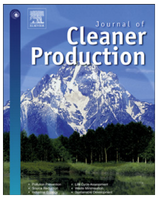
Journal of Cleaner Production 163 (2017) 84–98

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany

Marlene Arens [a,*], Ernst Worrell [b], Wolfgang Eichhammer [a], Ali Hasanbeigi [c], Qi Zhang [d]

[a] *Fraunhofer Institute for Systems and Innovation Research (ISI), Breslauer Strasse 48, 76139 Karlsruhe, Germany*
[b] *Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands*
[c] *China Energy Group, Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road MS 90R2121, Berkeley, CA 94720, USA*
[d] *SEPA Key Laboratory on Eco-industry, Northeastern University, Box 345, 3-11, Wenhua Road, Heping District, Shenyang 110819, PR China*

ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form
27 November 2015
Accepted 28 December 2015
Available online 6 January 2016

Keywords:
CO_2 emissions
Iron and steel industry
Innovative technologies

ABSTRACT

The iron and steel industry is a major industrial emitter of carbon dioxide globally and in Germany. If European and German climate targets were set as equal proportional reduction targets (referred to here as “flat” targets) among sectors, the German steel industry would have to reduce its carbon dioxide emissions from about 60 million metric tons currently to 28–34 million metric tons by 2030. Technical options to further reduce CO_2 that are based on existing production processes are limited. Hence, in the future, the CO_2 emissions of the steel industry could be reduced by alternative and new production processes and variations in production levels. This paper describes four production pathways from 2015 to 2035 that reveal the impact of constant, increasing and decreasing production levels as well as different production processes. The diffusion of energy-efficient technologies, the increase of renewables in the German electricity mix and the age and lifetime of blast furnaces are considered as well. The findings suggest that the German steel sector will only manage to achieve its European CO_2 emissions reduction target for 2030 if it strongly decreases its production levels. Furthermore, it is highly unlikely that the German steel sector will meet its German climate target regardless of the production pathway selected. The findings suggest that efforts to reduce CO_2 emissions in the steel industry should focus on two areas. First, alternative steelmaking processes need to be developed. Besides low-CO_2 process technologies, CO_2-free processes should be considered as well. Direct reduced iron could be produced based on hydrogen and then fed into an electric arc furnace powered by electricity generated using CO_2-free sources. Steel could also be produced using electrolysis based on CO_2-free electricity. However, because these technologies might take decades to develop and introduce, there should be a second focus on incremental CO_2 reductions in the short to medium term.

1. Introduction

The steel industry is a major carbon dioxide (CO_2) emitter (e.g. Fischedick et al., 2014; Hasanbeigi et al., 2014; IEA Clean Coal Center, 2012). In Germany, it accounts for 4% of the country's total greenhouse gas (GHG) emissions (Fischedick et al., 2014). Within the framework of the extended Kyoto Protocol (Kyoto II), the European Union (EU) has agreed to reduce its GHG emissions (among these, CO_2 emissions have the largest share) by 20% until 2020 compared to 1990 (Umweltbundesamt, 2014a,b; Bundesministerium für Wirschaft und Energie, 2015). The European Council has set a further GHG reduction target of 40% by 2030 compared to 1990 to be shared among the sectors covered by the European Emission Trading Scheme (ETS) and sectors not included in the ETS. This target is aimed to be met collectively by the EU with the reductions in the ETS and non-ETS sectors amounting to 43% and 30% by 2030 compared to 2005, respectively (European Council, 2014). Germany adopted the *Energiekonzept* in 2010 that aims to reduce CO_2 emissions by 55% by 2030 compared to 1990 (Bundesregierung, 2010). This study assumes targets set as equal proportional reductions (flat targets) for all sectors (Table 1), since no more specific targets have been set so far.

---

[*] Corresponding author. Tel.: +49 721 6809 408.
E-mail address: marlene.arens@isi.fraunhofer.de (M. Arens).

http://dx.doi.org/10.1016/j.jclepro.2015.12.097
0959-6526/

Table 1

Estimated CO_2 emission reduction targets for the German steel industry according to current policy if targets have to be met equally across sectors (sources: European Council, 2014; Bundesregierung, 2010; Wirtschaftsvereiniung Stahl and Stahlinstitut VDEh, 2014).

		1990	2005	Estimated target 2030 (Mt CO_2)
Specific CO_2 emissions	t CO_2/t crude steel	1.59	1.35	–
Crude steel production	Mt crude steel	38.4	45.5	–
Total CO_2 emissions	Mt CO_2	61.3	60.2	–
European target (2030/2005)	–	–	−43%	<34.3
German target (2030/1990)	–	−55%	–	<27.6

Further significant improvements and reductions in CO_2 emissions by *best available technologies* seem to be limited (Fischedick et al., 2014; Boston Consulting Group, 2013). Therefore, several global initiatives are underway to develop *breakthrough technologies* that drastically reduce CO_2 emissions (e.g. Tonomura, 2013; World Steel Association, 2009; Han et al., 2014). In Europe, the ULCOS initiative aims to bring four innovative steelmaking technologies to the market (e.g. a new smelt reduction technology *HIsarna*) (IEAGHG, 2014).

Here, the German steel industry is taken as a proxy for the European Union (EU) and beyond. What opportunities does it have to drastically reduce its emissions in the medium term? – In order to answer this question, likely production developments of the German steel industry have been defined that consider the path dependencies due to existing facilities (i.e. blast furnaces) and historical high and low production levels. How can the German steel industry reach lower CO_2 emissions within these pathways? What are the impacts due to a production decrease, or the introduction of low-CO_2 steelmaking processes?

Several studies have tried to estimate the future energy consumption and CO_2 emissions of the steel industry. Moya and Pardo (2013) used a bottom-up model and included economic data on best available technologies and emerging technologies. For 2030, they found CO_2 emission reduction potentials of 65% for the European iron and steel industry, if companies would permit payback periods of about 6 years. They assumed that two ULCOS technologies (i.e. top gas recycling blast furnace and ULCORED) and carbon capture and storage (CCS) will be ready for application by 2020. They consider site-specific payback periods. However, they do not include the age of the plants in their analysis, nor do they consider changing future production levels.

Brunke and Blesl (2014) also constructed a site-specific model to show how energy-efficient technologies can compensate rising energy prices till 2035. They assumed constant production throughout the studied period and did not examine total CO_2 emission reductions in the German steel industry. They found that primary steelmaking will face increasing production costs in the future since energy-saving potentials are limited, while secondary steelmaking can compensate rising energy prices to some extent by implementing energy-efficiency measures.

Kuramochi (2016) analyzed medium-term CO_2 emission reduction potentials in the Japanese steel industry. He focused on an increased use of domestically-recovered steel scrap in primary steelmaking. According to his findings, 5.4% of the CO_2 emissions in 2010 could be cut by 2030. Total CO_2 emissions could be reduced by 12% in 2030 compared to 2010 using other best available technologies and increasing the use of coke substitutes in blast furnaces.

Fischedick et al. (2014) analyzed the economical and technical potential of innovative primary steel production technologies in Germany up to 2100 (i.e. top gas recycling blast furnace with CCS, direct reduction based on hydrogen, electrolysis of iron ore). They find that climate targets can be achieved in the long term by applying these technologies.

This paper analyzes future pathways to reach lower CO_2 emissions levels in the German iron and steel industry until 2035. Although the current climate targets are set for 2030, this paper's timeframe is 20 years from 2015 in order to reflect the industry's longer investment periods. The study constructs a model to estimate energy consumption and CO_2 emissions in the German steel industry between 2015 and 2035. Blast furnaces (i.e. the key CO_2 emitting plants within the steel industry) are modeled plant-specifically, considering age and capacity. Other structural factors are included: scrap availability, CO_2 emission factor of the power system, the diffusion of energy-efficient technologies, and a new iron-making process. Future energy consumption on the energy carrier level and CO_2 emissions are estimated by multiplying the specific energy consumption per steelmaking process and CO_2 intensity by the respective production level of the steelmaking process considered. Four future production pathways are defined to show the impact of constant, increasing and decreasing crude steel production. The paper aims to show how likely it is that the German steel industry will meet future climate targets.

Section 2 gives a short introduction to the German steel industry. Section 3 describes the model, and section 4 shows the structural parameters that shape energy intensity and CO_2 emissions in the steel industry. Section 5 defines the resulting production pathways and presents the estimated future energy consumption and CO_2 emissions of the German iron and steel industry until 2035. The paper ends with a sensitivity analysis, discussion and conclusions in sections 6, 7 and 8.

2. The steel industry

Currently, there are two predominant steelmaking processes globally and in Germany, i.e. the blast furnace/basic oxygen furnace route (BF/BOF) and the scrap/electric arc furnace route (scrap/EAF). The former is the most energy-intensive primary route, since it includes the energy-intensive reduction of the raw material from iron ore to iron, while the latter recycles scrap and is therefore less energy-intensive. The main inputs to the blast furnace are iron ore and coke, which is made of coal. The main inputs to scrap/EAF steelmaking are scrap and electricity.

There is a third process route, the production of direct reduced iron (DRI), that also falls under primary steelmaking since it is based on iron ore. This process can either be based on natural gas or on coal, although gas-based DRI processes are dominant. If natural gas is used instead of coal, gas-based DRI/EAF steelmaking is less CO_2 intensive than BF/BOF steelmaking (e.g. Moya and Pardo, 2013; Kobe Steel Ltd, 2013; International Energy Agency, 2007). Under current economic conditions, DRI plants are not seen as a viable option for Europe (Boston consulting Group, 2013; Moya and Pardo, 2013; International Energy Agency, 2007). Notably, because of currently low gas prices due to shale gas, DRI plants are again being built, e.g. in the USA (Kobe Steel Ltd, 2013; Midrex, 2014). In Germany, there is only one direct reduction plant in Hamburg with a capacity of about 0.5 Mt/year that is also the only DRI plant in Europe.

The production of BF/BOF-steel varied between 28.8 and 34.4 Mt/year in Germany between 1980 and 2014, while the production of EAF-steel increased from 6.5 in 1980 to 15.0 Mt in 2007. DRI production is included in EAF steel production and is about 0.5 Mt/year (Midrex, 2013). The economic crisis in 2008/2009 caused a structural break in steel production trends and post-crisis production is still below pre-crisis production levels (Fig. 1). From 2010 to 2014, the average BF/BOF production was 29.7 Mt/year, which is 6.2% below the average of the period 1980–2007 (i.e. 31.7 Mt/year). EAF steelmaking production decreased in the same period. In 2014, EAF production was 8.4% below the production level of 2011, while BF/BOF steel production increased again slightly in 2013 and 2014.

