INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2008; **32**:1092–1106
DOI: 10.1002/er.1447

A model on CO_2 emission reduction in integrated steelmaking by optimization methods

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SUMMARY

The iron and steel industry is a large energy user in the manufacturing sector. Carbon dioxide from the steel industry accounts for about 5–7% of the total anthropogenic CO_2 emission. Concerns about energy consumption and climate change have been growing on the sustainability agenda of the steel industry. The CO_2 emission will be heavily influenced with increasing steel production in the world. It is of great interest to evaluate and decrease the specific CO_2 emission and to find out feasible solutions for its reduction. In this work, a process integration method focusing on the integrated steel plant system has been applied. In this paper, an optimization model, which can be used to evaluate CO_2 emission for the integrated steel plant system, is presented. Two application cases of analysing CO_2 emission reduction possibilities are included in the paper. Furthermore, the possibility to apply the model for a specific integrated steel plant has been discussed. The research work on the optimization of energy and CO_2 emission has shown that it is possible to create a combined optimization tool that is powerful to assess the system performance from several aspects for the steel plant. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: process integration; modelling; CO_2 emission; optimization; steel industry

1. INTRODUCTION

The iron and steel industry is the largest energy-consuming manufacturing sector in the world. Therefore, concerns about energy consumption and climate change have been growing on the sustainability agenda of the steel industry. The world's annual steel production has been steadily

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Contract/grant sponsor: Swedish Governmental Agency for Innovation Systems
Contract/grant sponsor: Knowledge Foundation
Contract/grant sponsor: Swedish Foundation for Strategic Research
Contract/grant sponsor: Luossavaara-Kirunavaara AB
Contract/grant sponsor: SSAB Tunnplåt AB
Contract/grant sponsor: Rautaruukki Oyj

Received 15 October 2007
Revised 18 February 2008
Accepted 18 March 2008

increasing during the past decades, and a particularly rapid increase is noticed since 2000. According to IISI [1,2], the world's crude steel production was 1058 Mt in 2004, exceeding 1000 Mt for the first time in the steel production history. The BF/BOF (blast furnace/basic oxygen furnace) route and the electric arc furnace (EAF) route are the two dominating process routes. The share of the BF/BOF and EAF-based production of crude steel in 2005 was 65.4 and 31.7%, respectively. The CO_2 emission from the steel industry links to the production process. As for the BF/BOF route, the reduction and melting of iron ore to hot metal (HM) in the BF is almost entirely based on coal. Consequently, the steel production industry emits large amounts of carbon dioxide, accounting for about 5–7% of total anthropogenic CO_2 emission [3]. The CO_2 emission will be heavily influenced by increasing steel production in the world. It can be anticipated that CO_2 emission from the steel industry will increase with the increase in crude steel production in the near future unless significant changes in the current process route shares or significant energy/production efficiency can be made, or some effective CO_2 emission reduction technologies, e.g. carbon capture and storage, can be employed widely in the iron and steel industry. It is of great significance to develop a method to analyse potential CO_2 reduction possibilities in the steel industry. Some studies [4–6] have analysed CO_2 emission reduction options within the iron and steel industry. Most of these studies applied a simple top–down econometric approach, neglecting complex interactions of different process units for the steelmaking. In this study, a process integration (PI) method focusing on the integrated steel plant system (the conventional system of the BF/BOF) has been applied. An optimization model, which can be used to evaluate CO_2 emission by optimizing ferrous burden material use in the BF–BOF system, is presented. The study also covers carbon-trading schemes in order to find out the lower abatement cost option(s). Finally, a possibility of applying the model for a specific integrated steel plant is discussed.

2. MODEL DESCRIPTION

The model developed is based on a PI technique, mathematical programming, to analyse CO_2 emission by optimizing material and energy systems in the steel industry. A survey on mathematical programming applications indicates that a broader application of optimization has been focusing on chemical and petroleum engineering. For the metallurgical industry it has been mainly restricted to the application of linear programming for inventory control, blending, scheduling and similar purposes [7]. Deo *et al.* [8] described the possibilities to use either mathematical programming or genetic algorithms to find the optimum operating conditions in integrated steelmaking. However, till now unexpectedly few reports on how to solve the complex steelmaking by PI tools are available. In this paper, the method described is based on the mixed integer linear programming (MILP). The method uses a graphical interface equation editor *Re*MIND, which was developed in cooperation between two Swedish Universities of Linköping University and Luleå University of Technology, to generate the mathematical equations to be optimized. Figure 1 shows the flow chart of the model structure. There are several numerical solvers available, which can be used for optimization. In the presented work, the ILOG CPLEX linear programming solver is used. Microsoft Excel is used to analyse the modelling results with some MACRO commands.

The principle of *Re*Mind model is presented in Figure 2. The model is represented by nodes and branches where the branches represent energy or material flows and a node may represent a process

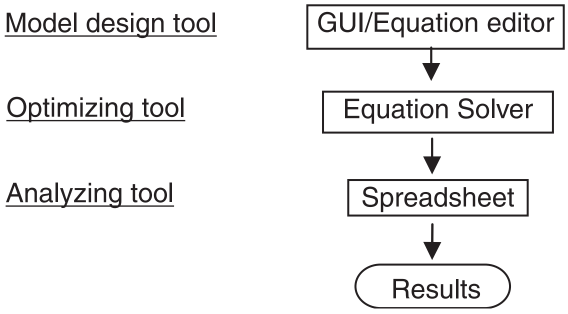


Figure 1. Flow chart of the optimization model.

unit as well as a production line or a whole factory. Each process node has its own energy demand in the form of electricity and/or heat demand. These demands depend on the amount of material processed in the unit and may be described by linear or piecewise linear relations. The variations are described in the system with boundary conditions, for instance, production capacity, limited availability for various resources such as fuels, electricity or raw materials. Each system is adjusted to the situation in each individual case. The adjustment is made to answer the questions in the individual case and to make the model as efficient as possible.

