Energy efficiency improvements in the German steel sector – more than window dressing?

Marlene Arens
Fraunhofer Institute for Systems and Innovation Research (ISI)
Breslauer Str. 48
76139 Karlsruhe
Germany
marlene.arens@isi.fraunhofer.de.

Joachim Schleich
Fraunhofer Institute for Systems and Innovation Research (ISI)
and Grenoble Ecole de Management
12 rue Pierre Sémard
BP 127 Grenoble
France

Ernst Worrell
Utrecht University
Heidelberglaan 2
3584 CS Utrecht
The Netherlands

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Abstract
Improving energy efficiency has been recognized as the key short- to medium-run strategy to reduce CO_2 emissions and energy consumption in a cost-efficient way, in particular for energy-intensive industry sectors like steel production. To improve energy efficiency, voluntary agreements (VAs) between industry associations and governments have been implemented in Germany in 2001 as the main policy instrument. For the iron and steel sector the VA is specified as a 22 % reduction of the CO_2 emissions per ton of crude steel between 1990 and 2012. To shed some light on the effectiveness of the VA this paper analyses the development of the specific energy consumption (primary energy use per unit of product) in the German steel sector between 1991 and 2007. We find that the total energy intensity declined by 0.4 %/year. Of this 75 %, or 0.3 %/year, is due to a structural change towards more electric arc furnaces (EAF). Energy efficiency improvement accounts for about 25 % of the observed change in energy intensity, or 0.1 %/year. Energy efficiency improvements are found, especially in rolling (1.4 %/year). The specific net energy consumption of blast furnaces decreased due to increased top gas recovery by 0.2 %/year per ton iron. Improvements in other processes were very limited or non-existent. In basic oxygen furnaces (BOF) net energy consumption increased due to a 60 % decrease in BOF gas recovery between 1993 and 2007. In electric arc furnaces and sinter plants the specific energy consumption remained constant or, respectively, even increased by 9 % between 1991 and 2007 per ton sinter. In sum, our findings do not support the view that the VA has led to noticeable improvements in the energy efficiency of the single processes in the German iron and steel industry. Improvements could only been observed for steel rolling. Instead, observed reductions in the SEC for crude steel originate mainly from the production shift towards EAF.

Introduction
The global iron and steel industry is one of the largest industrial energy consumers and CO_2 emitters. It accounts for about 3–5 % of the global CO_2-emissions [10]. Germany is one of the largest steel making countries in the world with a production of nearly 44 Million tons in 2010, making it the largest steelmaker in Europe and the 7th largest in the world [30]. Hence, the steel making industry in Germany and other EU countries may be expected to contribute substantially towards achieving national and international greenhouse gas (GHG) emission targets. Among others the reduction targets for future GHG emissions include 40 % of 1990 levels by 2020 for Germany [14], 20–30 % of 1990 levels by 2020 and 80–95 % by 2050 for the EU [3], or 50–85 % of 2000 CO_2-emissions by 2050 at the global level [9]. More specifically, the EC "Low Carbon Roadmap" (COM/2011/0112final) envisages CO_2 reductions for the EU industry sector of 34–40 % by 2030 and 83–87 % by 2050 compared to 1990 levels.

Improving energy efficiency has been recognized as one if not the key measures to reduce CO_2 emissions and energy consumption in industry and other sectors in a cost-efficient way [9, 10], but the magnitude of cost-efficient potentials are controversially discussed [17]. To improve energy efficiency, voluntary agreements (VAs) between industry associations and governments have been implemented in many industrial countries (e.g. [16, 29]) but their effectiveness has been questioned (e.g. [1, 12]). In 2000 the German Industry signed a voluntary agreement in order to reduce its GHG emissions (estimated in CO_2 equivalents) by 35 % between 1990 and 2012. In return, the German government promised to abstain from implementing further policies, such as obligatory energy audits. The whole agreement consists of 19 sub-agreements by the individual industrial sectors. In particular, the iron and steel sector committed to a reduction of CO_2 emissions per ton of crude steel of 22 % between 1990 and 2012.

This paper attempts to shed some light on the effectiveness of the VA in the German steel sector by analysing in detail the development of energy efficiency at the level of individual processes. In particular, distinguishing specific energy consumption (SEC) – expressed as primary energy use per unit of product – between the major steel-making processes, allows us to separate the impact of structural change (i.e. changes in production shares between processes) and energy efficiency improvements (at the level of individual processes).

The remainder of the paper is organised as follows. Section 2 briefly describes the German steel sector and the main production processes. Section 3 summarizes the challenges of empirically analysing the development of energy efficiency in steel making based on the literature. Our own methodology is presented in section 4. Section 5 presents the findings. The concluding section 6 summarizes and discusses the main findings.

Iron and Steelmaking Processes

Currently there are four routes to produce steel. The main route is the primary route using blast furnace and basic oxygen furnace (BF/BOF) to produce steel from iron ore. The EAF route uses scrap as raw material and remelts it in the Electric Arc Furnace (EAF). Two further routes exist, which are little or not used in Germany, i.e. direct reduction and smelting reduction. Direct Reduction reduces iron ore with the help of gas to Direct Reduced Iron (DRI), which is then fed to the EAF. This process is used in Germany by a single DRI-plant with an annual production of about 500,000 t (or about 1 % of German crude steel production). Worldwide 64.7 Mio t of DRI was produced in 2007, equivalent to a share of 5 % of world crude steel production [30]. Smelting Reduction is a technology that produces crude steel from iron ore, without the need for coke production as used in the blast furnace. Only two processes are commercially used (i.e. Corex and Finex). A few plants have been built in Africa and Asia, though in Europe this technology has not been implemented so far. Figure 1 gives an overview of the steel producing routes in Germany.

BLAST FURNACE/BASIC OXYGEN FURNACE ROUTE

The main steel producing route in Germany and worldwide is the BF/BOF route. It is also the main route to produce steel from iron ore. Four processes belong to this route. First, iron ore is agglomerated to sinter in (1) sinter plants or in pellet plants. Pellet plants are most often located at the iron ore mine, and hence excluded from this analysis. Iron ore and fossil solid fuels (e.g. coke breeze) are mixed and baked at temperatures of about 1,000 °C after ignition in a gas-fired furnace. Therefore in sinter plants the main energy carrier is coke breeze. Electricity is required for fans, flue gas treatment equipment, conveyers and other electrical devices.

In the (2) coke oven, hard coal is converted to coke by removing volatile substances. Coke is a solid and porous energy carrier which sustains permeability in the blast furnace. Sinter and coke, as well as further substances are fed from the top to the (3) blast furnace. Hot wind at temperatures of about 1,100 °C from hot blast stoves is introduced at the bottom of the blast furnace to sustain the reduction of iron ore to iron [11]. The hot stoves are mainly fed with the top gas of the blast furnaces, i.e. the blast furnace gas (BFG). The blast furnace is a shaft furnace which works in the counter flow principle. Sinter and coke are fed from the top while the reducing gas streams from the bottom to the top. Counter flows have the best heat transfer known. Temperatures in the blast furnace range from 2,200 °C at the bottom to 120 °C at the top. The main chemical reaction in the blast furnace is the reduction of iron ore (Fe_2O_3) to pig iron (Fe) with the help of carbon (C) and releases carbon dioxide (CO_2). This step is the most energy intensive step in steelmaking. As a by-product Blast Furnace Gas (BFG) leaves the blast furnace at the top. BFG is a low energetic gas with a heating value of about 4 MJ/Nm³ [2]. Pig iron contains about 4 % carbon.

