Reduction of the Specific Energy Use in an Integrated Steel Plant—The Effect of an Optimisation Model

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Analysing the potential for improving the specific energy use in a steel mill can be difficult due to the interactions between the different subsystems. Changes in one unit can lead to several changes throughout the system. A process integration model taking into account the different interactions within the system is presented. The model is based on an optimising routine, making it a total analysis method for the steel plant system including the surroundings. The model is used to analyse the different possibilities for energy savings and practice changes within the system. The effect of optimising the total system versus separate optimisation of the different sub-processes is illustrated. The method development can serve as a benchmark for different steelmaking operations and constitute a basis for the continuous work involved in energy, material or economic analyses for the steel production system.

KEY WORDS: iron and steel making; process modelling; energy use; CO\textsubscript{2} emission; process integration.

1. Introduction
Steel is produced today using two distinct steelmaking routes: the integrated route (BF/BOF route) using iron ore as the main iron source and the electro steel plant (EAF route) using scrap as the main iron carrier. According to IISI\textsuperscript{1} the total world steel production in 2001 was 845 Mt. The hot metal production from the blast furnace (BF) was 576 Mt. The oxygen processes, e.g. the BF/BOF route, account for nearly 57.7\% of the total world steel production. The rest, 7.7\%, was produced in other processes. The total steel production in Sweden was 5.5 Mt and the BF/BOF share of this was 66.1\%. The production from the integrated route has a high share of both the world and the Swedish steel market. The energy use for the integrated steelworks is reported to be in the range of 15.3–20.6 GJ/t of liquid steel (tLS) or 17.6–22.8 GJ/t of coil product, including both ore preparation and coke making\textsuperscript{1}. The main energy use is associated with coke consumption for the blast furnace. The variations in energy use for the hot strip mill are not as large. Heat recovery and the use of process waste gases, as well as the energy efficiency factors for different processes, affect these figures.

In order to minimize the CO\textsubscript{2} emission from the integrated steel plant, a natural step is to minimize the energy use and material consumption. This can be achieved by improving the performance of each individual process or by looking at the whole system. An analysis of the total system is to be preferred, because the processes in an integrated steel plant are connected through both primary and secondary products within the system. Changes in one sub-process can and will affect the total system.

Several ways have been proposed to analyse and improve the energy efficiency of the integrated steel plant. Mathematical modelling of processes has been practice within several steel plants.\textsuperscript{2,3} Different total analysis methods have also been presented. Gielen and Moriguchi\textsuperscript{4} presented a linear model for analysing the global potential for CO\textsubscript{2} reduction in the Japanese steel industry. There are several recent publications analysing the energy efficiency, energy efficiency and benchmarking of the steel industry processes, e.g. Worell et al. 2001\textsuperscript{5}, Costa et al. 2001\textsuperscript{6}, Andersen and Hyman, 2001.\textsuperscript{7} However, in order to make energy savings and CO\textsubscript{2} emission reductions at a specific plant, a total analysis method for the plant system in question is needed. Birat et al.\textsuperscript{8} have studied the CO\textsubscript{2} emission from the production of liquid steel from both the EAF and the BF/BOF route including some new process steps for producing hot metal. They have analysed the total system by calculating the total material consumption and energy use (including electricity) and the corresponding CO\textsubscript{2} emission resulting from the different production practices by using a total modelling approach. By comparing the different production routes, it was possible to analyse the effect of different practices.

When analysing the steelmaking system, several differences between the processes can be seen. This brings out the importance of a sufficiently accurate representation of different parts of the system in order to achieve the purpose

\textsuperscript{1} Information received from SSAB Tunnplåt AB.
of the study. Traditionally there are several ways of modelling processes. Mathematical models of different structures can be used, ranging from simple 1-D simulation models to more complex CFD models. These models are reaching a higher and higher level of sophistication, which is usually achieved at the expense of model transparency. This can lead to a model almost as complicated as the real process. There clearly must be a trade-off between complexity and accuracy. Heidari et al.\textsuperscript{9)} presented a process integration method, an optimising analysis model, for a BOF converter based on a mass and energy balance. The objective of the present authors is to propose a method that can be used to analyse the potential for reduction of the energy use and the related CO\textsubscript{2} emission through the use of process integration. In our research a total analysis model based on an optimisation routine for an integrated steel plant has been created. This makes it possible to find the total system optimum based on the objective in question within specified bounds. The model is applied to analyse the specific energy use for the steel production system at an integrated steel plant.