In Germany, BF/BOF steel is usually converted into flat products, while scrap/EAF steel is mostly used for long products. Flat products are mainly high quality products used in appliances such as automotive, mechanical engineering, tubes, steel construction and metal ware, while long products are usually used in construction. However, globally, there is an increasing share of EAF steelmakers that also produce high quality flat products (International Labour Organization, 1997; de Beer, 2000). The quality of the steel produced in electric arc furnaces depends on the quality of its feedstock. To produce high quality steel in electric arc furnaces, either high quality scrap has to be used, or direct reduced iron (DRI) (International Labour Organization, 1997; de Beer, 2000). High quality scrap is both expensive and scarce, while DRI production is both expensive and energy-intensive. Thus, producing high quality products using electric arc furnaces is more energy and CO_2 intensive than scrap/EAF steelmaking.

The German steel industry currently supplies high quality steel markets. Since DRI is not economically viable in Europe, high quality products cannot be provided by scrap/EAF steelmaking only.

3. Methods

The analysis derives and estimates specific energy consumption values for BF/BOF and scrap/EAF steelmaking for Germany based on data from 2011. Since our analysis is based on the energy carrier level, CO_2 emissions are derived by applying CO_2 emission factors for each fuel/energy carrier. The total energy consumption and total CO_2 emissions are calculated by multiplying these values by the respective production volume in each production process.

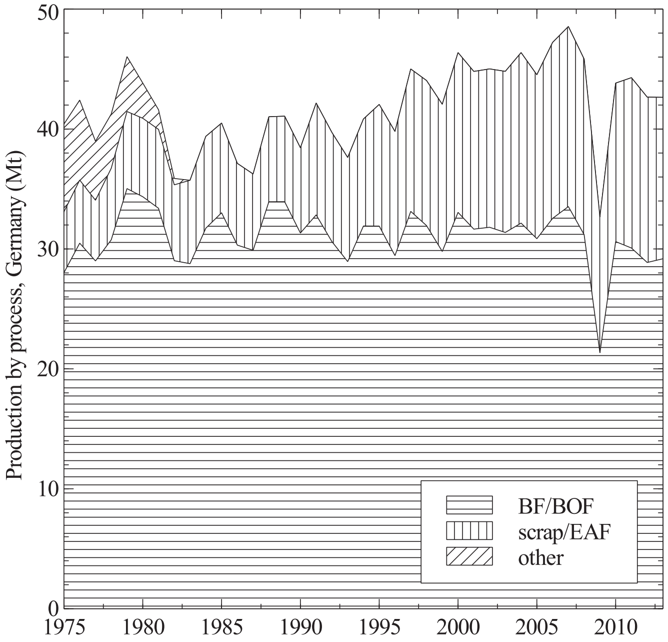


Fig. 1. Annual steel production by BF/BOF, scrap/EAF or other processes in Germany 1975–2013 (source: Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

Several structural factors shape the future energy consumption and CO_2 emissions of the steel industry (Fig. 2).

The model encompasses four steel production processes: the current primary steelmaking process with blast furnaces and basic oxygen furnaces and, the scrap-based secondary route via electric arc furnaces. Secondary steelmaking requires less energy than primary steelmaking, but is limited by scrap availability and product quality (e.g. Arens et al., 2012). The direct reduction route is also included that currently has only a minor share in Germany as is an innovative smelting reduction technology (*HIsarna*) that is predicted to be commercially available from 2030 onwards.

For the two main production processes today, further diffusion of energy-efficient technologies is considered.

The CO_2 emission intensity of the German power system determines the CO_2 intensity of steelmaking especially when electric arc furnaces are involved. In line with current German energy policy, the analysis assumes that the CO_2 intensity of the German power system will decrease because one objective is to increase the share of renewable energy carriers in the power mix.

Total energy consumption and CO_2 emissions are driven by production levels. The analysis assumes four production pathways that show the impacts of constant production (pathway 0), the replacement of blast furnaces by scrap/EAF and DRI/EAF (pathway 1), decreasing production (pathway 2) and increasing production including smelt reduction (pathway 3).

The model assumes that secondary steel is produced depending on scrap availability. Hence, future scrap availability is estimated. All production pathways assume that scrap availability is assured.

Furthermore, the analysis includes the age and expected technical lifetime of blast furnaces, which are the major energy consumers and the most capital-intensive plants in the steel industry. It is assumed that, under current conditions, blast furnaces will operate at least until the end of their technical lifetime.

3.1. Key mathematical equations

The specific energy consumption from BF/BOF and scrap/EAF steelmaking is affected by the diffusion of energy-efficient technologies (Eq. (1)).

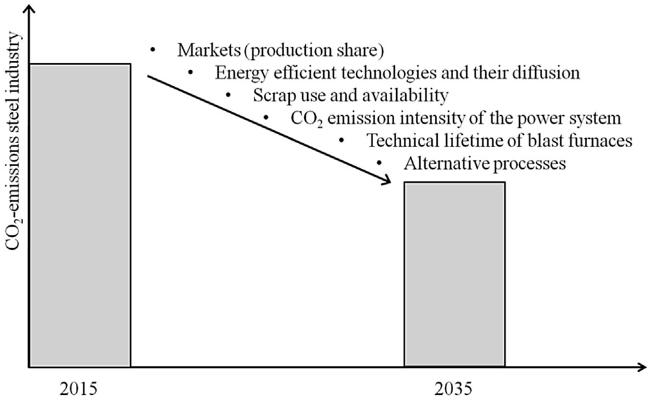


Fig. 2. Parameters for estimating current and future CO_2 emissions in the German steel industry.

$$\mathrm{SEC}_{i+1,j,k}\left[\frac{\mathrm{GJ}}{\mathrm{t}}\right] = \mathrm{SEC}_{i,j,k}\left[\frac{\mathrm{GJ}}{\mathrm{t}}\right] - \sum_{l}\left(\mathrm{ESP}_{k,l}\left[\frac{\mathrm{GJ}}{\mathrm{t}}\right] \bullet (\mathrm{DR}_{i+1,l} - \mathrm{DR}_{i,l})\right) \quad (1)$$

where SEC – specific energy consumption; ESP – energy saving potential; DR – diffusion rate; **i** – year; **j** – process; **k** – energy carrier; **l** – energy-efficient technology.

CO_2 emission factors are used to convert energy consumption into CO_2 emissions. Total energy consumption and CO_2 emissions are calculated using production pathways (Eqs. (2) and (3)).

$$\mathrm{EC}_{\mathrm{Germany},i}[\mathrm{GJ}] = \sum_{j}\sum_{k}\mathrm{SEC}_{i,j,k}\left[\frac{\mathrm{GJ}}{\mathrm{t}}\right] \bullet \mathrm{P}_{i,j}[\mathrm{t}] \quad (2)$$

$$\mathrm{TCE}_{\mathrm{Germany},i}[\mathrm{t\ CO_2}] = \sum_{j}\sum_{k}\mathrm{SEC}_{i,j,k}\left[\frac{\mathrm{GJ}}{\mathrm{t}}\right] \bullet \mathrm{P}_{i,j}[\mathrm{t}] \bullet \mathrm{CEF}_{i,k}\left[\frac{\mathrm{t\ CO_2}}{\mathrm{GJ}}\right] \quad (3)$$

where $\mathrm{EC}_{\mathrm{Germany},i}$ – total energy consumption of the German steel industry in the year *i*; P – production; $\mathrm{TCE}_{\mathrm{Germany},i}$ – total CO_2 emissions of the German steel industry in the year *i*; CEF – CO_2 emission factor.

3.2. Model input parameters

The model estimates the future energy consumption and CO_2 emissions of the German steel industry until 2035. It is based on three main input parameters, i.e. the specific energy consumption and CO_2 emissions per steelmaking process, the diffusion of energy-efficient technologies, and the definition of future production pathways.

3.2.1. Specific energy consumption and CO_2 emissions of the steelmaking processes considered

For BF/BOF and scrap/EAF steelmaking, data are analyzed based on the energy consumption data of the German steel industry in 2011 (Wirtschaftsvereinigung Stahl, 2011). These data have the same structure and boundaries as the data used in Arens et al. (2012). However, this analysis focuses on the development of the total energy consumption of the German steel industry, while the former study estimated energy efficiency improvements on the process level. Energy consumption is given by energy carrier and plant type at a national level in physical units; internal energy flows are excluded from the analysis (Fig. 3). Energy consumption in energy units is calculated by applying heating values and the energy required to supply the energy carriers (Table 2).

Reported energy consumption is allocated to BF/BOF steelmaking or scrap/EAF steelmaking using both plant type and type of energy carrier. The energy consumption of sinter plants, blast furnaces, basic oxygen furnaces, onsite power plants, steam generation and other plants is allocated entirely to BF/BOF steelmaking. Electric arc furnaces are only allocated to scrap/EAF steelmaking. Rolling is assigned to either BF/BOF or scrap/EAF steelmaking by the share of flat and long products. For rolling, the consumption of top gases and electricity generated onsite is reported. The consumption of top gases and electricity generated onsite is likely to take place in BF/BOF steelmaking and not in scrap/EAF steelmaking. Thus, the consumption of top gases and electricity generated onsite is completely attributed to BF/BOF steelmaking.

The processes of BF/BOF steelmaking are highly integrated. For instance, blast furnace gas is used to produce steam, which is then converted into electricity in onsite power plants, which is used for rolling (Fig. 3). This makes it difficult, perhaps impossible, to derive the net specific energy consumption for each process which can be multiplied by the production volume to yield the overall energy input to the steel industry. In this study, we found that the energy carriers generated onsite and leaving the steel industry were roughly the same as the coke oven gas entering the boundary as defined in Fig. 3. In Germany, BF/BOF steelmaking purchases coke oven gas from coke ovens that produce coke for the steel industry. Therefore, the specific energy consumption of BF/BOF steelmaking was estimated considering energy carriers entering the steel industry, neglecting coke oven gas consumption and credits for energy carriers generated onsite and leaving the steel industry.

Specific energy consumption is converted into CO_2 emissions by applying CO_2 emission factors (Table 2). Table 3 shows the specific energy consumption as well as CO_2 emission intensity for both BF/BOF and scrap/EAF steelmaking.

Values for DRI/EAF were derived following Worrell et al. (2008). When EAFs are fed with DRI, electricity consumption will increase by 40–120 kWh/t liquid steel depending on the amount and degree of metallization of the DRI. This study considers DRI/EAF steelmaking with 100% DRI input, so the total energy consumption in our analysis is higher than in Worrell et al. (2008) (Table 3).

