Development of a method for analysing energy, environmental and economic efficiency for an integrated steel plant

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Abstract

The steel industry has faced several challenges during the years. There has always been an aspiration towards higher economic profitability for the system. During the mid 70s and 80s the energy crises caused a dramatic rise in energy costs, which led to an increased awareness in energy conservation. In recent years, climate change issues have become more important for the industry. The operating practises for an industrial system are often affected by external restrictions concerning the economical, energy and environmental efficiency of the system. There are a large number of ways to increase the system efficiency e.g. installation of new process equipment, and practice changes. However, industrial systems such as an integrated steel plant consist of a system of several processes connected together with product and by-product interactions, where changes in one unit may result in changes throughout the total system.

A process integration method focusing on the total integrated steel plant system by a simultaneous approach is adopted. An optimisation model is developed and used to study the effect of changes in the existing material and energy system. Applications of the model on the energy and material system have been made. The model can be used to analyse energy, environmental and economic aspects making it a powerful complement as a decision making tool. Conclusions about energy, environmental and economic effects are presented.
Introduction

Interest in the use of energy has increased in recent years for several reasons. The energy crises in the mid 70s and 80s led to increasing energy cost for industry and an increased awareness of energy conservation. The industry’s dependency on oil and electricity was shifted towards other energy carriers such as coal. The specific use of oil for energy related purposes, which is a measure of the energy conservation, has decreased continuously from the 1970s for most industry branches, it has fallen by over 50% since 1970 due to a shift to other energy carriers and new energy efficient equipment. Oil used as a reductant in the blast furnaces has been replaced by other injectants such as pulverized coal or natural gas. Oil used as fuel in heating ovens has been replaced by natural gas. Energy recovery in the form of energy rich process gases has increased and is in many cases used internally as fuel for various processes. In integrated steel production the energy content in the off-gases from the different processes can be as high as 6-10 GJ/tonne of steel. The efficient use of this energy is therefore of great importance for the total energy use or specific energy use related to the steel production. Today, with increased environmental concern, the greenhouse gas emissions are put on the environmental agenda, and it might lead to a shift from coal based to other energy carriers.

According to the Swedish Energy Agency [1], the Swedish energy use in 2002 was approximately 400 TWh compensated for energy losses and non-energy use such as lubricating oils etc. The industry accounts for nearly 38% of this (152 TWh). The process industry, with energy intensive branches such as the pulp and paper (47%), iron- and steel works (15%) and the chemical industry (7%) accounts for a substantial part of the industrial related energy use. Obviously small efficiency changes in these industries could result in large absolute energy savings.

In the energy proposition (prop. 2001/02:143), the Swedish government has stated that effective resource management, including energy, constitutes the foundation for economic growth and is essential for a sustainable development. The governmental support should be concentrated on the use of existing energy effective technology and the development of new energy effective technologies. As for the industry in general and particularly for the steel industry a major task will be to minimize the consumption of energy and raw materials as well as the environmental impacts.

A natural step is to improve the behaviour of the individual processes. However, the system steel plant - power plant - district heating forms a complex network, where a change of practice in one unit influences the behaviour and energy economy of the other units. Energy saving in one individual unit will not necessarily lead to energy saving for the total system. Methods are needed to optimize the consumption of energy and raw materials for the total system. In principle three techniques emerged from the extensive studies carried out after 1970 to create general models for global optimization: Pinch Analysis, Exergy Analysis and Mathematical Programming. This progress also meant the start of Process Integration (PI) as an acknowledged science in itself.

In this paper a PI analysis method allowing for economical and environmental analysis possibilities for an integrated steel plant is presented. Actual applications of this method to the material and energy network in an integrated steel plant have been preformed in various publications. The possibilities of using this method are discussed here, general conclusions from these studies are presented.
Steel production in the world, EU and in Sweden

Steel production can be divided into two main process routes: the integrated plant with the blast furnace / basic oxygen furnace (BF/BOF route) and the electro steel plant with the electric arc furnace (EAF route). The world steel production in 2002 was 902 Mt, the oxygen processes, e.g. BF/BOF route, accounted for nearly 60%. The EAF accounted for 34% and the rest, 6%, was produced in other processes [2]. For the Swedish steel industry, the total production was 5.8 Mt and the BF/BOF share of this was 66.3%. The annual increase in the steel production is predicted to be about 2%, where the main production increase is in China.