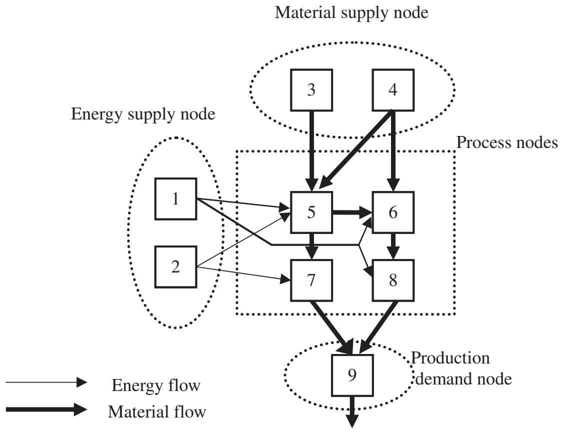
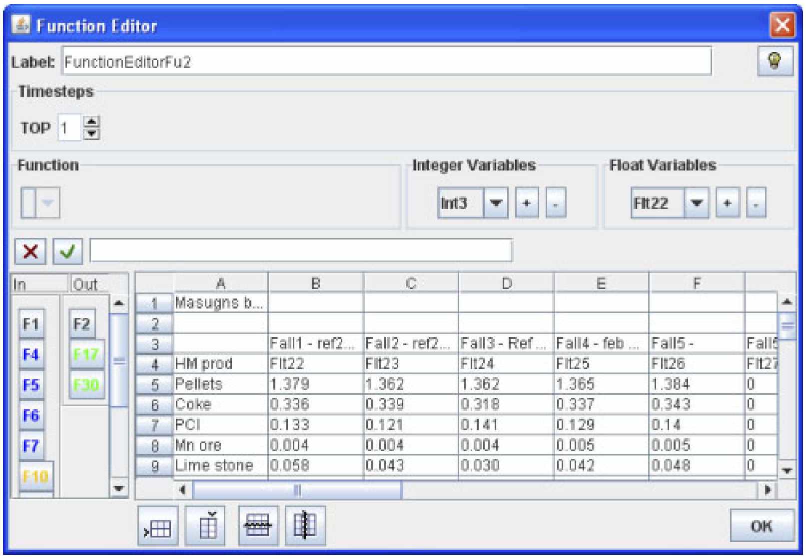


Figure 2. Schematic description of the principle of the *Re*Mind model.

In this work, *Re*MIND has been used for the integrated steelmaking system, which covers processes of coke oven plant (COP), lime furnace, BF, BOF, ladle metallurgy, continuous casting (CC) and combined heat and power (CHP). The model includes four kinds of nodes: material flow nodes, energy flow nodes, process nodes and end product nodes. Material and energy flow nodes are the input nodes for the model. The core nodes for the model are the process nodes that contain the basic metallurgy processes. Processes are described by mass and energy balance to link ingoing material and energy flows, thereby connecting the different processes. An example process node, the BF node, is shown in Figure 3. The end nodes include the main product from the processes, for instance, slabs for the whole system, HM or liquid steel if we are only looking at the BF or the BF+BOF, etc. The other end nodes could be heat and power generation, gas to flare, etc.



Label: FunctionEditorFu2

TOP 1

Int3

Flt22

	A	B	C	D	E	F	
1	Masugns b...						
2							
3		Fall1 - ref2...	Fall2 - ref2...	Fall3 - Ref ...	Fall4 - feb ...	Fall5 -	Fall
4	HM prod	Flt22	Flt23	Flt24	Flt25	Flt26	Flt2
5	Pellets	1.379	1.362	1.362	1.365	1.384	0
6	Coke	0.336	0.339	0.318	0.337	0.343	0
7	PCI	0.133	0.121	0.141	0.129	0.14	0
8	Mn ore	0.004	0.004	0.004	0.005	0.005	0
9	Lime stone	0.058	0.043	0.030	0.042	0.048	0

Figure 3. An example of the function editor in the BF node.

2.1. Objective function(s)

There is a possibility of defining several objectives in the model depending on the objective problem studied. These can either be analysed one a time, i.e. single objectives, or combined, i.e. as multi-objective function. Generally, the objective can be expressed in mathematical terms as follows:

$$\min z(x,y) = \sum c_j x_j + b_j y_j, \quad j = 1,\ldots,n \qquad (1)$$

$$\begin{aligned} &\text{s.t.} \\ &A_1 x \le b_1 \\ &A_2 x + By \le b_2 \\ &x \in R^n, \quad y \in \{1,0\} \text{ or integer} \end{aligned}$$

where z is the objective function for minimizing CO_2 emission, x represents the studied variables (x_i means the ith variable), y represents the binary variables, c_j is the coefficient for the jth variable in the objective function and b_j is the coefficient for the jth binary variable in the objective function.

Engineering design often deals with multiple, possibly conflicting, objective functions or design criteria. For instance, one may want to maximize the performance of a system while minimizing its cost. Such design problems are the subject of multi-objective optimization. Thus, the multi-objective function is needed when optimizing more objectives at a time is required. It is useful to find out an optimum solution with a lower production cost and at the same time with a lower CO_2 emission. There are several different approaches for multi-objective optimization, e.g. weighted sum, ε-constraint and goal programming. A more detailed description on each approach can be found in [9]. In this work, *ε-constraint* method is used for multi-objective optimization. For the *ε-constraint method*, only one objective is optimized, whereas the other objectives are bounded by some constraints.

