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Variables affecting energy efficiency and CO_2 emissions in the steel industry

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ABSTRACT

Specific energy consumption (SEC) is an energy efficiency indicator widely used in industry for measuring the energy efficiency of different processes. In this paper, the development of energy efficiency and CO_2 emissions of steelmaking is studied by analysing the energy data from a case mill. First, the specific energy consumption figures were calculated using different system boundaries, such as the process level, mill level and mill site level. Then, an energy efficiency index was developed to evaluate the development of the energy efficiency at the mill site. The effects of different production conditions on specific energy consumption and specific CO_2 emissions were studied by PLS analysis. As theory expects, the production rate of crude steel and the utilisation of recycled steel were shown to affect the development of energy efficiency at the mill site. This study shows that clearly defined system boundaries help to clarify the role of on-site energy conversion and make a difference between the final energy consumption and primary energy consumption of an industrial plant with its own energy production.

1. Introduction

The improvement of energy efficiency is seen as one of the most promising measures for reducing global CO_2 emissions and dependence on imported fossil fuels. Manufacturing industry accounts for one-third of global energy use (IEA, 2008a) and therefore improvement of energy efficiency and reduction of CO_2 emissions are high on the agenda of industrial actors. The iron and steel industry is one of the most energy-intensive industrial sectors and the largest emitter of CO_2 emissions. In 2005, it accounted for about 20% of global industrial energy use and 30% of energy and process CO_2 emissions from industry (IEA, 2008a). The International Energy Agency (IEA) states in the WEO-2009 report that by 2030 the energy saving and CO_2 reduction achieved by national policies and measures compared to baseline emissions[1] will be bigger in the industrial sector than in any other final energy consumption sector. The biggest emission reduction compared to baseline emissions can be achieved in iron and steel and cement sectors: more than half of the reduction of global industrial energy-related CO_2 emissions (IEA, 2009).

Many studies have considered the energy efficiency and CO_2 emissions of the iron and steel industry. International benchmarking studies (Karbuz, 1998; Farla and Blok, 2001; Phylipsen et al., 2002; IEA, 2007) on energy consumption/blast furnace reductant use and CO_2 emissions in the steel industry were found in the literature. According to a comparison of specific energy consumption among major steelmaking nations, made under the Asia Pacific Partnership (JISF, 2007), Japan and Korea are the most energy-efficient countries: the EU is 10% and 5% behind Japan and Korea, respectively. Also, the CO_2 emission reduction potentials based on best available technology are lowest in Japan and Korea, followed by OECD Europe (IEA, 2008a). However, inside the EU there are differences between countries and individual steel mills. The member companies of World Steel Association (worldsteel) are involved in benchmarking for improvements in energy use and material efficiency (worldsteel, 2008). In addition, by 2010, a global steel sector approach to reduce CO_2 emissions, including the collection and reporting of CO_2 emissions data by steel plants in all major steel producing countries, will be delivered. Unfortunately, the data on individual mills are confidential and the benchmark database is available only for the member companies of worldsteel. The benchmarking approach has also been applied in some countries, such as the Netherlands and Belgium, to allocate emission allowances under the EU emissions trading scheme (EU ETS). The possibility of using an EU-wide benchmark-based allocation methodology to the industrial sectors under international competition, such as iron and steel industry, from 2013 onwards has been studied. It has been proposed that the allocation would be based on an energy efficiency benchmark, a fuel mix benchmark, a process emission benchmark as well as activity level (Neelis et al., 2008). Also, country-specific (Sakamoto et al., 1999; Sandberg et al., 2001;

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[1] The difference between the WEO-2009 Reference Scenario and 450 Scenario (based on the target to stabilise the atmospheric concentration of greenhouse gases at 450 ppm of CO_2-equivalent).

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Nomenclature

η	efficiency of energy production
BAT	best available technology
BF	blast furnace
BOF	basic oxygen furnace
CDQ	coke dry quenching
CSPA	Canadian Steel Producers Association
E	energy consumption
EAF	electric arc furnace
EEI	energy efficiency index
EU ETS	EU emissions trading scheme
IEA	International Energy Agency
IISI	International Iron and Steel Institute
JISF	Japan Iron and Steel Federation
NRCAN	Natural Resources Canada
OECD	Organization for Economic Co-operation and Development
PLS	partial least squares projection to latent structures
r	ratio between primary energy consumption and final energy consumption
SEC	specific energy consumption
WEO	World Energy Outlook

Price et al., 2002; Ozawa et al., 2002; NRCAN/CSPA, 2007) and mill- and process-specific (Petela et al., 2002; Worrell et al., 2008) analyses have been made. In addition, potentials for reducing energy consumption and CO_2 emissions in the steel industry have been studied widely (Worrell et al., 2001; Gielen and Moriguchi, 2002). However, the principles upon which the energy consumption and CO_2 emissions have been calculated are seldom presented unambiguously. In addition, many simplifications and assumptions may have been made.

It has been found that there are many issues causing problems when energy efficiency and its development are measured. Karbuz (1998) and Farla and Blok (2001) emphasise the selection of appropriate data when energy efficiency indicators are used as a basis for policy making or international comparisons. Among others, the following potential problems were identified: the definition of system boundaries, the calorific values used, the non-energetic use of fuels, the fuel classification and utilisation of unconventional fuels, as well as the quality of data collection. In addition, double counting of the coke input and utilisation of coke oven gas and blast furnace gas occurred in some statistical sources.

Both international comparisons and national-level studies often use weighted averages for energy consumption and CO_2 emissions, and do not usually make any distinction between iron-ore-based production and recycled-steel-based production. Therefore, those studies often tell more about the structure of the steel industry than they do about the energy efficiency of steel production in a certain country.