The specific energy consumption for the BF/BOF route is typically in the range of 15 - 17 GJ/tls (tls = tonne liquid steel) or 18 - 22 GJ/tc (tc = tonne coil), with full credit given for energy in process off gases, while the energy consumption for the EAF route is in the range of 4.4 - 5.4 GJ/tls. The difference is mainly due to the different raw materials. The EAF route uses scrap as main iron carrier for the production while the BF/BOF route uses iron ore. The reduction of iron ore is energy intensive, resulting in the higher specific energy use. The theoretical minimum energies needed to reduce iron ore* and heat the reduced iron to its melting point is 8.6 GJ/tonne. The corresponding minimum energies for heating scrap† to its melting point are 1.3 GJ/tonne. However, due to the different raw materials, different steel grades are produced in the two process routes. The contamination element in the scrap makes some steel grades more favourable to produce from ore rather than from scrap.

Description of the integrated steel plant system

In the steel plant, processes are connected together both through primary products from each process and through different by-products or re-circulated materials. The integrated steel mill uses agglomerated iron ore as the main iron source, usually in the form of sinter or pellets, produced either in the sinter plant or in the pelletising plant. The agglomerated ore is reduced and melted in the blast furnace (BF). For this, coke and other reductants such as coal, natural gas or oil are used. The coke is produced in the coke oven plant. The hot metal (HM) produced from the BF is refined in the oxygen metallurgy process (BOF converter) and alloying units. The liquid steel (LS) is finally cast into steel slabs, which in turn are rolled into coils at the rolling mill.

The system studied in this work, SSAB Tunnplåt AB in Luleå, differs in some respects from the traditional integrated steel plants. Firstly, the BF is operated with 100% pellets, the system is therefore not equipped with a sinter plant. Secondly, the steel chain is limited to the processes up to the slab casting, the rolling mill is located in another geographical part. The system studied includes therefore only the process up to the slab casting, i.e. the coke oven plant, BF, BOF melt shop, secondary metallurgy processes (refining units) and continuous slab-casting (CC) units, see Figure 1. Furthermore, the recovered high calorific gases are instead of the rolling mill, used as the main fuel for a nearby power plant.

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* Idealized iron ore (100% Fe₂O₃) reduced at 298K, melting point for Fe 1535 °C
† Idealized scrap (100% Fe) initially at 298 K, melting point for Fe 1535 °C

p. 3
Development of a process integration tool for the steel industry

Existing process integration methods

The common aim of all PI methods is to minimise the energy use, but the approach to achieving this varies between the different methods. Due to the high temperatures and the different characteristics of the different flows in the steel industry, i.e. liquid and solid steel, steam, chemical energy, the area of application for the different PI methods varies.

In the pinch analysis method [3], the system is analysed with respect to the external heat and cooling demand and possibilities for heat recovery within the network. The method is preferably used in systems with heat exchange possibilities between different process streams, e.g. in heat and steam networks but also for heating ovens etc. The Reichhardt diagram‡, which has been used in the steel industry for characterising the energy balance in the blast furnace since the 1920s, is an early energy analysis method, similar to the pinch analysis method.

In the exergy analysis method, the processes and process steps are analysed based on energy quality levels (usefulness). The processes can be analysed with respect to the exergy losses and from this, different practices can be compared. Costa et al [4] presented an exergy study comparing different process routes where exergy analyses with a life cycle inventory were applied to analyse the effect of diverse technological options for the different process routes. For instance, the use of excess energies or material flows was analysed. Petela et al [5] used a similar approach to analyse the effect of different blast furnace injection materials for an iron making process.

In the mathematical programming method, different optimisation models are used to analyse the system. The method is suitable for defining process behaviour, the interplay between different processes and for analysing the total system effect of changes in a sub-system.

The development of a process integration model

A study using the exergy concept for analysing and quantifying the losses in the steel making chain [6] had already been used and proved useful for analysing the steel plant with respect to energy analysis for the SSAB steel making chain. This can also be seen from more recent publications where the exergy concept in some sense has been used. Initial tests with the pinch analysis method applied to the coke oven process and a heating oven showed that it was possible to use this approach. The characteristic pinch diagrams had however a quite different

‡ P. Reichhardt, Arch. Eisenhuttenw., 1927/28, vol. 1, pp. 77-101
appearance due to the high temperature. Meanwhile, the experience of early modelling at SSAB [7] showed that a global approach was needed in order to assess correctly the effect of changes. On the basis of this it was realised that the flow characteristics (high temperature, solid and liquid material etc.) made it difficult to analyse the effect of changes in the system using the exergy analysis and pinch analysis method. Instead, the mathematical programming approach was identified as a potential option which led to the development of an optimising PI method for the steel industry.