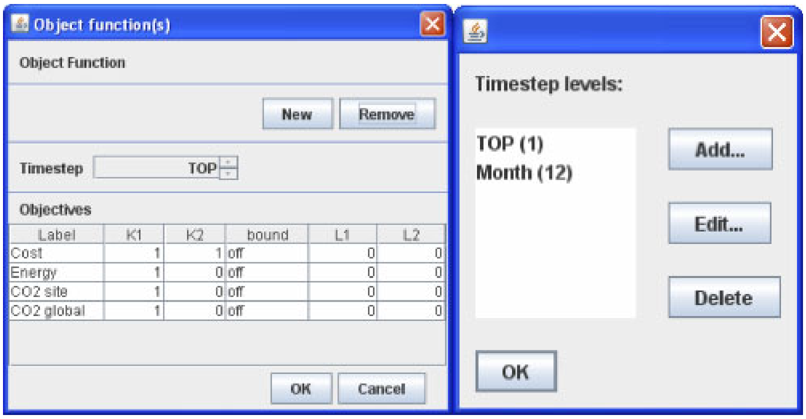
In this study, for the multi-objective optimization problem based on *Cost* and *CO_2 emission* minimization, it can be expressed by the following equation:

$$\min \sum_n a_n b_n \sum_t \sum_m (C_{m,t,n} x_{m,t}) \qquad (2)$$

where n denotes objective, e.g. the objective will be the cost when $n = 1$, and CO_2 emission when $n = 2$, etc., $x_{m,t}$ is the flow m for the time step t, $c_{m,t,n}$ is the coefficient for the flow m of objective type n in time step t, a_n is a coefficient making it possible to normalize each objective function n, whereas b_n is a coefficient making it possible to weight the objectives (note that one constant could also have been used, but two constants were used to facilitate the study). The constants also provide the possibility to exclude any objectives from the optimization by setting them to zero. a_n and b_n correspond to K1 and K2 in Figure 4.

The studied objective is bounded according to the following equation:

$$\sum_t \sum_m C_{m,t,n} x_{m,t} \le C_{n}, t \quad \forall n \qquad (3)$$



Timestep TOP

Label	K1	K2	bound	L1	L2
Cost	1	1	off	0	0
Energy	1	0	off	0	0
CO2 site	1	0	off	0	0
CO2 global	1	0	off	0	0

Timestep levels:

TOP (1)
Month (12)

Figure 4. Scope and time step of the model.

where $C_{n,t}$ is a constraint for the objective, either cost or CO_2 emission, during the time step *t*.

As shown in Figure 4, the scope of the CO_2 emission can be defined locally for direct emission from a specific plant or globally including both upstream and downstream emissions. The latter can be used when doing a life cycle assessment (LCA) for the studied system. The model can simulate CO_2 emission for a fixed time or during a time span; therefore, a time-step function is needed, see Figure 4. For example, the time-step function is needed when analyzing the CO_2 emission for different periods for the steel plants in the emission-trading program.

In connection with the multi-objective optimization, it is possible to find Pareto-optimal solutions [10]. A Pareto-optimal solution is a solution where no objective can be improved without another deteriorating. The plot of the objective functions is called the Pareto front, an example of a Pareto front is shown in Figure 5. As for the bi-objective optimization problem, the Pareto front curve represents all the solutions from minimizing one objective with upper-level constraints bounded by the other objective, and *vice versa*. This allows the decision maker to choose an acceptable trade-off between the two goals by considering the different solutions along the Pareto front.

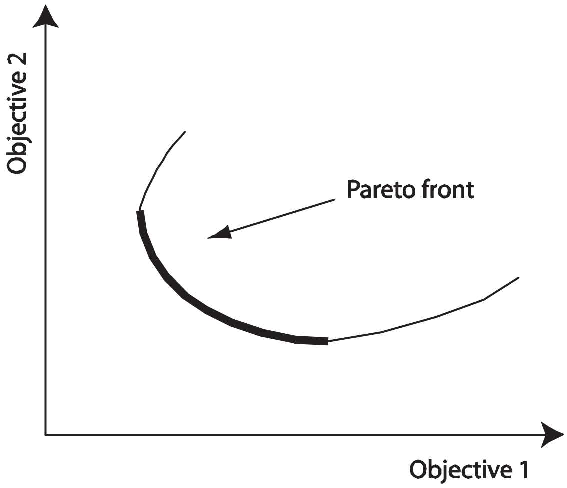


Figure 5. Example of a Pareto front for a bi-objective minimization problem.

2.2. System definition

Figure 6 shows the system boundary. At the first step, the model boundary covered the main process units of the BF and the BOF, i.e. System I. The model was further extended to cover COP, CC and CHP in System II. Finally in System III a sub-model of a rolling mill (RM) is included; thus, the model boundary has covered a fully integrated steel plant, i.e. COP → BF → BOF → CC → RM. The model can be used to analyze the CO_2 emission either for the whole system jointly or for one or a few sub-models separately depending on the research interests. Two application cases covered by this paper correspond to different system boundaries in Figure 6, optimizing ferrous burden materials in BF–BOF [11] and emission-trading schemes' (ETS) influence on CO_2 emission reduction [12]. A customized model for a Swedish steelmaker, SSAB Tunnplåt AB, with two integrated production sites of steelmaking and RM, as an example of a fully integrated steel plant, will be discussed in the paper as well (System III).

2.3. Validation

The model used in this work is based on an existing model that was initially developed for analysis of the energy use for an integrated steel plant, and the model has been validated by using actual production data [13]. This model has been successfully used in several studies mainly focusing on material, energy use and production cost

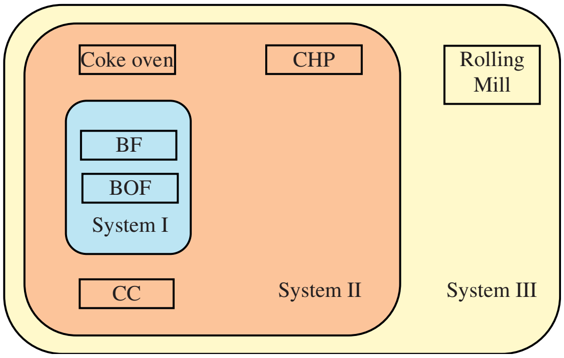


Figure 6. Scheme of the model development layout. Note: Material and energy flows between and within processes/sub-models are not included in the figure.