The energy consumption of the smelt reduction technology *HIsarna* is assumed to be 80% of current BF/BOF steelmaking (Tata Steel Europe, 2013). HIsarna is designed to replace coke by coal. Applying 80% energy consumption of BF/BOF steelmaking to HIsarna, the CO_2 intensity of HIsarna is about 74% of the BF/BOF route, since coke is replaced by coal (Table 3).

3.2.2. Diffusion of energy-efficient technologies

The diffusion of energy-efficient technologies (EET) is based on Arens and Worrell (2014). The EETs will be described in more detail in section 4.4. According to Arens and Worrell (2014) of all the technologies studied, the BOF was the one that most quickly reached the point of complete diffusion in Germany, 27 years after its introduction. More recent technologies may have diffused faster than the BOF to start with, but did not reach the point of complete diffusion as quickly. However, to acknowledge that technologies can diffuse faster than the BOF, this analysis modifies the diffusion curve of the BOF in such a way that a) complete diffusion is reached within 20 years, and that b) 5%-diffusion is reached after 3 years instead of after 5 years (Fig. 4).

Currently applied technologies with additional diffusion potential are assumed to spread from their current level according to this diffusion rate.

3.2.3. Production pathway definition

Four production pathways are developed for the German steel industry to show the impact of varying production levels and processes on CO_2 emissions and energy consumption (Table 4). The resulting production pathways are discussed in section 5.1.

Besides two pathways showing the impact of constant steel production levels, two other pathways are constructed, one assuming an increase and the other a decrease in production levels. Since crude steel production in Germany has varied over the last 40 years between 30 and 50 Mt (Fig. 1), these values are chosen for the pathways assuming an increasing or decreasing production level. The highest crude steel production by far occurred in 1974 (53.2 Mt), while the lowest level was reached during the economic crisis in 2009 (32.7 Mt) (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

Primary steelmaking first produces hot metal from iron ore in the blast furnace which is then fed to the BOF where it is converted

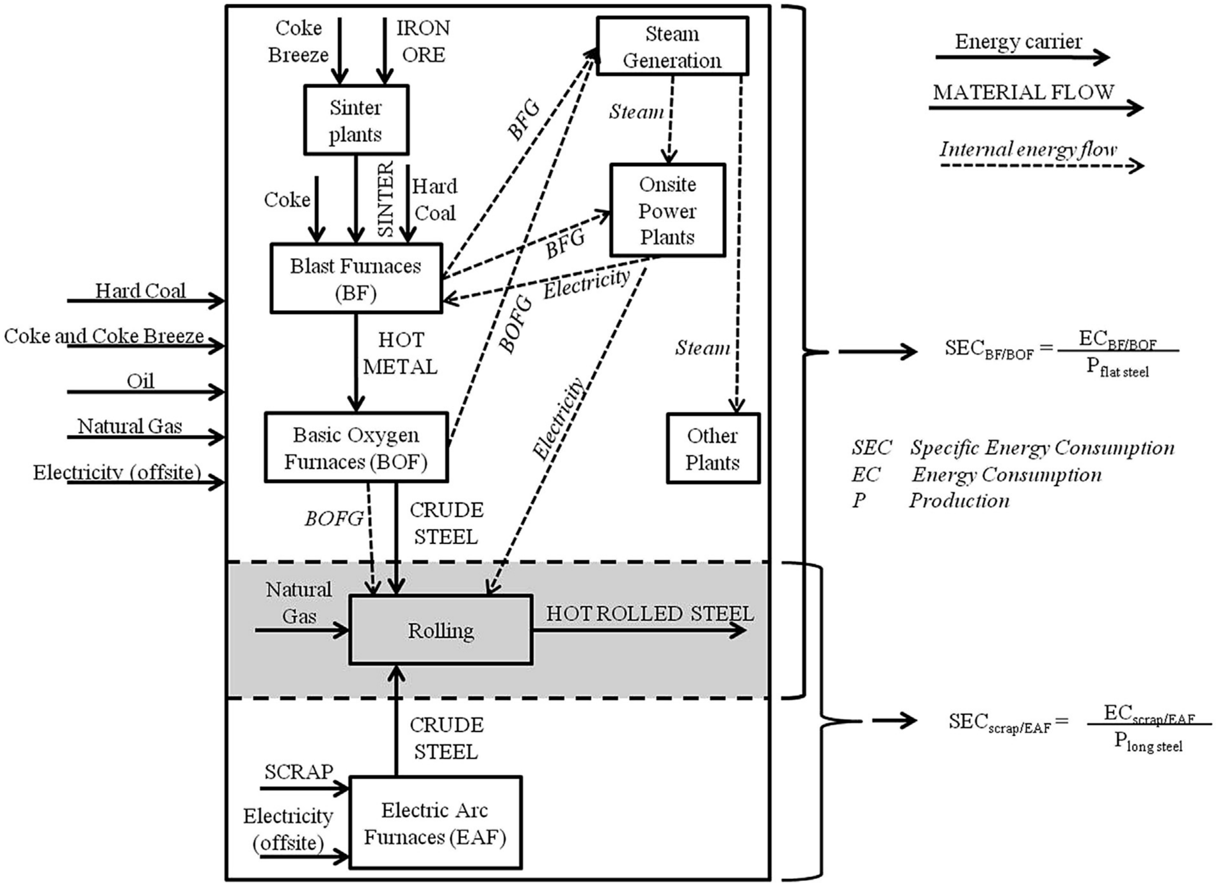


Fig. 3. Boundary settings to estimate the specific energy consumption for BF/BOF and scrap/EAF steelmaking in Germany (BFG: Blast Furnace Gas; BOFG: BOF-gas).

Table 2
Assumed lower heating values, energy required to derive the energy carriers and CO_2 emission factors per energy carrier 2015–2035 (electricity only 2011) (sources: Umweltbundesamt and Deutsche Emissionshandelsstelle, 2012; Umweltbundesamt, 2014a; Statistisches Bundesamt, 2009; Steelinstitute VDEh, 2010); own calculations).

Energy carrier	Unit	Value	Unit	Value
Hard coal	GJ/t	29.31	kg CO_2/GJ	95
Coke	GJ/t	28.43	kg CO_2/GJ	107
Oil	GJ/t	40.61	kg CO_2/GJ	77
Natural gas	GJ/1000 m^3	35.17	kg CO_2/GJ	56
Oxygen	GJ/1000 m^3	7.33	kg CO_2/GJ	115
Electricity (offsite)[a]	GJ/1000 kWh	10.34	kg CO_2/kWh	0.570

[a] 2011.

to steel. The production of iron from iron ore in the blast furnace is the most energy intensive step in the steel industry.

This study assumes that the German steel industry currently supplies high quality steel markets and that therefore the German steel industry has a high share of BF/BOF steelmaking. However, this study aims at identifying production pathways that are likely to meet future climate targets, presumably ones with decreasing production levels. Such pathways are probably not able to continue supplying the current markets.

- *Pathway 0 – constant production and current technologies*: Pathway 0 assumes that the total current production level remains constant throughout the studied period at 45 Mt/year. Blast furnace capacity has a utilization rate of 95%. The ratio of BF/BOF steel and hot metal is assumed to be 1.07 (this value is the average ratio of BF/BOF steel divided by hot metal production for 2009–2011 (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014)). Any end-of-life blast furnace capacity is replaced by new blast furnace capacity. It is assumed that current BFs are as efficient as new BFs would be. The share of primary and secondary steelmaking remains constant over the studied period. The single German DRI plant stops operating

Table 3
Assumed specific primary energy consumption per metric ton of final product for each process (source: Wirtschaftsvereinigung Stahl, 2011; Worrell et al., 2008; Tata Steel Europe, 2013; own calculations).

Specific energy consumption, CO_2 emissions (2011)	Hard coal	Coke	Oil	Natural gas	Oxygen	Electricity (offsite)	CO_2 emissions
	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	kWh/t	kg CO_2/t
BF/BOF	4.03	10.79	0.44	1.71	0.71	115	1815.8
Scrap/EAF	0.12	0.00	0.00	1.19	0.27	739	530.6
DRI/EAF	0.10	0.00	0.00	17.40	0.30	819	1487.0
Smelt reduction (HIsarna)	11.86	0.00	0.36	1.37	0.57	92	1349.0

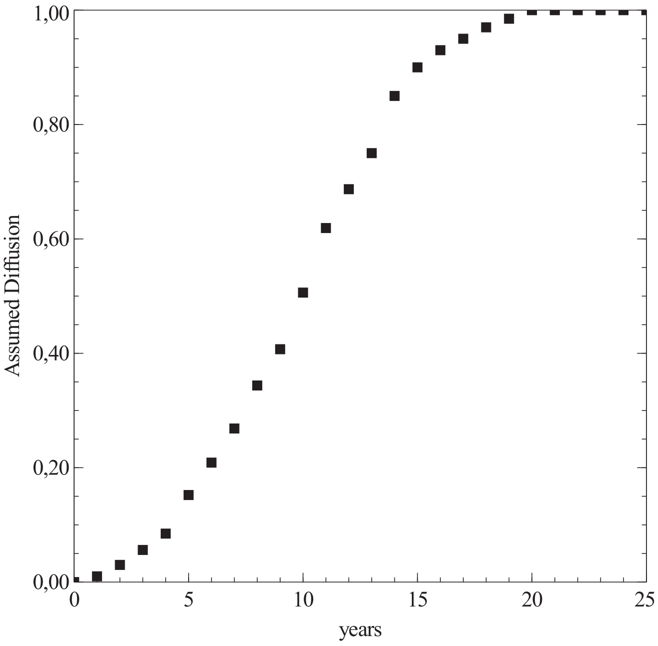


Fig. 4. Assumed diffusion rate for energy-efficient technologies.

after 50 years in 2021. Its capacity is replaced by scrap/EAF steelmaking. Energy-efficient technologies diffuse still further and the CO_2 emissions of the power sector decrease in line with current policy.

This pathway aims to show the impact of the further diffusion of EET and increased renewable electricity generation on energy consumption and CO_2 emissions in the German steel industry.

- *Pathway 1 — constant production and DRI/EAF steelmaking*: Pathway 1 also assumes a constant total production of 45 Mt/year. Again, blast furnace capacity has a utilization rate of 95% and the ratio of BF/BOF steel and hot metal is assumed to be 1.07. Any end-of-life blast furnace capacity is mainly replaced by scrap/EAF capacity. Scrap availability is assured. The remaining capacity is replaced by DRI/EAF steelmaking with 100% DRI input.

This pathway aims to show the CO_2 emission reduction potential for constant total production, maximum possible scrap/EAF share, not replacing old blast furnaces with new ones and the introduction of DRI steelmaking even though DRI is not economically viable at current energy prices.

