Technological change and industrial energy efficiency

Exploring the low-carbon transformation of the German iron and steel industry

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Technological change and industrial energy efficiency

Exploring the low-carbon transformation of the German iron and steel industry

Technologische veranderung en industrielle energie-efficiëntie

Verkenning van de transitie van de Duitse ijzer- en staalindustrie naar lage CO_2 emissies
(met een samenvatting in het Nederlands)

Technologischer Wandel und industrielle Energieeffizienz

Analyse einer CO_2-armen Transformation der deutschen Eisen- und Stahlindustrie
(mit einer Zusammenfassung in deutscher Sprache)

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door

Marlene Arens

geboren op 23 maart 1981 te Lippstadt, Duitsland

Promotoren:	Prof.dr. E. Worrell
	Prof.dr. W. Eichhammer

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Abbreviations

BF	blast furnace
BFG	blast furnace gas
BOF	basic oxygen furnace
BOFG	basic oxygen furnace gas
BOFGR	basic oxgen furnace gas recovery
CCM	continuous casting machines
CCS	carbon capture and storage
CDQ	coke dry quenching
CO_2	carbon dioxide
COG	coke oven gas
CS	crude steel
DRI	direct reduced iron
EAF	electric arc furnace
EEG	Renewable Energies Act, *Erneuerbare-Energien-Gesetz*
EET	energy efficient technology
EJ	exajoule
EU ETS	EU Emissions Trading System
GJ	gigajoule
HBI	hot briquetted iron
HKM	Hüttenwerke-Krupp-Mannesmann, a German steel company
LHV	lower heating value

MJ	megajoule
Mt	million metric tonnes
NG	natural gas
OHF	open hearth furnace
PCI	pulverized coal injection
SEC	specific energy consumption
SR	smelt reduction
S.T.P.	standard pressure and temperature
tcs	tonne crude steel
thm	tonne hot metal
tls	tonne liquid steel
TRT	top-pressure recovery turbine
TWh	terawatt hour, used for final energy of electricity
Ulcos	Ultra-low CO_2 steelmaking, a European research programme

Chapter 1

Introduction

1.1 Energy consumption and climate change

1.1.1 Energy consumption and technological change

Global energy consumption has increased drastically over the past two centuries, especially in the past 60 years. Today, global energy consumption is about 600 EJ per year, while a century ago it was about a tenth of this (60 EJ/year), and only a third of this (20 EJ/year) a hundred years before that in 1810 (Fig. 1.1).

The consumption of energy is related to population, income, and technological change (Grubler et al., 2012). We would not consume this amount of energy without the invention and vast diffusion of technologies and if there were not so many of us that could afford demanding these energy services and these technologies.

Similar to global energy consumption, the world population and the gross domestic product per capita have increased strongly over the past two decades as well (Fig. 1.2, measurement of purchasing power parity according to Geary-Khamis, GK). However, the global population has not grown as much as energy consumption. While the population increased sevenfold over the past two centuries, global energy demand is 25 times higher than it was in 1810 (Fig. 1.1). Economic welfare expressed in per capita gross domestic product increased by a factor of eleven between 1810 and 2010 (Maddison, 2010).

Technological change is the third factor affecting global energy consumption (Grubler et al., 2012). Technological change enabled the drastic transformations taking place during the industrial revolution. However, the industrial revolution would not have happened without changes on a broader scale such as political and cultural transitions

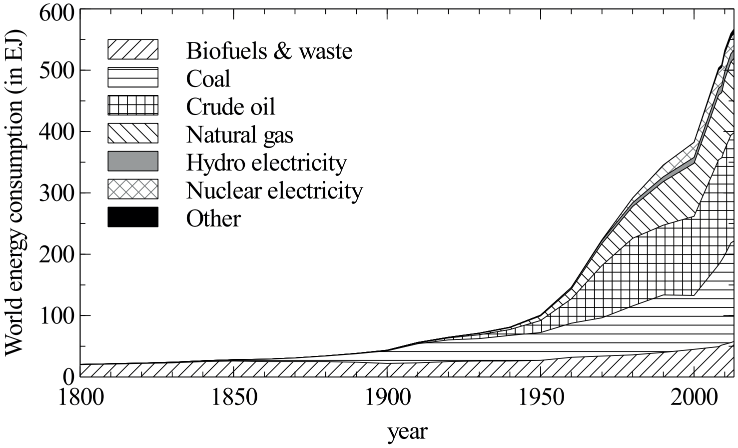

Figure 1.1: Global energy consumption (sources: Roser, 2016; updated by International Energy Agency, 2009-2015).

(Freeman and Soete, 1998). Technologies developed during and after the industrial revolution, especially steam and internal combustion engines, electric motors, and airplanes, have caused the vast increase in global energy demand.

1.1.2 Technological change and steel production

The diffusion of steel as a material and steel products was a key element enabling the technological change that happened in the period 1890 to 1940, the so-called age of electricity and steel (Freeman and Soete, 1998). The mass production of cheap steel and the development of new alloys with improved properties triggered many developments. In the 1880s, steel enabled the construction of skyscrapers. The steel for the steam shovels that dug the Panama Canal was developed in the 1890s. Cans for storing food and bicycles are other examples of steel application (Freeman and Soete, 1998).

The development of steel production throughout the past two centuries has followed a similar pattern as energy consumption, population and income growth (Fig. 1.2). By 2014, world crude steel production was about 1.6 billion tonnes, of which China alone accounted for half, while less than two decades earlier, global steel production was only about 0.8 billion tonnes (World Steel Association, 2014).

World steel production is currently being driven by China, so that economic developments in China will continue to shape steel production in the short to medium term. Chinese steel demand and production might have already peaked and are likely to

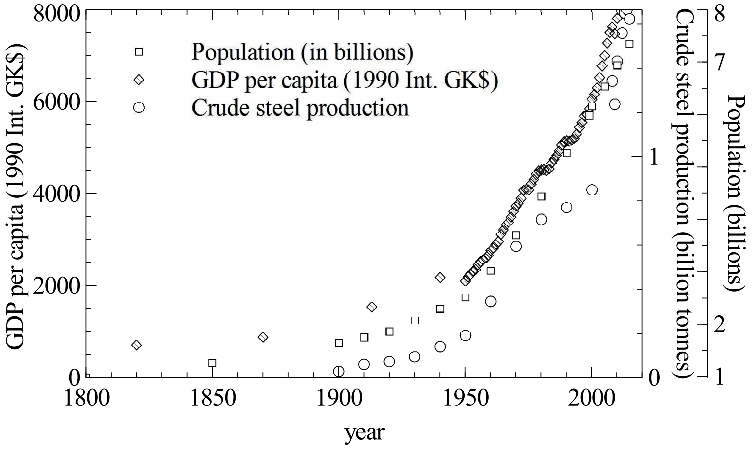

Figure 1.2: World crude steel production, global population and gross domestic product (GDP) according to Geary-Khamis, GK, per capita (sources: World Steel Association, 1978-2016; Maddison, 2010; Maddison Project, 2010; United Nations, 1999; United Nations, 2015).

stabilize in the next few years (Sekiguchi, 2015), or even decline since the Chinese government has announced cuts to the country's annual steel production capacity by 100 to 150 million tonnes by 2020 (Bloomberg, 2016).

1.1.3 Steel production and its climate impact

Steel making is one of the energy-intensive industries. The steel sector consumes about 20 % of global industrial final energy (Banerjee, 2012). Primary steelmaking drives energy consumption the most because it includes the energy-intensive reduction of the raw material iron ore to iron in blast furnaces. Steel recycling consumes only about a third of the primary energy that primary steelmaking uses (International Energy Agency, 2008). But steelmaking from scrap is currently limited by the availability of scrap and the quality of the steel grades that can be produced. Currently, primary steelmaking dominates steelmaking on a global level with a share of more than 70 % (World Steel Association, 2014), and global steel consumption is still growing.

Coal remains the key energy carrier for primary steel production, either as coke or as pulverized coal. The iron and steel industry is globally one of the largest coal consumers, even though its share in global coal consumption is decreasing (Fig. 1.3). While in 1971 about 15.5 % of global coal consumption was used by coke ovens and blast furnaces, the main coal consuming plants in the iron and steel industry (Arens et al., 2012), in 2013 it was 11.8 %.

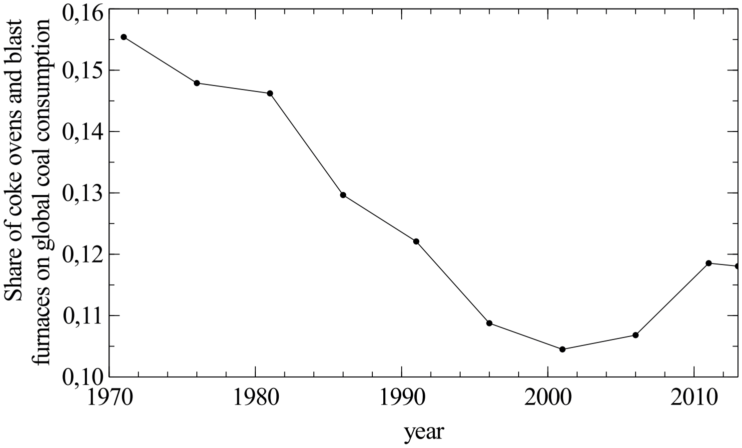

Figure 1.3: Share of coke ovens and blast furnaces on global coal consumption (sources: derived from International Energy Agency, 2015a).

Next to coal, natural gas and oil are other fossil energy carriers used in iron and steelmaking. Natural gas is used for reheating furnaces and other heating purposes. From the 1970s until recently, oil was used to replace coke in the blast furnace.

Using fossil fuels leads to emissions of carbon dioxide, a major greenhouse gas, into the atmosphere. Industry as a whole accounted for about 29 % of total greenhouse gas emissions in 2010 (Victor et al., 2014). The iron and steel industry accounts for approximately 6.7 % of total global CO_2 emissions (World Steel Association, 2015).

Rising anthropogenic CO_2 emissions are associated with climate change and global warming. There is broad scientific consensus that the average global world temperature is rising and that human activities are responsible for this development. Over the past decades, the atmosphere and oceans have warmed, the amounts of snow and ice have diminished, and sea level has risen (International Panel on Climate Change, 2014). Climate change is likely to have widespread impacts. Millions of people in densely populated coastal areas will have to move if the sea level continues to rise (World Bank, 2010).

1.2 Industrial climate and energy policy

Total anthropogenic CO_2 emissions should be limited to about one trillion tonnes of carbon in order to keep global warming to not more than 2 °C. But by 2011, 515 billion tonnes of carbon had already been emitted, leaving a carbon budget of 485 billion tonnes. There is therefore the necessity to cut global anthropogenic CO_2 emissions immediately and drastically. If today's emission trends proceed, by 2045 the carbon budget will be used up (World Ressource Institute, 2016). Accordingly, from 2045 onwards global net emissions should be zero.