To produce crude steel, which contains about 1.5 % carbon (or less), pig iron is fed to the BOF (4). Part of the carbon is removed by an exothermic reaction with oxygen to carbon monoxide (with repressed combustion) or carbon dioxide at temperatures of about 1,700 °C [2]. Basic Oxygen Furnace Gas (BOFG) is produced, containing about 70 % carbon monoxide (CO) and has a heating value of about 9 MJ/Nm³ [2]. If basic oxygen furnace gas (BOFG) is recovered, BOFs could be net energy producers. Main energy carriers are oxygen, electricity, Natural Gas (NG), Coke Oven Gas (COG) and steam.

Blast furnaces are usually located in integrated steelworks along with sinter plants, basic oxygen furnaces, rolling mills, a power plant and often coke ovens. Top gases and by-products are reused in other plants. BFG is fed to the hot stoves; BOFG is used for reheating furnaces in hot rolling mills, or for power generation. Figure 2 shows the system of energy flows in integrated steel works. Although coke ovens are located and energetically embedded within integrated steelworks, within energy statistics they are not associated with the steel sector but to the energy conversion sector.

ELECTRIC ARC FURNACE ROUTE

To recycle steel, scrap is melted in the EAF. Scrap and additives are fed from the top into the furnace and are heated by an electric arc. The temperature of the molten steel can increase up to 1,800 °C. Oxygen and other fuel gases are injected in order to accelerate the melting process. This process requires only about one third of the energy needed in the BF/BOF route to produce steel as the main energy intensive step in the steel sector (i.e. the reduction of iron ore to iron) has been carried out in the BF/BOF route.

SECONDARY METALLURGY/CASTING/ROLLING

Secondary metallurgy or ladle refining improves the quality of the liquid steel which leaves the BOF or the EAF. This is done in vacuum degassing plants or ladle furnaces. In energy statistics

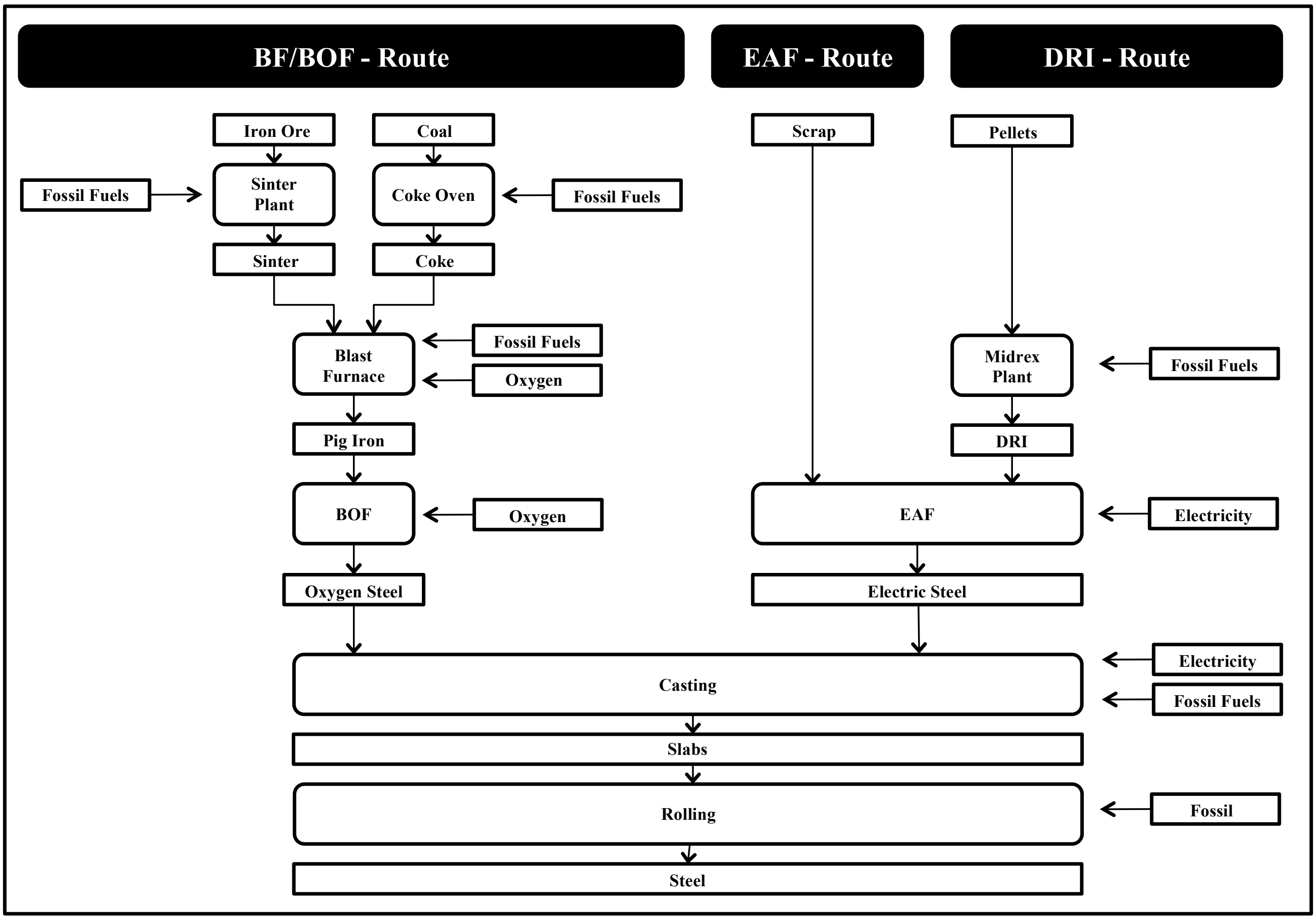

Figure 1. Steel production routes in Germany.

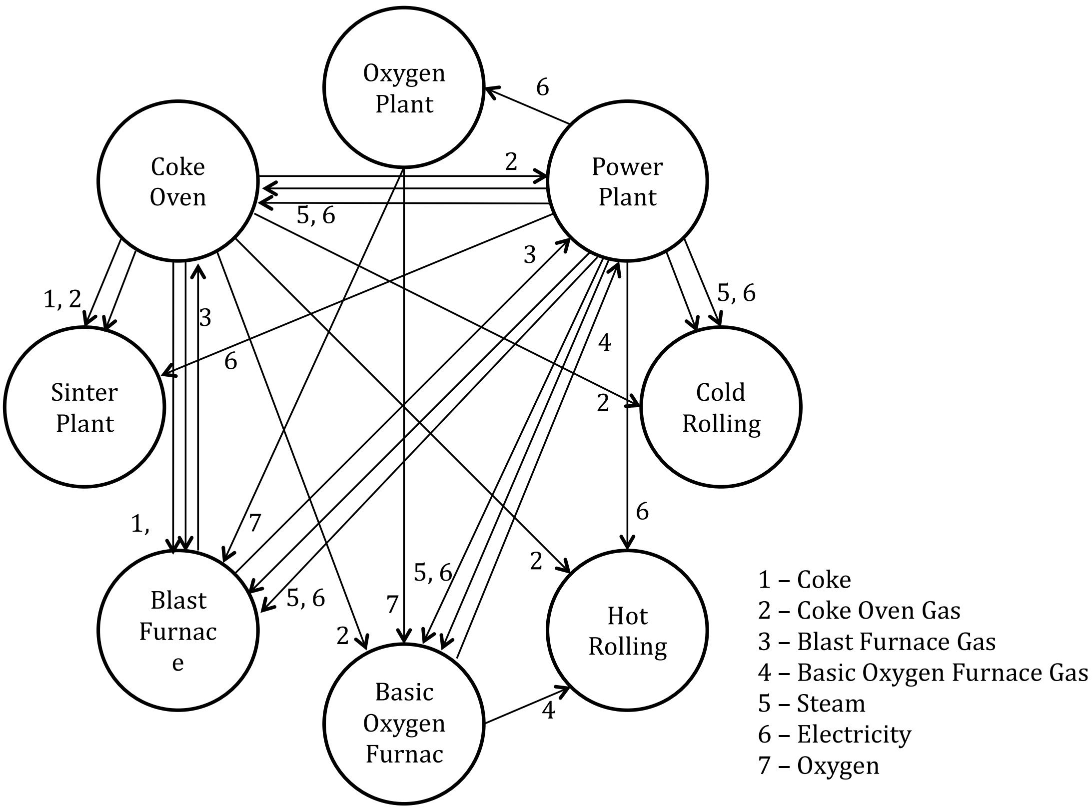

Figure 2. Energy flows in an integrated steel work [23].

secondary metallurgy is assigned to the steel making process (i.e. BOF or EAF).