The importance of clearly defining the system boundary has been noted in some studies, such as Larsson et al. (2004); IEA (2007) and Tanaka (2008). The study made by Tanaka (2008) showed that the specific energy consumption of crude steel production in Japan can range from 16 to 21 GJ/t, depending on the system boundaries set for the analysis and the conversion coefficient used for electricity production. One problem related to the definition of system boundaries is that the losses from self-production (or auto-production) of electricity might be included in the specific energy consumption of steel production or, alternatively, in the energy sector (Farla and Blok, 2001).

The IEA (2007) lists multiple factors that affect energy intensities, such as: (1) plant size, (2) impacts of system boundaries like buying intermediate products such as pellets, sinter, coke, scrap, oxygen and lime or buying/selling electricity and heat, (3) used technologies, such as coke dry quenching (CDQ) and continuous casting, (4) efficiency of processes such as hot stoves and recovery of blast furnace gas, (5) quality of raw materials like iron ore, coal and coke (6) level of waste energy recovery that is affected by energy prices and ambitiousness of energy policies. Kuusinen et al. (2002) stated that changes in the operating conditions of a steel mill, such as the production rate, affect the specific energy consumption, and therefore make it difficult to separate the effect of energy efficiency improvement actions from the effects of other changes.

The aim of this study is to find out how different variables affect energy consumption and CO_2 emissions in the steel industry. This is done by analysing the development of an energy efficiency index and a CO_2 index in a case mill with different definitions for system boundaries. The focus is on the measurement of energy efficiency in the iron-ore-based steelmaking process.

2. Energy consumption in the steel industry

2.1. Energy efficiency and CO_2 indicators used in industry

Energy efficiency is often defined as the ratio between the useful output of a process and the energy input into a process, as presented by Patterson (1996), or vice versa. In the process industry, such as the steel industry, the useful output is typically measured as tons of products produced. Therefore, physical-thermodynamic indicators such as specific energy consumption (SEC) are most commonly used for measuring the energy efficiency in industry. Sometimes, the terms 'energy intensity' (IEA, 2007; NRCAN/CSPA, 2007), 'energy intensity value' (Worrell et al., 2008) or 'energy consumption intensity' (Tanaka, 2008) are used instead of SEC.

Specific energy consumption (SEC) is defined as follows (EC, 2008):

$$\mathrm{SEC}=\frac{\text{energy used}}{\text{products produced}}=\frac{\text{energy imported}-\text{energy exported}}{\text{products produced}} \tag{1}$$

where SEC is measured in GJ/t.

Industrial processes often use energy in different forms, such as fuels, steam and electricity, and the SEC of that kind of processes is calculated as follows (EC, 2008):

$$\mathrm{SEC}=\frac{E_{\text{Fuels}}+E_{\text{Steam}}+E_{\text{Electricity}}}{\text{products produced}} \tag{2}$$

where E_{Fuels} is fuel consumption, E_{Steam} is steam consumption and $E_{\text{Electricity}}$ is electricity consumption of the process. Eq. (2) defines SEC as final energy consumption. If the energy consumption of steam and electricity production is taken into account, the SEC as primary energy consumption is defined according to the following equation (EC, 2008):

$$\mathrm{SEC}=\frac{E_{\text{Fuels}}+\frac{E_{\text{Steam}}}{\eta_{\text{Steam}}}+\frac{E_{\text{Electricity}}}{\eta_{\text{Electricity}}}}{\text{products produced}} \tag{3}$$

where η_{Steam} is the efficiency of steam production and $\eta_{\mathrm{Electricity}}$ is the efficiency of electricity production. Primary energy consumption presented here includes the energy consumption of the installation in question but not the energy consumption during the previous stages of the fuel cycle, such as fuel production, transportation or storage.

In order to monitor the progress of energy efficiency, an energy efficiency index is defined as follows:

$$\mathrm{EEI} = \frac{\mathrm{SEC}_{\mathrm{ref}}}{\mathrm{SEC}} \tag{4}$$

where $\mathrm{SEC}_{\mathrm{ref}}$ is the reference value for the specific energy consumption. The reference value can be defined on the basis of the best available technology (BAT), a benchmark value of the product in question, or a specified reference period.

Similarly, the specific CO_2 emissions, also called CO_2 intensity (IEA, 2007) or CO_2 emission-intensity indicator (NRCAN/CSPA, 2007), of industrial products can be calculated as follows:

$$\text{Specific } CO_2 = \frac{CO_2 \text{ emissions}}{\text{products produced}} \tag{5}$$

where specific CO_2 is measured in t CO_2/t product.

2.2. Reference values for energy consumption and CO_2 emissions in the steel industry

Mill- and process-specific SEC figures for the steelmaking process with proper background information are presented in a few sources (Phylipsen et al., 2002; Worrell et al., 2008):

According to Phylipsen et al. (2002), the SEC of the best commercially operating plant observed worldwide is used as a reference SEC in international benchmarking. The reference SEC for blast-furnace-based steelmaking is the 1994 performance at Hoogovens (Corus IJmuiden), the Netherlands. The SECs are based on 50% pellet feed and 50% sinter feed, and coke-making is excluded. The SECs are 14.89 GJ/t and 0.23 GJ_e/t for fuel use and electricity, respectively. The SEC as primary energy consumption is 15.47 GJ/t, taking into account a conversion efficiency of 40% for electricity conversion.

Worrell et al. (2008) provides information on the world best practice energy intensity values for selected industrial sectors, including iron and steel production. The report lists the process-specific energy intensity values both as final energy and primary energy consumption. As shown in Table 1 for integrated blast-furnace-based ironmaking and BOF-based (basic oxygen furnace) steelmaking, the SECs for final energy and primary energy consumption are 16.3 and 18.0 GJ/t, respectively. These figures include the coke-making and a different amount of sinter utilisation from that presented by Phylipsen et al. (2002), and therefore the SECs from two different sources are not comparable. In fact, Worrell et al. (2008) remark that the energy intensity values depend on the feedstock and material flows and differ from plant to plant, and therefore should not be used to compare individual plants.