Cutting greenhouse gas emissions of energy-intensive industries is a key challenge due to their reliance on coal also for chemical conversion processes. Primary steelmaking strongly depends on the consumption of coal.

Building on the Millennium Goals, the United Nations agreed on the Sustainable Development Goals in 2015. These goals should be met by 2035. 169 targets have been set to achieve the 17 goals. The Sustainable Development Goals cover a broad range of topics including ending poverty, gender equality, and clean and affordable energy. Energy efficiency in industry is addressed in goal 9 *industry, innovation and infrastructure*. Target 9.4 demands that, by 2030, industries should be retrofitted to make them sustainable with greater adoption of clean and environmentally sound technologies and processes. Industrialized countries are addressed in particular to exert themselves to meet this goal since all countries should take action according to their respective capabilities (United Nations, 2016b).

Developed countries started to negotiate legally binding obligations to reduce their greenhouse gas emissions within the United Nations Framework Convention on Climate Change in the mid-1990s. Since top-down international agreements on greenhouse gas emission reduction targets are hard to negotiate, sectoral agreements represent a bottom-up alternative. Sectoral targets, i.e. joint binding agreements between sectors and national governments, are a means to incorporate developing countries into international climate agreements, reduce inequalities of competiveness and address competitiveness issues and carbon leakage. Sectoral targets have mainly been considered for energy-intensive industries including the iron and steel industry (Duscha et al., 2015).

While previous climate summits have failed to produce a top-down target for future emissions, countries at the United Nations climate summit in Paris in December 2015 agreed on bottom-up Nationally Determined Contributions (NDC). At this conference, 195 countries adopted a legally binding global climate deal. The agreement is due to enter into force in 2020 and sets out a global action plan to limit global warming below 2 °C. National climate action plans show the measures planned to be taken by the respective country. As part of the Paris agreement, governments committed to meet every five years to set more ambitious targets as required by science and to report to each other and the public their progress towards their targets (United Nations, 2016a).

Emission trading systems are one key policy to try and reduce industrial greenhouse gas emissions. They have been implemented or are under construction in several regions of the world. South Korea and some states of the United States and Canada have implemented or have planned emission trading systems (World Bank, 2015). China has introduced pilot emission trading systems in different provinces and plans to extend them to a nation-wide emission trading system (World Bank, 2016).

The European Union set up an emission trading system in 2005 that aims at reducing European greenhouse gas emissions by the covered sectors by 21 % by 2020 compared to 2005 in the sectors covered by the scheme. By 2030, greenhouse gas emissions covered by the European emission trading system should be lowered by 43 % (European Commission, 2015b).

The European emission trading system is part of a set policies that help the European Union achieving its legally binding *2020 climate and energy package*. Greenhouse gas emissions have to be reduced by 20 % in 2020 compared to 1990, 20 % of the final energy consumption of the European Union has to be provided by energy from renewable sources, and energy efficiency has to be improved by 20 % compared to energy forecasts.

The *2030 climate and energy framework* requests a reduction in greenhouse gas emissions of 40 % by 2030 compared to 1990 levels, a share of 27 % of energy from renewable sources, and a 27 %-improvement in energy efficiency. During the Paris climate conference, the European Union announced that it was already taking steps to implement a target to reduce emissions by at least 40 % by 2030 (European Commission, 2016d). The *2050 low-carbon roadmap* suggests a reduction in greenhouse gas emissions of 80 % by 2050 compared to 1990 (European Commission, 2016b).

The Energy Efficiency Directive is another measure aiming at reducing greenhouse gas emissions in the European Union. Established in 2012, it covers a set of binding measures also affecting greenhouse gas emissions from industry. The directive requires all countries of the Europena Union to use energy more efficiently at all stages of the energy chain from production to final consumption. Measures include mandatory energy audits for large companies and incentives for small and medium-sized companies to undergo energy audits (European Commission, 2015a).

Several other policies aiming at reducing energy consumption and greenhouse gas emissions in industry have been announced or introduced recently. For example, China has implemented measures that aim to phase-out outdated production capacity in the steel and cement industry including retiring or updating coal-fired boilers (International Energy Agency, 2014b).

1.3 Climate change mitigation strategies for industries

Technological options to transform energy consumption in households, services and transport are available, even though there is still a long way to go untill their energy consumption can be provided sustainably. In industry, however, and especially in the iron and steel industry, proven technological concepts for far-reaching reductions of CO_2 emissions are still rare. The reduction of iron ore to iron in blast furnaces still depends to a large extent on the consumption of coal. While several alternative processes are being piloted or researched, it is not expected that these technologies will be commercially available in the medium term.

Energy-intensive industries consider the four strategies to respond to climate change, i.e. fuel switch from fossil fuels to less carbon-intensive or renewable energy carriers; carbon capture and storage (CCS); material efficiency strategies; and energy efficiency improvement.

1.3.1 Switch from fossil fuels to renewable energy carriers

One way to reduce industrial CO_2 emissions is to switch from fossil fuels to less carbon-intensive or renewable energy carriers. Most prominently, electricity can be produced using renewables such as solar, wind or water. In 2013, renewables accounted for almost 22 % of global electricity generation (International Energy Agency, 2016) and for 24 % of German electricity production (Bundesministerium für Wirtschaft und Energie, 2016b). In industry, electricity accounts for about 20 % of final energy demand (International Energy Agency, 2009), which could be supplied by renewables. Electricity is the main energy carrier for secondary steelmaking. In primary steelmaking, electricity is typically generated from by-product gases. At present, generating electricity from by-product gases is an energy-efficient and climate mitigation measure, since 42.2 % of the German electricity mix depended on coal in 2015 (Bundesministerium für Wirtschaft und Energie, 2016b).

If the electricity mix included a higher share of renewables, generating electricity from fossil fuel-based by-product gases in primary steel production would be less attractive from a climate perspective. By-product gases would then be better used, e.g. as a reducing gas to replace coke consumption in primary steelmaking. So far, the production and use of electricity from renewable sources is limited. Germany aims to cover 50 % of its total gross electricity consumption using renewable electricity by 2030 (Bundesministerium für Wirtschaft und Energie, 2010). Load balancing with high shares of intermittent renewables remains a challenge that may require back-up power generation provided by fossil fuels.

Fossil fuels provide about 70 % of industry's final energy demand (International Energy Agency, 2009; Fleiter et al., 2013) and are typically used to generate heat. Alternatives to fossil fuels include biomass, solar thermal energy, heat pumps and geothermal energy (International Renewable Energy Agency, 2015). In total, renewables including biomass and solar thermal energy delivered 11 % of the total industrial process heat in Germany in 2014 (Bundesministerium für Wirtschaft und Energie, 2016b).

Biomass is assumed to have the largest renewable energy potential in industry. The largest potential for biomass is in providing process heat below 400 °C. Temperatures up to 800 °C can be reached using biomass gasification. And even temperatures up to 1,000 °C can be realized using charcoal (International Renewable Energy Agency, 2015). However, costs and the availability are currently limiting biomass use. In Germany, biomass supplies only 4 % of industrial final energy consumption (Bundesministerium für Wirtschaft und Energie, 2016b). Even in the future, biomass consumption in the steel industry is assumed to make up only 2 to 4 % of total biomass consumption in industry by 2050 (United Nations, 2010).

Biomass could also be used as a feedstock or, in the case of the steel industry, as a reducing agent. Some research projects deal with the substitution of fossil fuels by biomass in the steel industry (e.g. ACASOS under the European research programme Horizon-2020; European Commission, 2016a). However, biomass would have to be treated before it is suitable for industrial applications, e.g. compacting it can increase its heating value. Even then, the processes might be adversely affected due to more volatile components. Limiting factors for the use of biomass in industry include resource availability, economics and competition from other energy sources (United Nations, 2010).

Other options to use renewables in industry include solar process heat. Common solar thermal technologies such as unglazed flat plate or evacuated tubular collectors can supply temperatures up to 250 °C (International Energy Agecny, Solar Heating and Cooling Programme, 2016). Higher temperatures can be provided with solar concentrator technologies (International Renewable Energy Agency, 2015). The potential for solar thermal energy depends on the climatic region. Its energy supply varies with the intensity of the sun's radiation. Furthermore, the technologies are still rather expensive. Some demonstration plants have been installed in Germany and solar process heat can receive funding of up to 50 % from the government (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2015).

Geothermal energy accounted for 7.6 % of the heat from renewable sources in Germany in 2014. The major driver of geothermal heat in Germany is near-surface geothermal energy, while deep geothermal energy constitutes only 9.1 % of the total geothermal heat supply in Germany (Bundesministerium für Wirtschaft und Energie, 2016b). It can be assumed that the share of geothermal heat supply in industry is much lower than the national average. Furthermore, the temperature level is not sufficient for the main processes in steelmaking.

To sum up, optimistic estimations assume that renewable energies can cover 30 % of the energy demand in energy-intensive industries by 2030 (International Renewable Energy Agency, 2015). More conservative estimates find a renewable potential in total industry of about 20 % by 2050 (United Nations, 2010). Charcoal already substitutes coke in the iron and steel industry in Brazil at competitive prices (United Nations, 2010). From a European perspective, this is a less attractive option for European steelmakers due to limited land availability and a different climate. In the long term, electrowinning, i.e. the reduction of iron ore to iron using electricity, seems to be one option to increase the consumption of renewable energy in the iron and steel industry. This is currently being done on a laboratory scale in France as part of the Ulcos project (Allanore et al., 2010). Scaling up the process may still be a long way off (Wiencke et al., 2015).

Hydrogen from renewable energies is a promising technology providing a low CO_2 energy carrier to industry. Electricity from renewable energy sources is used in an electrolyser to split water into hydrogen and oxygen. Methane or synthetic natural gas (SNG) can be produced using this hydrogen with the addition of carbon dioxide and can replace fossil natural gas in the industry. Hydrogen may also be directly used in industrial application like fuel refineries or in the chemical industry. In the steel industry hydrogen can be used for ironmaking in direct reduction plants (Deutsche Energieagentur, 2015).

1.3.2 Carbon capture and storage

The capture and underground storage of carbon dioxide (CCS) is one way to reduce the CO_2 emissions into the atmosphere. This option is especially relevant for the iron and steel industry because it is so dependent on coal and economically viable and technologically feasible coal substitution does not seem to be available in the medium term. Although CCS is the only large-scale technology available to make deep emission cuts in several industries, such as iron and steel and cement (Global CCS Institute, 2013), there has been limited progress on developing CCS for industrial processes, especially the iron and steel sector (International Energy Agency, 2013). Advanced CCS projects in industrial applications are scarce, and some Ulcos projects in the iron and steel industry have been cancelled. There are currently only two development projects in the iron and steel sector.

In Europe, a top-gas recycling blast furnace is being developed in the Low Impact Steelmaking project. In the Middle East, Emirates Steel Industries is developing carbon capture and storage at a direct reduction plant. The start-up of the carbon capture plant was expected for 2015, but so far no announcement to that effect has been made. Considerable promotion efforts are still needed for capture demonstrations and CCS technology development for industrial sectors (Global CCS Institute, 2013). Since CCS is envisioned to be routinely used in iron and steel industry only by 2030 (International Energy Agency, 2013), it is not included in this thesis.