The definition of a good model can be made on the basis of several general principles. In the ghg protocol (Greenhouse Gas Protocol Initiative) [8] which is developing and promoting internationally accepted greenhouse gas accounting and reporting standards, the following definition is used:

- Relevance: the system boundary chosen should appropriately reflect system.
- Completeness: the calculation should include all important activities within the system.
- Consistency: the result should allow for meaningful comparisons of performance over time.
- Transparency: the analysis should be conducted in a factual and coherent manner, based on a clear audit trail.
- Accuracy: The calculations should have the precision needed for the intended use, and provide reasonable assurance on the integrity of the calculations.

However, there is a conflict among several of these. E.g. higher accuracy usually leads to a less transparent model which might affect the outcome from the modelling due to decreased understanding. A complete model (including all activities) increases the accuracy, but will probably decrease the transparency and so forth.

The process integration tool developed is a mathematical programming tool based on mixed integer linear programming (MILP). The method is derived originally from the MIND method [9] and has been further developed to meet the modelling requirements of the steel industry processes. The tool, where the optimising model is created, is object oriented with a graphical user interface (GUI).

The model core is an overall mass- and energy balance for the production chain and separate sub-balances for the main processes which makes it possible to perform a total analysis for the steel plant and to assess the effect of a change in the operation practice for the different processes. In the model the different main processes (i.e. coke oven, BF, BOF, and CC) are connected together by each primary product and by-product interaction. The driving force for the model is the production of the final product of the system, i.e. first-rate steel slabs. Each sub-process is linked to the next processing step by the primary product from each process i.e. coke, HM and LS. The steel demand from the CC units will thus determine the production rate in the BOF, which in turn will determine the HM rate for the BF and so forth. The different processes included and the main process flows in the model are shown in Figure 2. The standard way of operation for the steel plant is possible to change by integrating new process equipment or materials and defining the interplay with the total system.
The material and energy use are based on the process requirements for each sub-process, which are determined from the individual process description relating the ingoing resources with the outgoing main product. The consumption and excess of by-products are also determined from each sub-process model, Figure 3.

Specific details regarding the modelling of the coke oven
In the coke oven, coke is produced by dry-distillation of coal. In the coking process, the coal is heated without access of air. During this process, the volatile matter in the coal is released and recovered (coke oven gas). Thus, important reactions to include in the model are the conversion of coal to coke, the production of the coke oven gas and the energy balance for the coking process. The model is based on a mass and energy balance for the heat balance and empirically derived process relations based on engineering practice for the coke conversion and the production of the coke oven gas.
Specific details regarding the modelling of the blast furnace

In the BF, HM is produced by reduction of the iron ore \((\text{Fe}_2\text{O}_3, \text{Fe}_3\text{O}_4)\) to liquid iron. 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. The coke and coal that are used as the main reductant (oil or natural gas are other supplementary reductants that can be used) 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. There are many chemical reactions taking place in the BF, which are needed to successfully depict the behaviour of the furnace, and which are complex to describe mathematically. Instead of modelling all the important reactions, the BF is modelled as a black box, taking into account the different mass- and heat balances. Both real process- and simulated process data can be used as input for the model.

For off-line simulations of the BF behaviour, SSAB Tunnplåt AB employs an in-house model [7] in which the chemical and thermal reactions in the furnace are taken into account. There has been a further developed of this model into a more general web based BF simulation tool (raceway.nu) which instead can be (and has been) used to generate BF cases that describe possible operation practices. By choosing the cases wisely, it is possible to determine a region (map) of possible operation practices that covers the need for the present investigation. The feasible region in which the BF can be operated is limited in these cases. Totally 10 different operation practices have been included in the model, which describes the interaction of the BF in the overall mass and energy balance for the total steel plant system. The developed model is valid for a predetermined hot metal composition§ (Fe 94.4%, C 4.7%, Si 0.4%), slag basicity§ (defined as the ratio \(\text{CaO}/\text{SiO}_2 = 0.98\)) 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 pre-heated combustion air (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 in the model as well.

Specific details regarding the modelling of the basic oxygen process

In the BOF process the HM and to some extent scrap/iron ore are processed into crude steel. During the processing of mainly the HM, process off-gases (BOF gas) are produced and recovered mainly from the oxidised carbon. Other oxidised compounds e.g. silica, manganese, phosphorus, form a slag. The important reactions to take into account are thus the total mass and energy balance for the process and balances for each element.

The different iron carriers, i.e. HM, scrap and pellets, are limited by the mass and heat balance and the contamination (tramp elements) in the scrap. A hot metal exchange between the HM coming out of the BF and the HM entering the BOF is introduced. Hot metal cast on the ground, due to disturbances between the BF and BOF, is included as pig iron (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 \(\text{CaO}/\text{SiO}_2 = 4\)§ 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

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§ Information from SSAB Tunnplåt AB
ratio, defined as the ratio between the CO$_2$ and the sum of the CO$_2$ and CO in the BOF gas, is set as a constant (not depending on the steel type). 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.