Ingot Casting means pouring liquid steel into stationary molds to form ingots. Only 3 % of crude steel in Germany is cast in ingots. The dominant route to produce semi-finished billets, blooms or slabs is continuous casting.

In hot rolling mills semi-finished steel products are first heated to a temperature of about 1,200 °C and then rolled to sheets or long products. The main energy carriers are gas for the furnaces and electricity for the rolling mill.

Figure 3 shows the development of the steel production per process in Germany from 1991–2007. While the production of BF/BOF steel varies between 29 and 33.5 Mt/year, the production of EAF-steel increases constantly from 8.5 to 15.0 Mt/year. From 1991–1993 there is also a small share of Open Hearth or Siemens-Martin (SM) steel that was produced by a single plant in the former German Democratic Republic (until 1990). With 0.8, 0.5 and 0.6 Mt SM steel production had a share of 1.3–1.8 % of the total steel production in Germany in those years [28].

Empirical analyses of energy efficiency in the steel sector

Complex production processes and data availability render empirical estimations of the energy performance of steel production challenging. For example, data on the energy consumption of the steel industry on an international level is often not accurate, not collected in a consistent manner (use of definitions, system boundaries etc.), or not verifiable. As shown by Farla and Blok (2001) [4], assessing energy efficiency in the steel industry in international comparisons tends to suffer from considerable uncertainties. In her assessment of the energy performance in the steel industry of Japan, Tanaka (2008) [26] points out that depending on the system boundaries chosen SEC varies from 16 to 21 GJ/t crude steel. In addition, since data on the energy consumption in the steel industry tends to be aggregated at the sector level, calculating energy efficiency improvements at the level of individual processes is hardly feasible.

Existing studies on energy efficiency in the steel industry can mainly be divided into two groups. First, studies on the comparison of the energy performance of the steel industry on an international level should be mentioned. Worrell et al. (1997) compared the specific energy consumption in selected countries (e.g. Germany, China, Brazil) between 1980 and 1991 using a decomposition method [32]. Kim and Worrell (2002) compared energy and CO_2 intensity in the steel sector among seven countries [13]. Farla et al (1995) analyzed options for the reduction of CO_2-emissions in industrial processes [5]. Studies by the IEA show on a global level energy savings potentials and energy savings technologies [10]. Second, a set of studies exists on the energy performance of the steel industry of selected countries. Worrell et al. (2001) identified energy efficiency technologies for the steel industry in the US [31]. Zhang and Wang (2008) analyzed the influence of two energy efficiency technologies for selected steelworks in China between 1990 and 2000 using data on individual steel plants [33]. Wei et al. (2007) analyzed provincial panel data in order to estimate energy efficiency improvements in the Chinese state owned steel plants using the Malmquist Index Decomposition [27]. Ozawa et al. (2002) analyzed the development of the specific energy consumption in the steel industry in Mexico and estimated the effect of structural changes and efficiency improvements using a decomposition method [18]. Price et al. (2010) analyzed China's Top-1000 program which is designed to reduce energy consumption in the largest industrial companies [20]. Price et al. (2011) evaluated Chinas 11th Five Year Plan concerning energy efficiency [19]. Due to the limited availability of disaggregated energy consumption data, most studies use decomposition methods to estimate the impact of structural changes (e.g. a production shift to an increased share of EAF), and energy efficiency improvements.

Studies on the energy performance of the German steel sector are rather limited. Lutz et al. (2005) used an integrated bottom-up/top-down approach to simulate policy-induced technological change, quantifying the shift from the BF/BOF (Blast Furnace/Basic Oxygen Furnace) route towards the EAF

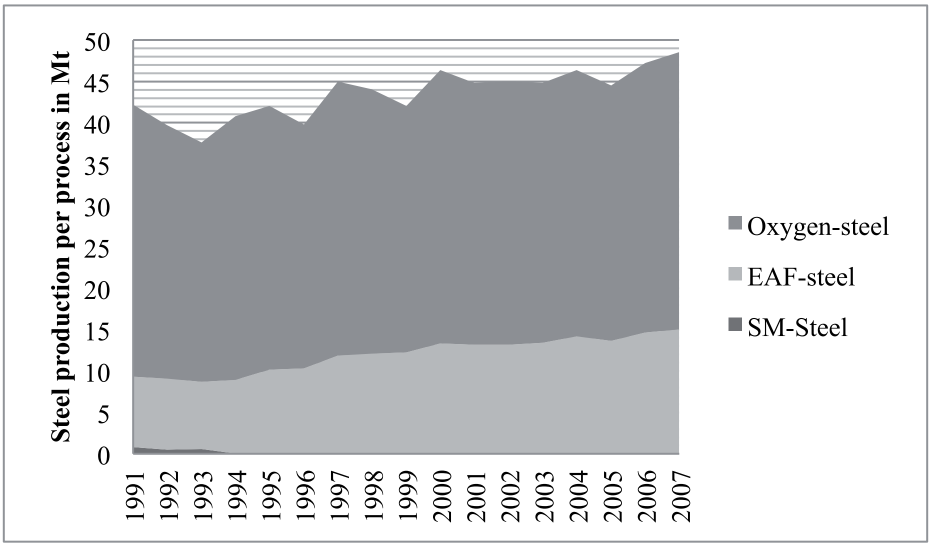

Figure 3. Steel production (in Mt/year) in Germany per process from 1991–2007. (Data from [28].)

route as well as price-induced efficiency improvements for both routes [15]. Schumacher and Sands (2007) integrated bottom up information on iron- and steel-making technologies in a computable general equilibrium model for Germany to simulate macroeconomic effects of energy policies [22]. Frondel et al. [6] analyze the specific energy consumption (expressed per ton of crude steel) in Germany since 1990 using data on the sector level. They mention the influence of an increasing share of the EAF over the BF/BOF-route on the reduction of the SEC, but do not evaluate the impact of this development on overall energy use and intensity. Furthermore, the Stahlinstitut VDEh[1] publishes annual reports on CO_2-emissions of the iron and steel industry in Germany. They analyze in detail developments of the energy consumption of single (or groups of) energy carriers per process. However, in recent reports they do not publish the SEC for all energy carriers and processes. The reports also discuss activities to reduce CO_2-emissions (e.g. diffusion of energy efficiency technologies) (e.g. [7]).

To summarize previous analyses we found that studies are restricted to aggregated levels as there is a lack of data on the process level. The conclusions of these studies are restricted to aggregated observations as well, e.g. showing the effect of structural changes on the development of the SEC. Furthermore we did not find any time series of the SEC in the iron and steel sector on the process level. Problems with data consistency occur if data stems form different sources.

Methodology

We analyze the development of the SEC of the main processes in the German iron and steel industry between 1991 and 2007 based on data of the German Federal Statistical Office. We expect to find improvements in energy efficiency due to technological progress, diffusion of best available technologies, retiring of older plants, and improved energy management. The period covers 16 years, which is sufficiently long to identify trends in energy efficiency improvement in the iron and steel industry. Furthermore the time period begins after German unification (1990), so that we could expect efficiency improvements due retiring plants in the former GDR. The analysis ends before the economic crisis in 2008/2009 due to data availability and to avoid efficiency effects from decreased capacity utilization.