1.3.3 Material efficiency

Reducing material losses during steelmaking and steel consumption during steel use improves efficiency (International Energy Agency, 2008). Reducing the number of processing steps also improves efficiency. For instance, directly injecting coal into blast furnaces reduces the need for coke. New reactors are designed to completely omit coke (i.e. Corex-process) and sinter making (i.e. Finex-process) (International Energy Agency, 2008). Belt-casting technologies process coils directly from liquid steel and thus skip reheating processes (Salzgitter AG, 2016).

Reductions in steel consumption also decrease the CO_2 emissions from steel use. For instance, high-strength lightweight steels reduce the weight of automobiles and therefore reduce their CO_2 emissions (Allwood et al., 2011).

This thesis primarily focuses on energy efficiency innovations in the production of iron and steel.

1.3.4 Energy efficiency

Due to the so far limited potential of renewable energy sources and the current low probability that carbon capture and storage will be applied to industrial processes in the medium term, energy efficiency is the most promising option to reduce energy consumption and CO_2 emissions in industry. There are various measures to improve energy efficiency in the steel industry.

First, the energy consumption of individual processes can be reduced. In the German steel industry, coke consumption in blast furnaces was reduced from about 1,000 kg in the 1950s to about 350 kg by 2008. This was achieved by various measures, including the use of increased ore quality, oxygen injection, or increasing hot blast temperatures to above 1,200 °C. Additionally, coke consumption was partly replaced by the injection of oil and coal.

Steel produced via the primary route consumes about three times more energy than steel recycled from steel scrap. Thus increasing the use of scrap or the production of secondary steel helps to reduce the energy consumption and CO_2 emissions of the total steel industry. However, steel production from scrap is limited by scrap availability and by the quality of steel grades that can (currently) be produced via secondary steelmaking.

Reducing the number of process steps helps to lower heat and material losses. Injecting coal into blast furnaces omits coke making in coke ovens. The production of coils from liquid steel via strip or belt casting technologies skips reheating steps and reduces oxidation losses.

The recovery of waste heat or by-products can also improve energy efficiency. In the steel industry, several processes emit top-gases that are typically collected and re-used. These gases, i.e. coke oven gas, blast furnace gas, and basic oxygen furnace gas, have heating values ranging from 4 MJ/m^3 to about 20 MJ/m^3. After collecting and cleaning, these gases are used in sinter plants, in reheating furnaces or in onsite power plants. The high pressure blast furnace gas can be fed through a top-pressure recovery turbine to generate electricity using the pressure difference between the top of the blast furnace and ambient pressure. Heat recovery is another option to increase energy efficiency. Coke dry quenching, for instance, cools hot coke with nitrogen. The heated nitrogen is then used to generate steam and electricity. Energy can also be recovered from e.g. sinter coolers, furnaces, blast furnace slag, or hot slabs.

1.4 Scope and outline of this thesis

Technological change is an important driver lowering energy consumption. There are different options to reduce energy consumption and thus CO_2 emissions in the steel industry as discussed above. This thesis investigates the drivers of technological change in the German iron and steel industry and its impacts on energy use and CO_2 emissions. The German iron and steel industry is the largest in Europe, one of the largest in the world, and the largest industrial energy consumer in Germany. As discussed above, the very nature of the processes used in the iron and steel industry also makes it more challenging for this industry to reduce emissions compared to other industries and sectors. Therefore, it is important to better understand the dynamics of technological change in this industry. The approach focuses on (a) the assessment and understanding of past trends in energy intensity, and (b) the assessment of future options to reduce CO_2 emissions (Fig. 1.4).

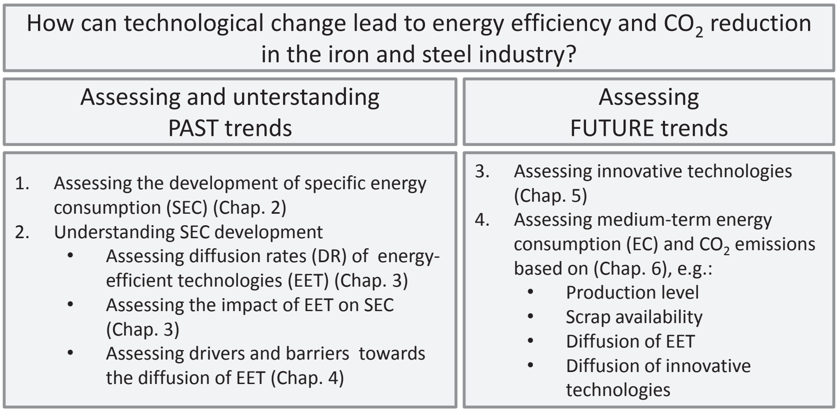

Figure 1.4: Overview of research questions.

The main research question of this thesis is:

How can technological change lead to energy efficiency and CO_2 reduction in the German iron and steel industry?

The main issue is addressed in five groups of sub-questions:

1. How did energy intensity change on the process level in the German iron and steel industry between 1991 and 2007? What is its impact on the development of the energy intensity of the total German iron and steel industry?

2. What are the diffusion rates of key energy-efficient technologies in the German iron and steel industry? What impact do they have on energy intensity development of the total German iron and steel industry? What is their remaining energy efficiency potential?

3. What are drivers for and barriers to the implementation of key energy-efficient technologies in the German iron and steel industry?

4. Which are the promising low-carbon ironmaking technologies in research and development or at an early stage of commercialization?

5. How does technological change impact the energy consumption and CO_2 emissions of the German iron steel industry until 2035 considering the findings from chapters 2 to 5?

The sub-questions are answered in chapters 2 to 6. The next section outlines the research questions and chapters.

1.5 Measuring the impact of technological change on energy efficiency in the steel sector

1.5.1 Assessing energy intensity

Measuring and monitoring the success of climate and energy efficiency policies depends on reliable, accurate indicators able to compare the energy and CO_2 intensity of different companies, sectors or countries correctly. Phylipsen et al. (1998) discussed methodologies for indicators that allow an international comparison of energy efficiency in the manufacturing industry. In general, energy intensity is referred to as the energy consumption per economic activity. Economic activity can either be expressed using economic activity indicators e.g. gross domestic product, value of shipments, value of production, value added or a production index. Physical activity indicators can be used to express economic activity as well. Typically, these are expressed in weight units of products (i.e. metric tonnes). Thus, energy efficiency can be expressed as the energy consumption per economic output or the energy consumption per physical output. The latter is usually referred to as specific energy consumption.

Worrell et al. (1997) applied economic and physical indicators to the iron and steel industry. They found that physical indicators are more appropriate than economic indicators when analyzing energy efficiency trends in the iron and steel industry. Economic indicators may be more appropriate for more complicated products such as machines (Worrell et al., 1997). Using specific energy consumption enables the efficiency of processes to be compared and helps to explain the observed trends.

Boundary setting is important when comparing energy efficiency in the iron and steel industry based on specific energy consumption (Tanaka, 2008). The generation and further use of by-product gases such as blast furnace gas needs to be treated equally among energy efficiency comparisons. Commonly, credits are given for the export of by-product gases. Moreover, key plants like coke ovens or onsite power generation plants are not always considered to be part of the iron and steel industry, even though they are closely connected energetically, e.g. coke oven gas is used for firing sinter plants or for onsite electricity production in power plants. Onsite generated electricity is used in rolling mills as well as other processes. Tanaka (2008) showed that boundary setting is very important and that the specific energy consumption can vary by one third depending on the chosen boundaries.

Chapter 2 assesses the energy intensity development of selected processes in the German steel industry between 1991 and 2007, i.e. after German unification and before the economic crisis. It thus provides insights into improvements in energy efficiency on the process level.

1.5.2 Technological change and energy intensity developments

Energy efficiency is shaped by technological change. Technological change is the process by which a superior technology supersedes another technology (Jaffe et al., 2000). This process consists of three steps of which the first is *invention*, i.e. the development of a new product or process. If an invention reaches commercialization, it becomes an *innovation*. *Diffusion* describes the process of gradual widespread adoption of an innovation (Jaffe et al., 2000). For example, in the steel industry, the replacement of the open hearth furnace by the basic oxygen furnace led to vast energy savings.

The basic oxygen furnace was developed by an Austrian firm, Vöest (today's Voestalpine) in 1949 (Oster, 1982). Its first large-scale implementation was in 1952 at the Vöest site in Linz (Poznanski, 1983). While the open hearth furnace was fed with preheated air, oxygen is injected in the basic oxygen furnace, reducing the need for additional fuel use and reducing tap times from eight hours to 45 minutes (Oster, 1982). Nowadays, open hearth furnaces have been phased out almost completely and the basic oxygen furnace is the state-of-the-art process. The diffusion of the basic oxygen furnace was intensively studied (Poznanski, 1986; Ray, 1989).

Diffusion is a process in which an innovation is communicated through certain channels over time among the members of a social system (Rogers, 2003). Four elements constitute diffusion, i.e. the innovation, communication channels, time, and a social system. An innovation is an idea, practice or object that is perceived as new by an individual or by another unit of adoption. Energy-efficient technologies are thus a special case of innovation (Fleiter, 2012).

Adoption rates show whether an innovation diffuses properly. The way an innovation is adopted helps to assess factors that shape its diffusion. One aim of the research on diffusion is to find out how to speed up the adoption rate of an innovation (Rogers, 2003).

Chapter 3 traces the diffusion rates of five major energy-efficient technologies in the German steel industry from their introduction until 2014. Based on the derived diffusion rates, the impact of the selected energy-efficient technologies on specific energy consumption is evaluated. Finally, the remaining energy saving potential is calculated, assuming the selected technologies reach complete diffusion.

1.5.3 Explaining the diffusion of energy-efficient technologies

Although the advantages of new technologies are sometimes obvious, adoption is often slow. It took the basic oxygen furnace 27 years to reach complete diffusion in the German steel industry (Arens and Worrell, 2014). Even today, more than 50 years after the introduction of the basic oxygen furnace, a few open hearth furnaces are still operating in Russia, Ukraine and India (World Steel Association, 2014).

Diffusion theory explains the slow adoption of innovations by the third element of diffusion, i.e. time (Rogers, 2003). Time is a dimension of the innovation-decision process, of the attitude of the individual or the unit of adoption towards an innovation, and of the diffusion process. The innovation-decision process is time consuming since an individual or decision-making unit first needs to acquire knowledge about the innovation. Then, the individual or decision-making unit needs to form an attitude towards the innovation (persuasion) and then decide whether to adopt or reject it. If the decision is in favour of the innovation, then it will be implemented. Finally, the innovation needs to prove that it fulfils the expectations about it in order to confirm its implementation.