[14,15]. In each paper one reference simulation has been performed where the model has been delimited in production practice accordingly. Agreement between the model result and the reported data has been good.

3. APPLICATION FOR OPTIMIZING FERROUS BURDEN MATERIALS IN THE BF–BOF SYSTEM

This modelling work corresponds to System I (see Figure 6), which consists of the BF and the BOF modules. These two processes are interconnected to each other by HM. Two sub-models can be optimized separately or combined together.

This model has been used to analyse how conversion costs and CO_2 emissions can be influenced by use of different ferrous burden materials; for instance, iron ore pellets, steel scrap or direct reduced iron/hot briquette iron (DRI/HBI) when producing crude steel. In this study, the use of DRI/HBI has not been separately analysed as they have a similar behaviour as scrap in the BF–BOF system. The coefficients for the objective functions and some base constraints set for the main processes are presented in Tables I and II. A crude steel demand of $500\,t\,h^{-1}$ has to be satisfied for all cases. In the BF, the HM silicon content has been allowed to vary in the range 0.2–1.0% to extend the feasible operating range for the model. The scrap use in the BF process has been restricted to 20% of the Fe input for HM production. In a general study, some parameter combinations cannot be used in every plant (e.g. scrap charging in the BF).

3.1. *BF+BOF baseline optimization*

Table III shows the modelling results for the two sub-models of the BF and the BOF combined and separately. For the combined optimization, the results are related to optimization of the objective functions in relation to the produced steel leaving the BOF. In general terms, the most cost-efficient solution, with the given cost values, is to produce a HM with low silicon content on a 100% pellet burden in the BF, and to use iron ore pellets as coolants in the BOF process. The strategies to produce crude steel with low CO_2 emissions and low energy use are completely different from the cost-optimized solutions. To minimize CO_2 the

Table II. Base model constraints for the BF and the BOF.

		BF	BOF
Production	($t\,h^{-1}$)	—	500
Pellet use	(%)	—	—
Scrap use	(%)	<20	—
% C in product	(%)	4.5	0.05
% Si in product	(%)	0.2–1.0	0
Coal injection	($kg\,t^{-1}$ HM)	160	0
Slag volume	($kg\,t^{-1}$ HM)	165	—
Slag CaO/SiO_2	—	1	3.3
Tap temperature	(°C)	1468	1675

(—) means that the variable is unconstrained.

Table I. Coefficients used for different objective function [11].

	Unit	Energy (GJ)	CO_2 emission (ton)	Cost (USD)
Iron ore pellet (KPBO)	(ton)	—	—	90
Scrap (~97% Fe)	(ton)	—	0.0147	230
Purchased coke	(ton)	28.05	3.035	250
Pulverized coal injection (PCI)	(ton)	27.21	2.468	50
Natural gas	(GJ)	1	0.0565	5
Lime	(ton)	—	—	60
Quartz	(ton)	—	—	10
Limestone	(ton)	—	0.44	10
Dolomite	(ton)	—	0.477	10
Oxygen	($1000\,m^3n$)	—	—	25
Power	(MWh)	3.6	—	50

Table III. Optimization results for systems of BF+BOF and BF.

		BF+BOF combined system			
		No opt.	Min. CO_2	Min. energy	Min. cost
Objective value					
CO_2 emission	(t t^{-1} LS)	1.25	**0.99**	0.99	1.43
Energy	(GJ t^{-1} LS)	12.56	9.95	**9.95**	14.29
Cost	(USD t^{-1} LS)	246	256	256	**238**
BF					
Pellets	(kg t^{-1} HM)	1425	1124	1124	1431
Scrap	(t t^{-1} HM)	0	197	197	0
HM quality	(% Si)	0.60	1.0	1.0	0.20
Coke+PCI	(kg t^{-1} HM)	475	425	425	468
Fluxes	(kg t^{-1} HM)	117	149	149	109
Slag volume	(kg t^{-1} HM)	165	165	165	165
BOF					
Pellets	(kg t^{-1} LS)	24	0	0	56
Scrap	(kg t^{-1} LS)	170	296	296	0
Oxygen	(m^{3}n t^{-1} LS)	48	50	50	48
Fluxes	(kg t^{-1} LS)	53	76	76	24
Slag volume	(kg t^{-1} LS)	110	147	147	62
		BF system only			
		No opt.	Min. CO_2	Min. energy	Min. cost
Objective value					
CO_2 emission	(t t^{-1} HM)	1.25	**1.07**	1.07	1.23
Energy	(GJ t^{-1} HM)	13.97	12.13	**12.13**	13.78
Cost	(USD t^{-1} HM)	224	228	228	**223**
BF					
Pellets	(t t^{-1} HM)	1425	1146	1146	1431
Scrap	(t t^{-1} HM)	0	197	197	0
HM quality	(% Si)	0.60	0.20	0.20	0.20
Coke+PCI	(t t^{-1} HM)	475	412	412	468
Fluxes	(kg t^{-1} HM)	117	132	132	109
Slag volume	(kg t^{-1} HM)	165	165	165	165

Note: The bold figures indicate the optimization objective values.

model prescribes that the scrap addition to the BF is maximized and that the HM should have the highest possible silicon content to allow massive scrap melting capacity in the BOF. The strategy for energy minimization is similar. It is noticeable that the cost-optimized practices cause more than 45% higher CO_2 emission compared with the CO_2 and energy-optimized practices. On the other hand, the CO_2 and energy-efficient practices are more costly.