- *Pathway 2 — decreasing production*: Pathway 2 assumes decreasing total production. From 2015 to 2035, total production declines from 45 Mt/year to 30 Mt/year. In contrast to pathways 0 and 1, blast furnace capacity utilization is assumed to be 92% instead of 95% throughout the studied period. The DRI plant stops operating in 2021 as well. Any closed down BF capacity is replaced by scrap/EAF capacity and scrap availability is guaranteed. Since this pathway assumes a shrinking German steel industry, no innovative technologies are introduced.

This pathway illustrates the impact on CO_2 emissions and energy consumption of a strong reduction in total steel production, while increasing the share of scrap/EAF steelmaking.

- *Pathway 3 — increasing production*: Pathway 3 assumes a growing German steel industry. Total steel production increases from 45 Mt in 2015 to 50 Mt in 2035. As in pathways 0 and 1, blast furnace capacity utilization is assumed to be 95%. Any closed down BF capacity as well as production increase is provided by scrap/EAF steelmaking as long as scrap is available. Otherwise, phased out BF capacity is replaced with new BF capacity. From 2030 onwards, a new iron-making technology is implemented.

This pathway shows the impact of a growing German steel industry that uses a new iron-making technology from 2030 on CO_2 emissions and energy consumption.

Table 4
Overview of parameters of future production pathways 0–3.

	Pathway 0	Pathway 1	Pathway 2	Pathway 3
Short description	Constant production and current technologies	Constant production and DRI/EAF steelmaking	Decreasing production	Increasing production
Total production development	Constant	Constant	Decreasing	Increasing
Total production in 2035	45 Mt	45 Mt	30 Mt	50 Mt
Major steelmaking routes	BF/BOF; scrap/EAF	BF/BOF; scrap/EAF; DRI/EAF	BF/BOF; scrap/EAF	BF/BOF; scrap EAF; new iron-making technology (*HIsarna*)
BF capacity utilization rate	95%	95%	92%	95%
Ratio BF/BOF steel and hot metal	1.07	1.07	1.07	1.07
Shutdown BF capacity is replaced by …	new BF capacity	scrap/EAF capacity	scrap/EAF capacity	2015–2030: scrap/EAF capacity; new BF capacity 2030–2035: new iron-making technology (*HIsarna*)
Current German DRI plant stops operating in …	2021	–	2021	2021
Scrap availability	Scrap availability is assured because the pathways are constructed to use only the amount of scrap actually available.			
Aims to show the impact of	further diffusion of EET and increased renewable electricity generation	constant total production, maximum possible EAF share and end-of-life blast furnaces replaced partly by DRI/EAF	a strong reduction in total steel production with increased share of scrap/EAF	a growing German steel industry that implements a new iron-making technology from 2030 onwards

4. Structural parameters that determine energy intensity and CO_2 emissions in the German steel industry

The energy consumption and CO_2 emissions of the German steel industry are influenced by several structural factors. This study considers scrap availability, the CO_2 emission intensity of the power mix, the technical lifetime of blast furnaces, energy-efficient technologies, and a new iron-making process.

4.1. Current and future scrap availability

This study considers overall scrap availability (i.e. the sum of obsolete, prompt and home scrap (Boston Consulting Group, 2013)). Scrap consumption in the German steel industry is published in Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2014). While scrap availability is given for the different scrap types, scrap consumption is given as one value only. In 2012, the German steel industry used 19.7 Mt scrap in both primary and secondary steelmaking. However, in the same year, the net export of scrap by Germany was 4.0 Mt. Germany has been a net exporter of scrap since at least 2002. This study assumes that scrap availability in 2012 is given by the following equation (Eq. (4)):

$$\begin{aligned} \text{Scrap availability}_{2012} = {} & \text{scrap consumption}_{2012} \\ & + \text{net scrap export}_{2012}; \\ & \text{net scrap export}_{2012} > 0 \end{aligned} \tag{4}$$

Determining future scrap availability depends on the product lifetime and the recycling rate. For instance, Oda et al. (2013) estimated future scrap availability by analyzing product shares, product lifetimes and the recycling rate. They find that scrap availability will rise by approximately 1.8% per year from 2011 to 2050 at the global level and that primary steelmaking will remain the dominant global route at least until 2050 due to the lack of scrap.

In contrast, Pauliuk et al. (2013) conclude that scrap/EAF production can more than double globally until 2050.

A study on behalf of the Steel Institute VDEh assumes an increase in overall scrap availability in the EU-27 of 0.9% per year for the same period (Boston Consulting Group, 2013).

This analysis assumes that German scrap availability increases at the same rate as found in Boston Consulting Group (2013), i.e. by 0.9% per year from 2012 (Table 5). The impact of much bigger scrap availability (e.g. Pauliuk et al., 2013) is tested in a sensitivity analysis (Chapter 6.4). All production pathways assume constant scrap consumption for primary and secondary steelmaking (Table 6). Furthermore, the model is constructed to not exceed the amount of scrap actually available in any year for each production pathway.

4.2. CO_2 emission intensity of the power system

Since the current German energy policy aims to increase the share of renewable energies, the CO_2 emission grid factor is likely to decrease. The future CO_2 emission grid factor is derived for 2011–2035 based on Öko-Institut and Fraunhofer ISI (2015) and the scenario that includes all policies enforced by October 2012 (*Aktuelle-Maßnahmen-Szenario, AMS*, Table 7).

Table 5
Assumed scrap availability in Germany for selected years (assumed scrap availability growth rate of 0.9%/year (Boston Consulting Group, 2013)).

[Mt/year]	2012	2015[a]	2020[a]	2025[a]	2030[a]	2035[a]
Assumed scrap availability	23.7	24.3	25.5	26.6	27.8	29.1

[a] Estimated.

Table 6
Assumed specific scrap consumption in primary and secondary steelmaking (source: Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

	Scrap consumption
	t scrap/t steel
BF/BOF steelmaking	0.2
Scrap/EAF steelmaking	1.0

BF/BOF steelmaking usually has a high share of electricity generated onsite and only purchases a minor share from the public grid. According to the analyzed data and based on the assumptions made, this study postulates that 23% of the total electricity consumption in BF/BOF steelmaking is purchased from the public grid, while the rest is produced in onsite power plants. The secondary steelmaking route usually purchases all its electricity from the public grid.

4.3. Technical lifetime of blast furnaces

The analysis includes the age and nominal capacity of each blast furnace in Germany except for two small blast furnaces that do not produce iron (Steelinstitute VDEh, 2013). The database encompasses 16 blast furnaces. A database of Steelinstitute VDEh (2015) on plants closed down in Europe since 2000 indicates that the lifetime of blast furnaces usually varies between 40 and about 50 years. There are likely to be major blast furnace capacity shutdowns after 2023 (Fig. 5).

The production pathways therefore assume the blast furnaces in Germany to have a technical lifetime of 50 years. Three large blast furnaces were opened in 1973 (i.e. Schwelgern 1, Bremen 2, HKM A). To harmonize the development of blast furnace capacity, the expected lifetimes of Bremen 2 and HKM A are modified slightly (Bremen 2: 52 years, HKM A: 48 years).

4.4. Energy-efficient technologies

There are various energy-efficient technologies (EET) that reduce both the energy intensity and the CO_2 emissions in BF/BOF and scrap/EAF steelmaking. Several studies have researched promising EET and their energy reduction potentials (e.g. Moya and Pardo, 2013; Brunke and Blesl, 2014; Worrell et al., 2008).

This analysis covers 15 energy-efficient technologies (Table 8).

4.5. Future iron and steelmaking processes

The European research project ULCOS focuses on steelmaking processes able to apply carbon capture. Three of the four researched technologies aim to collect CO_2 from the off-gas (top gas recycling blast furnace, HIsarna, ULCORED). A fourth technology, which is still at a very early stage of development, intends to use electricity as a reducing agent instead of carbon-intensive fossil fuels (i.e. electrolysis). The development of the top gas recycling blast furnace is currently on hold since the planned demonstration plant has not yet been built, nor have any plans to do so been announced. HIsarna is currently being tested on a pilot scale. ULCORED and electrolysis are expected to enter the market in 2030 and 2040, respectively (Fischedick et al., 2014). This study includes the innovative smelt reduction technology HIsarna in the model.

This paper aims to shed light on future technological developments in the medium term. However, the implementation of carbon capture and storage on a broad scale is unlikely before 2030. The International Energy Agency (2013) believes CCS will have been

Table 7
Assumed CO_2 emission grid factor for the German electricity grid (Umweltbundesamt, 2014a; Öko-Institut and Fraunhofer ISI, 2015).

		2011	2020[a]	2030[a]	2040[a]
Gross electricity generation	TWh	–	634.0	633.0	631.0
CO_2 emissions by power plants	Mt	–	312.6	263.7	201.4
Grid emission factor	kg CO_2/kWh	0.570	0.493	0.417	0.319

[a] Estimated.

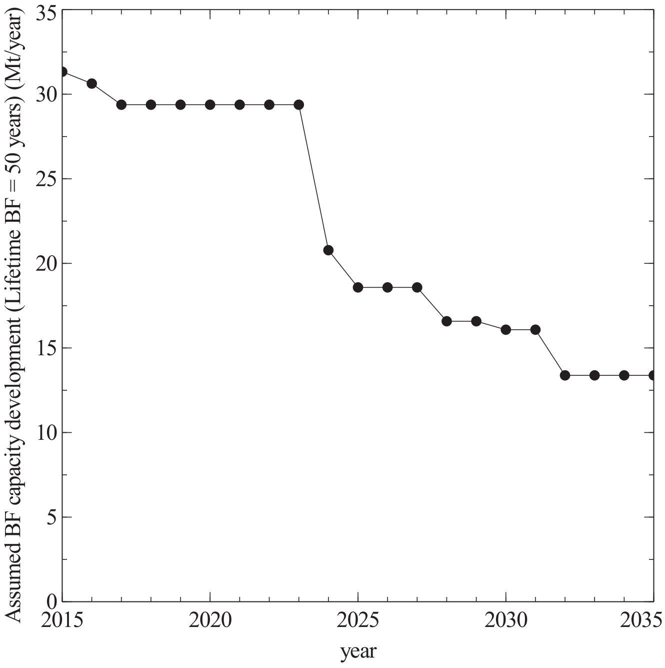


Fig. 5. Development of blast furnace capacity considering a technical lifetime of 50 years (source: Steelinstitute VDEh, 2013; own calculations).

demonstrated successfully in iron and steelmaking by 2030. From 2050 onwards, it expects CCS to be routinely used in applicable processes including industry. However, carbon capture is excluded from this analysis because we only consider the period up to 2035.