The system boundaries of our quantitative analysis include input of energy carriers to the preparation of ore, sinter plants, blast furnace operations, oxygen steelworks, electric steel works as well as hot rolling mills and cold rolling mills for sheets. Since we are interested at the development of the energy efficiency at the process level consumption for transportation, for example, is excluded in our analysis.

We define the specific energy consumption as primary energy use per unit of product. Energy use is defined as the sum of energy carriers per plant and year. To each plant we assign one product and to each energy carrier we assign a specific heating value. In German energy statistics all gases are reported as natural gas equivalent, hence the heating value is similar to that of natural gas (see SEC_j is the specific energy consumption for product j; EC_i refers to the heating value or the energy needed to produce energy carrier i; m_i is the amount of the consumed energy carrier i to produce product j; x_j is the production of product j in the investigated year in the German iron and steel Industry.

Throughout the paper we use the lower heating value (LHV) of the fuels. We include the following energy carriers: hard coal and hard coal briquettes, coke and coke breeze, other solid fuels, liquid fuels, gases (COG; BFG; BOFG, Natural Gas (NG), other gases) as well as electricity, steam and oxygen. Plants include sinter and ore preparation plants, blast furnace operations, electric steel works, (oxygen) steelworks, and rolling mills. Products are sinter, pig iron, electric steel, oxygen steel, and hot rolled steel, respectively.

We calculate the specific energy consumption for each product according to equation 1:

$$SEC_i = \sum_i EC_i * \frac{m_i}{x_j} \qquad (1)$$

SEC_j is the specific energy consumption for product j; EC_i refers to the heating value or the energy needed to produce energy carrier i; m_i is the amount of the consumed energy carrier i to produce product j; x_j is the production of product j in the investigated year in the German iron and steel industry.

The energy consumption per plant is obtained by applying heating values to the energy carriers entering the plant. In the case of oxygen and steam, primary energy consumption for its production is used instead of a heating value. Electricity is accounted for based on the primary energy value. We assume an average power generation efficiency of 34.5 % throughout the studied period. We do not include energy consumption for transportation nor for recycling and processing of by-product streams, other than included in the described processes.

Data is obtained from the German Federal Statistical Office which annually publishes the so-called Iron and Steel Statistics [24] for the German steel sector. These statistics provide data on the consumption of energy carriers used in different plants of the German steel industry. Some data is confidential, which is the case when three or less German companies provided data. Data may also be confidential to avoid identification of individual producers from the aggregated data. However, for this analysis we received the confidential data and it is incorporated in our analysis, without compromising confidentiality (see below).

We use a four-step approach in the analysis. First, for each process, we collect the consumption data of the different energy carriers in the investigated period. Then we calculate the energy consumption per energy carrier, process and year using the assumed heating values (see SEC_j is the specific energy consumption for product j; EC_i refers to the heating value or the energy needed to produce energy carrier i; m_i is the amount of the consumed energy carrier i to produce product j; x_j is the production of product j in the investigated year in the German iron and steel Industry.

Table 1. In a third step we check how to treat confidential data. If for a single plant in a single year the energy consumption of three or more energy carriers is confidential then we aggregate the energy carriers and define them as *Other Fuels*. If only the consumption of one or two energy carriers per process

1. Stahlinstitut VDEh (Verein Deutscher Eisenhüttenleute)

Table 1: Assumed heating values.

Fuel/energy carrier	Value	unit	Heating value/ energy consumption	Source
Hard coal, -briquettes	29.31	GJ/t	Heating value	Statistisches Bundesamt Fachserie 4, Reihe 4.1.1.
Coke	28.43	GJ/t	Heating value	Statistisches Bundesamt Fachserie 4, Reihe 4.1.1.
Coke breeze (CB)	28.43	GJ/t	Heating value	Statistisches Bundesamt Fachserie 4, Reihe 4.1.1.
Other solid fuels (OSF)	25.00	GJ/t	Heating value	Assumption by authors.
Liquid fuels	40.61	GJ/t	Heating value	Statistisches Bundesamt Fachserie 4, Reihe 4.1.1.
Steam	2.80	GJ/t	Energy consumption to produce steam	Personal communication with industry experts.
Blast furnace gas (BFG)	35.17	GJ/1000Nm³	Heating value	Statistisches Bundesamt (2006): Qualitätsbericht Fachstatistik Eisen und Stahl. Wiesbaden.
Coke oven gas (COG)	35.17	GJ/1000Nm³	Heating value	Statistisches Bundesamt (2006): Qualitätsbericht Fachstatistik Eisen und Stahl. Wiesbaden.
Natural gas (NG)	35.17	GJ/1000Nm³	Heating value	Statistisches Bundesamt (2006): Qualitätsbericht Fachstatistik Eisen und Stahl. Wiesbaden.
Basic oxygen furnace gas (BOFG)	35.17	GJ/1000Nm³	Heating value	Statistisches Bundesamt (2006): Qualitätsbericht Fachstatistik Eisen und Stahl. Wiesbaden.
Other gases	35.17	GJ/1000Nm³	Heating value	Statistisches Bundesamt (2006): Qualitätsbericht Fachstatistik Eisen und Stahl. Wiesbaden.
Oxygen	7.33	GJ/1000Nm³	Energy consumption to produce oxygen	Frondel et al. (2011) [6]
Electricity	10.43	GJ/1000kWh	Primary energy	Frondel et al. (2011) [6]

and year is confidential we either neglect them (i.e. when the total volume is very small, as for blast furnaces) or we interpolate (i.e. for hot rolling). Finally, we show the development of the SEC over time for each process. In the case of the blast furnace and BOF we also analyse the development of the net energy consumption, correcting for the production of fuels (i.e. gas recovery).

Results

SINTER AND ORE PREPARATION PLANTS

Apart from sinter plants the statistical group furthermore covers ore preparation plants (e.g. crushing, milling, filtering, ore blending beds). Unfortunately, no separate information about the energy consumption of the ore preparation plants is available. But their main energy carrier should be electricity, which amounts for 15 to 22 % of the total energy consumption of this group.

In contrast to our expectations, energy intensity of the sinter plants did not decrease continuously. We even find an increase of the SEC between 1991 and 1998 and between 2002 and 2006. The SEC peaks in 1998 with 2.28 GJ/t sinter. This is 0.26 GJ/t sinter or 11 % higher than in 1991 (2.04 GJ/t). The first increase is caused by an increase in the consumption of coke breeze. The second increase (2002–2006) results from am increase in hard coal consumption. The specific consumption of electricity, coke oven gas and natural gas remain more or less constant over the studied period.

Figure 4 shows the development of the SEC of sinter and ore preparation plants per ton sinter. The main energy carrier is coke breeze with a share of 63 to 74 % of the total energy consumption. The group 'other fuels' strongly increases over the investigated period. The main driving factor for this increase is the partly substitution of coke breeze with hard coal. In 1998 hard coal amounted for 0.2 GJ/t sinter and its share increased till 2007 to 0.3 GJ/t sinter. Between 1998 and 2007 hard coal accounts for 60–80 % of the fuels within the group *Other Fuels*. Coke oven gas and natural gas make up between 4 to 6 % of the total energy consumption.

BLAST FURNACE OPERATIONS

Besides blast furnaces this group includes plants for the transport of ore, hot stoves, water treatment, blast furnace gas treatment and pumps. Reducing agents blown into the blast furnaces are included as well. Power may be recovered from the top gas through pressure recovery turbines. The only DRI plant in Germany belongs also to this group. With an annual production of approximately 500,000 t we neglect its influence. The energy carriers are mainly reducing agents for the blast furnaces [25].