2. Description of the System at SSAB Tunnplåt

The integrated steel plant system analysed consists of one coke oven plant, one blast furnace with hot blast stoves, two BOF converters, secondary metallurgy processes (a CAS-OB and RH vacuum degassing unit) and two slab casting machines, see Fig. 1. Since the blast furnace is operated 100\% with pellets, no sinter plant is needed. The processes are connected through the primary products from each of these primary processes, e.g. coke, hot metal and liquid steel, and through secondary products such as process gases and recycled materials, such as BOF slag or internal steel scrap. The final products from this system are first-rate steel slabs from the two slab casting machines.

Traditionally the process gases are used as internal fuel within the plant. The coke oven plant is under-fired with pure coke oven gas. The hot stoves are fired with a mixture of BF gas and coke oven gas adjusted to a desired blast temperature. Coke oven gas is also used as a fuel for various burners within the steel plant and as the primary fuel for the lime kiln. The excess of the coke oven gas and the recovered BF gas and BOF gas is mixed in a gas holding bell. The mixture of the gases is used as the primary fuel in the combined heat and power plant (CHP). Oil is used as a backup fuel if the heat value comes close to the lower limit and as an additional fuel if the heat input from combustion of the gaseous fuel is insufficient. The CHP produces heat and electricity. The heat generation meets the demand from the district heating network of the city of Luleå during most of the year. The electricity production covers the needs of the
steel plant and some electricity is sold to the national electricity grid.

3. Development of an Optimisation Model for the SSAB Tunnplåt Steel Plant

3.1. Overview

The steel production chain can be described simply as a series of connected metallurgical reactors (e.g. a coke oven plant, BF, BOF converter, etc.), supporting systems and by-product processing systems. In order to analyse a large industrial energy system, structured methods are needed. These methods can be termed as process integration (PI) methods. The common goal for all PI methods is to minimize the use of energy in the system. Such methods are usually divided into three types: pinch analysis, exergy analysis and mathematical programming.

In the mathematical programming method, the system is modelled with mathematical relationships. The different process equations are usually optimised. There are different optimisation methods used, ranging from linear programming (LP) to non-linear programming (NLP). The choice of optimisation method is based on the problem in question. The total optimisation model for the steel plant is based on a MILP (mixed integer linear programming) routine and a commercial optimisation solver (ILOG CPLEX 7.1). The MILP routine makes it possible to describe and approximate non-linearities, discrete linear relations and constraints, thereby improving the representation of the system.

The analysis basically includes the four steps shown in Fig. 3. The information flow is indicated as arrows in the figure. In the first step the important processes are identified. In order to describe the system mathematically the real problem must be delimited, important processes identified and reasonable boundaries and simplifications introduced. In the second step of the analysis the optimisation model is created from a set of equations based on the simplified, delimited problem identified in the first step. In the third step the appropriate optimisation routine is applied, in our case a MILP optimisation routine. Finally in the fourth step the result is analysed and the model is validated. The validation includes both the verification of the solution from the model and the verification that the model created describes the problem adequately.

The different processes have been modelled separately and connected together by each primary product and any possible by-product interactions. The model sophistication varies between simple linear process models, empirically derived process relations based on engineering practice, and models based on mass and energy balances for the different processes. The driving force for the model is the production of the final product from the system (first-rate steel slabs). Each sub-process, identified in Fig. 1, is linked to the next processing step by the primary product from each process (coke, HM, LS, etc.). Hence, the steel demand from the slab-casting units will determine the production rate in the BOF, which in turn will determine the hot metal rate for the BF and so forth. The external material use is based on the process requirements of each sub-process. The use and excess of by-products are also determined from each sub-process model. The problem is broken down into identified sub-processes, with delimitations and simplifications identified from the prior analysis in Fig. 1. The arrows indicate the main product flow within the model. The efficiencies and specific process-related data used are based on actual production data from either the steel plant of SSAB Tunnplåt AB or the CHP run by Lulekraft AB.