5. Results

Results are presented for the different future production pathways, the energy consumption per energy carrier and the CO_2 emissions by process.

5.1. Resulting production pathways

Pathway 0 reflects a constant production level and production shares. Any end-of-life blast furnace capacity is replaced by new blast furnaces (Fig. 6a).

Pathway 1 shows the results for a constant production level but a shift to scrap/EAF and DRI/EAF steelmaking (Fig. 6b). Scrap/EAF steelmaking increases by 2.5%/year from 2016 onwards, while the current BF/BOF capacity is gradually phased out. The residual steelmaking capacity is replaced by DRI/EAF steelmaking.

Pathway 2 shows the impact of decreasing production (Fig. 6c). BF/BOF capacity gradually ohases out, while the remaining steel production capacity is provided by scrap/EAF steelmaking.

Pathway 3 represents increasing production (Fig. 6d). It is assumed that an innovative smelt reduction technology (HIsarna) enters the market in 2030. Limited scrap availability encourages replacing end-of-life blast furnace capacity with new blast furnace capacity from 2024 onwards, which reaches a capacity of 11 Mt in 2032. The construction of new blast furnaces impedes a strong uptake of the smelt reduction technology from 2030 onwards.

5.2. Energy consumption

The specific primary energy consumption of flat products via the primary steelmaking route is about four times higher than the specific energy consumption of flat products in secondary steelmaking. The results indicate there is a limited energy-saving potential in current processes of primary steelmaking (9% lower in

Table 8
Characteristics of the selected energy-efficient technologies (sources: Moya and Pardo, 2013; Brunke and Blesl, 2014; Worrell et al., 2008; Okazaki and Yamaguchi, 2011).

Process	Name	Maximum reduction potential						Diffusion		Max. diff.
		Hard coal	Coke	Oil	Natural gas	Oxygen	Electricity (offsite)	2011	2014	–
		GJ/tcs	GJ/tcs	GJ/tcs	GJ/tcs	GJ/tcs	kWh/tcs			
BF/BOF	Top-pressure recovery turbine	0.00	0.00	0.00	0.00	0.00	−20.44	0.58	0.76	1.00
BF/BOF	Pulverized coal injection	0.00	0.00	−0.79	0.00	0.00	0.00	0.69	1.00	1.00
BF/BOF	BOF gas recovery	0.00	0.00	0.00	−0.91	0.00	0.00	0.61	0.61	1.00
BF/BOF	Coke dry quenching	0.00	0.00	0.00	0.00	0.00	−50.17	0.00	0.00	1.00
BF/BOF	Heat recovery at sinter plant	0.00	−0.18	0.00	0.00	0.00	2.51	0.10	0.10	1.00
BF/BOF	Strip casting	0.00	0.00	0.00	−0.88	0.00	0.00	0.05	0.05	0.50
BF/BOF	Regenerative burners	0.00	0.00	0.00	−0.34	0.00	0.00	0.30	0.32	0.50
BF/BOF	Advanced controls	0.00	−0.11	0.00	−0.02	−0.01	3.00	0.00	0.15	1.00
BF/BOF	Efficient power use (e.g. motors, oxygen production)	0.00	0.00	0.00	0.00	0.00	−1.15	0.00	0.15	1.00
scrap/EAF	Regenerative burners	0.00	0.00	0.00	−0.34	0.00	0.00	0.20	0.22	0.50
scrap/EAF	Heat recovery at EAF	0.00	0.00	0.00	0.00	0.00	−57.50	0.00	0.05	1.00
scrap/EAF	Strip casting	0.00	0.00	0.00	−0.88	0.00	0.00	0.05	0.05	0.50
scrap/EAF	Advanced controls	−0.01	0.00	0.00	−0.10	−0.03	−14.78	0.00	0.15	1.00
scrap/EAF	Efficient power use (e.g. motors, oxygen production)	0.00	0.00	0.00	0.00	0.00	−1.15	0.00	0.15	1.00
scrap/EAF	Fuel injection	0.70	0.00	0.00	0.00	0.00	−194.44	0.00	0.15	1.00

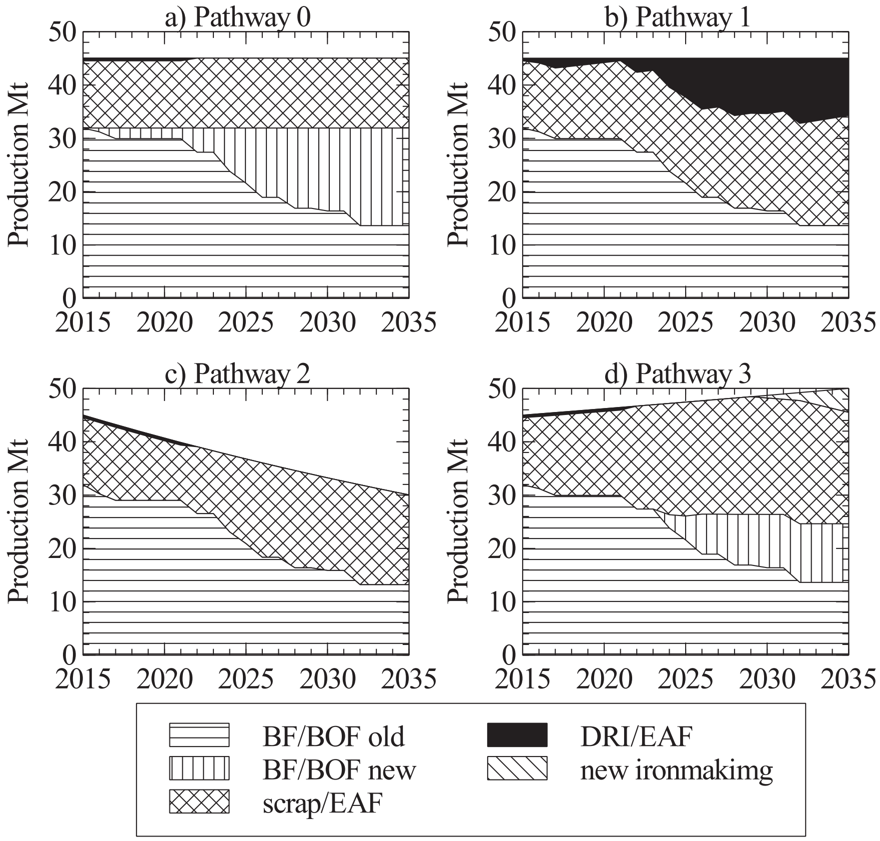


Fig. 6. Resulting production pathways for the German steel industry by process from 2015 to 2035 for a) and b) constant, c) decreasing, and d) increasing crude steel production considering a technical lifetime of blast furnaces (50 years) and guaranteed scrap availability.

2035 than in 2011, Fig. 7a), while energy savings in secondary steelmaking could be more significant (21% lower in 2035 than in 2011, Fig. 7b). In primary steelmaking, especially the lack of options to reduce energy consumption in the blast furnace (coke consumption) impedes major efficiency gains.

In secondary steelmaking, major savings of electricity (0.96 GJ/t lower in 2035 than in 2011) and natural gas (0.59 GJ/t lower in 2035 than in 2011) could be realized, while fuel injection causes an increase in coal consumption (+0.60 GJ/t higher in 2035 than in 2011). Natural gas savings are mainly due to the diffusion of regenerative burners and the expected introduction of strip casting. Electricity savings mainly originate from fuel injection and heat recovery from EAF off-gas.

The energy consumption level in 2035 is similar in pathways 0, 1 and 3but only slightly lower than today's level, although the production level of pathway 3 is higher than pathways 0 and 1. This means that the energy efficiency gains in pathway 3 compensate the production increase (pathway 0: 572 PJ; pathway 1: 517 PJ;

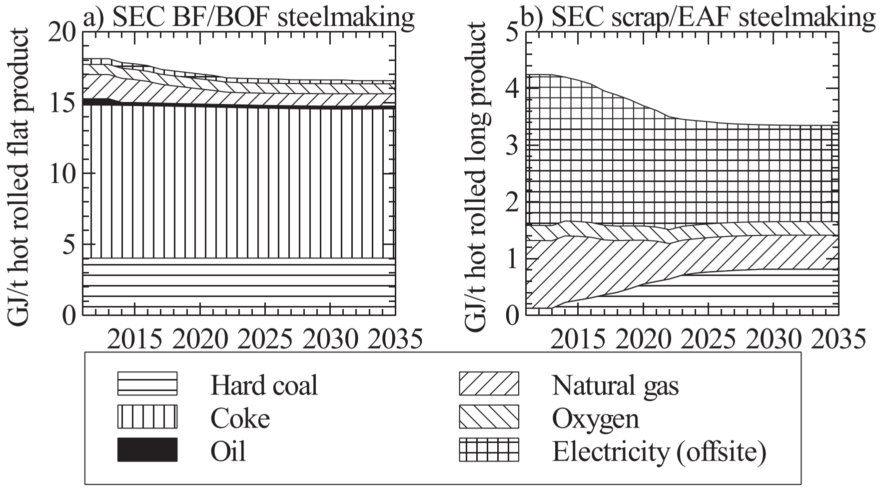


Fig. 7. Development of the specific energy consumption of a) BF/BOF and b) scrap/EAF steelmaking in Germany between 2015 and 2035 considering the diffusion of energy-efficient technologies.

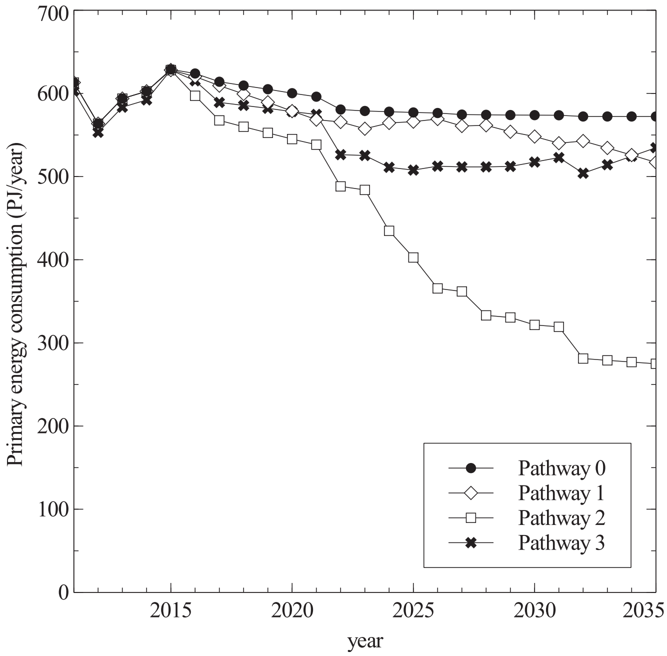


Fig. 8. Development of total primary energy consumption per production pathway in Germany 2015–2035.

pathway 3: 535 PJ) (Fig. 8). Significant reductions in energy consumption can only be realized in pathway 2 (decreasing production, high share of scrap/EAF steelmaking), where energy consumption is more than halved in 2035 compared to today. This stresses the importance of scrap/EAF steelmaking in a low carbon society.