Due to confidentiality, we neglect the use of basic oxygen furnace gas (BOFG), coke breeze (CB) and other solid fuels (OSF). For the published years BOFG and coke breeze amount to a maximum of total energy consumption of 0.5 % and 0.6 % respectively. Other solid fuels are zero, except in 1992. Hard coal consumption is confidential in 2002 and 2003. We therefore interpolate these values from the specific hard coal consumption of 2001 and 2004.

Figure 5 shows the specific energy input in blast furnace operations. The main energy carrier is coke, though its consumption was partly reduced by injecting hard coal in the studied period. In 1991 coke consumption amounted for 93 % of the total SEC, or 11.64 GJ/t. The specific coke consumption was reduced by 14 % from 1991 to 1999. Coke consumption increased from 10.06 GJ/t to 10.66 GJ/t from 1999 to 2000. From 2000 onwards, coke consumption decreased continuously to

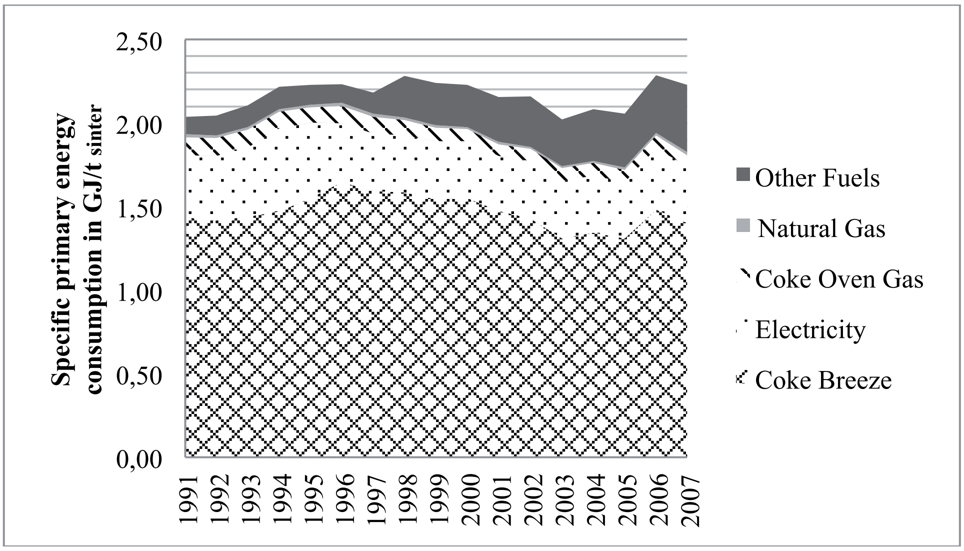

Figure 4. Specific energy consumption in sinter plants, expressed in primary energy per ton of sinter.

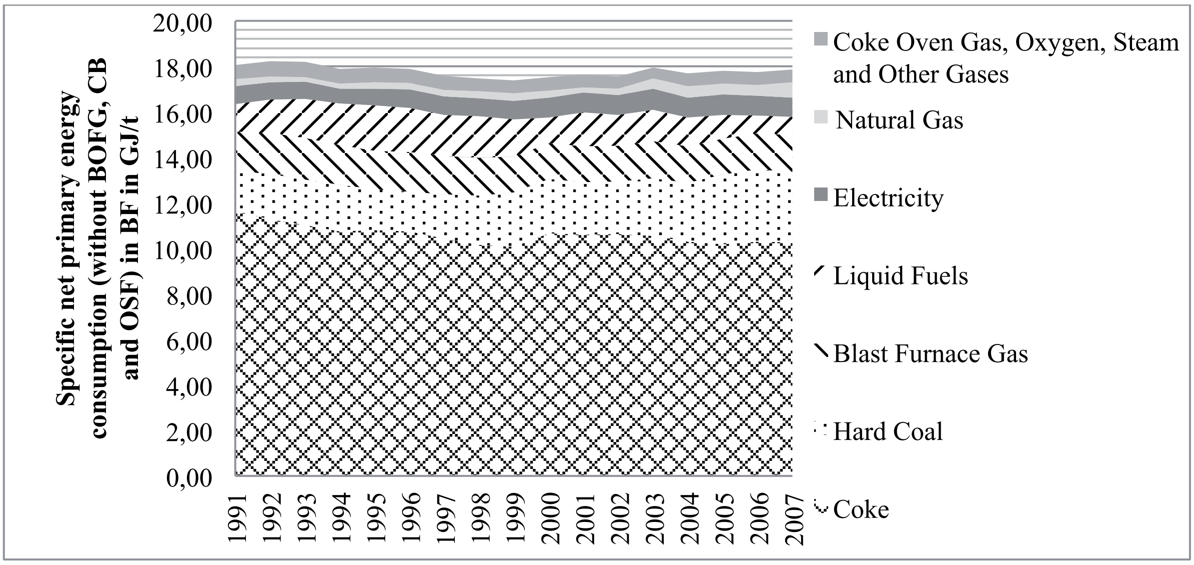

Figure 5. Specific energy input in blast furnace operations, expressed in primary energy per ton of pig iron.

10.18 GJ/t though in 2006 and 2007 its consumption increased slightly again. In 2007 coke is only 88 % of the total energy consumption in the blast furnace. The specific hard coal consumption has nearly doubled in the studied period, from 1.74 GJ/t in 1991 to 3.09 GJ/t in 2007. We found a reduction in the use of liquid fuels. The consumption of blast furnace gas and electricity remained almost constant while the consumption of natural gas and oxygen increased slightly.

The reduction of iron ore to iron in the blast furnaces produces blast furnace gas (BFG), and is used as an energy carrier within the integrated iron and steel plants. It is mainly used to heat the hot stoves and to produce electricity in onsite power plants. To calculate the net SEC of blast furnace operations we reduce the specific energy input by the specific amount of BFG production. Figure 6 shows the specific net energy consumption of blast furnace operations in the German steel sector between 1991 and 2007. Apart from 2003 we observe with some exceptions a slight and continuous decrease of the net SEC by 3.8 % over the studied period, equalling about 0.2 %/year.

Our analysis of the blast furnace operations shows slight reductions of the SEC. Bear in mind that due to confidentiality we neglected the influence of basic oxygen furnace gas, coke breeze, and other solid fuels, which equals about 1 % of total energy use in the BF. The specific net energy consumption and the specific energy input were reduced by average 0.2 %/year.

BASIC OXYGEN FURNACE

From 1991 to 2002 in energy statistics the group was called *Oxygen steelworks*. From 2003 onwards the group is called *Other Steelworks*, though the same group of plants is included. In 1991 there were 38 BOF-vessels operating in Germany. This number was reduced to 21 in 2007 of which only 18 were operating at that time [28].

Due to confidentiality we aggregate the following energy carriers as *Other Fuels*: hard coal, coke, coke breeze, other solid fuels, liquid fuels, BFG, BOFG, and other gases.

The production of BOFG was published firstly in 1993. We analyze the net energy consumption from 1993 onwards, while we show the specific energy input from 1991 onwards.

Figure 7 shows the specific energy input in the BOF in Germany between 1991 and 2007. The two main energy carriers are oxygen and electricity each amounting for about 0.40 GJ/t. While the consumption of oxygen remained approximately on the same level, the consumption of electricity was reduced by 16 % between 1991 and 1997 and then increased again to approximately the same amount as in 1991. The specific consumption of natural gas, coke oven gas and other fuels were reduced over the studied period while the specific consumption of steam slightly increased.

To calculate the net energy consumption of the BOF we reduce the specific energy input by the specific BOFG production. Figure 8 shows the specific net energy consumption of BOFG in Germany between 1993 and 2007. We found a net SEC for 1993–1995 and 1995–2007 of about 0.4 GJ/t oxygen steel and about 0.6 GJ/t, which equals an increase of about 50 %.

