588 t CO₂/t LS are direct emissions.

5.4. CO₂ Minimisation Strategies at TSR Higher Than 20%

At higher scrap rates the analysis has to be made with care. A common opinion is that scrap works as a CO₂ diluent when introduced in iron ore based steelmaking. This is partly true. When comparing Figs. 2 and 3 the consequence of introducing more scrap into the system differs depending on factors like choice of emission factors, and the strategy to distribute the scrap between the BF and BOF.

When looking upon direct emissions, improved scrap melting capacity by introducing Ferro-silicon is an effective way of reducing the CO₂ emission. This effectively increases the chemical melting potential beyond the limits of normal operation. However, silicon has to be produced either in the system or in an upstream process. When taking into account the global aspects of production of Ferro-silicon the effect can be adverse. An exaggerated strive to decrease the HMR can result in increased specific CO₂ emissions at a given TSR. When optimising the direct emissions it is important to determine the available means to increase the scrap melting capacity. If the use of Ferro-silicon is legitimate, the strategy should primarily be to minimise the HMR until the lower limit is reached and thereafter route scrap to the BF to decrease the IOR.

Figure 4 illustrates the proper strategy to reduce the specific direct+indirect CO₂ emissions:
1. Add scrap to the BOF until the balanced HMR is reached,
2. Add scrap to the BF until the practical IOR boundary.

Note that there is no need to make any particular changes in HM composition or to increase any other additions to the system. The most important aspect is to minimise other coolants in the BOF and conserve the energy for scrap melting. This strategy shows the potential to reduce the specific emissions to 1.360 t CO₂/t LS which is 20% lower than the balanced BOF. Also note that the given constraints of the system would allow another 10% increase of the TSR as mentioned earlier. However, in this case maximised scrap load does not result in minimised specific emissions.

In Fig. 5 the corresponding strategy to reduce the direct specific CO₂ emissions is illustrated:
1. Add scrap to the BOF until the balanced HMR is reached,
2. Add Ferro-silicon to stretch the melting capacity to the practical lower HMR,
3. Add scrap to the BF until the practical IOR boundary.

The suggested Ferro-silicon additions give an effective rise in HM silicon content from 0.2 to 1.3%. This strategy extends the scrap melting capacity and reduces the specific emissions to 1.113 t CO₂/t LS which is 30% lower than the balanced BOF. In this case the maximum emission reduc-

Fig. 4. Direct+indirect CO₂ emissions: Optimised scrap strategy for CO₂ reduction. 0) Starting point; TSR 0, IOR 100, HMR 100, 2.019 t CO₂/t LS. 1) Balanced HMR; TSR 20, IOR 100, HMR 81.2, 1.692 t CO₂/t LS. 2) Min CO₂; TSR 44.9, IOR 70, HMR 81.2, 1.360 t CO₂/t LS.

Fig. 5. Direct CO₂ emissions: Optimised scrap strategy for CO₂ reduction. 0) Starting point; TSR 0, IOR 100, HMR 100, 1.895 t CO₂/t LS. 1) Balanced HMR; TSR 20, IOR 100, HMR 81.2, 1.588 t CO₂/t LS. 2) Min HMR; TSR 37.2, IOR 100, HMR 70, 1.403 t CO₂/t LS. 3) Min CO₂; TSR 54.7, IOR 70, HMR 70, 1.113 t CO₂/t LS.
It is important to recognise that there are a lot of factors that can have an effect on the results of the described analysis procedure. Practical constraints can be something else than defined here e.g. restrictions in tramp element content, emission factors can be more or less site specific, and costs and productivity are factors which might point in other directions than described above. This, in combination with the influence of new raw materials, ideas to take advantage of internal energies to stretch scrap melting capacity and other future process developments are ideas in focus for the further development of process integration models.

6. Conclusion

The CO₂ reduction problem during production of crude steel has been analysed with an optimisation method. The demonstrated method is effective both for finding solutions to the minimisation problem and for analysis of counterbalancing factors in a defined production system. This has been demonstrated on CO₂ emission calculations for a hypothetical steel plant located in Europe operated on a credible mix of imported and domestic raw materials. Since many of the coefficients for the emission factors are site specific the conclusions are not generally applicable. Instead, it is highly recommended to make this type of analysis with site specific parameters. An important aspect of the demonstrated calculations is that high scrap additions to an integrated system does not always act as a linear CO₂ diluent. It is important to optimise and balance the different processes in the considered system to ensure a global optimal solution.

Acknowledgements

Support from the Swedish Agency for Innovation Systems and the Knowledge Foundation in Sweden is kindly acknowledged.

REFERENCES