As for only the BF optimization, the results are interesting because the way of minimizing CO_2 and energy is different compared with the former combined optimization. Now the strategy is to produce a low silicon HM, as low as allowed, in order to keep the specific coke use as low as possible. However, when looking at the combined BF+BOF system, it is more beneficial to allow a higher specific coke consumption in the BF to gain a higher scrap melting capacity in the next process step. This result demonstrates the benefits that can be gained by using a system-oriented analysis approach compared with the optimization of each process separately.

3.2. The effect of scrap distribution between BF and BOF

Scrap offers effective means to lower the CO_2 emissions in the BF–BOF system, however the previous calculations have delivered inconsistent solutions on which combination of the BF and BOF practice that is the most effective. Scrap is possible to charge to both the BF and the BOF processes.

Figure 7 shows the different scrap distributions between the two considered processes. Constant quantities of scrap (50, 100, 150, 200 and 225 $\mathrm{t\,h^{-1}}$) have been added to the system and have been allocated in different proportions to the BF and the BOF. The propagation of each of the filled lines in the figure corresponds to the feasibility region of the defined system. The minimum CO_2 objective of the system is 0.99 $\mathrm{t\,t^{-1}}$, which was given earlier in Table II. This corresponds to a singular point in the diagram situated directly below the 200 $\mathrm{t\,h^{-1}}$ line. The minimum CO_2 objective when there will be no scrap charged to the system is 1.43 $\mathrm{t\,t^{-1}}$, corresponding to the singular point situated on the right upper side of the diagram. The dotted line in Figure 7 represents the distribution that corresponds to the minimum CO_2 objective for different scrap addition levels to the system. It can be seen that the CO_2 emission is decreasing with adding more scraps to the system. When the scrap addition level is lower than 100 $\mathrm{t\,h^{-1}}$, the optimized solution will always choose to add scraps into the BOF in order to have a lower CO_2 emission. The minimum CO_2 objective when 100 $\mathrm{t\,h^{-1}}$ (200 $\mathrm{kg\,t^{-1}}$ LS) of scrap is available to the system is 1.20 $\mathrm{t\,t^{-1}}$, which corresponds to the right end point of the 100 $\mathrm{t\,h^{-1}}$ line. When the addition level is above 100 $\mathrm{t\,h^{-1}}$, the scraps to system will be distributed between the BF and the BOF for the minimum CO_2 emission. Thus, when seeking a lower CO_2 emission by increase of the scrap additions, it is possible to find an optimum distribution between scrap charging in the BF and the BOF for each scrap-charging level.

3.3. Pareto front analysis

A Pareto-optimal solution is a solution where no objective can be improved without another deteriorating. The two objectives of *Cost* and *CO_2* can be weighed *versus* each other as shown in Figure 8, where the Pareto front defined by minimum cost at different CO_2 emission levels have been drawn with a line between A_1 and A_2. The point's A_1 and A_2 represent the solutions *Min CO_2* and *Min Cost* from the optimization of the BF–BOF system. A simplistic description of the conditions A_1 and A_2 is that the use of scrap is maximized in A_1 and the use of iron ore pellets is maximized in A_2. There are several breakpoints for the Pareto front illustrated in Figure 8, which relates to the

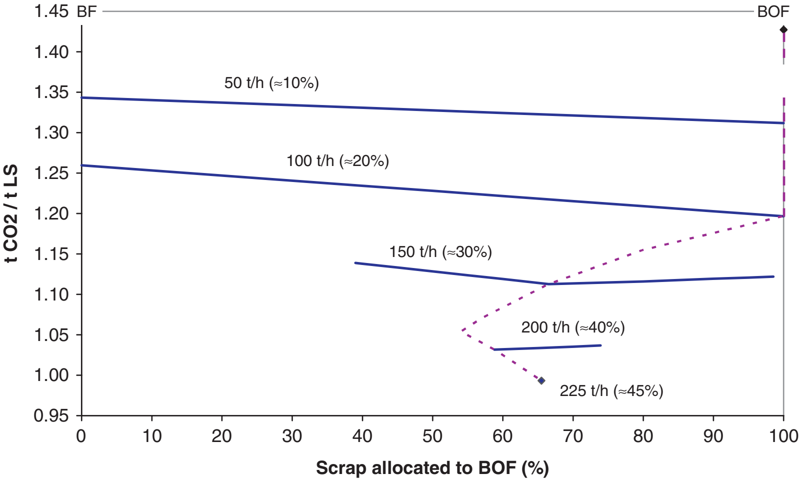


Figure 7. CO_2 emissions at different scrap distributions between the BF and BOF.

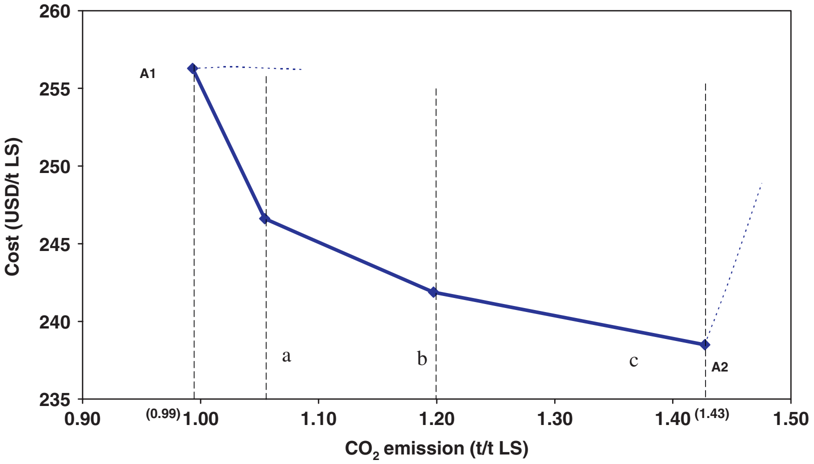


Figure 8. Optimization of Cost and CO$_2$ for the studied BF–BOF system. The Pareto front is the solution on the thicker line.

different regions of *a–c* in Figure 8. These breakpoints clearly show the borderlines for the technical solutions for the different Pareto front lines. For purposes of illustration and better understanding, the solutions outside the Pareto front are also shown with a dotted line.