Our analysis shows a strong decrease in the specific energy input in BOFs between 1991 and 1994 by 13 %. Main drivers are the reduction of electricity, natural gas, and other fuels. But from 1995 to 1997 the specific energy input increased by 7 % and this level was roughly kept till 2007. Main drivers for this development were an increase in the consumption of electricity and steam.

Figure 9 shows the specific BOFG production in the studied period. The increase of the specific net energy consumption originates from the reduction of the BOFG production. Between 1994 and 1996 3 BOFs have been shut down [28]. According to the Stahlinstitut VDEh among these three BOFs have been some with BOFG recovery. Currently only 60 % of the BOFs in Germany are equipped with BOFG recovery systems [8].

ELECTRIC ARC FURNACE

From 1991 to 2002 in the statistics electric steel works are in one group with so called *Other Steelworks*. Therefore this group also contains Siemens-Martin-Furnaces from 1991 to 1993. These furnaces were run in the former GDR and were shut down in 1993. In the data we cannot distinguish electric arc furnaces from Siemens-Martin-Furnaces in this period; therefore we start our analysis of electric arc furnaces in 1994. The name of the group was changed in 2003 to *Electric Steel Works*. We might observe statistical differences from 2002 to 2003.

The SEC of electric steel works varies only slightly over the studied period. Taking 1994 as the reference, the SEC varies between +2 % (e.g. in 1996, 2004 and 2007) and -2 % (in 1998). In 2003 the SEC is 4 % lower than the year before. Over the total period studied, we see no real improvement in energy efficiency of electric steel works in Germany between 1994 and 2007.

Figure 10 shows the development of the consumption of the different energy carriers. The main energy carrier is electricity accounting for 86 to 88 % of the total SEC. Natural gas and oxygen count for 5–7 % and 3–4 % respectively. Steam and other fuels amount for 2–3 %. Excluding 2003, the SEC varied between -4 % to +1 % compared to 1994. In 2006, the same amount of electricity per ton electric steel was used than in 1994. We observe a slight increase in the use of oxygen (1994: 0.21 GJ/t; 2007: 0.26 GJ/t) and a slight decrease in the use of steam (1994: 0.05 GJ/t; 2007: 0.03 GJ/t). The use of natural gas and other fuels remained nearly constant over the studied period.

We would have expected at least a slight energy efficiency improvement due to technological progress such as process management and increased usage of oxygen. It might be that the scrap quality decreased as there was a big demand for scrap especially from Asia (i.e. China) between 2000 and 2007. Under these circumstances we could suspect that without any technological progress energy efficiency would have decreased in this period. However, there is insufficient data on scrap quality and the impact on the EAF SEC to evaluate this hypothesis.

ROLLING

This group covers hot rolling mills as well as rolling turneries, hot extruder plants, finishing plants and glow systems as far as they belong to hot rolling mills. Cold rolling mills also belong to this group [25]. We refer the energy consumption of this group to the production of hot rolled steel. We neglect the influence of the other processes. The share of cold rolled steel of hot rolled steel decreased from 35.0 % 1994 to 31.4 % in 2007 [28]. A decrease in the share of cold rolled steel could lead to a reduction in the specific energy consumption per ton hot rolled steel.

Due to confidentiality we have to make assumptions for the use of other fuels between 1999 and 2003, as well as 2006. In 1999 *Other Fuels* amount to 0.29 GJ/t hot rolled steel and in 2004 this is 0.34 GJ/t. Therefore we assume for the years in between the following values: 0.295; 0.305; 0.314; 0.324 (2000–2003). For 2006 we assume 0.41 GJ/t for 'other fuels'.

For rolling we found a continuous decreasing energy intensity of about 1.5 % per year, for nearly all energy carriers, although especially for coke oven gas and electricity.

The main energy carriers are natural gas and electricity amount to 1.24-1.52 GJ/t and 1.51-1.83 GJ/t respectively (Figure 11). The specific consumption of natural gas increased from 1991 to 2001 from 1.37 GJ/t to 1.52 GJ/t. From 2002 onwards its consumption decreased to 1.24 GJ/t in 2007, resulting in an efficiency improvement of 10 % comparing to 1991. The consumption of electricity continuously decreased from 1.83 GJ/t to 1.51 GJ/t, which equals 18 % or 1.1 % per year. The specific consumption of coke oven gas decreased continuously even stronger from 1.02 GJ/t to 0.38 GJ/t or 3.9 % per year. The use of steam and oxygen was reduced by 2.3 % and 4.2 % per year respectively. The consumption of other fuels decreased from 1991 to 1998 from 0.40 GJ/t to 0.29 GJ/t, but then increased till 2007 to 0.40 GJ/t.

OVERALL TRENDS

As we base our analysis of the energy efficiency of the German steel industry on data on the energy consumption of the different processes, we can calculate, bottom up, the effect of the structural change towards an increasing share of EAF on the development of the specific energy consumption per ton crude steel. While the production of BF/BOF-steel remained between 30 and 34 Mt/year, the production of EAF-steel nearly doubled

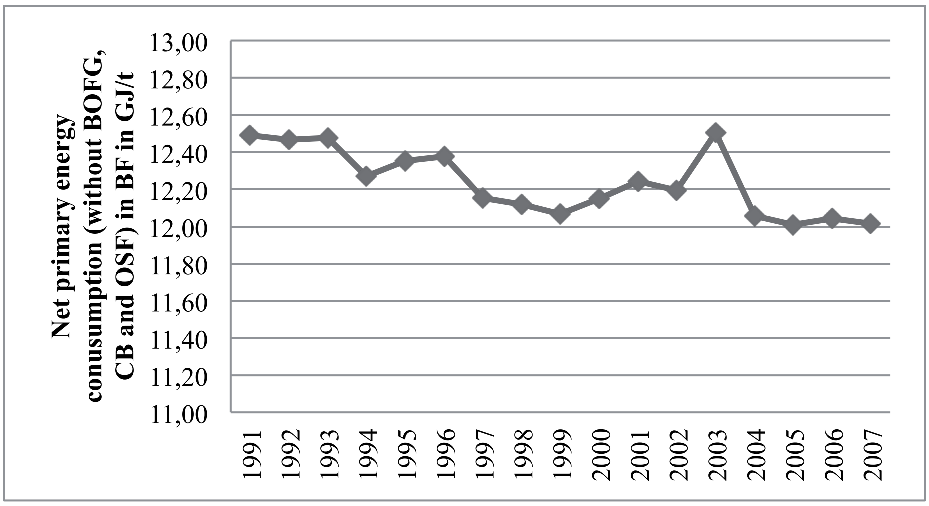

Figure 6. Specific primary net energy consumption in blast furnace operations.