Specific details regarding the modelling of the continuous casting
In the CC process the LS is cast to steel slabs which are further processed in the rolling mill. In order to make an adequate model for the CC units it is important to model the losses between LS and the cast product as well as to characterise the type of loss i.e. recovered or non recovered losses. The model for the CC units is based on the casting yield and a specific electricity demand.

Specific details regarding the modelling of the surrounding system
The steel plant interacts with its surroundings in several aspects. The surplus of the recovered energy rich gases is utilised in a combined heat and power plant (CHP). The solid rest materials generated from the process are recovered, sold or put to landfill.

The energy interaction with the surroundings is included through a CHP model utilising the excess of the process off-gases in a boiler. Two operation modes for the power plant, pure back-pressure mode and the partly condensing mode, are included. In the 100% back-pressure operation mode, 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 at 0.44**. In the complete condensing operation mode, all the heat is cooled by an external cooling circuit. The steam is further expanded in the steam turbine leading to extra power generation. The energy efficiency for the electricity generation is set at 0.32**. The mixture of the incoming fuel gases and oil are limited by the heat value of the mixed gas.

The solid waste interaction with the surroundings is included through a residue material handling model. The rest materials produced from various processes are recovered to some extent, either as rest products or recycled into the process. For the waste handling system, the important recycling possibilities and rest products are described and the interaction with the steel making chain is included.

Objective function / objectives
A good industrial system should be operated in a way that maximises the profit, and minimises the energy use and environmental impacts. The minimisation goal, the objective, for the MILP model is described by the objective function that is independent of the model. Hence, several objectives can be used for the same model but only one objective function at a time. The objective functions defined in the analysis are minimisation of production cost [10], energy use [11], CO$_2$ emission and residue material to landfill [12].

The objective function, minimising of production cost, comprises material and energy flows that affect the system and its corresponding costs. The other objectives are included on the same principle, but instead of costs these are “CO$_2$ coefficients”, “energy coefficients” and “landfill coefficients”.

** Information from Lulekraft AB
Analysis of energy use, economic efficiency and environmental impact

The model has been used to analyse the integrated steel plant from several aspects [10, 11, 12], and a brief summary of these papers is given.

Ways to minimise the energy use

The alternative process configuration analysed for decreasing the specific energy use for the SSAB Tunnplåt steel plant, can be divided into two main groups: practice changes within the existing production system and installation of new process equipment. The options included in the analysis, Table 1, have been analysed in ten different cases. As the basis for comparison a reference case, Ref. SEC, simulating the production and energy system for 2001 has been included. In the first seven cases the possible changes in the coke oven, BF and BOF are analysed one at a time. For case 1, the effect of changes in the coal mix for the coke production is analysed. For case 2, the effect of changes in the current burden materials for the BF and in case 3, the metallic charge in the BOF (the HM/scrap ratio) are analysed. For cases 4-5 installation of new process equipment is included in the analysis, firstly heat recovery from the hot stove exhaust gas and secondly increased scrap rate in the BOF through scrap pre-heating. For cases 6-7 a new iron source (direct reduced iron, DRI/HBI) used together with pellets in the burden material for the BF is analysed. For case 6 the coke-to-PCI rate is fixed, and in case 7 the burden material is set free. Three optimised cases for the energy use are analysed. In case 8, the current system is optimised on the basis of the present technologies and raw materials. In case 9, new process alternatives and raw material (DRI/HBI, heat recovery and scrap pre-heating) are included in the optimisation. In case 10, the effect of efficiency improvements is analysed (otherwise as case 9), which include yield improvements for HM and LS by 1% each, decreased flaring (50% of the normal operation) and a 5% decreased heat loss from the coke oven battery.

Table 1 Process variations and equipment changes included in the study

<table>
<thead>
<tr>
<th>Coke Plant</th>
<th>Blast furnace</th>
<th>BOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practice change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable coal blend</td>
<td>All coke practice</td>
<td>Variable metallic charge</td>
</tr>
<tr>
<td>Production rate</td>
<td>Pulverized coal injection (PCI)</td>
<td>Decreased pellets cooling</td>
</tr>
<tr>
<td></td>
<td>Variable Fe burden:</td>
<td>Production rate</td>
</tr>
<tr>
<td></td>
<td>Pellets – DRI/HBI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BOF slag &amp; dust recovery</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production rate</td>
<td></td>
</tr>
<tr>
<td>New process equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot stove exhaust gas recovery</td>
<td>Increased scrap rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>through:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- scrap preheating</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased energy</td>
<td>Decreased disturbances</td>
<td>Increased LS efficiency</td>
</tr>
<tr>
<td>demand for under-firing</td>
<td>BF/BOF route</td>
<td></td>
</tr>
<tr>
<td>Increased HM efficiency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The corresponding energy use for the different cases is shown in Figure 4. Cases 1-7 simulate the effect on the specific energy use of including the new process technologies and raw materials as well as practice changes within the existing steel plant system. For the
optimisation of the existing system, case 8, the reduction potential is calculated to ~17% (15.4 compared to 18.6 GJ/tslabs for the reference). Measures suggested by the optimisation are:

- Lowered volatile matter in the coking coal mix.
- Increased PCI rate in the BF to replace the use of external coke, and coke rate in BF balanced against the coke oven production rate.
- The metallic charge in the BOF (HM/scrap rate) was increased by decreasing the use of pellets.

With new process alternatives and raw materials, case 9, the energy consumption could be decreased to 14.5GJ/tslabs, by introducing DRI/HBI into the BF and increasing the scrap rate into the BOF by scrap pre-heating. By increasing the efficiency, case 10, the energy use can be decreased additionally 0.4 GJ/tslabs.

![Figure 4 Specific energy consumption](image)

When the total system is optimised, cases 8-10, the different options (cases 1-7) may be seen to act simultaneously, at individual levels different from those proposed in the study of the single effects. This is due to interaction between the different processes that are difficult to foresee. The production from each system (coke oven, BF and BOF) is balanced against the demand from the total system, which results in that the energy use for the total system is decreased. The effect of the different measures and the total specific energy decrease for the optimised system, case 10, is shown in Figure 5.

![Figure 5 Effects of measures for energy saving](image)

The largest influence on the energy use is the HM/scrap ratio in the metallic charge for the BOF. Scrap pre-heating enables more scrap to be utilised in the steel production. It might seem logical to introduce iron carriers with a lower energy cost than HM, but the amount of
scrap is regulated by the mass- and heat balance for the BOF. The burden materials for the BF have a significant impact on the overall energy use of the system. Increasing the PCI rate, matching the coke rate to the production in the coke oven and introducing DRI/HBI as burden material in the furnace are effective measures to decrease the energy use. A decrease of the volatile matter in the coking coal mix also decreases the energy use significantly. A lower volatile matter results in a slightly higher coke production and decreased gas generation.

Ways to minimise the production cost

A major renovation of the coke oven battery was carried out during the period 2002-2003 which resulted in a coke and coke oven gas deficit. The economic effect on the production and energy system of the coke and coke oven gas deficit was analysed.

The total renovation period was analysed. Initial investigations made at the steel plant with regard to the coke oven gas supply showed that there was an impending risk of having a coke oven gas shortage in the system due to the reduced coking capacity. The worst case scenario could be that internal production units would be affected resulting in production disruptions. Two different renovation scenarios are analysed in three different cases. The two scenarios differed in renovation duration and coking capacity. For case 1 the coke oven system is optimised to meet the requirement from the rest of the steel making chain. In case 2, the steel making system is optimised while the CHP is operated as the reference. For case 3 the total system including the CHP is optimised to meet the requirement of heat to the community and slab production. A reference case, according to the operation practised used at the steel plant and renovation scenario 1, is used as the basis for comparison of the three different cases.

The change in total cost during the total renovation period is shown in Table 2. It is shown that by widening the system boundary the system cost can be decreased. The lowest cost is achieved when including the total system in the optimisation. By choosing the wider system boundary it is possible to decrease the system cost by ~5.3 % for scenario 1 and 5.7 % for scenario 2. This is achieved mainly by decreasing the cost for the coke oven system while the cost for the BF system is slightly increased.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Coke Oven</th>
<th>BF</th>
<th>BOF</th>
<th>CHP</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long renovation duration, High coking capacity</td>
<td>Case 1</td>
<td>-3.2%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>-1.1%</td>
</tr>
<tr>
<td>Case 2</td>
<td>-12.0%</td>
<td>1.0%</td>
<td>-3.0%</td>
<td>0.0%</td>
<td>-3.9%</td>
</tr>
<tr>
<td>Case 3</td>
<td>-13.2%</td>
<td>0.7%</td>
<td>-3.0%</td>
<td>-6.9%</td>
<td>-5.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2</th>
<th>Coke Oven</th>
<th>BF</th>
<th>BOF</th>
<th>CHP</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short renovation duration, Low coking capacity</td>
<td>Case 1</td>
<td>-4.4%</td>
<td>-0.1%</td>
<td>0.9%</td>
<td>-1.5%</td>
</tr>
<tr>
<td>Case 2</td>
<td>-12.4%</td>
<td>0.7%</td>
<td>-3.0%</td>
<td>0.0%</td>
<td>-4.2%</td>
</tr>
<tr>
<td>Case 3</td>
<td>-13.6%</td>
<td>0.4%</td>
<td>-3.0%</td>
<td>-7.2%</td>
<td>-5.7%</td>
</tr>
</tbody>
</table>

The share of the production cost, including income from sold by-products and energy, between the different production units is approximately 28-30 % for the coke oven, 56-59 % for the BF and 14-16 % for the BOF. Cost reduction from the CHP is 10-15%.