Farla and Blok (2001) state that the energy consumption of coking, pelletising and sintering has to be included in the energy efficiency indicator, since these intermediate products are directly coupled to the primary steel production route. If the intermediate products are purchased outside the mill and their energy consumption is excluded, the steel mill seems to be more efficient than mills with their own coking, sintering and pelletising plant.

The most significant energy consumer in the iron-ore-based steelmaking process is the blast furnace. Blast furnaces consume about 60% of the total energy demand of steelworks (EC, 2001). As Table 1 shows, the world best practice energy intensity value for the blast furnace is 12.2 GJ/t, which is equivalent to 75% of the final energy consumption in integrated steelworks (Worrell et al., 2008). So, CO_2 emissions from integrated steel mills are mainly related to the reduction process of iron in the blast furnace. The CO_2 emissions of a typical Western steel mill reach about 1.93t CO_2/t of steel (Reinaud, 2004).

2.3. Variables affecting SEC and CO_2 emissions in the steel industry

In addition to process specification, the SEC and specific CO_2 emissions of an industrial plant depend on process performance parameters such as the production rate, operation time and product quality. A case study made in the paper industry (Sivill and Ahtila, 2009) shows that there is a clear correlation between the energy consumption and production rate of a paper machine. Therefore, reference baselines for the process energy consumption have to be accurately defined so that energy efficiency indicators can be used for process energy efficiency monitoring in industry.

In the steel industry the use of recycled steel, also called scrap, as a substitute for primary raw materials is an important factor reducing SEC and CO_2 emissions. However, due to increased demand for steel and the long life cycles of steel products, there would be insufficient recycled steel available to meet society's demand for steel even if all used steel products were recycled at the end of their life time. In addition to the limited availability of the recycled steel, its price restricts the amount that can be added to the production process. According to worldsteel (2008), the amount of recycled steel in 2006 was equal to about 37% of the crude steel produced that year. In 2004, the same figure was 42.7% (IISI, 2005). Most recycled steel is utilised by melting it in the electric arc furnace (EAF) process, but it can also be used in the converters of the BOF process. One kilogram input of recycled steel into the BOF process saves approximately 0.017 $\mathrm{GJ/t_{Crude\ steel}}$ (Michels, 2000). Typically, the share of scrap added to the BOF process varies between 10% and 25% (Reinaud, 2004), but shares

Table 1
World best practice energy intensity values for the BF–BOF steelmaking route (GJ/t) (Worrell et al., 2008).

	Fuel	Steam	Electricity	Oxygen	Final energy	Primary energy *
Coking	0.6	0.1	0.1		0.8	1.1
Sintering	2.0	−0.2	0.2		1.9	2.2
Blast furnace	11.4	0.4	0.1	0.2	12.2	12.4
Basic oxygen furnace	−0.7	−0.2	0.1	0.4	−0.4	−0.3
Refining			0.1		0.1	0.4
Continuous casting	0.0		0.0		0.1	0.1
Hot rolling-strip	1.3	0.0	0.3		1.6	2.2
Total	14.6	0.1	0.9	0.6	16.3	18.0

* Primary energy includes electricity generation, transmission, and distribution losses of 67%.

up to 40% are sometimes used (EC, 2001). According to de Beer et al. (1998), the maximum scrap input is limited to about 25–30% of the charge without additional fuel injection. In absolute figures the consumption of hot metal and scrap in the BOF process is 820-980 and 170-255 kg/$t_{\text{Crude steel}}$, respectively (EC, 2001).

3. Methodology

3.1. The case mill and definition of system boundaries

This study is based on the energy data for the years 2000–2007 collected from an existing steel mill located in Europe. The production process is based on ironmaking in a blast furnace and steelmaking in a basic oxygen furnace (BF–BOF steelmaking route).

In the blast furnace process, sinter and pellets are used as raw materials of ironmaking. Sinter is produced in the sinter plant of the mill using iron ore as a raw material, but pellets are purchased from a stand-alone pelletisation plant off the mill site. In the blast furnace, the iron in the sinter and pellets is reduced to hot metal using coke and some other carbon carriers as the reducing agents and energy sources. The coke is mainly produced in the mill's own coking plant, but small amounts of additional coke are often purchased from outside suppliers.

In the steelmaking process, the hot metal and recycled steel are fed to the converters, where the carbon content of the iron is reduced by oxygen from 4%…5% to the desired level, typically below 1% or even 0.2%, depending on the quality requirements of the steel products. After the converters, the steel is processed in the ladle furnace to receive its final properties. Finally, the molten iron is cast into slabs and rolled into plates or strips (coils) in the rolling mill.

Fig. 1 presents the system boundaries considered in this study: (A) process; (B) mill and (C) mill site. Earlier, similar system boundary definitions have been used by Larsson et al. (2004). The system boundary of the mill consists of the following processes: coking plant, sinter plant, ironmaking, steelmaking and rolling mills. In addition, the system boundary of the mill site includes the energy unit producing electricity, process steam and heat at the mill site as well as purchasing and selling energy. Process gases, such as coke oven gas and blast furnace gas, are used for energy production at the mill site.

We consider the energy supply as a separate unit outside the system boundary of the steel mill, but included in the system boundary of the mill site. This makes it possible to analyse the effects of energy production integration into the steel mill. Both final energy and primary energy consumption can be considered. Thus, we also avoid another major problem found in publicly available energy data, i.e. double counting of the energy content of the coke and process gases.