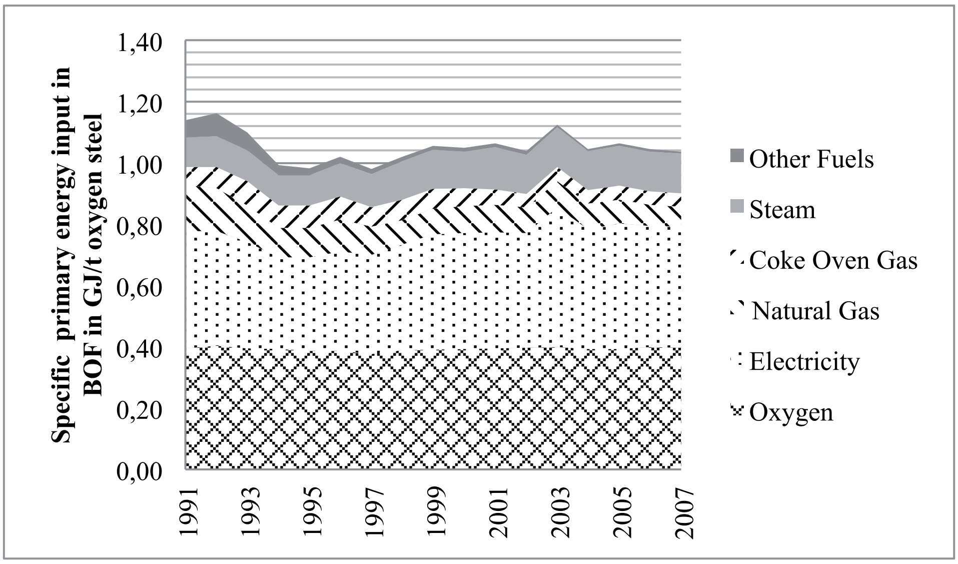

Figure 7. Specific energy input to basic oxygen furnaces expressed in primary energy per ton oxygen steel.

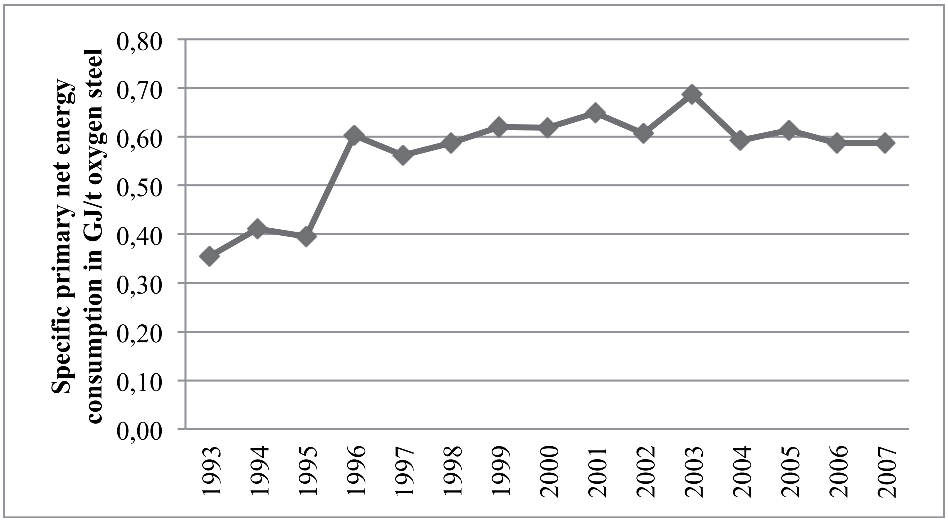

Figure 8. Specific primary net energy consumption in basic oxygen furnaces, expressed in primary energy per ton of oxygen steel.

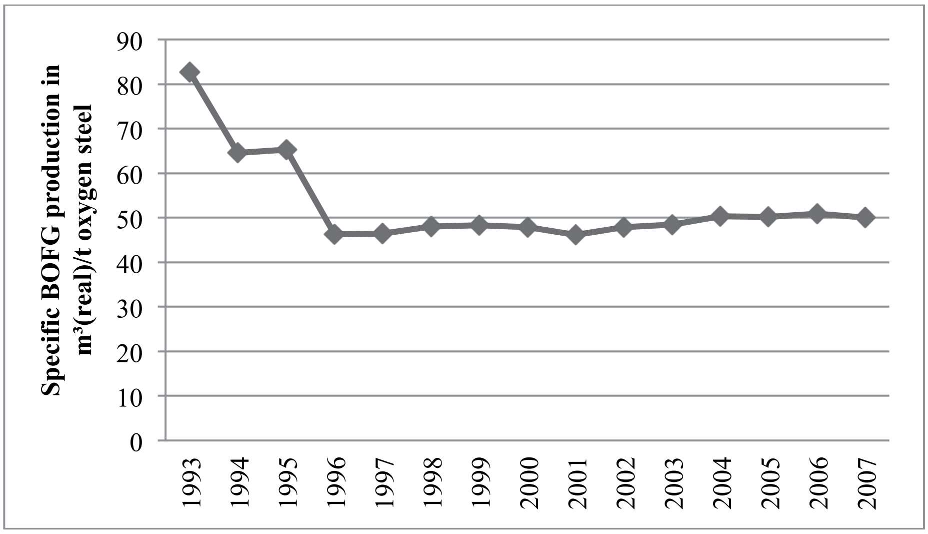

Figure 9. Specific BOFG production, expressed in energy (LHV) per ton of oxygen steel.

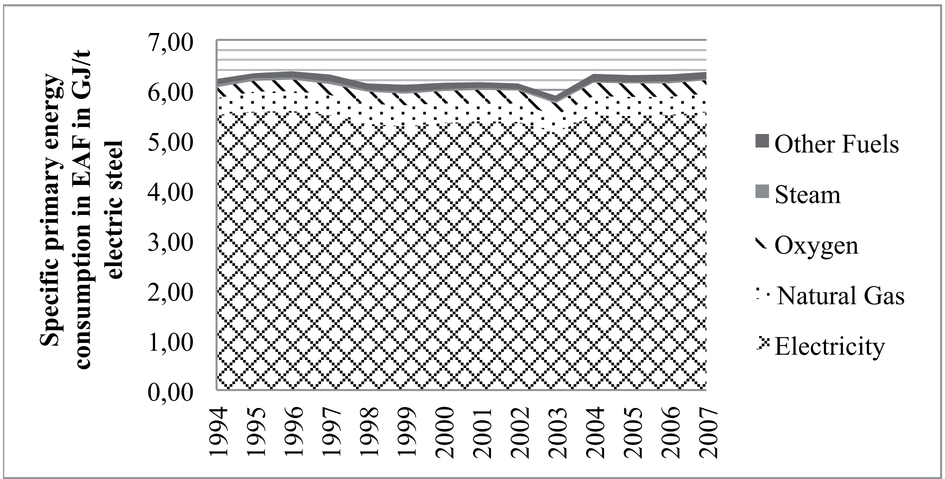

Figure 10. Specific energy consumption in electric arc furnaces, expressed as primary energy consumption per ton of electric steel.

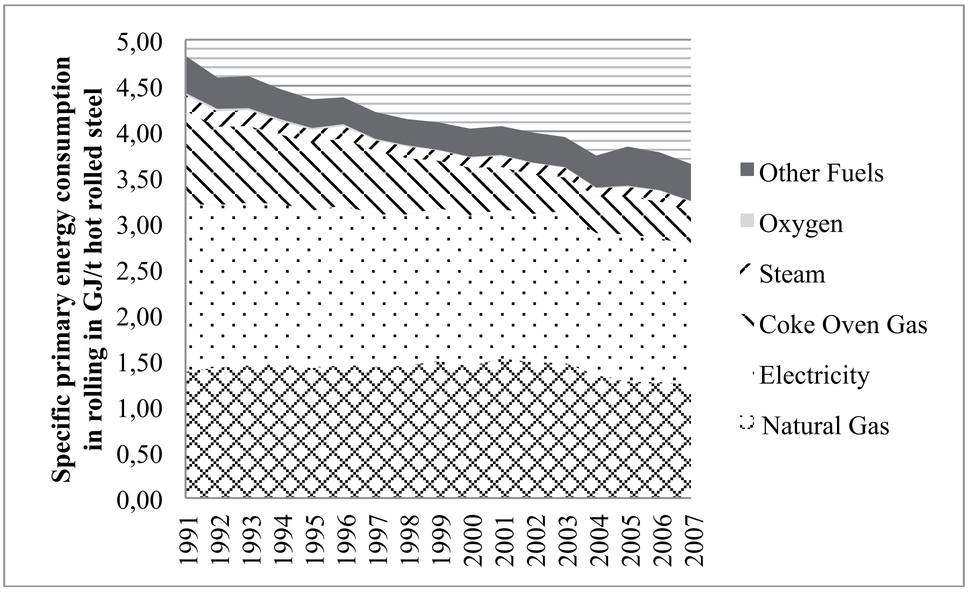

Figure 11. Specific energy consumption in rolling, expressed as primary energy per ton of hot rolled steel.