3.2. Model Description for the Main Processes

3.2.1. The Coke Oven Model

The coke oven model meets the coke requirements from the BF model. The core of the model is an empirical model for the coke yield (coal-to-coke conversion factor) used internally within the SSAB coke oven department. The conversion factor is based on the dry coal properties, e.g. the volatile matter (wt% VM) and the ash content (wt% ash). The model also includes a gas conversion factor derived in a similar way. The energy use within the system, e.g. the coke oven gas for the under-firing, is based on mass and energy balances. In addition, the model includes the specific electricity demand for the fans and the coal preparation and the specific steam demand for the gas-cleaning plant. The outputs from the model are coke divided into size classes 10–20 mm and <20 mm and coke breeze. By-products from the gas-cleaning system, e.g. tar, sulphur and benzene, as well as coke oven gas, are also included. In the model the volatile matter is assumed to have the same composition. The heat value will therefore be constant, but the produced gas volume flow will vary depending on the volatile content in the coal mix.

3.2.2. The Blast Furnace Model

The raw materials for the BF are normally top-charged, except for pulverised coal (PC), which is injected through the tuyeres together with the hot blast. Coke and coal are combusted when the oxygen-enriched hot blast is blown into the BF. The combustion products form a hot reduction gas, which passes up through the blast furnace, while the burden materials are reduced and melted in their passage down the furnace. Due to the many chemical reactions taking place in the BF, the behaviour is complex to describe mathematically. For off-line simulations SSAB Tunnplåt AB employs an in-house model using a spreadsheet environment (MS Excel)\(^2\). In which the chemical and thermal

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\(^2\) An in-house model used for off-line simulations within SSAB Tunnplåt, further described by Grip et al.\(^2\)
reactions in the furnace are divided into the different sections: the zones above and below the reserve zone and the reserve zone.

In order to formulate the blast furnace model in a format suitable for MILP description, a model has been created partly on the basis of linear regression, which has been used for different important parameters, e.g. the reduction rate, the BF gas, the raceway flame temperature, the hot blast, etc. The regression database has been created using the more sophisticated blast furnace model used at SSAB Tunnplåt AB. The database includes a number of predetermined cases. These cases have been chosen roughly to cover the “map” needed for the present investigation. The model then calculates the material and energy flows for the cover the “map” needed for the present investigation. The temperatures in the situation in question. The mass balances for ingoing materials and outgoing products determine the slag amount and composition and the amount of fluxes. The developed model is valid for a predetermined hot metal composition\(^*3\) (Fe 94.4\%, C 4.7\%, Si 0.4\%, the other elements being Mn, S, V), slag basicity\(^*3\) (defined as the ratio CaO/SiO\(_2\)=0.98) and raceway flame temperature. The model also includes a specific electricity demand for the blast furnace and the surrounding equipment.

The hot stoves, used for production of the hot blast for the BF, are modelled on the basis of heat and mass balances. The primary fuels for the stoves are a mixture of BF gas and coke oven gas. The mixture’s heat value corresponds to a hot blast temperature. The electricity demand for the blower is included.

3.2.3. The Basic Oxygen Process Model

The BOF model is based on heat and mass balances. The different iron carriers, e.g. hot metal, scrap and pellets, are limited by the heat balance and the contamination (tramp elements) in the scrap. A hot metal exchange, \(\eta_{\text{HM}}=0.98^*3\), between the HM coming out of the BF and the HM entering the BOF is introduced. Hot metal casted on the ground, due to disturbances between the BF and BOF, is included as cold HM (e.g. scrap with an HM composition) corrected for additional impurities.

The different flux additives, e.g. lime and dolomite, are calculated on the basis of the ratio CaO/SiO\(_2\)=4\(^*3\) in the slag. This is the slag basicity practice used for the present mix of raw materials. The oxygen demand is calculated on the basis of the total carbon content oxidised and the metals oxidised in the slag. The infiltrate air is based on the post-combustion in the BOF hood. The post-combustion ratio, CR, defined as the ratio between the CO\(_2\) and the sum of CO\(_2\) and CO in the BOF gas, is set as a constant (not depending on the steel type) to 0.3\(^*3\). The temperatures in the heat balance are set in advance, on the basis of actual measurements at the steel plant. An energy loss term is introduced in the heat balance to simulate the steam recovery from the recovery boiler in the BOF hood. The model also includes a specific electricity demand from the BOF and the surrounding equipment.