The different steelmaking processes impact energy consumption on the energy carrier level (Fig. 9a–d). Introducing DRI (pathway 1, Fig. 9b) increases the consumption of natural gas by 290% between 2015 and 2035 (2011: 76 PJ; 2035: 211 PJ). At present, this does not seem very likely although new developments like liquefied natural gas (LNG) are underway. Pathway 3 (Fig. 9d increased production, new iron-making technology) implies a shift from coke to coal from 2030 onwards due to the replacement of blast furnaces with smelt reduction technology.

5.3. *Future developments in CO_2 emissions*

Major CO_2 reductions are achieved in the pathway with the lowest assumed production level that additionally has a high share of secondary steelmaking (Fig. 10, 56% in 2035, pathway 2).

At a constant production share and level (2014), the CO_2 reduction potential is limited in 2035 (pathway 0, i.e. 6% between 2014 and 2035). The limited impact of renewables stems from the fact that electricity is not widely used in this pathway as there is no increase in the production of EAFs. In pathway 2, the impact of renewables in the power sector on the steel industry's CO_2 emissions is higher due to the higher share of scrap/EAF steelmaking.

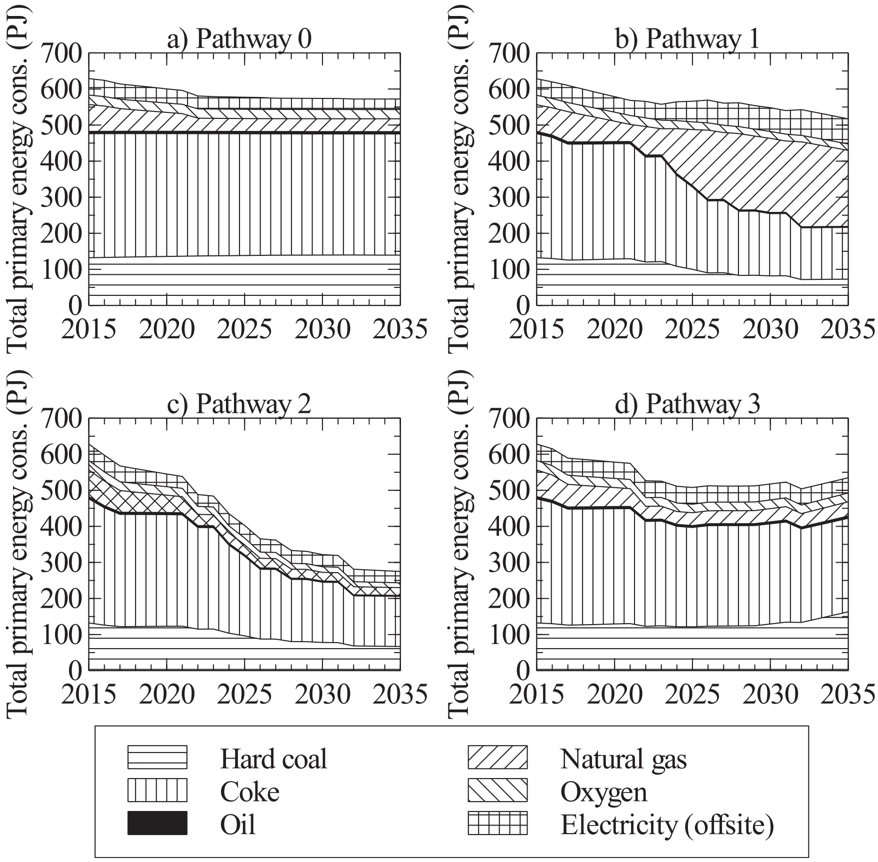


Fig. 9. Development of total primary energy consumption in the German steel industry 2015–2035 by energy carrier and pathway; a) and b) constant, c) decreasing, and d) increasing crude steel production.

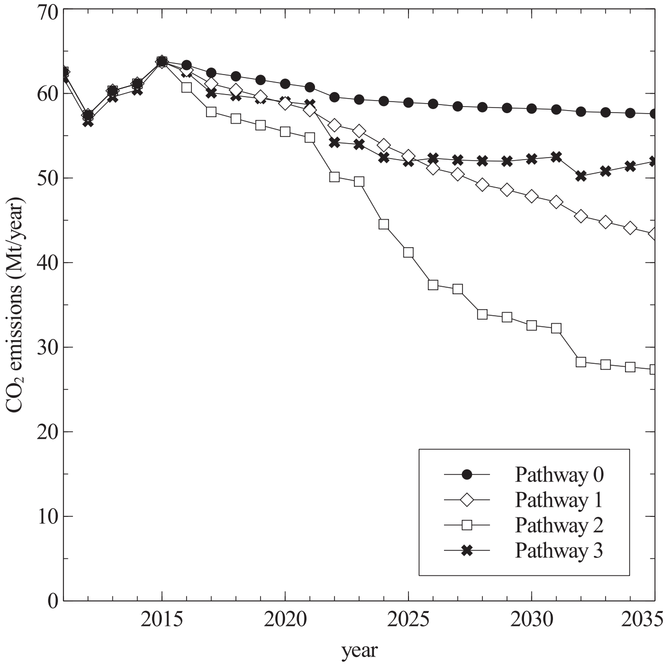


Fig. 10. Development of total CO_2 emissions in the German steel industry 2015–2035 by pathway.

At constant production levels, CO_2 emission reductions can be realized when alternative steelmaking processes (here DRI/EAF) are considered (Pathway 1, 43.2 Mt CO_2 in 2035). CO_2 emissions could be reduced even in case of increasing production if there were a shift towards more scrap/EAF steelmaking and if an alternative steelmaking route (here HIsarna) were applied (Pathway 3, 52.0 Mt CO_2 in 2035). However, the impact of the new smelt reduction technology will still be limited in 2035 because it was only introduced in 2030. Moreover, the likely shutdown of blast furnaces from 2023 onwards might lead to the erection of new blast furnaces and thus impede a strong uptake of HIsarna from 2030 onwards.

In every pathway, BF/BOF steelmaking accounts for the lion's share of total CO_2 emissions in the German steel industry throughout the studied period. Therefore, major CO_2 emission reductions are either due to increased scrap/EAF steelmaking or the replacement of blast furnaces by alternative processes. Pathway 0 shows the window of opportunity to replace current BFs (Fig. 11a). According to this analysis, a large share of BF capacity is expected to finish operating after 2023. By this point at the latest, there should be economically viable solutions available to reduce the CO_2 emissions from BF/BOF steelmaking.

Pathway 1 shows the impact of DRI/EAF steelmaking on the development of total CO_2 emissions. Although total steel production remains constant, CO_2 emissions can be reduced by 29% (Fig. 11b). Moreover, total steel production can even be increased with decreasing CO_2 emissions (pathway 3, 14% lower in 2035 than in 2014, Fig. 11d).

The lowest CO_2 emissions are achieved if total production decreases and has a high share of EAF, which enhances the impact of renewables in the power sector (pathway 2, 55% lower in 2035 than in 2014, Fig. 11c). However, this depends on the capacity of German scrap/EAF steelmakers to produce the same high quality steel as BF/BOF steelmakers currently do in order to supply the German steel industry's current customers' demand for high quality steel.

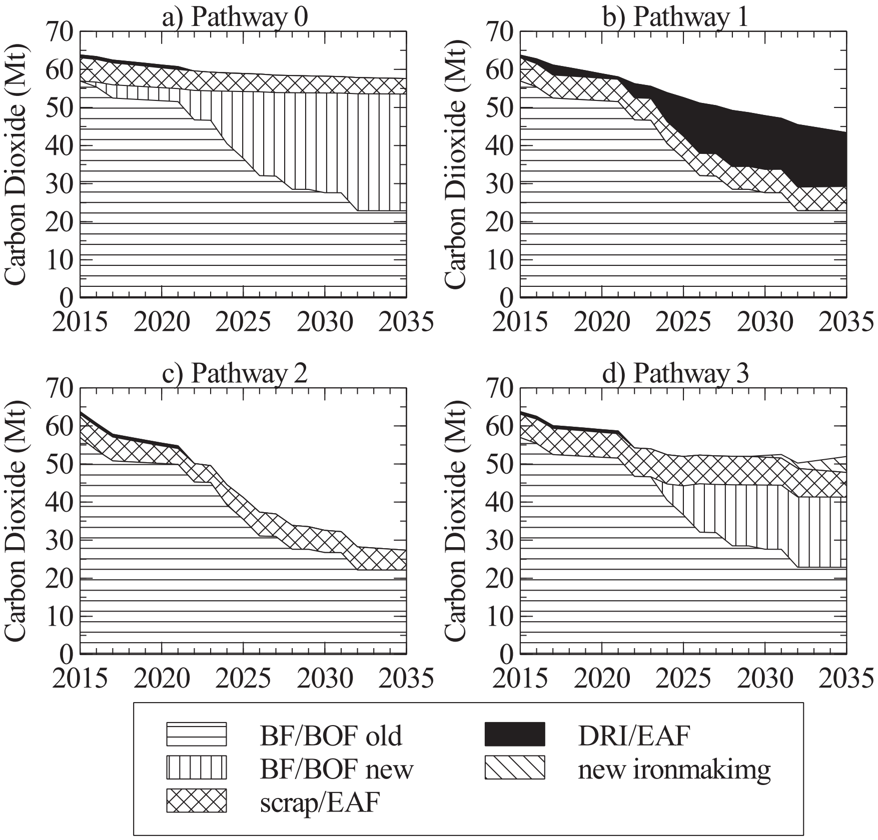


Fig. 11. Development of CO_2 emissions in the German steel industry 2015–2035 by process and pathway; a) + b) constant, c) decreasing, and d) increasing crude steel production.

According to these results, only one pathway meets the European CO_2 emission reduction target (European Council, 2014), i.e. pathway 2 with decreasing production, a high share of scrap/EAF steelmaking and no BF capacity replacement (Table 9). German energy policy's targets are not reached by any pathway (Bundesregierung, 2010). If the German steel industry continues to operate as it does today (pathway 0), CO_2 emissions will surpass the targets by a factor of 1.7 or 2.1 (European and German target, respectively).