4. APPLICATION FOR ANALYSING CO$_2$ EMISSION REDUCTION IN THE STEEL INDUSTRY BY USING ETS

To comply with Kyoto Protocol (KP) commitments, the EU decided to introduce a cap and trade program, the so-called ETS, to curb Europe's industrial emissions. EU ETS is an internal market within EU countries to trade carbon dioxide emissions, enabling companies exceeding individual CO$_2$ emission targets to buy allowances from 'greener' ones. It is permissible to use Certified Emission Reductions (CERs) gained from CDM[‡] projects to meet the CO$_2$ emission allowance for EU countries. This practice has not yet been fully accepted for Swedish conditions. Instead, a general study, using the optimization model on a given example, has been carried out to evaluate how steel plants in European countries can meet their emission reduction commitment [12].

As shown in Figure 6 (System II), the model boundary was extended to cover the ETS (in this case, they are CDM and EU ETS). In the model, the function of the time step is used as both CDM and ETS are time-step-based schemes. The time steps set in the model are the following: before the Kyoto Protocol (BKP), the KP, and the post Kyoto Protocol (PKP), as shown in Table IV. The table also presents the production forecast and assumed CO$_2$ emission allowance during the time steps.

The following cases are simulated in the model:

- Reference case—business as usual (BAU): This scenario is a projection based on a series of consistent assumptions. In this scenario, no measures (internal or external) were taken to reduce CO$_2$ emissions at the steel plant. The driving force in the model is the projected production during time steps.
- Case 1—ETS simulation: In this simulation, the EU ETS is used to fill up the emission gaps. The model was bounded by the CO$_2$ emissions

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[‡] CDM is one of the three so-called 'flexible mechanisms' defined in the Kyoto Protocol enabling Parties to access cost-effective opportunities to reduce emissions or enhance carbon sinks in other countries. It is generally considered that these mechanisms have the capacity to lower the overall costs of achieving the emission targets of the Protocol. In addition to CDM, the other two mechanisms are the International Emissions Trading (EIT) and the Joint Implementation (JI).

allowance, i.e. the steel plant needs to buy the excess emission via the emissions-trading market within the EU. An average carbon permit price of 29.6 US\$ t^{-1} CO_2 indicated in Hidalgo *et al.*'s study [5] has been used in the model.

- Case 2—ETS and CDM optimization: In this scenario, the emission gap will be filled up by either buying allowance permits via ETS or purchasing CERs via CDM. The types of CDM projects in the study are recovery of BF gas, injection of natural gas, pulverized coal injection system for BF and waste gas recovery from BOF.
- Case 3—Optimization scenario: The optimized cost objective strives to decrease the production cost for the system to its minimum while satisfying the CO_2 emissions limitation, and hence minimizing the CO_2 reduction cost. Besides the EU ETS and CDM, internal changes within the steel plant are included. The examples of internal changes are coking coal mixing in the COP; different coal injection rates, BOF slag charging and flue dust injection into the BF; HM/scrap rate and decreased iron ore pellet charging into BOF; back pressure/condensing operation in CHP, etc. The model was set free to optimize among the different alternatives.

The simulation results of CO_2 emission are presented in Figure 9 indicating lower predicated CO_2 emission than the emission allowance allocated for the first 2 years in the BKP period. However, the predicted CO_2 emission will exceed the allocated emission from the last year (2007) in the BKP period through the entire time step.

Figure 9 also shows the CO_2 emission gaps during the different time steps and the cost for CO_2 emission reduction in the different cases. The abatement cost shown in the figure is calculated

Table IV. Time steps used in the model and steel production forecast in the studied system.

Time step	BKP	KP	PKP
Year span	2005–2007	2008–2012	2013–2020
Production projection (%)*	~107	108	108
CO_2 emission allowance (kt $year^{-1}$)	~4000	~3800† (−4%)	~3600† (−10%)

*Production forecast change is based on the production for the reference year with an assumed increased production by 8% at the end of each period. For the year of 2007 in the BKP, the production forecast is assumed as a 7% increase compared with the first 2 years. Note that the increased production is only a calculation scenario and not a decided production plan.
†Assumed emission levels for the KP (−4%) and the PKP (−10%) of the BKP level.

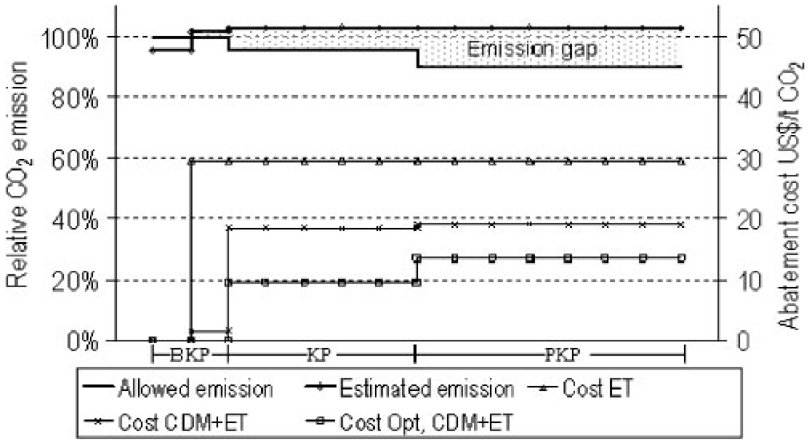

Figure 9. CO_2 emission allowance, calculated CO_2 emission (BAU scenario) and abatement cost during different periods at the studied system.

based on the assumed permit price from EU ETS and CDM, and the amount of CO_2 emission gap during different periods.