3.2.4. The Casting Model

For the slab casting model, a liquid steel exchange efficiency, \(\eta_{\text{LS}}=0.95^*3\), between the liquid steel and the cast product is introduced. There are two different kinds of losses: recovered and un-recovered losses. It is possible to re-circulate the recovered losses into the BOF melt shop, e.g. iron losses due to heavy boiling in the BOF, start-up losses in the slab caster, losses due to tundish change and losses associated with changes in the quality grade. Examples of un-recovered losses are dusts, iron losses in ladles and unexplained weight losses due to measurement uncertainties. The electricity demand is included as a normalised electricity consumption per tonne of cast steel.

\(3.2.5.\) The Surrounding System Model (the Power Plant)

The off-gases from the steel plant are used as the primary fuel in the CHP. If the energy content in the mixed gas is not sufficient or if the heat value is too low, below 2.9 MJ/Nm\(^3\), oil is used as a backup or supplementary fuel. The power plant has two modes of operation, the pure back-pressure mode or the partly condensing mode. In the 100 \% back-pressure mode of operation, the district heating demand of the city of Luleå is used as a heat sink. For this operation mode, the alpha (\(\alpha\)) value, defined as the ratio between the power and the heat generation, is set to 0.44\(^*4\). In the completely condensing mode of operation, all the heat is cooled by an external cooling circuit. The steam is expanded further in an extra turbine stage in the steam turbine. This results in extra power generation. The energy efficiency for the electricity generation is set to 0.32.

In practice both the \(\alpha\)-value and the electricity energy efficiency will vary depending on the cooling possibilities, e.g. seasonal temperature variations within the district heating system and the external cooling circuit. In reality the operation mode is a mix between the back-pressure and the condensing operation mode depending on the district heating demand and the fuel availability.

\(3.2.6.\) The Objective Function

The model was developed to optimise the energy use for the production at the steel plant. The model is described mathematically as a minimization problem generally defined according to:

\[ \min z = \sum_{i=1}^{m} c_i x_i \] ..........................(1)

when

\[ A_1 x \leq b_1 \]
\[ A_2 x + By \leq b_2 \]
\[ \begin{bmatrix} A_1 & 0 \end{bmatrix} \begin{bmatrix} x \end{bmatrix} \leq \begin{bmatrix} b_1 \end{bmatrix} \] ..........................(2)
\[ x \in \mathbb{R}^n, \quad y \in \{0, 1\} \]

where \(z\) is the objective function for the minimization problem. The objective function is defined by the variables, \(x_i\), of interest for the problem task and the relating energy contents, \(c_i\). It is based on both direct and indirect energy use. Direct energy use is actual energy use within the boundary system. Indirect energy use is up-stream and down-stream
energy use outside the system boundary. The up-stream energy is related to the material preparation, for instance pelletizing and production of external coke. The down-stream energy is related to outgoing products, such as power generated in the CHP outside the system boundary. In the objective function, the direct energy use and the up-stream energy use form debit entries, while the down-stream energy is a credit entry. The energy contents for the different flows are based on the heat values, the up-stream energy loads and the down-stream energy in recovered process flows. Energy related to transport is neglected. The variables, $x$, are defined and solved from the problem matrix of equations (Eq. (2)).

The energy contents are expressed as GJ/t for material flows, GJ/kNm³ for gaseous flows and GJ/MWh for energy flows. The energy content for pellet are based on magnetite ore, the low energy consumption for the pelletizing process are due to the exothermic oxidization reaction $\text{Fe}_3\text{O}_4 \rightarrow \text{Fe}_2\text{O}_3$. For DRI used means pre-reduced iron ore in the form of DRI or HBI (direct reduced iron, hot briquetted iron). The different energy coefficients for the different entries in the objective function are listed in Table 1.