According to the model, the specific CO_2 emissions of both the currently dominant steelmaking routes (i.e. BF/BOF and scrap/EAF) can be reduced due to the diffusion of energy-efficient technologies and the increase of renewables in electricity generation. More renewable generation in the power sector has a limited impact on primary steelmaking, but is a major driver of CO_2 reductions in secondary steelmaking.

The results indicate that CO_2 emission reductions in primary steelmaking are limited to about 6% until 2035 compared to 2015 (Fig. 12a).

In contrast to the limited CO_2 reduction potential of primary steelmaking, the specific CO_2 reduction potential of secondary steelmaking is significant (36%; 2035–2015, Fig. 12b). Applying the 2035 grid CO_2 emission factor to the CO_2 emission intensity calculation of 2015 shows the CO_2 emissions of scrap/EAF steelmaking would drop to 115 kg CO_2/t steel. The impact of energy-efficient technologies is in the range of 61 kg CO_2/t steel. Thus the impact of a higher share of renewables in the German electricity mix is about twice as strong as the further diffusion of energy-efficient technologies.

The replacement of electricity by coal in EAFs (*fuel injection*) should only be considered if the CO_2 emissions from electricity production are higher than the CO_2 emissions from coal. Increasing the share of renewables in the power sector will decrease the CO_2 emission factor of electricity generation. The turning point for fuel injection is achieved at a CO_2 grid emission factor of about 342 kg CO_2/kWh$_{el}$ which should occur in about 2036 according to the assumed development of the CO_2 emission grid factor. Hence, throughout the period of our analysis, fuel injection is favorable in terms of CO_2 emissions. From about 2036 onwards, fuel injection will increase the CO_2 emissions in EAF steelmaking.

6. Uncertainty and sensitivity analysis

The estimated CO_2 emissions were checked by comparing them to Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2014). The results of this study are highly dependent on the considered factors. Therefore, sensitivity analyses are conducted for the CO_2 emission intensity of the power system, the lifetime of blast furnaces and scrap availability.

6.1. Estimation of CO_2 emissions

Data on the specific CO_2 emissions per metric ton crude steel for the German steel industry in 2011–2013 are provided by the Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2014). Our analysis slightly overestimates the CO_2 emissions of the German steel industry in 2011 and 2013 but mirrors the reported CO_2 emissions in 2012 (Table 10).

6.2. Variation of CO_2 emissions of the power system

If the CO_2 intensity of the power system were to remain constant throughout the studied period, the CO_2 intensity of secondary steelmaking would decrease to 404.1 kg CO_2/t, while a strong increase in the share of renewables in the power system would lead to a CO_2 intensity of 243.1 kg CO_2/t (Table 11).

Table 9
Estimated fulfillment of CO_2 emission reduction targets in 2030 by pathway.

Pathway	Estimated CO_2 emissions in 2030 (Mt)	Estimated CO_2 emissions/European target	Estimated CO_2 emissions/German target
Pathway 0	58.1	169%	211%
Pathway 1	47.6	139%	173%
Pathway 2	32.4	95%	118%
Pathway 3	52.0	153%	190%

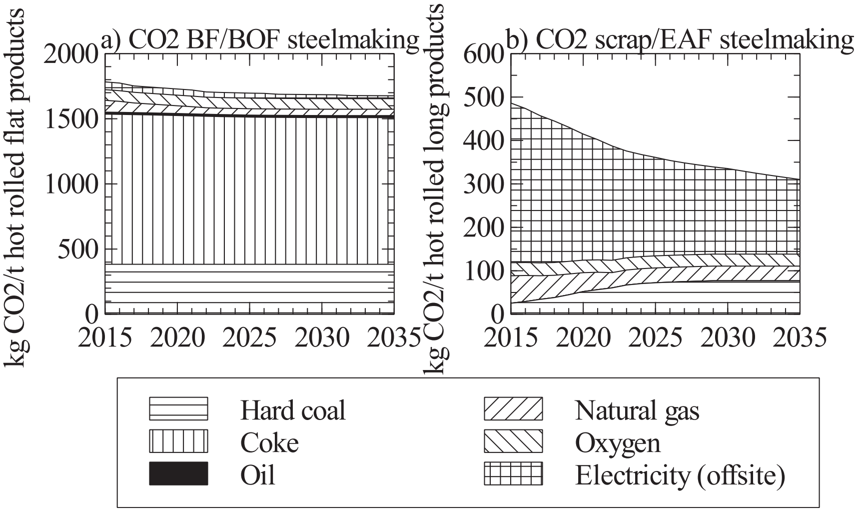


Fig. 12. Development of specific CO_2 emissions in the German steel industry 2011–2035 by a) BF/BOF, and b) scrap/EAF steelmaking considering the diffusion of energy-efficient technologies and the CO_2 emission factor of the public electricity grid.

Table 10
Comparison of the CO_2 emissions of the German steel industry estimated using the applied method with data provided by Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2014).

year	Method results	Data by Steelinsitute VDEh			Comparison
	Total CO_2 emissions	Crude steel production	Specific CO_2 emissions	Total CO_2 emissions (calculated)	Pathway results/data by Steelinstitute VDEh
	Mt	Mt crude steel	t CO_2/t crude steel	Mt CO_2	–
2011	62.6	44.3	1.362	60.3	104%
2012	57.5	42.7	1.350	57.6	100%
2013	60.3	42.6	1.328	56.6	107%

Table 11
Variation of CO_2 intensity of the power system for pathway 1 (constant crude steel production).

		Pathway 1	Pathway 1*	Pathway 1**
CO_2 grid emission factor (2035)	kg CO_2/kWh	0.365	0.564	0.222
CO_2 intensity scrap/EAF (2035)	kg CO_2/t steel	310.1	404.1	243.1
CO_2 emissions (2035)	Mt	43.4	47.3	40.6

Pathway 1 has the largest amount of scrap/EAF steelmaking in 2035 (20.6 Mt). However, CO_2 emissions of the German steel industry in 2035 would only be 14% lower with a high share of renewables in the power sector (Pathway 1**) compared to no further increase in renewables (Pathway 1*) (Table 11). This shows the dominant influence of BF/BOF steelmaking on the CO_2 emissions of the German steel industry.

6.3. Variation of blast furnace lifetimes

To show the impact of longer BF lifetimes on the production pathways, energy consumption and CO_2 emissions, pathway 2 (decreasing production) is modified to assume a BF lifetime of 65 years.

Under this assumption, primary steelmaking would even increase its production share to 96.5% in 2035. Secondary steelmaking would be phased out with a marginal production of 1.0 Mt in the same year. CO_2 emissions would decrease by 22% (Pathway 2*) instead of 56% (Pathway 2) compared to 2011 (Table 12).

The decision which production process to run depends on the economics of each process.

6.4. Variation of scrap availability

Pauliuk et al. (2013) estimate that secondary steelmaking could more than double by 2050. Therefore, it is assumed that scrap availability doubles until 2050, resulting in a scrap availability of 34 Mt in Germany in 2035. In the modified increased production pathway (pathway 3*), the maximum scrap/EAF production of 31.3 Mt is found in 2035. The CO_2 emissions of the German steel industry would be 19% lower in pathway 3* (Table 13).

Table 12
Variation of the lifetime of blast furnaces.

		Pathway 2	Pathway 2*
Lifetime blast furnaces	years	50	65
BF/BOF production (2035)	Mt	13.2	29.0
Scrap/EAF production (2035)	Mt	16.8	1.0
Share BF/BOF (2035)	–	44.0%	96.5%
CO_2 emissions (2035)	Mt	27.4	48.9

Table 13
Variation of scrap availability for pathway 3 (increasing crude steel production).

		Pathway 3	Pathway 3*
Scrap availability (2035)	Mt	29.1	42.9
Scrap/EAF production (2035)	Mt	17.2	31.3
CO_2 emissions (2035)	Mt	46.1	37.3

7. Discussion

One main goal of this study was to find a production pathway of the German steel industry able to meet the current European and German climate targets by 2030. The results indicate that only a pathway with a strong decrease in total steel production can meet the European climate target – if set as a flat target. However, none of the four production pathways considered would be able to meet the German climate target.

The results also revealed that the primary steelmaking route dominates the CO_2 emissions of the steel industry in every pathway throughout the studied period. Consequently, the CO_2 emissions of the steel industry are only marginally affected by increasing the share of renewables in the German electricity mix.

Moya and Pardo (2013) assumed that new steel production processes (e.g. ULCORED, Top Gas Recycle Blast Furnace) and carbon capture and storage would be ready from 2020 onwards. They find a CO_2 reduction potential of 65% for the European steel industry by 2030. In contrast, this study assumes that new steelmaking processes (e.g. HIsarna) will only be commercially available in 2030 at the earliest. This study further assumes that carbon capture and storage (CCS) will be employed in the steel industry not earlier than 2035. As a result, we find a much smaller CO_2 reduction potential for the German steel industry up to 2030. This study also finds that HIsarna does not help to meet climate targets by 2030.

The results of this study for the pathways assuming a constant production level are similar to those of Kuramochi (2016), who finds a CO_2 reduction potential for the Japanese steel industry of about 6.6% by 2030 from applying best available technologies.

This analysis is limited by the assumption that a switch from primary steelmaking to alternative steelmaking routes only occurs at the end of the primary steelmaking facility's lifetime, i.e. the blast furnace. However, this assumption reflects the current decision-making in the industry.

8. Conclusions

The analyses of future CO_2 emissions by the German steel industry as presented in this paper rely on technologically detailed pathways and variations in assumed production levels. This study finds that CO_2 emissions can only be reduced by 5% between 2014 and 2030 using the currently available technologies. The CO_2 emissions of the German steel industry will continue to be dominated by the blast furnaces of primary steelmaking until 2035 and beyond. New processes that are currently being developed such as HIsarna will not help to meet the climate targets set for 2030, because they are unlikely to be commercially available in time. Thus, the findings suggest that the German steel sector is unlikely to meet the CO_2 emission reduction targets – assuming that targets are set as flat-rate reductions and that steel production does not decrease dramatically. According to this analysis, a large share of BF capacity is expected to cease operating after 2023. By this point at the latest, there should be economically viable solutions available to reduce the CO_2 emissions from BF/BOF steelmaking.

This study considers both direct and indirect emissions and finds that the CO_2 emissions reductions are partly due to the assumed increase in the share of renewables in the German electricity mix, i.e. the reduction of indirect emissions. However, a high share of renewables in the German electricity mix does not significantly reduce the CO_2 emissions of the steel industry since primary steelmaking is likely to dominate the industry's CO_2 emissions until 2035 and beyond.