3.2. Energy efficiency and CO_2 indicators for the case mill

In this paper, energy efficiency indicators, such as SEC and EEI introduced above, are used to analyse the energy consumption of the case mill. The SEC is calculated for different system boundaries, i.e. the processes, the mill and the mill site. The process-specific SECs as final energy consumption can be defined either as energy consumption per ton of the product of each

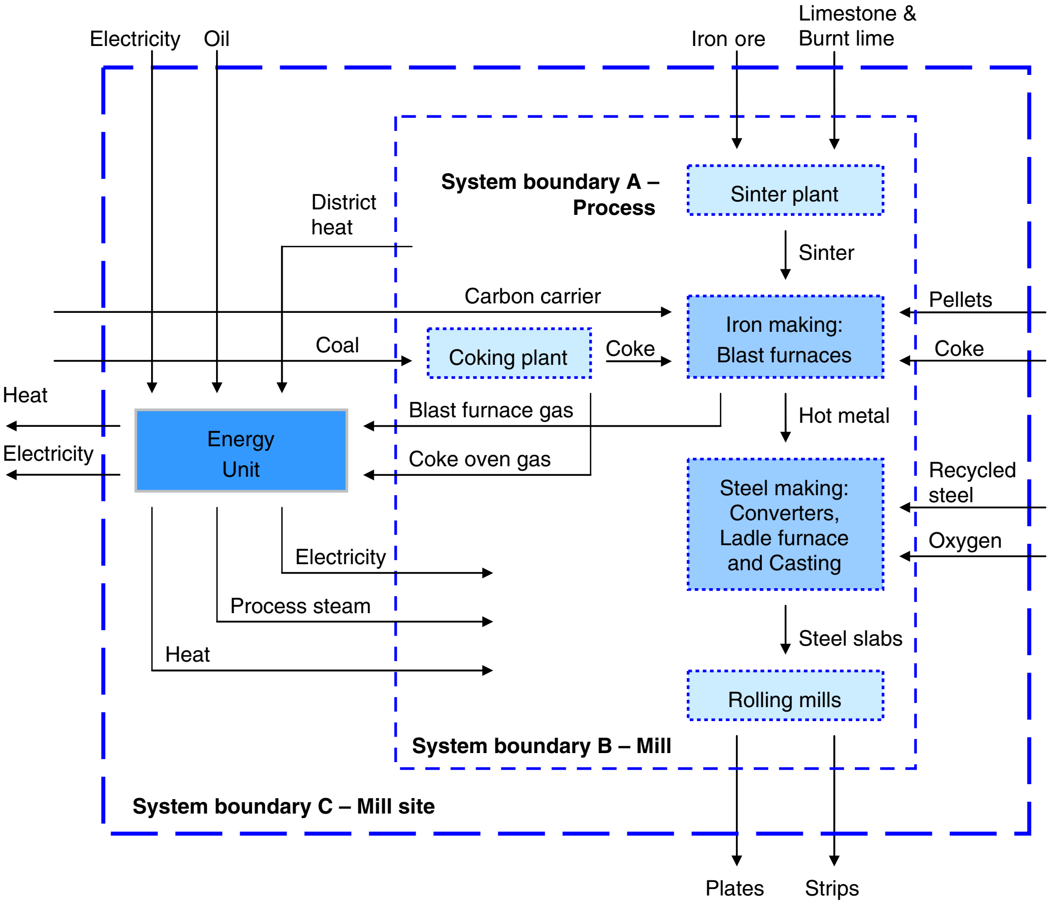

Fig. 1. System boundaries of a steel mill.

process, i.e. coke, sinter, hot metal and crude steel, or per ton of crude steel. Different organisations use different specifications to calculate process-specific SECs. In this study, the specifications used by IISI are used (IISI, 1998).

If the SECs per ton of crude steel are used, the mill-specific SEC (SEC_{Mill}) can be calculated by summing up the process-specific SECs. In our case study, some pellets and small amounts of coke and oxygen are purchased from outside the mill and, as stated by Farla and Blok (2001), the energy consumption of these intermediate products has to be included in the analyses. So, the specific energy consumption of the mill (SEC_{Mill}) can be defined as follows:

$$SEC_{Mill} = \sum SEC_{Process} + \sum SEC_{Intermediate} \tag{6.a}$$

where

$$\sum SEC_{Process} = SEC_{Coking\ plant} + SEC_{Sinter\ plant} + SEC_{Iron\ making} + SEC_{Steel\ making} + SEC_{Rolling\ mills} \tag{6.b}$$

$$\sum SEC_{Intermediate} = SEC_{Pellets} + SEC_{Oxygen} + SEC_{Purchased\ coke} \tag{6.c}$$

Eq. (6.a) gives the SEC as final energy consumption of the steel mill. In our case mill, the SEC as primary energy consumption can be calculated by widening the system boundary so that the energy consumption (or losses) of the energy unit is included. In addition to the production of electricity, steam and heat in the mill's own power plant, the energy unit purchases a part of the electricity needed by the mill. On the other hand, in some circumstances the energy unit sells energy outside the mill. To take account of the primary energy consumption of energy supply to the mill, the losses of energy supply have to be included. In our case study the amounts of intermediate products are small, so the difference between the final energy consumption and primary energy consumption of these products has minor effect on $SEC_{Mill\ site}$ (approx. 0.3%). Thus, it has not been taken into account in the analysis. The specific energy consumption of the mill site ($SEC_{Mill\ site}$) is calculated as follows:

$$SEC_{Mill\ site} = SEC_{Mill} + SEC_{Energy\ unit} \tag{7.a}$$

where

$$SEC_{Energy\ unit} = SEC_{Power\ plant} + \left(\frac{E_{Electricity\ purchase}}{\eta_{Electricity\ purchase}} - E_{Electricity\ purchase}\right) - \left(\frac{E_{Heat\ sales}}{\eta_{Heat\ sales}} - E_{Heat\ sales}\right) \tag{7.b}$$

In Eq. (7.b) the term $SEC_{Power\ plant}$ describes the lost primary energy in the power plant of the mill. Therefore, the actual efficiency of energy self-production is used in the analysis. The other two terms describe the lost primary energy for energy purchases and sales. Eq. (7.b) does not include the energy supplied by the energy unit to the mill because that energy supply is included in the final energy consumption of the processes. For purchased electricity, an efficiency of 33% is used in a similar way to Worrell et al. (2008). For heat production, an efficiency of 90% is assumed here.