Second, the diffusion process itself, i.e. the rate of adoption in a certain period, is a process that occurs over time as well. The rate of adoption describes the speed with which an innovation is adopted by members of a social system. It is generally measured as the number of individuals who adopt a new idea within a specified period such as a year. The rate of adoption is thus a numerical indicator (Rogers, 2003). The rate of adoption of an innovation over time was found to follow an s-shaped curve (e.g. Rogers, 2003).

Third, the attitude of the individual or unit of adoption towards an innovation relative to other members of the system has a time component. The uptake of an innovation begins when the opinion leader of a social system or the *innovator* adopts the new idea or technology (Rogers, 2003). According to Rogers (2003) usually are innovators adventurous and actively seek new ideas. They also possess substantial financial resources to offset losses from unprofitable innovations. Additionally, innovators usually have extensive technical knowledge so that they are able to understand and apply a new technology.

Once innovators have successfully adopted an innovation, other early adopters join the diffusion process. They help to trigger a critical mass when adopting the innovation. They are also considered as a role model for other members of the social system. Members of the *early majority* category adopt the innovation just before the average member of the social system. They usually make up one third of the members of the social system. The *late majority* is the same size as the early majority, but these members are usually more skeptical about innovations. Adopting the innovation might be an economic necessity for them as their peers increasingly profit from it. The late majority may also lack financial resources, which slows their adoption. *Laggards* are the last in the social system to adopt the innovation. They are usually rather isolated from their peers and base their decisions more on past experience than future developments. Additionally, they may be in a precarious economic situation that does not permit any failure of an adopted innovation (Rogers, 2003).

Alongside time-dependent factors, time-independent factors also hinder diffusion. According to Rogers (2003), there are five variables that determine the rate of adoption of innovations. First, innovations are perceived as having five attributes (i.e. relative advantage, compatibility, complexity, trialability, and observability). The relative advantage is the degree to which an innovation is perceived as being better than the thing it supersedes. Compatibility is the degree to which an innovation is perceived as consistent with existing values, past experiences, and the needs of potential adopters. Complexity is the degree to which an innovation is perceived as difficult to understand and use. Trialability is the degree to which an innovation can be experimented with on a limited basis. Finally, observability is the degree to which the results of an innovation are visible to others.

While the five attributes of innovations have been investigated extensively, the remaining four variables of the rate of adoption have not received equal attention (Rogers, 2003). These variables are the type of innovation decision (optional, collective, authority), communication channels, the nature of the social system, and the extent of the change agents' promotion efforts.

Besides Rogers' (2003) variables that determine the rate of adoption of innovations, the concept of barriers to and drivers for the diffusion of innovations has been put forward. Drivers and barriers help to explain the varying pace of the diffusion process. Drivers are factors that accelerate the uptake of an innovation, while barriers are factors that impede its adoption (Fleiter et al., 2011). Different taxonomies of drivers and barriers have been developed, although most refer back to the taxonomy of Sorrell et al. (2000) (Brunke et al., 2014; Cagno et al., 2013). They derived a taxonomy of barriers combining findings from orthodox economics, transaction cost economics and behavioural economics. The six main classes of barriers are: risk, imperfect information, hidden costs, access to capital, split incentives, and bounded rationality.

Fleiter et al. (2012a) set up a methodology to derive the drivers for and barriers to the diffusion of energy-efficient technologies based on Rogers' (2003) attributes of innovations. They referred to three attributes (i.e. relative advantage, technical context and information context). Then they assigned several characteristics to the attributes (e.g. lifetime, non-energy benefits). Finally, they classified these characteristics using semi-quantitative categories, e.g. low, medium, high or small and large. Based on this classification scheme, they explained the diffusion rate of four selected energy-efficient technologies.

Chapter 4 uses theses concepts to analyse the underlying factors and investment/innovation behaviour of individual firms in the German iron and steel industry to better understand the barriers to and drivers for technological change. First, the diffusion of three energy-efficient technologies from their introduction until today is analysed on the company/site level as well as the national level. Second, the impact of drivers and barriers on the decisions of individual firms for or against implementing these technologies is explored.

1.6 Future pathways incorporating technological change

1.6.1 Assessment of new technologies

The uptake of new and better technologies plays a key role in improving energy efficiency and reducing CO_2 emissions. New technologies are usually identified through a broad review of literature, international research and development programmes, databases, and studies (Martin et al., 2000). Interviews may be held to obtain additional information and conference papers may be consulted as well. Martin et al. (2000) assessed emerging energy-efficient technologies from 12 industrial sectors plus cross-cutting technologies. They listed 57 technologies and assessed them technologically and economically. They also estimated their likelihood of diffusion.

More recent studies estimating future energy consumption in the iron and steel industry usually refer to other peer-reviewed studies and complement the data with interviews (e.g. Brunke and Blesl, 2014). Workshops with stakeholders (i.e. members from steel companies or plant manufactures) may also be organized. Their outcome is directly incorporated into the studies (e.g. Moya and Pardo, 2013; Fleiter et al., 2013).

International Energy Agency (2009) classified four groups of new technology options for the iron and steel industry. First, coal-based steelmaking processes such as smelting reduction and coal-based direct reduction. Both processes have reached commercialization although at a low adoption rate. The switch to coal-based steelmaking would omit the energy consumption for coke making, but would still require at least 80% of today's coal consumption for steelmaking.

The second option is fuel switching. This group includes the increased use of natural gas (which so far is not an economical option for the European steel industry, at least as long as CO_2 prices are low), the use of charcoal and waste plastics. The latter two are limited by their availability. Third, the use of electricity (based on renewables) is discussed which is assumed to be an option in the medium to long term. The same applies to the use of hydrogen as a reducing agent. Finally carbon capture and storage is mentioned as an option to decarbonize the steel industry by collecting and storing CO_2 terrestrially. Demonstration plants have been delayed.

Chapter 5 reviews promising emerging alternative ironmaking technologies based on literature review and interviews. In total 12 alternative ironmaking technologies are described and compared.

1.6.2 Technological change, future energy demand and CO_2 emissions

Based on the lessons learnt from chapters 2 to 5, chapter 6 assesses the impact of technological change on future energy consumption and CO_2 emissions for the German steel industry. Chapter 2 provides specific energy consumption values which are then converted into CO_2 emissions using CO_2 emission factors. Chapter 3 discusses realistic diffusion rates for energy-efficient technologies in the German steel industry and the rate of adoption of the selected energy-efficient technologies. Chapter 4 provides insights into the decision-making process for adopting innovations and chapter 5 identifies promising innovative and CO_2 reduction technologies for ironmaking.

The future energy demand of steelmaking is primarily driven by the amount of steel produced. Furthermore, the type of steel has a large impact on energy consumption. An increased share of secondary steel would decrease energy consumption. Secondary steelmaking is limited by the availability of scrap and by the quality of steel grades that can be produced. Besides the production level and the share of primary to secondary steel, the diffusion of energy-efficient technologies or the adoption of new technologies also influence the future energy consumption of the steel industry. The blast furnace is the most capital-intensive production facility in primary steelmaking. These usually are run for decades until they reach the end of their technical lifetime. The age of blast furnaces is therefore another main driver of primary steel production.

Carbon dioxide emissions depend heavily on the amount of fossil fuels used (when no CCS is installed). Thus, an increased share of secondary steel would reduce the total CO_2 emissions of the steel industry. A fuel switch to less CO_2-intensive energy carriers would also lead to fewer CO_2 emissions. The switch from coal to natural gas or biomass is one such step. Using renewable electricity would also lower the CO_2 emissions of the steel industry.

Chapter 6 estimates the future energy demand and CO_2 emissions of the German steel industry until 2035. Four production pathways are described 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 lifetime of blast furnaces are considered as well.

Chapter 2

Energy intensity development between 1991 and 2007[1]

Abstract

The iron and steel sector is the largest industrial CO_2 emitter and energy consumer in the world. Energy efficiency is key to reduce energy consumption and greenhouse gas emissions. To understand future developments of energy use in the steel sector, it is worthwhile to analyze energy efficiency developments over the past two decades. This paper analyses the development of the specific energy consumption (SEC) (measured as primary energy use per unit of product) in the German steel sector between 1991 and 2007. The total SEC 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 SEC, or 0.1 %/year. Energy efficiency improvements are found, especially in rolling (1.4 %/year). The net SEC of blast furnaces decreased due to increased top gas recovery by 0.2 %/year per tonne hot metal. Improvements in other processes were very limited or non-existent. In basic oxygen furnaces (BOF) net SEC increased due to a 60 % decrease in BOF gas recovery between 1993 and 2007. In EAF and sinter plants the SEC remained constant or, respectively, even increased by 9 % between 1991 and 2007 per tonne sinter.

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[1] The chapter has been published as Arens, M., Worrell, E., and Schleich, J. (2012): Energy intensity development of the German iron and steel industry between 1991 and 2007. Energy, 45:786-797.

2.1 Introduction

The global iron and steel industry is one of the largest industrial energy consumers and CO_2 emitters. It accounts for about 3 to 5 percent of the global CO_2 emissions (Stahlinstitut VDEh, 2007). Germany is one of the largest steel making countries in the world with a production of nearly 44 million metric tonnes in 2010, making it the largest steelmaker in Europe and the seventh largest in the world (World Steel Association, 2009b).

Energy efficiency is one of the key measures to reduce CO_2 emissions and energy consumption, as well as production costs. Estimating energy performance in the steel industry is a difficult task due to various reasons:

1. Data on the energy consumption of the steel industry on an international level is often not accurate. Therefore, estimating energy efficiency in the steel industry in international comparisons is often surrounded with considerable uncertainties, as shown by Farla and Blok (2001).
2. Tanaka (2008) studied differences in the assessment of the energy performance in the steel industry. She points out that system boundaries of the analysis strongly influence the results. According to her findings the specific energy consumption (SEC) can vary from 16 to 21 GJ/t crude steel depending on the chosen boundaries.
3. Data on the energy consumption in the steel industry is often aggregated at the sector level. Hence, data for the different processes are aggregated, making the calculation of the energy efficiency improvement per process (and over time) not possible.

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. Kim and Worrell (2002) compared energy and CO_2 intensity in the steel sector among seven countries. Farla et al. (1995) analyzed options for the reduction of CO_2 emissions in industrial processes. Studies by the International Energy Agency (e.g. 2007) show on a global level energy savings potentials and energy saving technologies. An in depth description of the production processes in the iron and steel sector, with a particular focus on best available low-emission technologies, may be found in the recent report by the Joint Research Center (2012).

Second, a set of studies exists on the energy performance of the steel industry of selected countries. Worrell et al. (2001) identified energy-efficient technologies for the steel industry in the United States of America. Zhang and Wang (2008) analyzed the influence of two energy-efficient technologies for selected steelworks in China between 1990 and 2000 using data on individual steel plants. 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. 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. Price et al. (2010) analyzed China's Top-1000 program which is designed to reduce energy consumption in the largest industrial companies. Price et al. (2011) evaluated China's 11th Five Year Plan concerning energy efficiency.