It is therefore probable that the German steel sector will be forced to purchase missing CO_2 emission allowances under the EU-ETS in the future if not less stricter targets are set for this sector.

The findings suggest that efforts to reduce CO_2 emissions in the steel industry should focus on two areas. First, alternative steelmaking processes need to be developed. Besides low-CO_2 process technologies like HIsarna, CO_2-free processes should also be considered. Direct reduced iron could be produced based on hydrogen and then fed into an electric arc furnace operated with electricity generated from CO_2-free sources. Steel could also be produced by electrolysis based on CO_2-free electricity. However, because these technologies will take decades to develop and introduce, there should be a second focus on incremental CO_2 reductions in the short to medium term. Options include heat recovery from blast furnace slag and from waste heat in electric arc furnaces, production of high quality steel from scrap-based secondary steelmaking, and the use of by-products for the production of base chemicals.

Acknowledgments

Major parts of this study were performed during the first author's stay as a visiting scientist to the Lawrence Berkeley National Laboratory, USA, which was funded by the home institution of the first author.

The authors are truly grateful for the valuable comments provided by the three anonymous reviewers as well as by Joachim Schleich, Jan Kersting and Tobias Fleiter. Special thanks to Marten Sprecher from Steelinsitute VDEh for the discussions about the production pathways.

Abbreviations

BF	blast furnace
BFG	blast furnace gas
BOF	basic oxygen furnace
BOFG	BOF gas
CCS	carbon capture and storage
CO_2	carbon dioxide
DRI	direct reduced iron
EAF	electric arc furnace
EET	energy-efficient technology
GJ	gigajoule
HBI	hot briquetted iron
HKM	*Hüttenwerke-Krupp-Mannesmann*, a German steel company
kg	kilogram
kWh	kilowatt hour
m^3	cubic meter
Mt	million metric tons
SR	smelt reduction
t	metric ton
tcs	ton crude steel
TWh	terawatt hour, used for final energy of electricity

References

Arens, M., Worrell, E., 2014. Diffusion of energy efficient technologies in the German steel industry and their impact on energy consumption. Energy 73, 968–977. http://dx.doi.org/10.1016/j.energy.2014.06.112.

Arens, M., Worrell, E., Schleich, J., 2012. Energy intensity development of the German iron and steel industry between 1991 and 2007. Energy 45, 786–797. http://dx.doi.org/10.1016/j.energy.2012.07.012.

de Beer, J., 2000. Potential for Industrial Energy-efficiency Improvement in the Long-term. Kluwer, Dordrecht.

Boston Consulting Group, 2013. Steel's Contribution to a Low Carbon Europe 2050. Technical and Economic Analysis of the Sectors CO_2 Abatement Potential. Study on Behalf of the Steelinstitute VDEh. www.bcg.de/documents/file154633.pdf (02.09.15.).

Brunke, J.-C., Blesl, M., 2014. A plant-specific bottom-up approach for assessing the cost-effective energy conservation potential and its ability to compensate rising energy-related costs in the German iron and steel industry. Energy Policy 67, 431–446. http://dx.doi.org/10.1016/j.enpol.2013.12.024.

Bundesministerium für Wirtschaft und Energie (BMWi), 2015. EU Climate Policy (EU-Klimaschutzpolitik). Webpage. http://www.bmwi.de/DE/Themen/Industrie/Industrie-und-Umwelt/klimaschutz,did=338374.html (02.09.15.).

Bundesregierung, 2010. Energy Concept for an Ecological, Reliable and Economic Energy Supply (Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung). Berlin.

European Council, 2014. EUCO 169/14, CO EUR 13. CONCL 5, Brussels, 24 October 2014. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/de/ec/145424.pdf (31.08.15.).

Fischedick, M., Marzinkowski, J., Winzer, P., Weigel, M., 2014. Techno-economic evaluation of innovative steel production technologies. J. Clean. Prod. 84, 563–580. http://dx.doi.org/10.1016/j.jclepro.2014.05.063. Special volume: The sustainability agenda of the minerals and energy supply and demand network: An integrative analysis of ecological, ethical, economic, and technological dimensions.

Han, K., Ahn, C.K., Lee, M.S., 2014. Performance of an ammonia-based CO_2 capture pilot facility in iron and steel industry. Int. J. Greenh. Gas Control 27, 239–246. http://dx.doi.org/10.1016/j.ijggc.2014.05.014.

Hasanbeigi, A., Arens, M., Price, L., 2014. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: a technical review. Renew. Sust. Energy Rev. 33, 645–658. http://dx.doi.org/10.1016/j.rser.2014.02.031.

IEAGHG, 2014. CO_2 Capture in the Steel Industry - Review of the Current State of Art. Presentation at Industry CCS Workshop. Austria by Stanley Santos, Vienna.

International Energy Agency, 2007. Tracking Industrial Energy Efficiency. Paris, France.

International Energy Agency, 2013. Technology Roadmap – Carbon Capture and Storage. Paris, France.

International Energy Agency Clean Coal Center, 2012. CO_2 Abatement in the Iron and Steel Industry. Profiles 12/1.

International Labour Organization, 1997. The Iron and Steel Workforce of the Twenty-first Century. Int. Labour Office, Geneva.

Kobe Steel Ltd, 2013. Potential for CO_2 emissions reduction in Midrex direct reduction porcess. In: Presentation by Hidetoshi Tanaka on November 3, 2013. http://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%202%20Secured%20presentations/2_1400%20Hidetoshi%20Tanaka.pdf (02.04.15.).

Kuramochi, T., 2016. Assessment of midterm CO_2 emissions reduction potential in the iron and steel industry: a case of Japan. J. Clean. Prod. 132, 81–97. http://dx.doi.org/10.1016/j.jclepro.2015.02.055.

Midrex, 2013. World Direct Reduction Statistics.

Midrex, 2014. World DRI Production Surpasses 75 Million Tons. News Release, 2013. http://www.midrex.com/assets/user/news (02.09.15.).

Moya, J.A., Pardo, N., 2013. The potential for improvements in energy efficiency and CO_2 emissions in the EU27 iron and steel industry under different payback periods. J. Clean. Prod. 52, 71–83. http://dx.doi.org/10.1016/j.jclepro.2013.02.028.

Oda, J., Akimoto, K., Tomoda, T., 2013. Long-term global availability of steel scrap. Resour. Conserv. Recycl. 81, 81–91. http://dx.doi.org/10.1016/j.resconrec.2013.10.002.

Okazaki, T., Yamaguchi, M., 2011. Accelerating the transfer and diffusion of energy saving technologies steel sector experience – lessons learned. Energy Policy 39, 1296–1304. http://dx.doi.org/10.1016/j.enpol.2010.12.001.

Öko-Institut, Fraunhofer ISI, 2015. Climate Protection Scenario 2050-2. Final Report [Klimaschutzszenario 2050 – 2. Endbericht]. Study on Behalf of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (forthcoming).

Pauliuk, S., Milford, R., Müller, D., Allwood, J., 2013. The steel scrap age. Environ. Sci. Technol. 47, 3448–3454. http://dx.doi.org/10.1021/es303149z.

Statisitsches Bundesamt, Wiesbaden, 2009. Lower Heating Values of Fossil Fuels [Heizwerte (Hu) fossiler Energieträger]. Fachserie 4 R. 4.1.1.

Steelinstitute VDEh, 2010,. 10th CO_2-Monitoring-progress-report [10. CO_2 Monitoringfortschrittsbericht], Düsseldorf. http://www.stahl-online.de/wp-content/uploads/2014/03/10_CO_2-Monitoring-Fortschrittsbericht_Stahlindustrie_2010.pdf (31.08.15.).

Steelinstitute VDEh, 2013. Database Plantfacts. Düsseldorf.

Steelinstitute VDEh, 2015. Plantfacts Database EU-28 - Shut Down Plants since 2000. Düsseldorf.

Tata Steel Europe, 2013. Innovative Revolutionary Ironmaking Technology for a Low Carbon Economy. Presentation. http://ec.europa.eu/clima/events/docs/0095/tata_steel_en.pdf (02.09.15.).

Tonomura, S., 2013. Outline of course 50. Energy Proc. 37, 7160–7167. http://dx.doi.org/10.1016/j.egypro.2013.06.653.

Umweltbundesamt, 2014a. Development of the Specific CO_2 Emissions of the German Electricity Mix 1990–2013 (Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2013). Dessau-Roßlau. http://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/climate_change_23_2014_komplett.pdf (31.08.15.).

Umweltbundesamt, 2014b. European Energy and Climate Goals (Europäische Energie- und Klimaziele). Webpage. http://www.umweltbundesamt.de/daten/klimawandel/europaeische-energie-klimaziele (02.09.15.).

Umweltbundesamt, Deutsche Emissionshandelsstelle, 2012. Uniform Material Values for Emission Factors, Heating Values and Carbon Content for Fuels, Raw Materials and Products (Einheitliche Stoffwerte für Emissionsfaktoren, Heizwerte und Kohlenstoffgehalte für Brennstoffe, Rohstoffe und Produkte). http://www.dehst.de/SharedDocs/Downloads/Archiv/Zuteilung_2008-2012/Anhang01_Stoffliste.pdf?__blob=publicationFile (31.08.15.).

Wirtschaftsvereinigung Stahl, 2011. Fuel, Gas and Electricity Consumption of Blast Furnaces, Steel and Rolling Mills as Well as Forge, Press and Hammer Mills Including Locally Connected Other Facilities (Excluding Own Coking Plants) (Brennstoff-, Gas- und Stromwirtschaft der Hochofen-, Stahl- und Walzwerke sowie Schmiede-, Preß- und Hammerwerke einschließlich der örtlich verbundenen sonstigen Betriebe (ohne eigene Kokerei)). BGS-Eh200, Düsseldorf.

Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014. Statistical Yearbook of the Steel Industry 2014/2015 (Statistisches Jahrbuch der Stahlindustrie 2014/2015). Verlag Stahl und Eisen, Düsseldorf.

World Steel Association, 2009. Fact Sheet Breakthrough Technologies. http://old.worldsteel.org/pictures/programfiles/Fact%20sheet_Breakthrough%20technologies.pdf.

Worrell, E., Price, L., Neelis, M., Galitsky, C., Nan, Z., 2008. World Best Practice Energy Intensity Values for Selected Industrial Sectors. Environmental Energy, Technologies Division, Lawrence Berkeley National Laboratory LBNL-62806 Rev. 2.