### 3.2.7. Limitation

The models are evaluated for hourly production. Each process model describes the material consumption and the use of energy related to the production. The energy and material demands depend on the amount of products being processed in the different units and are described by linear or piecewise linear relationships. The limitations introduced are used to govern the processes so that the results are reasonable and may be identified in the current system. The boundary conditions can be used to describe variations in the system according to:

$$x_i \leq b_{ij} \quad i = 1, \ldots, n; \quad j = 1, \ldots, m \quad \text{.............}(3)$$

where $b_{ij}$ describes the boundary for the $i$th variable $x$ during the time step $j$. The $x_i$ variables are the corresponding flow variables for coke production, HM production, etc. and the boundaries, $b_{ij}$ are the corresponding restrictions. For instance, the maximum production levels from the coke ovens, BF and BOF are set as flow restrictions according to the current concession limits for each unit respectively. The bounds introduced in the model are shown in Table 2.

### 3.3. Alternative Process Configurations

Two main groups of changes have been studied: practice changes within the current production system and the installation of new process equipment. The main options are listed in Table 3.

### 4. Results and Discussion

#### 4.1. Model Study

Ten cases and one reference case have been used to evaluate the system. For the reference case, the model has been set to simulate the material and energy use according to the production in 2001. The reference case is used as a base for comparison. Table 4 shows a list of the cases with a brief description.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optimisation of the coal mix and production rate at the coke oven</td>
</tr>
<tr>
<td>2</td>
<td>Optimisation of the current BF burden (pellets, BOF slag, re-circulated m/1 coke, PCI)</td>
</tr>
<tr>
<td>3</td>
<td>Optimisation of the metallic charge in the BOF (MH, scrap)</td>
</tr>
<tr>
<td>4</td>
<td>Preheating of the scrap for the BOF</td>
</tr>
<tr>
<td>5</td>
<td>Optimisation of the metallic charge (pellets and DRI/HBI) in the BF, coal/CO ratio as ref. case</td>
</tr>
<tr>
<td>6</td>
<td>Optimisation with free BF burden (pellets, DRI/HBI, coke, PCI, etc.)</td>
</tr>
<tr>
<td>7</td>
<td>Optimisation of the total system considering all the possibilities in the current system</td>
</tr>
<tr>
<td>8</td>
<td>Optimisation of the total system considering all the possibilities including new equipment and processes</td>
</tr>
<tr>
<td>9</td>
<td>Efficiency improvements, decreased heat loss from the coke oven battery, decreased flaring (from case 9)</td>
</tr>
</tbody>
</table>

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Possible changes within each production unit, the coke oven, BF and BOF, are evaluated one at a time in optimisation cases 1–3. In cases 4 and 5, the installation of new process equipment, hot stove exhaust gas recovery and scrap preheating are evaluated. In cases 6 and 7, DRI/HBI was introduced into the BF system, with a specified coke-to-PCI ratio and with free burden. In case 8, the total system is optimised with the current raw materials. No restrictions other than the specific process limitations are used. For case 9, DRI/HBI and new process equipment (heat recovery in hot stoves and scrap preheating) were introduced, but otherwise this case is the same as case 8. In case 10, (based on case 9) the effects of increased efficiency for HM and LS ($\eta_{\text{HM}}$ and $\eta_{\text{LS}}$ increased by 1%), decreased flaring (decreased by 50% for each gas) and a decreased heat loss from the coke oven battery (loss decreased by 5%) are analysed. The results of the energy calculations are summarized in Fig. 4 and the main material consumptions are summarized in Tables 5–8.

### 4.1.1. Validation of the Model

The specific production figures for the year 2001 have been used to validate the model. The main specific production figures are listed in Tables 5–7. The model for the reference case has been delimited according to the production during 2001. The agreement between the reported production data and the simulated data is fairly good. However, there are some differences between the reported data and the simulated data in the reference case. All the gas flows in the reported production data were corrected for the moisture content and reported as dry flows. All the flows calculated in the model are given as moist flows, which results in a discrepancy. The normal moisture content of coke oven gas is about 2.5%, that of BF gas is close to 5% and that of BOF gas is 12%. If the simulated gas flows are adjusted to compensate for the moisture content, the deviation between the measured and the calculated values is about 3%, which is a reasonably good agreement. Regarding the coke oven model, it can be seen that there is a small deviation con-

![Fig. 4.](image)

(a) Specific energy use for the steel plant–power plant system. (b) Summary of energy savings for the different cases.