Several changes were identified for the system, and the general observations found for the optimised operation are: Firstly, the coke demand for the BF is minimised. Secondly, there is a shift between the different users of the coke oven gas in the system. More gas is primarily used internally, in the BF system. Thirdly, for the BOF system, the HM share is increased and the use of pig iron, which in reality is a consequence of disturbances between different units.
In the system, is minimised. Finally, for the CHP, the primary gases changed to more BF and BOF gas.

In normal mode (i.e no renovation) the system should be operated with a low volatile mix in the coking coal. The lowered volatile mix in the coking coal results in decreased gas generation but increased coke production. For the BF, the hot blast temperature is increased, resulting in a decreased specific coke demand which at the same time will decrease coke deficit in the system. This operation requires a higher share of coke oven gas in the hot stoves.

In renovation mode the system has a decreased supply of both coke and coke oven gas. The deficit is decreased by changes in the system. The volatile mix in the coking coal mix is increased slightly (compared to the normal reference operation). The coke demand in the BF is reduced by increasing the hot blast temperature and increasing the PCI rate. The hot blast temperature is not increased as much as suggested for the normal operation.

**Ways to minimise the landfill**

Two existing residue material recycling alternatives and four new alternatives have been analysed. The existing recycling is through the BF either as top charged residue material briquette or as top charged BOF slag. The analysed new possible recycling alternatives have all been tested on a full scale for short periods at the steel plant. They are a new briquette for the BF replacing BF flue dust with mill scales (MSB), injection of BF flue dust (BF inj) through the tuyeres and two new cold bonded pellets (CBP1 and CBP2) to be used in the BOF. In Table 3 the different residues included and alternative recycling possibilities are shown. The effects of the different alternatives primarily on the landfill are analysed one at a time in seven cases and in one case where the amount to landfill is minimised (by optimisation). As the basis for comparison a reference case, Ref. recirc., simulating the existing steel plant system has been included.

Table 3 Recycling possibilities; BF briquette, top charging, injection and BOF cold bonded pellets, [%].

<table>
<thead>
<tr>
<th>Recycling unit</th>
<th>BOF sludge fine</th>
<th>BOF sludge coarse</th>
<th>BOF slag</th>
<th>BF flue dust</th>
<th>Mill scales</th>
<th>Steel scrap</th>
<th>Desulph. Scrap</th>
<th>Briq. fines</th>
<th>Filter dust</th>
<th>Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Briquette1, normal</td>
<td>Ref.</td>
<td>BF</td>
<td>-</td>
<td>14.8</td>
<td>-</td>
<td>26.0</td>
<td>-</td>
<td>23.2</td>
<td>8.8</td>
<td>8.7</td>
</tr>
<tr>
<td>Top charging</td>
<td>Ref.</td>
<td>BF</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>New possibilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Briquette2, mill scale</td>
<td>MSB</td>
<td>BF</td>
<td>-</td>
<td>14.8</td>
<td>-</td>
<td>26.0</td>
<td>23.2</td>
<td>8.8</td>
<td>8.7</td>
<td>8.0</td>
</tr>
<tr>
<td>Injection</td>
<td>BF inj</td>
<td>BF</td>
<td>-</td>
<td>-</td>
<td>100*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CB pellet1</td>
<td>CBP1</td>
<td>BOF</td>
<td>40</td>
<td>20</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CB pellet2</td>
<td>CBP2</td>
<td>BOF</td>
<td>51</td>
<td>26</td>
<td>-</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*BF flue dust mixed together with PCI, totally three cases corresponding to 5.0, 1.0 and 2.2 kg/tHM.

The effect of the different new recycling possibilities on the total amount of residue to landfill is shown in Figure 6. In the figure the residues are separated on the basis of the place for generation, e.g. all residues to landfill generated in the BF (BF flue dust, sludge and slag) are added up in “BF” in the figure. The total amount of residues to landfill for the reference case is 16.4 t/h. For the analysed recycling alternatives the corresponding value is 18.2-13.9 t/h. Using the optimising routine, minimising residue to landfill, the amount of residue to landfill decreases to 12.9 t/h. This is achieved by utilising a mix of the different recycling alternatives. The specific changes in the BF and BOF system are shown in Table 4.
Figure 6 Comparison of amount of residues to landfill for the different recycling alternatives and the corresponding amount from optimisation.