In order to monitor the progress of energy efficiency at the mill site, an energy efficiency index is defined as follows:

$$EEI_{Mill\ site} = \frac{SEC_{Mill\ site,\ ref}}{SEC_{Mill\ site}} \tag{8}$$

where $SEC_{Mill\ site,\ ref}$ is the reference value for the specific energy consumption. Similarly, the CO_2 index of the mill site is calculated as shown in the following equation:

$$CO_2\ index_{Mill\ site} = \frac{Specific\ CO_{2,\ Mill\ site,\ ref}}{Specific\ CO_{2,\ Mill\ site}} \tag{9}$$

where the Specific $CO_{2,\ Mill\ site}$ is calculated at the installation level as required by the regulations relating to EU emissions trading (EC, 2003; EC, 2004). So, the emissions from the on-site energy production are included, but the emissions from the production of the intermediate products are excluded since they belong to the emission balance of other actors.

Both the $EEI_{Mill\ site}$ and CO_2 $index_{Mill\ site}$ are defined on a monthly basis using the average monthly SEC and specific CO_2 emissions for the year 2000 as references, respectively.

3.3. Benchmarking to the world best practice energy intensity values

The case mill includes the same processes as the process configuration that Worrell et al. (2008) used to define the world best practice energy intensity values for the BF–BOF steelmaking route. Those values are based on the IISI's (IISI,1998) specifications for SEC calculation (Worrell et al., 2008). Therefore, the specific energy consumption of the case mill can be compared to the values presented in Table 1.

The focus in the comparison is on the ratio of primary energy consumption to final energy consumption. In our case the ratio also describes the difference in energy consumption inside the different system boundaries, and is defined as follows:

$$r = \frac{SEC_{Mill\ site}}{SEC_{Mill}}, \tag{10}$$

where the $SEC_{Mill\ site}$ and SEC_{Mill} are defined on the basis of Eqs. (7.a) and (6.a), respectively. In addition, the sensitivity analysis of electricity production efficiency is included in the comparison.

3.4. Analysis of variables affecting energy efficiency indicators and CO_2 emissions

To determine the effects of different variables on specific energy consumption ($SEC_{Mill\ site}$) and specific CO_2 emissions, the correlations between the selected variables were studied with Simca-P software. The software was developed by Umetrics AB for multivariate modelling and analysis. The partial least squares projection to latent structures (PLS) analysis is a statistical multivariate method that enables regression modelling between two data sets selected as the predictors (X) and responses (Y) of a linear system. The PLS method is able to handle multicollinearity, which is one of its major advantages.

Table 2 shows the variables used in the PLS model. Twenty variables related to iron and steel production and their energy consumption have been selected as predictors (X) when $SEC_{Mill\ site}$ and specific CO_2 emissions are the responses (Y). Monthly values from 2000 to 2007 are used as observations, i.e. 96 observations for each variable are included.

4. Results

4.1. Energy efficiency and CO_2 indicators for the case mill

The monthly EEI and CO_2 indexes were calculated on the basis of Eqs. (8) and (9). Fig. 2 shows the development of the EEI and CO_2 indexes. Both indexes developed favourable from 2000 to 2003. After that there was a decline in the indexes until 2006, regardless of numerous investments made to improve energy efficiency of the mill. In 2006 the capacity utilisation rate was at a high level and so were the indexes. By the end of 2007, the steel

Table 2
Variables used in the developed PLS model.

Symbol of variable		Unit	Name of variable
Coal cons.	X	GJ	Coal consumption
Coke prod.	X	GJ	Coke production
Coke oven gas prod.	X	GJ	Production of coke oven gas
Coke oven gas, flare	X	GJ	Coke oven gas to flare
Coke purch.	X	GJ	Coke purchase
Sinter prod.	X	t	Sinter production
Pellet use	X	t	Pellet use
Hot metal prod.	X	t	Production of hot metal
BF gas prod.	X	GJ	Production of blast furnace gas
Scrap cons.	X	t	Utilisation of recycled steel (scrap)
Crude steel prod.	X	t	Production rate of crude steel
Rolled coils	X	t	Rolled coils
Rolled plates	X	t	Rolled plates
Purch. coils	X	t	Purchased coils
Purch. plates	X	t	Purchased plates
Carbon carrier cons.	X	GJ	Consumption of carbon carrier
Heat sales	X	GJ	Heat sales
El. prod.	X	GJ	Electricity production
El. purch.	X	GJ	Electricity purchase
El. sales	X	GJ	Electricity sales
$\mathrm{SEC}_{\text{Mill site}}$	Y	$\mathrm{GJ}/\mathrm{t}_{\text{Crude steel}}$	Specific energy consumption at mill site
Specific $\mathrm{CO}_{2,\ \text{Mill site}}$	Y	$t\ \mathrm{CO2}/\mathrm{t}_{\text{Crude steel}}$	Specific CO_2 emissions at mill site

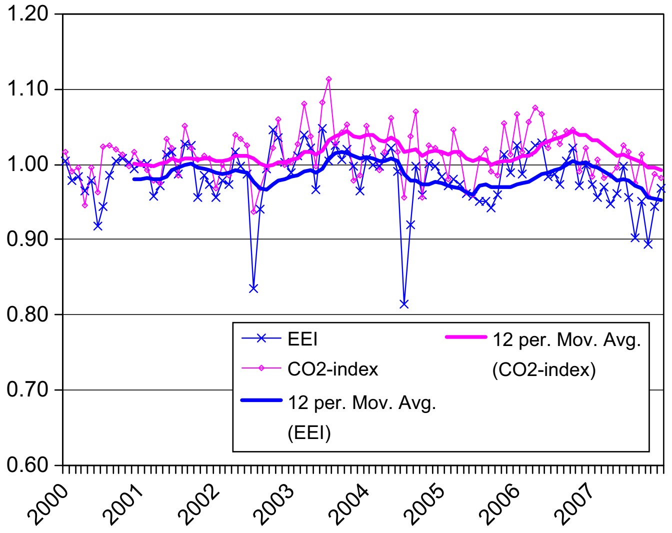

Fig. 2. Development of monthly EEI and CO_2 index.