<table>
<thead>
<tr>
<th>Table 5. Summarised results for the coke oven plant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke oven gas [Nm³/h]</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Case 1</td>
</tr>
<tr>
<td>Case 2</td>
</tr>
<tr>
<td>Case 3</td>
</tr>
<tr>
<td>Case 4</td>
</tr>
<tr>
<td>Case 5</td>
</tr>
<tr>
<td>Case 6</td>
</tr>
<tr>
<td>Case 7</td>
</tr>
</tbody>
</table>

1The CO₂ emission is based on the carbon use. The PCI carbon content is assumed to be 80%, the coking coal 82.2% and the coke 89.7%.
### Table 6. Summarised results for the BF system.

<table>
<thead>
<tr>
<th>Production for 2001</th>
<th>252</th>
<th>1379</th>
<th>335</th>
<th>133</th>
<th>n.a.</th>
<th>n.a.</th>
<th>9.7</th>
<th>97</th>
<th>40</th>
<th>215</th>
<th>n.a.</th>
<th>618</th>
<th>1859</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>252</td>
<td>1381</td>
<td>332</td>
<td>132</td>
<td>166</td>
<td>8.1</td>
<td>103</td>
<td>31</td>
<td>236</td>
<td>18.6</td>
<td>614</td>
<td>1850</td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>252</td>
<td>1389</td>
<td>295</td>
<td>175</td>
<td>155</td>
<td>5.84</td>
<td>4.7</td>
<td>101</td>
<td>29</td>
<td>227</td>
<td>18.5</td>
<td>621</td>
<td>1855</td>
</tr>
<tr>
<td>Case 3</td>
<td>252</td>
<td>1381</td>
<td>332</td>
<td>132</td>
<td>166</td>
<td>8.1</td>
<td>103</td>
<td>31</td>
<td>236</td>
<td>18.6</td>
<td>614</td>
<td>1850</td>
<td></td>
</tr>
<tr>
<td>Case 6</td>
<td>252</td>
<td>540</td>
<td>600</td>
<td>221</td>
<td>88</td>
<td>124</td>
<td>7.17</td>
<td>5.2</td>
<td>83</td>
<td>20</td>
<td>155</td>
<td>18.5</td>
<td>540</td>
</tr>
<tr>
<td>Case 7</td>
<td>252</td>
<td>532</td>
<td>607</td>
<td>221</td>
<td>85</td>
<td>118</td>
<td>7.11</td>
<td>4.8</td>
<td>83</td>
<td>20</td>
<td>157</td>
<td>18.4</td>
<td>416</td>
</tr>
<tr>
<td>Case 8</td>
<td>252</td>
<td>1387</td>
<td>328</td>
<td>136</td>
<td>157</td>
<td>6.93</td>
<td>6.6</td>
<td>93</td>
<td>28</td>
<td>214</td>
<td>15.4</td>
<td>551</td>
<td>1648</td>
</tr>
<tr>
<td>Case 9</td>
<td>252</td>
<td>1304</td>
<td>57</td>
<td>349</td>
<td>94</td>
<td>156</td>
<td>9.98</td>
<td>5.5</td>
<td>95</td>
<td>25</td>
<td>195</td>
<td>14.5</td>
<td>505</td>
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<tr>
<td>Case 10</td>
<td>252</td>
<td>1335</td>
<td>35</td>
<td>354</td>
<td>95</td>
<td>157</td>
<td>9.98</td>
<td>5.0</td>
<td>94</td>
<td>11</td>
<td>209</td>
<td>14.1</td>
<td>504</td>
</tr>
</tbody>
</table>

1 The CO₂ emission is based on the carbon use. The PCI carbon content is assumed to be 80%, the coking coal 82.2% and the coke 89.7%.