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 electric arc furnaces), and of 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 route as well as price-induced efficiency improvements for both routes. Schumacher and Sands (2007) integrated bottom-up information on iron- and steelmaking technologies in a computable general equilibrium model for Germany to simulate macroeconomic effects of energy policies. Dahlmann et al. (2010) present a factsheet on energy efficiency measures including a list of energy-efficient technologies for each type of plant in the steel sector.

Rheinisch-Westfälisches Institut für Wirtschaftsforschung (2010) analyzed the specific energy consumption (expressed per tonne 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 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. Stahlinstitut VDEh (e.g. 2007, 2010) also discuss activities to reduce CO_2 emissions (e.g. diffusion of energy-efficient technologies).

To summarize previous analyses, these are restricted to aggregated levels as there is a lack of data on the process level. The conclusions of these studies are limited by aggregated observations as well, e.g. showing the effect of structural changes on the development of the SEC. Time series of the SEC in the iron and steel sector on the process level have not been published yet. Problems with data consistency occur if data stems form different sources.

In this paper we analyse data of the German Federal Statistical Office on the energy consumption on the process level in the German iron and steel industry between 1991 and 2007. We calculate the SEC per process as primary energy use per unit of product and show the development of the energy efficiency per process in the studied period. As we rely on a single consistent data source and choose a single set of process boundaries we expect accurate results on the development of the SEC, while accounting for the development of energy efficiency in the German iron and steel industry and calculating the impact of an increasing share of EAF. First, we give an introduction of the methods of the analysis, of assumptions and data used for the analysis, followed by a description of the German iron and steel industry. Next, we discuss the development of the SEC by process and for the German iron and steel industry as a whole. We end with discussion and conclusions.

2.2 Methods

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 (Statistisches Bundesamt, 1991-2007). 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 to retiring plants on the territory of the former German Demoncratic Republic. The analysis ends before the economic crisis in 2008/2009 to exclude 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 rolling mills. Since we are interested in the development of the energy efficiency at the process level consumption for transportation, for example, is excluded from 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 the German energy statistics all gases are reported as natural gas equivalent, hence the heating value is similar to that of natural gas (Tab. 2.1). 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 (coke oven gas, COG; blast furnace gas, BFG; basic oxygen furnace gas, 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, hot metal, EAF-steel, BF/BOF-steel, and hot rolled steel, respectively.

We calculate the specific energy consumption for each product (Eq. 2.1):

$$SEC_{j,k} = \frac{\sum_i EC_i \times m_{i,k}}{x_{j,k}} \tag{2.1}$$

SEC_j	specific energy consumption for product j in year k,
EC_i	heating value or the energy needed to produce energy carrier i,
$m_{i,k}$	amount of energy carrier i to produce product j in year k,
$x_{j,k}$	production of product j in year k.

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* (Statistisches Bundesamt, 1991-2007) 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.

Table 2.1: Assumed heating values.

Fuel/energy carrier	Abbr.	Value	Unit	HV/EC	Source
Hard coal, -briquettes [a)]	HC	29.31	GJ/t	HV	d)
Coke	CK	28.43	GJ/t	HV	d)
Coke breeze	CB	28.43	GJ/t	HV	d)
Other solid fuels	OSF	25.00	GJ/t	HV	b)
Liquid fules	LF	40.61	GJ/t	HV	d)
Steam		2.80	GJ/t	EC	b)
Blast furnace gas	BFG	35.17	GJ/1000m^3	HV	c)
Coke oven gas	COG	35.17	GJ/1000m^3	HV	c)
Natural gas	NG	35.17	GJ/1000m^3	HV	c)
Basic oxygen furnace gas	BOFG	35.17	GJ/1000m^3	HV	c)
Other gases	OG	35.17	GJ/1000m^3	HV	c)
Oxygen		7.33	GJ/1000m^3	EC	b)
Electricity		10.43	GJ/MWh	PE	–

a) The heating value for hard coal varies slightly over time. Nevertheless, our analysis assumes a constant heating value for hard coal since it focuses on the development of energy efficiency at the process level. Also, from an empirical perspective, the heating values for coke and coke breeze hardly change over time.
b) Ghenda (2011)
c) Statistisches Bundesamt (2011)
d) Statistisches Bundesamt (1991-2007)

HV	Heating value
EC	Energy consumption to produce that energy carrier
PE	Primary energy terms

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 (Tab. 2.1). 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 are 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 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 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).

2.3 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 other route uses scrap as raw material and re-melts 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. In direct reduction iron ore is reduced 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 0.5 million tonnes (or about 1 % of German crude steel production). Worldwide 64.7 million tonnes of DRI was produced in 2007, equivalent to a share of 5 % of world crude steel production (World Steel Association, 2009b).

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 2.1 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 (International Iron and Steel Institute, 1998). 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

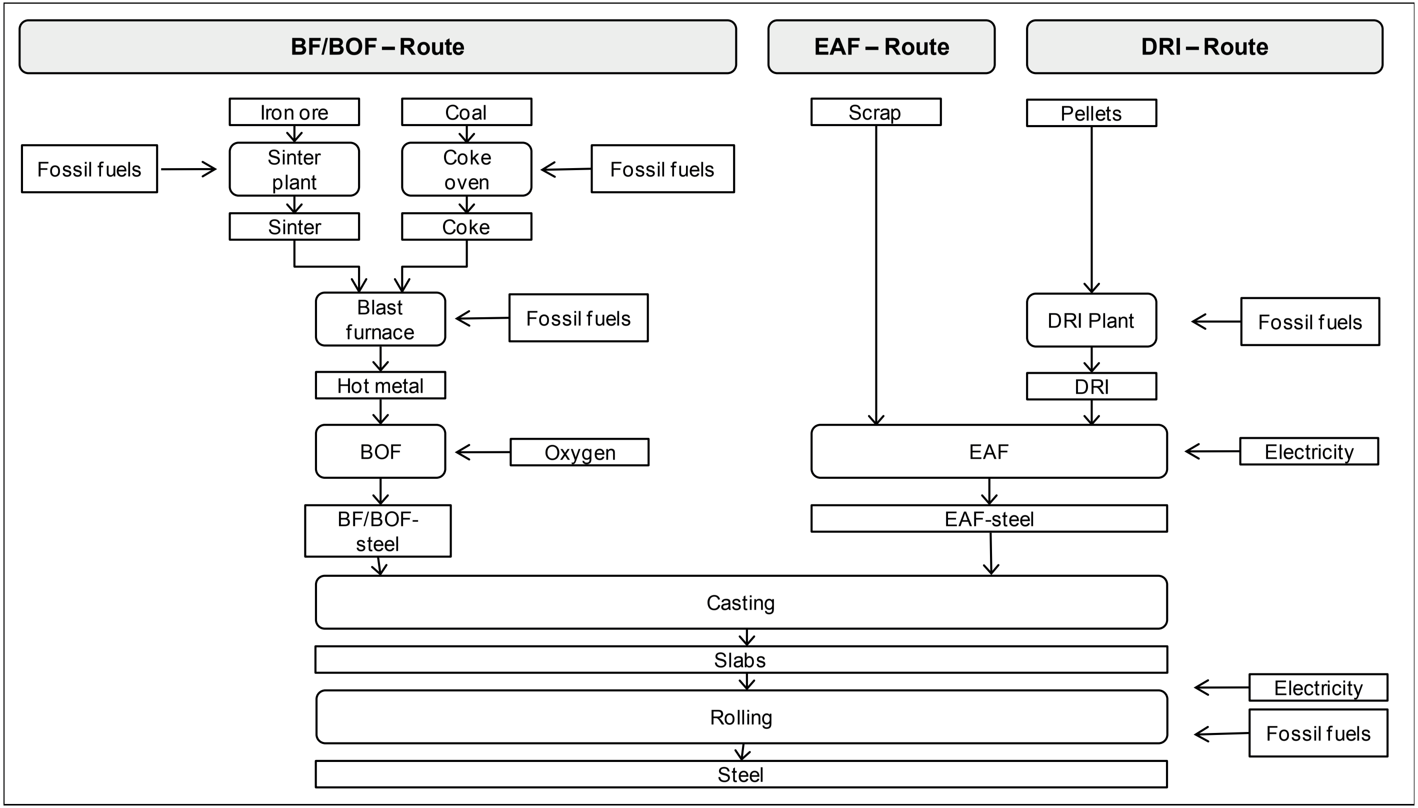

Figure 2.1: Steel production routes in Germany.

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 hot metal (Fe) with the help of carbon (C) that 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/Nm^3 (Brauer, 1996). Hot metal contains about 4 % carbon.

To produce crude steel, which contains about 1.5 % carbon (or less) hot metal is fed to the basic oxygen furnace (BOF). 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 (Brauer, 1996). Basic oxygen furnace gas (BOFG) is produced, containing about 70 % carbon monoxide (CO) and has a heating value of about 9 MJ/Nm^3 (Brauer, 1996). 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 2.2 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 with the energy conversion sector.

Electric arc furnace route

To recycle steel, scrap is melted in the electric arc furnace. 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 and 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.

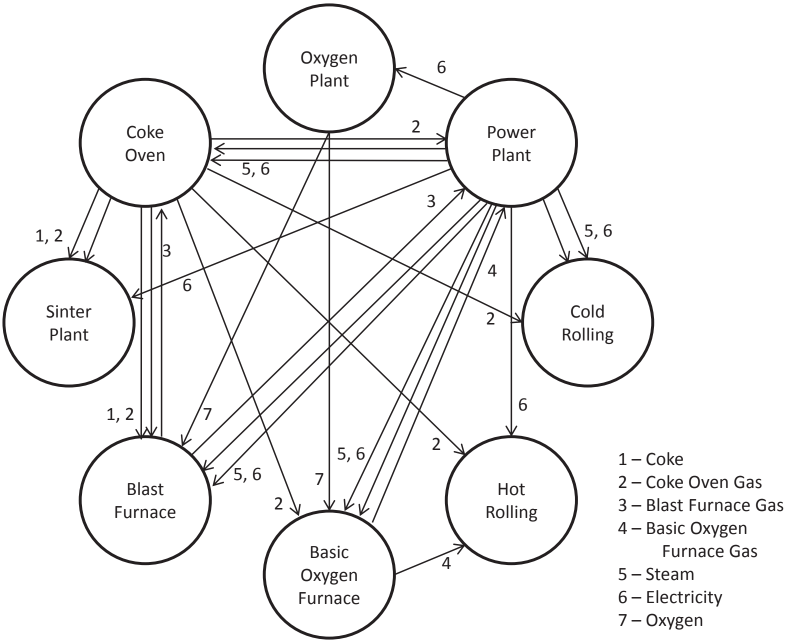

Figure 2.2: Energy flows in an integrated steel work (source: Stahlinstitut VDEh, 2010).

In energy statistics 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 (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009).

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. Cold rolling includes pickling, rolling, annealing and skin pass rolling in order to produce coils with a gauge as low as 0.15 mm (International Iron and Steel Institute, 1998).