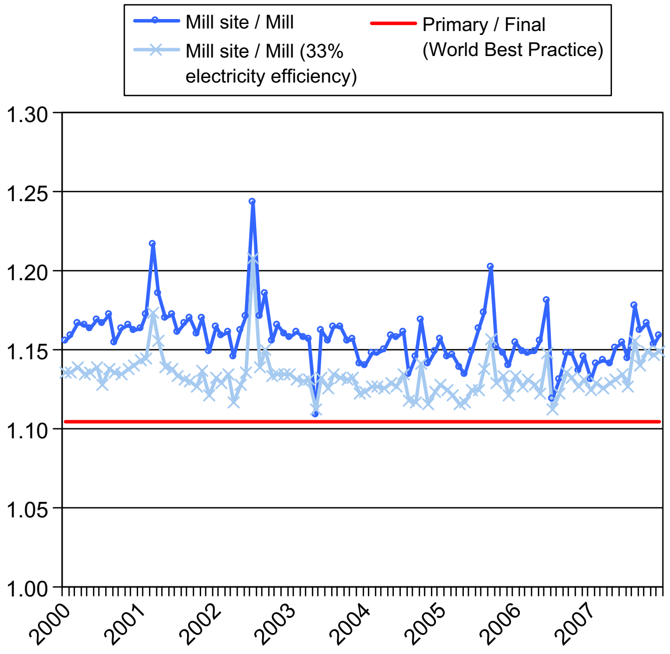

Fig. 3. Benchmarking of the ratio between primary energy consumption and final energy consumption.

production was reduced, which reflected the development of the indexes too.

Naturally, there is a clear correlation between those two indexes since fuel consumption is the main source of both energy use and CO_2 emissions at the mill site. During the whole period from 2000 to 2007 the correlation was 0.69. However, since the introduction of the EU emissions trading scheme, EU ETS, in 2005 (EC, 2003), the correlation has been 0.81. The main reason behind the improved correlation is probably the more accurate monitoring of CO_2 emissions required under the EU ETS (EC, 2004).

4.2. *Benchmarking to the world best practice energy intensity values*

The ratio between primary energy consumption and final energy consumption in an integrated steel mill is 1.10 based on the world best practice energy intensity values presented in Table 1. Fig. 3 shows the same ratio on a monthly basis for the case mill. The ratio varied between 1.11 and 1.24. The highest ratios occurred during unusual production situations, i.e. in the months when the annual shutdowns took place. When the sensitivity of the electricity production efficiency was studied, it was found that the deviation from the world best practice energy intensity values would be around 46% smaller on average if the electricity production efficiency were 33% instead of the actual efficiency of the power plant at the mill site.

If the specific energy consumption figures behind the ratio are examined more carefully, it can be noticed that 25% of the monthly figures of $\mathrm{SEC}_{\text{Mill}}$ were at the same level or even lower than the world best practice energy intensity values presented in Table 1 for final energy consumption. Especially, in 2003 and 2006 the final energy consumption of the case mill was very low. However, when the SEC as primary energy consumption was studied using the system boundary of the mill site (system boundary C in Fig. 1), the case mill did not reach the world best practice energy intensity values presented in Table 1 for primary energy consumption. However, in June 2003 the deviation from the world best practice level was negligible.

The sensitivity analysis made for electricity production efficiency, i.e. lower than 33% electricity production efficiency of the power plant at the mill site, explains almost half of the difference in primary energy consumption. Another difference found is around 10% higher electricity consumption of the case mill compared to the world best practice level. The higher electricity consumption occurs mainly in the steelmaking process, which might suggest differences in steel quality. However, there was no information available for an analysis of the effects of steel quality on the SEC.

4.3. Analysis of variables affecting energy efficiency indicators and CO_2 emissions

The importance of variables affecting the $\mathrm{SEC}_{\text{Mill site}}$ and specific $\mathrm{CO}_{2,\ \text{Mill site}}$ was analysed with PLS models created by Simca-P software. The input data from the years 2000–2007 was used. The PLS models explain 87% and 78% of the variation in the monthly $\mathrm{SEC}_{\text{Mill site}}$ and specific $\mathrm{CO}_{2,\ \text{Mill site}}$, respectively.

Fig. 4a shows the importance of variables affecting the $\mathrm{SEC}_{\text{Mill site}}$. The bars reflect the relative importance of each predictor (X) in the model with respect to the response $\mathrm{SEC}_{\text{Mill site}}$. The confidence intervals derived from jack knifing (Umetrics, 2002) show the variance of the observed data. The most important variables affecting specific energy consumption are the production rate of crude steel and the ratio of utilised hot metal and scrap. Fig. 4b shows the PLS regression coefficients, referring to scaled and centered data (Umetrics, 2002), for $\mathrm{SEC}_{\text{Mill site}}$ that express the relationship between the $\mathrm{SEC}_{\text{Mill site}}$ and all the terms in the model. A positive coefficient shows that an increase in value of a variable increases the $\mathrm{SEC}_{\text{Mill site}}$. Vice versa, negative coefficients reflect decreasing $\mathrm{SEC}_{\text{Mill site}}$. The developed PLS model confirms the theory that increasing the production rate of crude steel and utilisation of scrap decreases the energy consumption. Naturally, increasing the fuel consumption (coal and carbon carrier) and purchased energy (coke and electricity) increases specific energy consumption.