### Table 7. Summarised results for the BOF system. (including the slab casters).

<table>
<thead>
<tr>
<th>Production for 2001</th>
<th>249</th>
<th>956</th>
<th>63</th>
<th>39</th>
<th>9</th>
<th>218</th>
<th>4.1</th>
<th>17</th>
<th>237</th>
<th>n.a.</th>
<th>618</th>
<th>1859</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>249</td>
<td>955</td>
<td>62</td>
<td>42</td>
<td>9</td>
<td>257</td>
<td>3.6</td>
<td>21.8</td>
<td>237</td>
<td>18.6</td>
<td>614</td>
<td>1850</td>
</tr>
<tr>
<td>Case 2</td>
<td>249</td>
<td>869</td>
<td>202</td>
<td>8</td>
<td>23.6</td>
<td>3.5</td>
<td>20.0</td>
<td>237</td>
<td>15.8</td>
<td>565</td>
<td>1694</td>
<td></td>
</tr>
<tr>
<td>Case 5</td>
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<td>816</td>
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1 The CO₂ emission is based on the carbon use. The PCI carbon content is assumed to be 80%, the coking coal 82.2% and the coke 89.7%.

### Table 8. Summarised results for the CHP system.

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<th>Production for 2001</th>
<th>n.a.</th>
<th>n.a.</th>
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</table>

1 The CO₂ emission is based on the carbon use. The PCI carbon content is assumed to be 80%, the coking coal 82.2% and the coke 89.7%.
cerning the specific coking coal demand when pre-determined volatile- and ash contents are used. The deviation is less than 0.2%. For the BF model some small discrepancies exist concerning the metallic charge and the reduction rate. The deviations are ~0.2% and 0.6%, respectively. For the BOF and steel plant model the major discrepancies are related to the gas production discussed earlier.

4.1.4. The Basic Oxygen Furnace System

Changes in the coking oven practice to the use of a less volatile coal blend will lower the specific energy use. The number of external users of the coking oven gas has decreased since 2001. This has resulted in an excess of coke oven gas. From the results summarised in Table 5, it can be seen that the volatile content in the coal blend should be decreased for improvement of the specific energy use. The optimised system for cases 1 and 8–10 has resulted in a decreased amount of specific coking coal in comparison with the reference case. Since only the volatile content in the coal mix was allowed to change, this implies that the volatile content in the mix has decreased. (The specific coal consumption fell from 1 288 to 1 244 kg/t of coke and the volatile content from 25.7 to 22%, the lower limit.) This results in a slightly higher coke production but a significantly smaller gas production, more balanced against the gas demand. The effect of changing the coal mix to a less volatile content on the specific energy use is 0.25 GJ/t of slabs (1.3%). The specific CO₂ emission decreases at the same time by 45 kg/t of slabs (2.4%). The use of external coke is reduced for all the cases where possible.

4.1.5. The Surrounding System

The thermal demand from the district heating network is in all the cases assumed to be 80.8 MWh (the annual average). It is seen in Table 8 that the gaseous fuel recovered in all the cases is less than the maximum amount allowed. It can be noted that the minimum specific energy used in the system does not correspond to the highest amount of gases recovered. The maximum energy recovered is found for case 2 while the minimum specific energy use are in cases 8–10 (depends on the system, e.g. whether it is the current system, a system provided with new materials and equipment, or an improved system). Hence the crediting for energy in outgoing products from the CHP does not necessarily affect the final decision on the steel plant operation, even if the CHP might recover even more energy. The analysis also results in a higher specific energy use due to the fact that the energy is given for the produced electric power or heat and not the energy content in the gaseous fuel itself.

4.1.6. General Results from the Analysis

The different specific energy use calculations are summarized in Fig. 4(a). Figure 4(b) illustrates the effects which different measures have on the specific energy use on the basis of these calculations. The optimal solution for the specific energy use in the current production system (including only the present raw materials and equipment), case 8, involved a decrease of ~17% (from 18.6 to 15.4 GJ/t of slabs) and was found to be achieved when:

1. the coal blend in the coking oven was changed to a low volatile mix
2. external coke was replaced by PCI in the blast furnace
3. the coke rate in the BF was balanced against the internal production at the coke oven
4. the metallic charge in the BOF shop was increased (by decreasing the pellets cooling)
5. the HM production was balanced against the HM demand from the BOF shop

It might seem apparent to introduce iron carriers with lower energy evaluation than HM. However, the amount of scrap is regulated, as seen in the analysis, by the heat- and mass balance for the BOF system and it also affects the overall heat balance for the steel plant–power plant system.

By introducing DRI, scrap preheating and sensitive heat...
recovery from the exhaust gas at the hot stoves, the specific energy use is decreased even more (to 14.5 GJ/t of slabs). The use of DRI in the blast furnace will increase the productivity and the annual production even further if there is an HM shortage. (This effect is not implemented in the model.)