Steel production by process in Germany 1991-2007

While the production of BF/BOF steel varied between 29 and 33.5 million tonnes per year, the production of EAF-steel increased constantly from 8.5 to 15.0 Mt/year between 1991 and 2007 (Fig. 2.3).

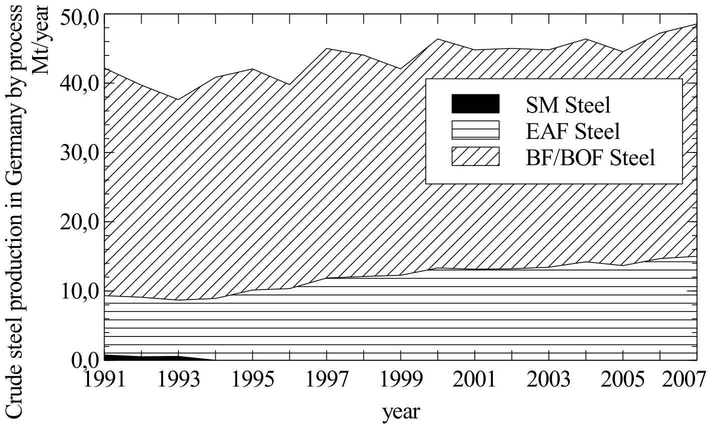

Figure 2.3: Crude steel production by process in Germany (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009).

From 1991-1993 there was 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. With 0.8, 0.5 and 0.6 million tonnes Siemens-Martin-steel production had a share of 1.3 to 1.8 % of the total steel production in Germany in those years (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009).

2.4 Results

2.4.1 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 12 % 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.

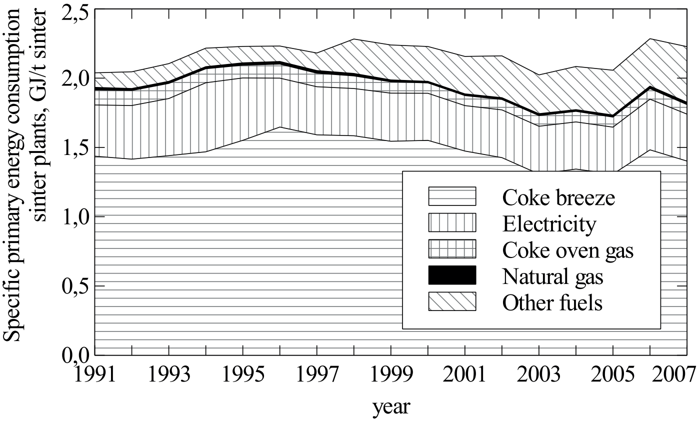

Figure 2.4: Specific primary energy consumption in sinter plants.

Figure 2.4 shows the development of the SEC of sinter and ore preparation plants per tonne 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 0.20 GJ/t sinter and its share increased till 2007 to 0.30 GJ/t sinter. Between 1998 and 2007 hard coal accounts for 60 to 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. Stahlinstitut VDEh (2010) assumes that the increased energy intensity in sinter plants since 2003 is due to increased basicity (CaO/SiO_2) of the used ores (2003: 1.72, 2007: 2.07).

2.4.2 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 (Statistisches Bundesamt, 2011).

Due to confidentiality, we neglect the use of basic oxygen furnace gas, coke breeze and other solid fuels. 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 2.5 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 10.18 GJ/t though in 2006 and 2007 its consumption increased slightly again. In 2007 coke makes up 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). This gas 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 produced. Seven out of 15 blast furnaces in Germany were equipped with top-pressure recovery turbines (TRT) in 2007 (Ghenda, 2011). The remaining blast furnaces were either too small, had a too low pressure, or were planned to be equipped with a TRT (Ghenda, 2011). In this study the electricity output of the TRTs is not treated as a credit, as its production value is summed up with the electricity output of the onsite power plants. Hence, no time series of the TRT electricity output is available. Yet for the year 2003 its production is published and has a value of 440 GWh, which equals 0.05 GJ per tonne hot metal or 5.8 % of the electricity consumed in blast furnaces (Stahlinstitut VDEh, 2007). Up to 0.4 GJ/thm electricity can be generated by TRT (Joint Research Center, 2012). Figure 2.6 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.

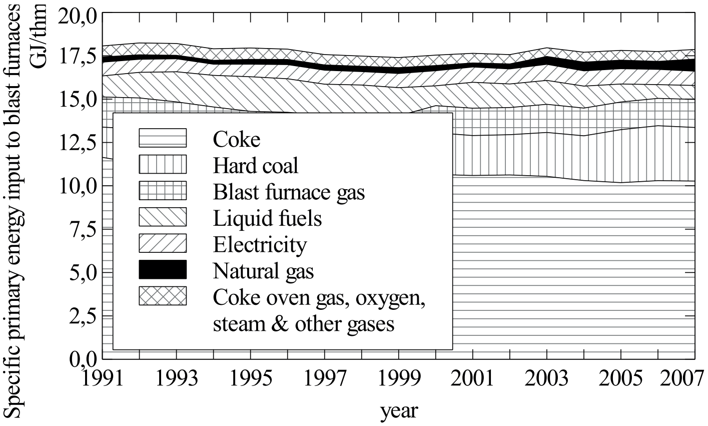

Figure 2.5: Specific primary energy input to blast furnace operations.

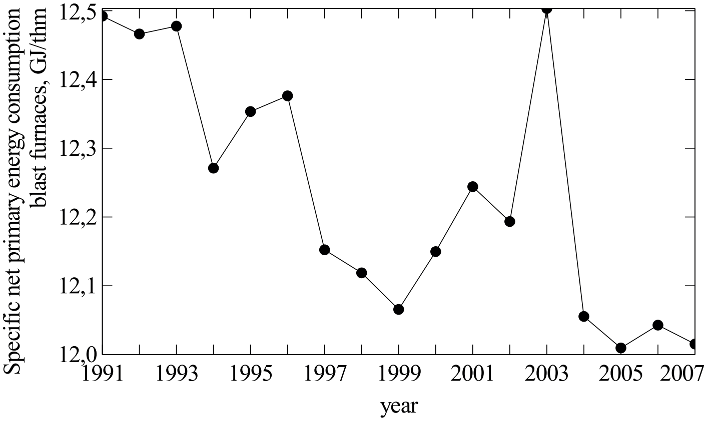

Figure 2.6: Specific net primary energy consumption in blast furnace operations.

2.4.3 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 (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009).

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 first published in 1993. Hence we analyze the net energy consumption from 1993 onwards, while we show the specific energy input from 1991 onwards.

Figure 2.7 shows the specific energy input in 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 2.8 shows the specific net energy consumption of BOFG in Germany between 1993 and 2007. We found a net SEC for 1993 to 1995 and 1995 to 2007 of about 0.39 GJ/t BOF-steel and about 0.61 GJ/t, respectively, which equals an increase of about 56 %.

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 1999 the specific energy input increased by 8 % and this level was roughly kept till 2007. Main drivers for this development were an increase in the consumption of electricity and steam.

Figure 2.9 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 three BOFs have been shut down (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009). According to the Stahlinstitut VDEh among these three BOFs have been some with BOFG recovery. Currently only about 60 % of the BOFs in Germany are equipped with BOFG recovery systems (Ghenda, 2011).

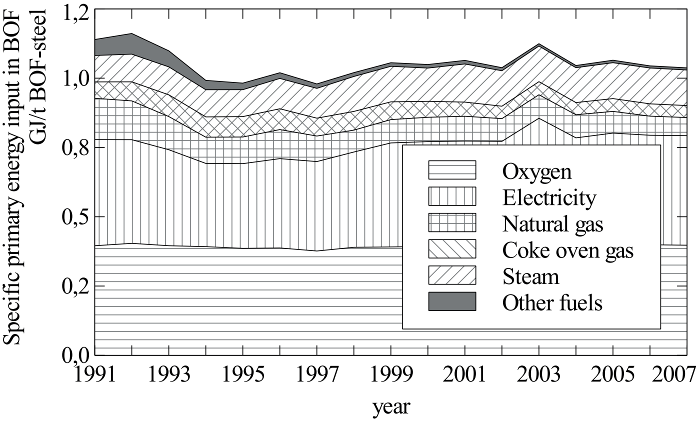

Figure 2.7: Specific primary energy input to basic oxygen furnaces.

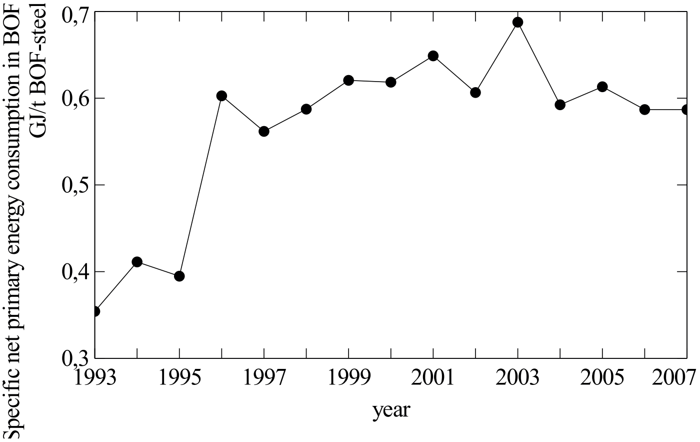

Figure 2.8: Specific net primary energy consumption in basic oxygen furnaces.

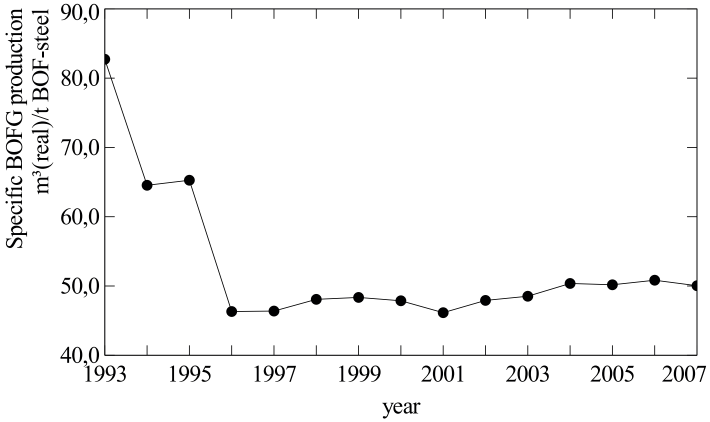

Figure 2.9: Specific production of basic oxygen furnace gas.

2.4.4 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 contained a Siemens-Martin-Furnace from 1991 to 1993 which was run on the territory of the former German Democratic Republic and was shut down in 1993. In the data we cannot distinguish electric arc furnaces from Siemens-Martin-Furnaces therefore we start our analysis of electric arc furnaces in 1994. The name of the group was changed in 2003 to *electric steel works*. Hence 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 studied period, we see no real improvement in energy efficiency of electric steel works in Germany between 1994 and 2007.

Figure 2.10 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 account for 5 to 7 % and 3 to 4 % respectively. Steam and other fuels amount for 2 to 3 %. In 2006, the same amount of electricity per tonne 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.