In case 1 (ETS simulation), the EU ETS is used to fill up the emission gaps. The steel plant needs to buy the excess emission via the emission-trading market within the EU with the price per unit allowance of 29.6US\$ t^{-1}-CO_2.

In case 2 (ETS and CDM optimization), purchasing allowance permits via ETS or CERs via CDM will fill the emissions gap. Compared with case 1, the abatement cost for the different time steps decreases to 15.4 US\$ t^{-1}-CO_2, on average.

In case 3 (optimization scenario), all possible alternatives are included in the model, i.e. internal measures, ETS and CDM scenarios. The model was set free to optimize among these different alternatives. The result from the optimization shows that through internal changes, the calculated CO_2 emissions are reduced for all periods. Consequently, the studied system will not make use of CDM and ETS during the first period (including the year of 2007), when the CO_2 saved through the internal changes will be enough to fill up the gap. However, from the KP period, the calculated CO_2 emissions will exceed the emission allowance allocated if the plant only makes internal changes. Thus, other measures are necessary. When further analyzing the modelling results, it was found out that ETS will not be used to fill up the emission gap even for the last two periods; instead the model will choose the alternatives from the CDM scenario due to its lower abatement cost. The resulting abatement cost in case 3 is the lowest (9.8 US\$ t^{-1}-CO_2 on average) compared with the other two cases.

It should be pointed out that for the studied case, internal changes can play a major role in reducing the abatement cost. When the internal changes are taken during the whole BKP period, there will be no emission gap at all; instead there is an allowance surplus, which can either be used to fill up future gap or bank them for the future trade. Consequently, in the optimization case, the cost for CO_2 reduction is further lowered to 9.6 US\$ t^{-1}-CO_2 during the period of the KP and to 13.6 US\$ t^{-1}-CO_2 during the period of the PKP.

5. A TWO-SITE MODEL OF SWEDISH STEELMAKER SSAB TUNNPLÅT AB

SSAB Tunnplåt AB is one of Europe's leading manufacturers of high-strength strip steels. The company has ore-based steel production and strip steel manufacture. Compared with a conventional integrated steel plant, SSAB has a unique feature in that the steel and sheet/strip production are located at the two different geographic locations, Luleå and Borlänge, approximately 800 km apart. The slabs produced from the steel work (Luleå) have to be transported by train to the RM (Borlänge) to produce hot-rolled and cold-rolled products. This creates several challenges for the steelmaker:

- Owing to the geographical situation it is necessary to extend the energy-saving methodologies compared with the situation at a normal integrated plant;
- A holistic view is needed to economize the use of resources, and to evaluate and incorporate new technologies and methods, in terms of a sustainable development.

As shown in Figure 10, the integrated steel plant in Luleå includes coke ovens, an ironmaking plant with one BF, a steelmaking plant with two BOFs, and a CC plant with 100% CC of slabs. The RM in Borlänge includes both hot and cold rolling. Depending on the customized products, the other process units such as pickling, annealing, aluzinkline and galvline are included. Both the sites provide hot water to communities via district heat system. Unlike the common integrated steel plant, in which some parts of process gases generated during steelmaking is used in the RM, the excess process gases are transported to a CHP plant for electricity production for both internal and external use. The excess electricity is transmitted to the power grid. Thus, the RM is connected to the steel plant to some extent as the electricity consumed at the RM is from the power grid.

Recently, a specific model for the RM has been created to analyse the energy system. It will be very interesting to link this two-site model to analyse

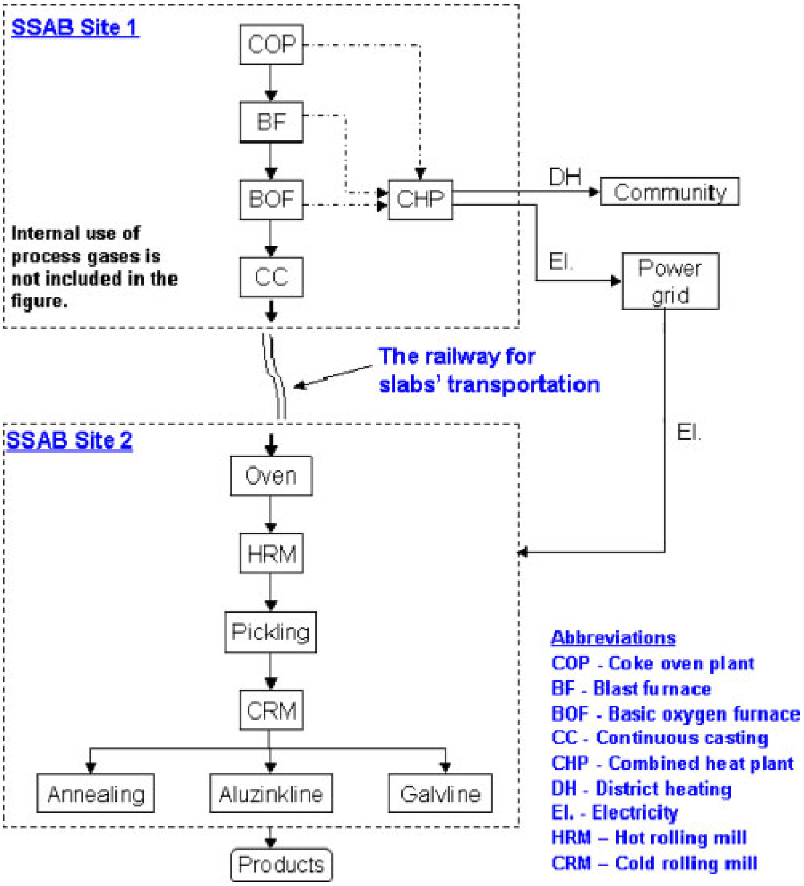

Figure 10. Schematic diagram of steel and sheet production line at SSAB Tunnplåt AB

the possibilities of reducing CO_2 emission from an integrated point of view.