When the total system is analysed, cases 8–10, it can be seen that the different effects are acting simultaneously and that the analysis for the total system proposes different operation modes (regarding material consumption and energy use) from those proposed by the analysis of the different effects alone. If all the constraints are released (cases 8–9), the optimal solution is not composed of the individual best cases (cases 1–7). For instance, the optimal solution when the blast furnace is analysed alone (cases 2, 4, 6 and 7) is found for case 7. The DRI/HBI use in the metallic charge for this case was 607 kg/HM, while in case 9 only 57 kg DRI/HBI/HM were used. This is due to the interactions between the different processes in the system and could not have been identified from the analysis of the blast furnace system alone. The production from each production unit is balanced so that the production meets the demand from the different systems, thereby lowering the total energy use in the system.

The different cases involve changes in the coke and PCI rate in the blast furnace (see Table 6). The carbon entering the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products. Since the amount dissolved into the system will end up either in the main product (steel slabs) or in by-products.

The objective function in the developed model is fairly easy to change, making it a useful tool for further analysis of the steelmaking system.

The model presented has evaluated the production/energy system on the basis of the average hourly production. In the real system several fluctuations occur over time. Some of these are the result of effects from the outer system, e.g. the effects of heat demand from the district heating network, energy prices, taxes, etc. Other fluctuations are the effects of process instabilities and variations. There are for instance large fluctuations due to the different time characteristics of the different processes. The coke ovens can be treated as a semi-batch process where the coke oven plant is continuous but each oven is a batch process. A similar line of reasoning can be applied to the BF, where the oven is mostly continuous but the HM is delivered batch-wise, while the BOF shop is in all respects a batch process. The process dynamics can explain several fluctuations that occur in the energy network. Some of these effects can be taken into consideration by the use of a flexible time scale.

5. Conclusions

5.1. Method Development

A process integration model (PI model) for the integrated steel plant has been developed. It has been shown that:

- The steel processes can be modelled and analysed in such a model and that it is possible to describe different process variants and plant practices with good agreement.
- The different sub-processes can be optimised either separately bounded by the surrounding plant or as whole.
- The different outputs from the model can be used to analyse the optimised result in respect of other aspects, e.g. CO₂ emissions.
- The objective function in the developed model is fairly easy to change, making it a useful tool for further analysis of the steelmaking system.
- The model is a good complementary tool in that it provides new insights into the energy system, but results should be handled with care.
5.2. System Analysis

Minimizing the specific energy use is widely used as a means of characterizing and comparing different plants. This is also in many cases a measure of the CO₂ emission from the system. The integrated steel plant was analysed in a PI-model in respect of the specific energy use. The following observations were made:

- The specific energy use can be improved significantly by changes in operation within the current production system.
- Concerning the external measures analysed, the installation of scrap preheating to increase the scrap rate in the BOF shop has the highest potential for decreasing the specific energy use. The installation of hot stove recovery has only a small potential for achieving such a decrease.
- The analysis will arrive at different results for the specific energy use when analysing the total system and the different processes separately.
- It is important to take into account the total system effect when making system improvements in order to avoid a sub-optimised system.
- CO₂ emission reduction is not necessarily proportional to the energy use reduction for the system.

6. Further Research

One of the most important means of decreasing the reaction rate for the BF-BOF steelmaking route is to lower the ash content in the coke. This will be implemented in the BF model, as well as a variable hot blast temperature.

The effect of transient variations within the system needs to be taken into consideration when conducting a process integration analysis of the steel plant system.

It was identified that the use of DRI in the BF not only decreased the energy use in the system, but also was the most efficient way by far of minimising the CO₂ emission from the system. This was due to the fact that no CO₂ for the DRI production was included at the plant, but if it were to be included, the CO₂ emission from the system using DRI would still be lower than the CO₂ emission from the reference system due to the decreased reaction rate for the BF. If the DRI were produced with natural gas and the CO₂ from the reduction were captured, there would be a zero emission case for the DRI production. The use of such a DRI will be analysed in the near future with respect to CO₂ emissions from the integrated steel plant system.

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REFERENCES