Regardless of the low efficiency of the mill's own electricity production, $\mathrm{SEC}_{\text{Mill site}}$ seems to decrease with increase in electricity production. This is linked to the more efficient use of process gases and the lower amount of coke oven gas fed to the flare. Similarly, sales of energy outside the mill improve energy efficiency. From the process integration point of view, an

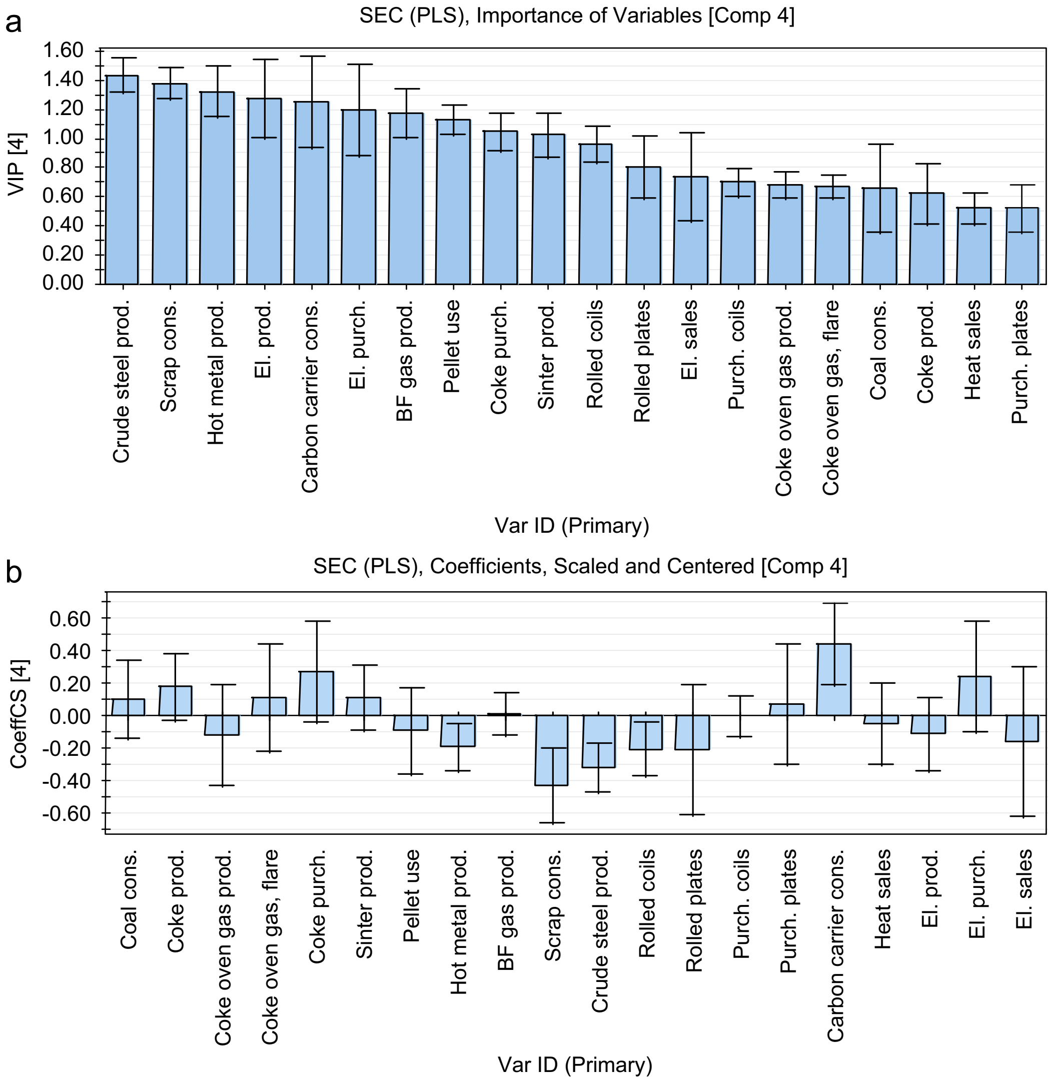

Fig. 4. (a) Importance of variables in the PLS model affecting the $\mathrm{SEC}_{\text{Mill site}}$. (b) Coefficients of different variables in the PLS model used for predicting the $\mathrm{SEC}_{\text{Mill site}}$.