6. DISCUSSIONS

The optimization model developed for the CO_2 emission analysis for integrated steelmaking can be used in different ways. The system boundary can be chosen depending on interests of the research work; correspondingly, CO_2 emission can be simulated for different process units, the whole steel plant or from a global point of view (e.g. LCA).

The model used for analyzing scrap addition into the BF/BOF system shows that different technical solutions have been chosen to minimize CO_2 emission. When looking at the combined system, it is more beneficial to allow higher coke consumption in the BF and higher silicon content in HM in order to gain a higher scrap melting capacity in the BOF; thus, lower CO_2 emission will be achieved. However, if only looking at the BF optimization, the solution will tend to a lower silicon content HM production and to keep a lower consumption instead. It can be seen from this analysis that it is important to actually have a systematic view in order to avoid a sub-optimal solution by just adding scrap, which will make it possible to decrease CO_2 emission by changing the raw materials in a clever way. However, it should be pointed out that the prerequisites for scrap charging in the processes are different, and there are also a number of other factors to consider, among other things charging technology, productivity effects, scrap availability and tramp element contamination.

The model can be used as an assistant tool to help the decision maker choose an acceptable trade-off between two goals by considering the different solutions when looking at the Pareto front. The use of the Pareto front for the BF/BOF system shows that the solution range is quite extensive. This means that there is a wide range of possibilities to operate the production system considering the trade-off between the two criteria's cost and CO_2 emission. The choice of solution will, of course, vary, depending on the decision maker's preference. This approach supports the insight that optimization can be used as a means to help the decision makers to make their decisions, especially for the future emission trading.

With the extension of the model boundary, the optimization model was used to investigate the opportunities of meeting the emission allowance with a lower cost for the studied steel plant via carbon-trading schemes, in this case EU ETS and CDM. The results show that compared with EU ETS, a lower CO_2 reduction cost could be achieved by use of CERs generated from CDM projects. The internal changes within the plant will also play an important role to help the studied steel plant to meet the emission-trading allowance and the further emission reduction comments, indicating the importance of the internal changes for the steel plant independent of carbon-trading schemes. Therefore, internal abatement should be encouraged as they can further improve the efficiency and promote the discovery of new technologies for creating a more sustainable energy supply both from an economic and an environmental point of view. It should be pointed out that the carbon prices from different trading schemes have been fluctuating. A sensitivity analysis would show the influence of carbon prices on potential CO_2 emission reduction options. However, the analysis shows that by using this kind of analysis it is possible to evaluate different measures for CO_2 reduction and their effects on the whole operation system. It should also be pointed out that this study is based on a Swedish steel plant as a calculation example. However, the model developed can with little modification be used in any similar steel plant within the EU countries and beyond.

As a specific integrated steel plant, it will be of great interest to investigate some energy-saving potentials within SSAB Tunnplåt AB. Considering the fact that these two sites are located in two different geographical locations, it is impossible for the RM to directly utilize process gases generated from the steel plant as an energy carrier. However, it would be possible if some process gases, e.g. coke oven gas, could be liquefied or transformed to other kinds of fuel. At the moment, at the steel plant there is excess coke oven gas for potential energy use. Two recent reports have studied the possibilities of coke oven gas liquification and methanol production from coke oven gas [15,16]. As a fuel that could be transported by using the current existing traffic tools between two sites, the possibility of substituting parts of fuels used at the RM, i.e. oil and LPG, will increase, which is worth investigating in the future.

7. CONCLUSIONS

A model on CO_2 emission reduction in integrated steelmaking is described in this paper. A few application cases have also been presented. The main conclusions drawn in this paper are as follows:

- A PI method has been used to analyze CO_2 emission for the steel industry with consideration of the material and the energy system. This model has a friendly interface, easy to be manipulated by non-programming persons and to make the analysis.
- The optimization model has the generality and flexibility to be extended to cover more processes, and it can be used to analyze CO_2 emission for a small, large or global integrated

steelmaking system depending on the research interest.

- The optimization of the BF process and the combined BF+BOF system resulted in different strategies to minimize CO$_2$ and energy use. The interaction between the processes can show a complex behaviour with several counteracting mechanisms that can be considerably influenced when constraints are introduced to the system. This demonstrates the benefits that can be gained by using a system-oriented analysis approach, and thus possibly avoid sub-optimization of the individual processes.
- The aids of the Pareto fronts analysis provide a comprehensive view of the trade-offs between the objectives of the *Cost* and the CO_2 emission, which can provide useful information for decision makers to generate strategies, for instance, their stance in the future emission trading.
- The case study of ETS' influence on CO$_2$ emission shows that internal changes and CDM scenario will both contribute to help the steel plant to meet the emission-trading allowance and future emission reduction commitments. The model developed can serve as a benchmark for the future emission-trading simulations purpose by steel plants within European countries and beyond.
- Some benefits regarding CO$_2$ emission reduction by integrating a two-site model could be achieved for the case of the specific integrated steel plant.

NOMENCLATURE

BF = blast furnace
BOF = basic oxygen furnace
CC = continuous casting
CDM = clean development mechanism
CER = certified emission reduction
CHP = combined heat and power plant
COP = coke oven plant
DH = district heat
EAF = electric arc furnace
El. = electricity
EU ETS = European Union emission-trading scheme
HM = hot metal
IISI = International Iron and Steel Institute
KP = Kyoto Protocol
LCA = life cycle assessment
MILP = mixed integer linear programming
PI = process integration
RM = rolling mill

ACKNOWLEDGEMENTS

We are grateful to the Centre for Process Integration in Steelmaking (PRISMA). The Centre for PRISMA is an Institute Excellence Centre (IEC) supported by the Swedish Agency for Innovation Systems, the Knowledge Foundation, the Foundation for Strategic Research and by the industrial participants Luossavaara-Kiirunavaara AB, SSAB Tunnplåt AB and Rautaruukki Oyj.

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