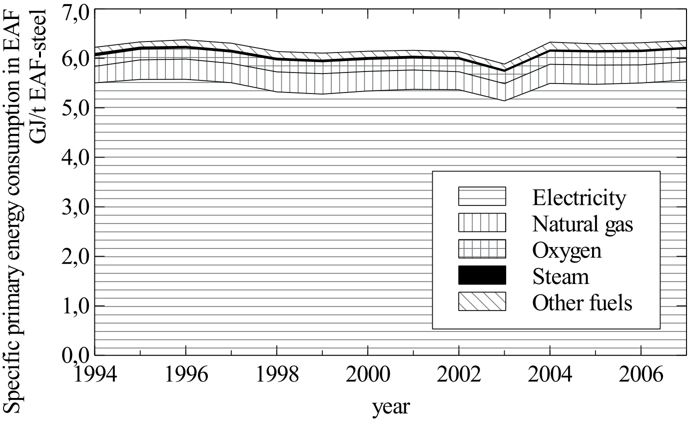

Figure 2.10: Specific primary energy consumption in electric arc furnaces.

We would have expected at least slight energy efficiency improvements 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 specific energy consumption of electric arc furnaces to evaluate this hypothesis.

2.4.5 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 (Statistisches Bundesamt, 2011). 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 (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009). A decrease in the share of cold rolled steel can lead to a reduction in the specific energy consumption per tonne 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 decrease in energy intensity of about 1.4 % per year for nearly all energy carriers, although especially for coke oven gas and electricity.

The main energy carriers are natural gas and electricity which amount for 1.24 to 1.52 GJ/t and 1.51 to 1.83 GJ/t respectively (Fig. 2.11). 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 17 % or 1.0 % per year. The specific consumption of coke oven gas decreased continuously even stronger from 1.02 GJ/t to 0.38 GJ/t or 3.7 % per year. The use of steam and oxygen was reduced by 2.1 % and 2.9 % 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.

Several technological and logistic improvements contributed to the continuous decrease in the specific energy consumption. First, improved process management, and, secondly, the replacement of recuperative burners by regenerative burners helped to reduce the specific fuel consumption (coke oven gas, natural gas). Due to improved logistics less waste was produced and therefore an improvement in energy efficiency was achieved. The usage of oxygen furthermore contributed to a decrease of the SEC (Ghenda, 2011). Apart from these technological or logistic improvements the increase in the import of semi-finished products or a decreasing share of cold rolled steel could influence the reduction of the specific energy consumption in rolling. To evaluate this effect a detailed study of the imports of semi-finished products and the development of the cold rolled steel production in the studied period would be necessary, which is a topic for further study.

2.4.6 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 tonne crude steel. While the production of BF/BOF-steel remained between 30 and 34 million tonnes per year, the production of EAF-steel nearly doubled from 8.9 million tonnes to 15 million tonnes per year (Fig. 2.3). The share of EAF increased from 21.8 % to 30.9 %.

Figure 2.12 shows the influence of the increase in the share of EAF production on the development of the SEC in Germany between 1994 and 2007. The dark line represents the development of the specific energy consumption per tonne crude steel based on the

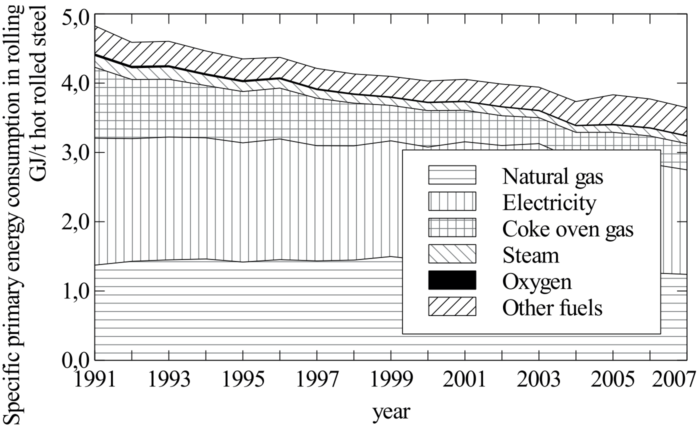

Figure 2.11: Specific primary energy consumption in rolling.

specific (net) energy consumption in blast furnace operations and electric arc furnaces. For the studied period we obtain a total decrease of 6.3 % of the SEC per tonne of crude steel, which equals an improvement of about 0.4 %/year.

The dotted line represents the hypothetic development of the specific energy consumption per tonne crude steel for the case that the specific energy consumption per tonne BF/BOF steel and EAF-steel remained constant at 1994 levels, and only the production values are changing. Now we can show the influence of an increasing share of EAF on the specific energy consumption per tonne crude steel. Efficiency improvements are not considered in the dotted line. We obtain that the specific energy consumption per tonne 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 tonne crude steel was reduced by 0.3 % 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.

2.5 Discussion

The specific energy consumption per tonne crude steel in the German steel industry decreased by 6.3 % of which 4.6 % between 1994 and 2007, or 0.3 % per year. This decrease in the SEC per tonne crude steel originates from the increase in the share of EAF production. Other effects among which energy efficiency improvements are an option, result in a decrease in the specific energy consumption of 0.1 %/year.

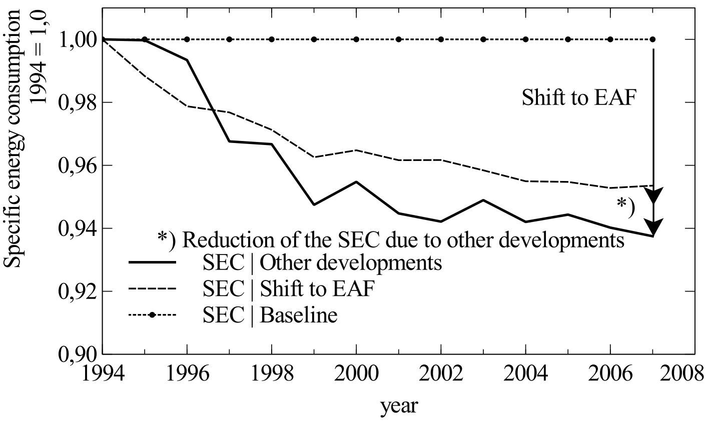

Figure 2.12: Influence of a production shift to electric arc furnaces on the reduction of the energy consumption per tonne crude steel in Germany.

In rolling the SEC decreased continuously in the studied period by 1.4 % per year. Yet in this study we cannot investigate the effect of production shifts or of increased shares of semi-finished products. The specific net energy consumption per tonne hot metal also decreased continuously but due to an increase of the top-gas-production, which we treated as a credit. The specific energy input in blast furnace operations was in 2007 of about the same order than in 1991, without considering credits for electricity production from top-pressure recovery turbines. The specific net energy consumption of basic oxygen furnaces increased strongly between 1993 and 1996 due to a decrease in the BOFG production. In electric arc furnaces the SEC remained relatively constant between 1994 and 2007. In sinter production the specific energy consumption even increased comparing 2007 to 1991.

These findings are based on data from the German Federal Statistical office on the energy consumption in the iron and steel industry in Germany between 1991 and 2007. In their quality report on the statistics a relatively high accuracy is assumed, as data is based on information from all steel producers in Germany and not just from a selected sample (Statistisches Bundesamt, 2011). Furthermore data was collected monthly and all data was validated based on the long-term experience of the institution. Finally, fluctuations in the sector are seldom, except for closure or mergers of companies.

Production data was obtained from Stahlinstitut VDEh and can be considered as the most accurate data available (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009). Nevertheless, in our study there are two caveats. First, misallocation from production data to the statistical group can cause inaccuracies. As mentioned in 2.4.1, the statistics allocate the energy consumption of sinter plants and ore preparation plants in one group, while our analysis assigns only the production of sinter to this group. Furthermore, hot rolling and cold rolling are summed in a single group in the statistics, but we only consider hot rolled steel for the calculation of the SEC. Second, further uncertainties lie in the assumption of heating values and the set of boundaries. As our key analysis is the time series of the SEC, these uncertainties do not matter.

Publications from Stahlinstitut VDEh on the SEC per product show similar results with similar tendencies as our research shows (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2009). It publishes a reduction of the SEC per tonne crude steel between 1994 and 2007 of 10.3 %, which equals 0.8 % per year and it uses a different method to calculate the SEC though they rely on the same data sources. It does not consider BFG and BOFG energy credits, neglecting the onsite consumption of these gases. Furthermore steam consumption is neglected.

While differences in methodology and system boundaries do not allow for a quantitative comparison of our results to those found for other countries, we nevertheless present key findings from the seminal studies analysing the development of energy efficiency in the production of iron and steel in other countries than Germany. Kim and Worrell (2002) provided CO_2 intensities for the iron and steel industry in selected countries. They showed slight increases in the CO_2 intensities from 1991 till 1994/1996 for India, China, the US, and Brazil. Only CO_2 intensities for Mexico and Korea were slightly decreasing. Wei et al. (2007) found that the energy efficiency in the iron and steel sector in China improved by 6.7 % per year between 1994 and 2003. Zhang and Wang (2008) published a decreasing SEC in the Chinese iron and steel industry of about 4.3 % between 1990 and 2000. Guo and Fu (2010) showed that the SEC per process in the Chinese steel industry decreased constantly for virtually each process between 1995 and 2005. Only the efficiency of blast furnaces decreased from 2000 onwards. Note that slight differences in system boundaries may affect the comparison of the trends. Hence, comparisons of trends should be done with care.

Energy efficiency of the processes in the German iron and steel industry between 1991 and 2007 did not improve significantly, apart from rolling. We identified a potential to increase the recovery of BOFG. Assuming that energy efficiency would improve continuously over time due to the diffusion of new technologies (e.g. strip casting, top gas recycling blast furnace, smelting reduction, heat recovery from electric arc furnaces, heat recovery from slag) and improved process management, we expect further potential to improve energy efficiency. Therefore, we suggest detailed studies on the remaining potential to identify energy efficiency improvement options and study the diffusion of best practices, both in technology and management/operation.

Finally, a similar empirical analysis as presented in this paper could be extended to also include the years of the recent financial crisis (2008/2009). Such an analysis may be expected to provide valuable insights into the effects of capacity utilisation on energy intensity in the iron and steel sector.

Chapter 3

Diffusion of energy-efficient technologies and their impact on energy consumption[2]

Abstract

We try to understand the role of technological change and diffusion of energy-efficient technologies in order to explain the trend of energy intensity developments in the German steel industry. We selected six key energy-efficient technologies and collected data to derive their diffusion since their introduction in Germany. Since all technologies have been applied in Germany for more than 30 years we would expect complete diffusion. We found complete diffusion only for basic oxygen furnaces and continuous casting. Newer technologies (i.e. basic oxygen furnace gas recovery, top pressure recovery turbine, coke dry quenching and pulverized coal injection) diffused quicker in the initial phase but then diffusion slowed down. Key improvements in energy efficiency are due to electric arc furnaces (24 %), basic oxygen furnaces (12 %), and continuous casting (6 %) between 1958 and 2012. The contribution of top pressure recovery turbines, pulverized coal injection and basic oxygen furnaces gas recovery accounts in total of about 3 %. If the selected technologies were diffused completely, the future energy consumption could be reduced by 4.5 % compared to 2012. Our findings suggest that our selection of six technologies is the key driver for energy intensity developments within the German steel industry between 1958 and 2012.