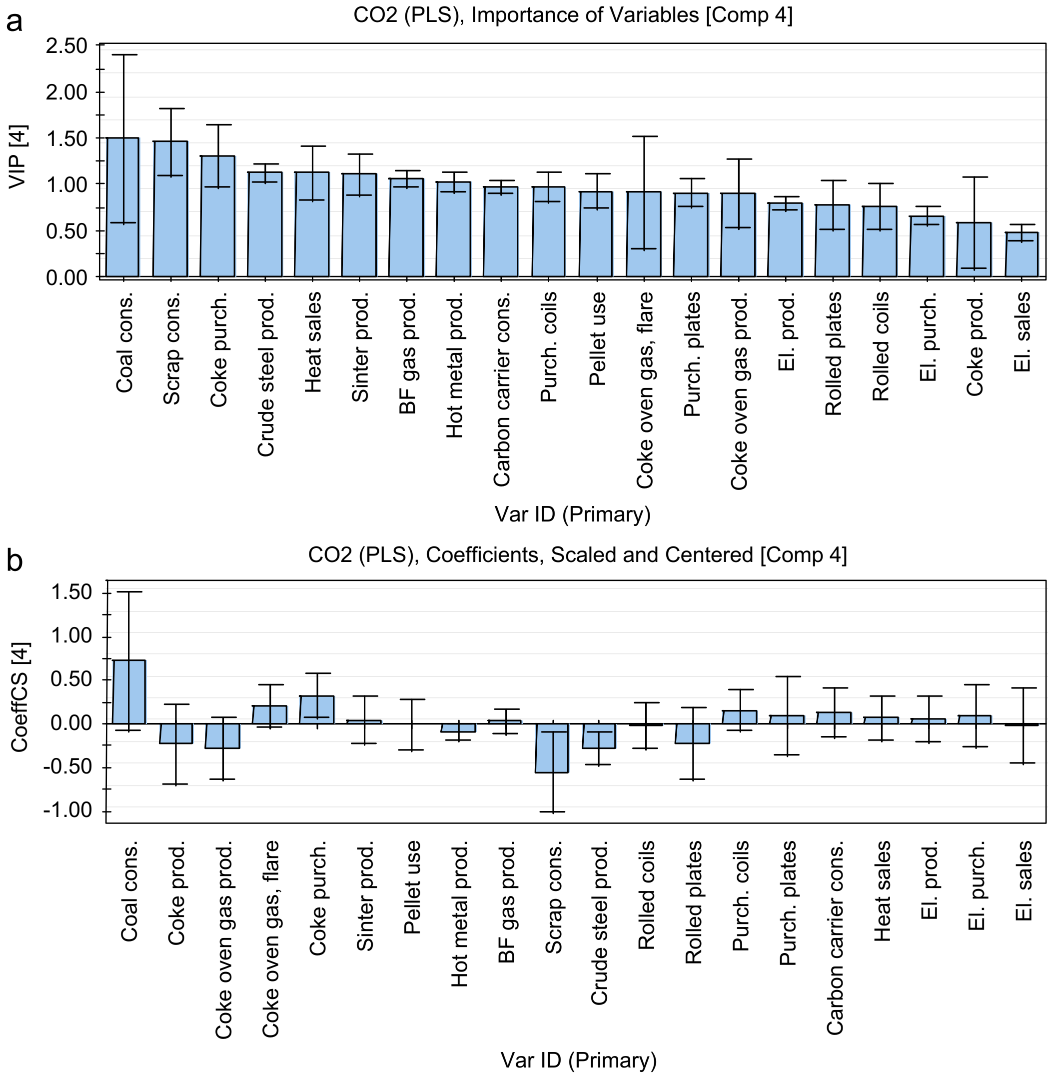

Fig. 5. (a) Importance of variables in the PLS model affecting the specific CO_2 emissions. (b) Coefficients of different variables in the PLS model used for predicting specific CO_2 emissions.

interesting aspect related to sinter production and pellet use can be found: since own sinter production can be replaced by purchased pellets, the lower integration rate can lead to lower SEC in our case mill. However, the SECs of sinter and pellet production differ case by case and therefore this result cannot necessarily be extrapolated to the other cases. The amounts of rolled steel coils and plates vary due to changes in purchased steel slabs, so the confidence intervals of these coefficients are wide.

The importance of variables affecting specific CO_2 emissions are presented in Fig. 5a. Naturally, the most significant variable is coal consumption since the coal used at the mill is the major source of CO_2 emissions. However, as shown in Fig. 5a, the confidence interval of coal consumption is wide, which can be partly explained by the variation in coal quality. So, in reality the variation in recycled steel consumption, purchased coke and crude steel production might have a greater influence on the specific CO_2 emissions. Fig. 5b shows the coefficients of different variables used to predict the specific CO_2 emissions. The increasing utilisation of recycled steel and crude steel production decreases the specific CO_2 emissions in a similar way as in the case of $SEC_{\text{Mill site}}$. On the other hand, increasing the variables related to energy consumption, such as coal consumption, purchased coke and the amount of coke oven gas to flare, increases specific CO_2 emissions. Also own sinter production seems to increase CO_2 emissions. Although energy sales seem to improve the energy efficiency of the mill site, they increase CO_2 emissions at the site. However, the PLS model created does not take into account whether there are alternative uses for the waste heat produced by processes or not. Some coefficients, for example in the case of coke production, seem to be illogical. This can be explained by cross-effects between coal consumption, purchased coke and coke production, also indicated by the wide confidence interval of the coefficient.

5. Conclusions and discussion

The analyses made here show that many common problems identified in energy efficiency studies of the steel industry can be avoided by clear definition of the system boundaries. At the same time it is easier to see the difference between the final energy consumption and primary energy consumption of an industrial plant with its own energy production. In addition to system boundaries, consideration of on-site energy conversion and energy consumption of intermediate products seems to be crucially important in the definition of energy efficiency indicators for steelmaking. The production rate of crude steel and the utilisation of recycled steel affect the development of energy efficiency at the mill site, and should be included in the energy efficiency indexes. The effects of these two factors are universally applicable, but the importance of some other variables, such as coal consumption, might differ from mill to mill. Therefore, the model developed here can be used to explain and predict the effects of changing operational conditions on the SEC of the case mill. However, the principles presented here can be used to develop mill-specific models which are capable of explaining the difference between the actual SEC and the world best practice energy intensity values.

Depending on the perspective, different system boundaries are needed for energy efficiency and emission reduction studies. From the benchmarking point of view, it is essential that the system boundaries of compared systems, such as industrial plants, are defined in a similar way. Each steel mill has its individual configuration. In particular, there are differences in the integration rates of the mills. Typically, the more integrated the mill, the more self-sufficient it is in intermediate products and energy. However, regardless of efficient utilisation of process gases, the energy consumption and CO_2 emissions of an integrated mill might be higher than in a mill using more intermediate products.

Under the EU emissions trading scheme, emission allowances are allocated at the installation level, so the definition of the system boundary should be clear. However, the self-production of energy, especially CHP production, raises the question of whether it should be part of the electricity sector or heat-consuming industrial sector (IEA, 2008b). Another challenge is how the integration rate of the mill can be taken into account in the allocation of emission allowances. For example, own coke or sinter production increases CO_2 emissions at the mill site and consequently the installation's need for emission allowances. Similarly, based on our case study, energy sales outside the mill site seem to increase CO_2 emissions.

Although reducing the integration rate of an industrial plant might seem an attractive option for cutting CO_2 emissions at the mill site, the global effects of lowering the integration rate might be negative. Therefore, the integration rate of an industrial plant should be taken into account in policy-making by widening the system boundary. For example, if a benchmark-based allocation methodology is applied in the future to allocate emission allowances to the energy-intensive industries for free, clear definition of the system boundary and inclusion of the climate effects of intermediate products used in the production process are crucial questions. Because the emission allowances have economic value, the accuracy and fairness of the allocation methodology have significant effects on the competitiveness of those industries. For reaching the global reduction of CO_2 emissions, the energy efficiency of industrial plants should be central criteria in CO_2 emission benchmarking as well.

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