Table 4 Specific material consumption figures for the BF and BOF in normal operation (Ref. recirc) and optimised operation (Opt.).

<table>
<thead>
<tr>
<th>Case</th>
<th>BF</th>
<th>BOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellets</td>
<td>1380.8</td>
<td>1371.8</td>
</tr>
<tr>
<td>Coke</td>
<td>336.1</td>
<td>335.9</td>
</tr>
<tr>
<td>PCI</td>
<td>129.9</td>
<td>134.1</td>
</tr>
<tr>
<td>Flue dust</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>Lime</td>
<td>59.0</td>
<td>46.5</td>
</tr>
<tr>
<td>Briquette1</td>
<td>40.3</td>
<td>42.3</td>
</tr>
<tr>
<td>Briquette2</td>
<td>0</td>
<td>5.4</td>
</tr>
<tr>
<td>BOF-slag</td>
<td>36.6</td>
<td>39.6</td>
</tr>
<tr>
<td>Slag</td>
<td>170.3</td>
<td>162.8</td>
</tr>
</tbody>
</table>

For the optimised BF operation practice the BOF slag, briquette and flue dust are increased while the amounts of lime and pellets are decreased compared to the reference case. The decreased use of lime and pellets are a direct consequence of the increased recycling of BOF slag and briquettes. For the optimised BOF operation, the pellets is replaced by the CB pellets and the use of scrap is increased. The different recycling alternatives also affect the energy use and CO2 emission from the system. The normalised energy objective and CO2 emission objective based on the results of the minimisation of landfill objective for the different cases are shown in Figure 7.

Figure 7 Effect of increased recycling on energy use and CO2 emission
Discussion

The development of a PI method/model

The need to analyse the energy and material system by using a general method was the starting point for the investigation of how and if the existing PI techniques could be used for the steel industry branch. The exergy method had already been used for analysing and quantifying the losses in the steel making chain [6], but the use was limited to the actual production cases. The initial tests with the pinch analysis method, applied to the coke oven process and a heating oven, showed that this approach was also possible to use, but the process characteristics of the steel industry (high temperature, solid and liquid material etc.) made the analysis more difficult. Instead, a mathematical programming approach was identified as a possibility which led to the development of the optimising PI method for the steel industry.

The development has been carried out in close cooperation with partners from both the steel industry and the university. This has several advantages:

- The model and model results are easier to validate by communication with the people (and experts) who own the processes and have the experience of what is reasonable as well as possessing process data to base the validation on.
- The close cooperation is also important in order to create a model that can and will be used. By knowing the “need” and “problem” in beforehand, it is more likely that the result is a model that can solve an industrial problem rather than a model that has a solution to a problem that no one has asked for.
- The acceptance of the model and model result, which is likely to increase, is another factor to take into account.
- Finally, the distribution and knowledge of the method and model is important if the results of the research are going to be used.

General aspects of the method/model

The PI method presented and used in this work is based a MILP optimisation routine. The use of an optimisation routine is a strong feature which is illustrated in the results. A comparison between the optimised objective and simulation of the different feasible process configurations shows that the lowest objective value is not found for one process configuration, but rather as a mix between these configurations found by the optimisation (compare minimisation of energy use and minimisation of residue flows). It is important to take into account the total system effect when making system improvements in order to avoid sub-optimal operation. By widening the system boundary to include the different units in the system a better system solution can be reached. Thus, the improvement can be taken one step further using the optimisation routine and a total analysis approach with an appropriate system boundary.

In the PI method it is possible to define different objectives for the same model. The analysed objectives in this paper are minimisation of the specific energy use, production cost, landfill, and CO₂ emissions. This makes it possible to use the same method for different types of analyses. In this paper the method and usability of the model have been exemplified from three different studies. In the first, minimising the specific energy use, analysing the potential improvements that can be achieved within the existing steel making route and from integration of new energy efficient process technologies or raw material. In the second, minimising the production cost, analysing the effects of a severe disturbance due to a coke oven renovation. The last, minimising the residue amount to landfill, analysing new potential
recycling alternatives. All these studies have been based on the same model, with some modifications to include the new features, to analyse two different aspects of the steel making chain. This is made possible because the core of the model is the overall mass and energy balance for the system, based on process relations describing the behaviour of the various processes in the system.