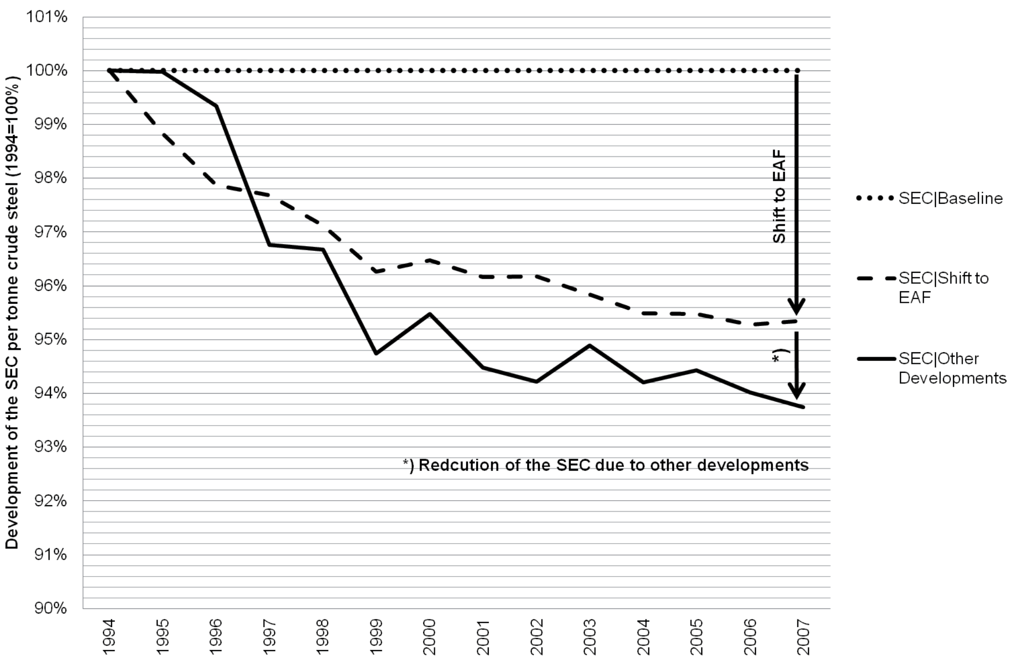

Figure 12. Illustration of the influence of a production shift to EAF on the reduction of the specific energy consumption (SEC) per ton crude steel in the German Iron and Steel Industry between 1994 and 2007. The dark line shows the development of the SEC per ton crude steel between 1994 and 2007 in the German Iron and Steel Industry. The dotted line represents the hypothetical development of the SEC per ton crude steel for the case that the SEC per t EAF- and per ton BF/BOF-steel remained on the value of 1994 while only the production of EAF- and BF/BOF steel changed.

from 8.9 Mt to 15 Mt/year (see Figure 12). The share of EAF increased from 21.8 % to 30.9 %.

Figure 12 shows the influence of the increase in the share of EAF production on the development of the SEC in Germany between 1994 and 2007[2]. The dark line represents the development of the specific energy consumption per ton crude steel based on the specific (net) energy consumption in blast furnace operations and electric arc furnaces. For the studied period we obtain a total decrease of 6.7 % of the SEC per ton of crude steel, which equals an improvement of about 0.5 %/year.

The dotted line represents the hypothetic development of the specific energy consumption per ton crude steel for the case that the specific energy consumption per ton BF/BOF steel and EAF-steel remained constant at 1994 levels, and only the production values are changing. We can now show the influence of an increasing share of EAF on the specific energy consumption per ton crude steel. Efficiency improvements are not considered in the dotted line. We obtain that the specific energy consumption per ton crude steel due to an increase of the share of EAF was reduced by 4.6 % in the studied period. Based on this calculation, we conclude that due to changes in the processes the specific energy consumption per ton crude steel was reduced by 0.4 % between 1994 and 2007. This equals a reduction of the specific energy consumption due to changes in the processes (among theses energy efficiency improvement is an option) of 0.1 % per year.

2. We exclude the years 1991–1993 in this calculation, as for these years, inefficient Siemens Martin-furnaces were included in the group of electric arc furnaces.

Conclusion

Our findings from analysing the development of SEC in the German steel industry at the level of individual processes suggest that only considering energy consumption in blast furnaces and electric arc furnaces the SEC per ton crude steel decreased by 6.3 % between 1994 and 2007. The lion's share (4.6 % in total or 0.4 % per year) originates from structural change, i.e. the shift in production towards more EAF. Efficiency improvements at the level of individual processes accounted for 1.7 % in the studied period to the reduction of the SEC per ton crude steel, corresponding to only 0.1 % per year between 1994 and 2007. Hence, somewhat surprisingly – apart from gains in steel rolling – efficiency appears to have barely improved over this period. Thus, our findings suggest that the voluntary agreement, which has been in place since 2001, had only marginal effects on the energy efficiency of the individual steel production processes in the German iron and steel industry. Any progress has likely been limited to steel rolling. Instead, observed reductions in the SEC for crude steel production are primarily due to a shift in production towards EAF. In the absence of a counterfactual baseline however, the conclusions on the (lack of) effectiveness of the voluntary agreement can only be tentative. Also, at least to some extent, and neither controlled by our analysis nor provided for in the voluntary agreement, observed development in energy performance may also be due to changes in the quality of input materials, and also due to changes in output quality. Lower input quality and higher output quality would result in higher energy use, ceteris paribus. To quantify the impact of changes in input or product quality on energy efficiency, very detailed data is required. In any case though, the iron and steel sector was found to have failed to fulfil its sectoral agreement in 2010 [6]. Since the voluntary agreement of the German industry of the year 2000 must only be fulfilled as a whole, and since most (but not all) other sectors like refineries, cement and electricity production over-fulfilled their sectoral targets, the voluntary agreement as a whole was met in 2010.

Hence, other policies would be needed to help realize existing potentials of energy efficiency improvement in the German steel sector [21].

In principle, a prime policy should be the EU emissions trading system (EU ETS), which requires operators of steel plants (but also other industry and energy installations) to surrender an amount of EU allowances (EUA) equivalent to their direct CO_2-emissions. The price of EUAs provides financial incentives to reduce direct emissions of existing and new installations (mainly in the BF/BOF route), but also the use of electricity (mainly in EAF plants) since power producers pass on the extra (opportunity) costs of their fossil fuel inputs to the power price. Although not directly targeted at energy performance, the EU ETS indirectly affects energy use through the additional costs of fossil fuel and electricity consumption. At current prices of EUAs of less than 10 Euros, these incentives fail to provide short- or long-term incentives for substantial energy-efficiency improvements.

To conclude, additional instruments to improve energy efficiency may include strategic energy management, energy audits, financial support for energy efficient technologies, or energy taxes. Ideally, an integrated policy program could be designed linking short-, medium- and long-term initiatives aimed at delivering meaningful improvements in energy efficiency and providing the guidance and direction necessary for collaboration in research and development or investments in energy efficient technologies.

Abbreviations

BF	Blast Furnace
BOF	Basic Oxygen Furnace
BFG	Blast Furnace Gas
BOFG	Basic Oxygen Furnace Gas
COG	Coke Oven Gas
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EUA	EU allowances
GHG	Greenhouse Gases
NG	Natural Gas
SEC	Specific Energy Consumption
VA	Voluntary Agreement

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