The steel making chain including the main processes, coke oven, BF, BOF and CC units constitutes the core of the model. As interaction with the surroundings, a CHP plant and a residue handling system have been included. A system boundary including these main processes has been shown to represent the system adequately. We think therefore that the first and second criteria in the definition of a good model have been fulfilled. The operation practice for the existing model is possible to change by introducing new material, operation practices or integrating new technologies. This makes it possible and meaningful to use the model to analyse the steel plant system over time, which satisfies the third criterion, consistency. The PI tool in which the model is made has a graphic user interface. This is a good starting point for creating a transparent model with a clear audit trail. However, the model for SSAB is relatively large which makes the overview of the model more difficult. A recent development of the tool to enable a more flexible mathematical description will improve this, but until this has been implemented, the fourth criterion will not be completely fulfilled. The modelling results show that the model can be used to analyse several aspects of the steel making chain. Validation of the model and model results has been made with good agreement for the different studies. The result of the analysis is however always dependant on the quality of input data. The accuracy of objective function coefficients is of great importance for the outcome of the analysis, and hence it is important to validate the model against a known reference case. The last criterion, accuracy, is therefore more difficult to assess and is dependent on good quality of input data.

General discussion regarding modelling results

It is natural that energy use and CO₂ emissions from the local production unit are higher for new production of steel than for melted scrap. The production of primary steel from iron ore is energy intensive mainly due to the dependence on coal as reducing agent for the iron ore in the BF. This is also the main source of the CO₂ emission from the system and a large part of the production cost. Residue produced in the plant can be recycled and reused on site as raw material in the production, or recycled in external applications outside the steel production chain, e.g. construction material, concrete aggregate, thermal insulation. Increased internal recycling might lead to reduced energy use and CO₂ emission from the system because recycled residues are reintroduced in the production chain closer to the primary product [13]. It has been shown that by minimising the residue to landfill, i.e. increasing the internal recycling, both specific energy use and CO₂ emissions from the system can be decreased.

There are great similarities between process integration and combined waste and resource optimisation (CWRO) which usually deals with residue material recycling analysis. Hence the minimisation of specific energy use, production cost and minimisation of residue material to landfill, which are usually treated as completely different disciplines, can be analysed using the same methodology and models. The spin-off from using the same system for different types of studies are two-fold: firstly rationalisation, the different methods usually use the same set of input data, however often gathered separately. Secondly, is a question of validation, development and survival of the method/model. If more users use the same model there will always be a further development of the system which is crucial for getting a model that survives personnel movements within any organisation.
The results of the modelling can be used to indicate a direction towards where the development and changes of operation practise should take place.

- The HM/scrap ratio has the largest influence on the energy use. This might seem obvious, but the scrap rate is limited by several factors such as purity, availability and the actual heat balance for the BOF converter. There are significant savings to be made by optimising the BF burden material as well as decreasing the volatile matter in the coal mix. Of the external measures analysed, the scrap preheating is an interesting option. General efficiency and yield improvements are good measures to decrease the specific energy use.
- From an economic point of view, changes are suggested to decrease the dependence on external coke and the use of pig iron, which is achieved by decreasing the disturbances between the BF and BOF.
- In the landfill minimisation study it was found that the recycling alternatives were limited due to a lack of a residue material. In order to decrease the landfill amount a new recycling alternative should be considered.

It is important to take into account the total system effect when making system improvements in order to avoid sub-optimal operation. It is equally important to be aware of the three aspects of energy, economy and environmental impacts. These are important factors to take into account when making analyses of the industrial system. In the PI model developed it is possible to analyse these three aspects of the steel making system simultaneously. This is an important step in the direction towards a sustainable optimisation system.

Conclusions

- A process integration method for the steel industry has been developed. Global mathematical models for the steel making processes have been developed in which the PI model for the integrated steel plant system, SSAB Tunnplåt AB, has been based on.
- The PI model has been used in several studies of the material and energy system for the integrated steel plant SSAB. From the modelling results, conclusions on economical, energy and environmental aspects have been drawn.
- The PI model is a good tool providing new insights into the material- and energy system from economical, energy and environmental points of view. It can serve as a benchmark for different steel making operations and constitute a basis for the continuous work of improving the material and energy efficiency.
- The PI-model developed is a powerful complement to the existing analysis- and decision making tools.
- The development of a method taking into account the various aspects of economy, energy and environmental impact is an important step towards sustainable system analysis.

Acknowledgments

This work has been financed by the process integration research programme at the Swedish Energy Agency. We would like to thank Professor Carl-Erik Grip at SSAB for valuable comments and guidance throughout this work. We would also like to thank SSAB Tunnplåt AB for allowing us to perform and assisting us in this research.
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