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[2] The chapter has been published as Arens, M. and Worrell, E. (2014): Diffusion of energy efficient technologies in the German steel industry and their impact on energy consumption. Energy, 73:968-977.

3.1 Introduction

Previously we studied the energy intensity development of processes in the German steel industry between 1991 and 2007, i.e. the period after German reunification and before the economic crisis in 2008/2009 (Arens et al., 2012). We found that only the primary energy efficiency of rolling improved by 1.4 % per year. In blast furnaces the specific energy consumption decreased due to an increased production and recovery of its top gas. In other processes (i.e. sinter production, steelmaking, and electric arc furnaces) we found changed energy intensity, but no continuous improvements.

In this paper we try to understand the role of technological change and diffusion of energy-efficient technologies to explain the trend in energy efficiency improvements. Historic diffusion rates and the impact of these technologies on energy intensity developments should be considered for both an accurate estimation of remaining energy efficiency potentials as well as for policy design. This paper aims to shed some light on the diffusion of key energy-efficient technologies in the German steel sector and the impact of these technologies on energy intensity developments. We further give an estimation of the remaining energy efficiency potential for the assumption the investigated technologies were diffused completely.

In literature, the diffusion of continuous casting machines (CCM) and basic oxygen furnaces (BOF) is well known (International Iron and Steel Institute, 1998; Poznanski, 1983; Oster, 1982). The diffusion of top-pressure recovery turbines (TRT) and coke dry quenching (CDQ) has been studied in detail for China and Japan (Oda et al., 2007; Okazaki and Yamaguchi, 2011). Still little has been published on the diffusion of pulverized coal injection (PCI) and BOF gas recovery (BOFGR) and the overall contribution of diffusion to energy efficiency improvement. Also, little is known about the diffusion of energy-efficient technologies in the German steel sector and impact on energy use. Today, many analyses of the energy efficiency potentials use experts' judgements on diffusion rates (Tanaka et al., 2006).

This paper aims to study the diffusion of key energy-efficient technologies in the steel industry and their impact on energy intensity. We evaluate whether the diffusion of energy-efficient technologies follow an s-shaped curve, as proposed by Tarde (1903) (Rogers, 2003). We selected six technologies and collected data to derive their diffusion since their introduction in Germany. We present diffusion rates of the technologies which were introduced between the 1950s to the early 1980s. The technologies belong mainly to the primary steel making route. All technologies have been applied in the German steel industry for more than 30 years. Hence, we would expect complete diffusion of all technologies. The technologies are the basic oxygen furnace (BOF), continuous casting machines (CCM), top-pressure recovery turbine (TRT), basic oxygen furnace gas recovery (BOFGR), coke dry quenching (CDQ) and pulverized coal injection (PCI). We estimate the impact of the diffusion of these technologies and electric arc furnaces (EAF) on the primary energy consumption per tonne crude steel over the whole period. Finally, we estimate the remaining energy efficiency potential for the case the investigated technologies reached complete diffusion. The paper provides analysts and policy advisors with a deeper understanding of the diffusion of energy-efficient technologies in heavy industries and the impact on energy intensity. The paper is organized as follows. Section 3.2 provides a review of the literature on the diffusion of technologies and steel sector specific diffusion studies. The methods and the results of the investigated technologies are presented in section 3.3 and 3.4. The final section provides conclusions.

3.2 Literature review

Research on the diffusion of innovations over the recent decades provides a large amount of literature. Fundamental research has been done by Rogers (2003). He defined four elements of diffusion (i.e. the innovation, communication channels, time, and a social system) and analysed the generation and implementation of innovations in detail. Freeman and Soete (1998) analyzed the impact of industrial innovations from the perspective of the firm as well as from a macro-economic perspective. They found that the firm size has an impact on the adoption of innovations. Tarde (1903) found that the rate of adoption of a new idea usually follows an s-shaped curve over time (Rogers, 2003).

The diffusion of the BOF has been studied, both using data on the national level (Poznanski, 1986; Ray, 1989) and on the plant level (Oster, 1982; Rosegger, 1980). Rosegger (1980) gave an in-depth analysis of the diffusion of BOF in comparison to its predecessor, the open hearth furnace (OHF). He took a sample of five U.S. steel companies and investigated the characteristics of the newly introduced BOF concerning its expected effects, costs, and system-specific conditions. Oster (1982) found that large firm size accelerate the diffusion of innovation in the steel industry. Though, according to her findings, the diffusion of the BOF in the U.S. steel industry is much slower than in the Japanese steel industry. Poznanski (1983) studied the fade out of OHF that were substituted by BOF. According to his findings extinguishing an obsolete process technology in the steel industry takes about 13 years. The pace of extinguishing the OHF has an impact on the diffusion rate of its successor (i.e. BOF). Ray (1989) studied the diffusion of mature technologies in industry, which are not necessarily energy-efficient technologies. Among other technologies he studied the BOF and CCM. Overall, he found three major factors driving the diffusion of technologies: profitability, management's attitude towards innovation, and access to capital.

Worrell and Biermans (2005) tracked the diffusion of new EAF plants in the U.S. between 1990 and 2002. They established a database on each individual EAF plant covering information such as production capacity, year of start-up and electricity use. They found that stock turnover and retrofit are essential parameters in energy efficiency improvements, since new plants are more efficient than older plants. Furthermore, they found the impact of stock turnover to be more important than the impact of retrofit. Moya and Pardo (2013) collected data of the steel industry on the plant level of all EU-27 member countries. In their model the future diffusion of energy-efficient technologies depends on the development of the payback period. They find a strong diffusion of best available technologies from 2010 to 2013 which to their findings will lead to a reduction of 0.27 t CO_2 /t crude steel or 3.6 % per year.

Studies on other energy efficiency potential use experts' judgements on the diffusion of current energy-efficient technologies. Tanaka et al. (2006) estimate the remaining global energy efficiency potential for the steel industry. Oda et al. (2007) developed a world energy model which models steel making routes in detail. Besides considering current energy-efficient technologies it also includes emerging technologies. To model the future diffusion of the technologies they assume diffusion rates for the selected technologies for the year 2000 and for each investigated region or country. For the non-policy scenario they find a worldwide diffusion of about 50 % for TRT and CDQ and a 42 % diffusion of BOFGR for the year 2015. All calculated diffusion rates are increasing continuously. Okazaki and Yamaguchi (2011) estimate the possible overall CO_2 emission reduction potential of selected technologies in the steel industry. They assume full diffusion of these technologies and calculate the CO_2 reduction.

In summary, most studies on the diffusion of EET in the steel industry focus on one or two technologies. The diffusion of BOF and CCM has been studied in detail, as for these technologies statistics are available, in contrast to other technologies. The diffusion of TRT and CDQ has been studied mainly for China and Japan (Oda et al., 2007; Okazaki and Yamaguchi, 2011). So far, there are no studies that estimate the diffusion rates of EET for the steel industry in Germany.

Our paper provides an in-depth analysis on the diffusion of six key energy-efficient technologies for the iron and steel industry in Germany using both data on the national level and on the plant level. Our study covers a time period of 60 years. We explain the impact of these technologies on the energy intensity development. Based on the diffusion rates we estimate the remaining energy efficiency potential if all technologies were diffused completely.

3.3 Methods

3.3.1 Diffusion rates

We focus on proved and key energy-efficient technologies (EET). We select energy-efficient technologies exceeding a specific energy saving potential of 0.1 GJ/t of product in order to detect an effect on the primary energy consumption per tonne crude steel. The energy intensity of the steel industry often is expressed as energy consumption per tonne crude steel. This approach does not distinguish between the two main steelmaking processes, i.e. BF/BOF and EAF steelmaking route. The EAF steelmaking route consumes only about one third of the energy of BF/BOF steelmaking. Thus, we include the diffusion of EAF steelmaking in the analysis of the impact of the diffusion of EET on the specific energy consumption.

We developed the diffusion rates based on two approaches. For the diffusion rates of BOF, CCM, PCI, BOFGR and EAF we collected data on the national level, such as steel produced by CCM or coal input to blast furnaces. The diffusion rates of TRT and CDQ are established using data on the plant level. We set up a database with all blast furnaces and coke ovens which were operated from 1979 and 1984, respectively, until today. We collected data of all entries and exits of the respective plants in the investigated timeframe. Then we collected data in which year the selected technology was installed or removed from that plant following the approach by Worrell and Biermans (2005). We used sources such as reports and databases by the Steelinstitute VDEh, scientific papers, press releases by companies, interviews with steel companies, and reference lists by technology suppliers. Whenever possible we triangulated the data. To each technology we assigned a maximum diffusion rate based on the characteristics of the German steel industry.

The diffusion rate DR of a technology i in the year k is the quotient of the diffusion D in the year k and the maximum diffusion D_{max} (Eq. 3.1):

$$DR_i(k) = \frac{D_i(k)}{D_{i,max}} \tag{3.1}$$

where

$DR_i(k)$	diffusion rate of a technology i in year k,
$D_i(k)$	diffusion of a technology i in year k,
$D_{i,max}$	maximum diffusion of a technology i.

Table 3.1 shows the definitions of the diffusion rates $DR_i(k)$ of the selected EET and EAF steelmaking.

Table 3.1: Overview on the definitions of the diffusion rates of the selected energy-efficient technologies and secondary steelmaking.

Technology	Definition of $DR_i(k)$	Variables	Explanation
EAF, CCM	$DR_i(k) = \frac{P_i(k)}{\sum_j P_j(k)}$	$P_i(k)$	Production of EAF steel per steel produced by CCM in the year k
		$\sum_j P_j(k)$	Production of crude steel by process j in the year k
		j	Thomas-, Bessemer-, Siemens-Martin-, BOF-, EAF-steelmaking (crude steel production processes)
		i	EAF, CCM
BOF	$DR_i(k) = \frac{P_i(k)}{\sum_j P_j(k) - P_{EAF}(k)}$	$P_i(k)$	Production of BOF steel in the year k
		$P_{EAF}(k)$	Production of EAF steel in the year k
		i	BOF
BOFGR	$DR_i(k) = \frac{P_i(k)}{P_{i,max}(k)}$	$P_i(k)$	National average of the production of BOFGR per tonne BOF steel in the year k
		$P_{i,max}(k)$	Maximum production of BOFGR per tonne BOF steel in the year k
		i	BOFGR
PCI	$DR_i(k) = \frac{CON_{PC}(k)}{CON_{PC,max}(k)}$	$CON_{PC}(k)$	National average of the coal consumption in blast furnaces per tonne hot metal
		$CON_{PC,max}(k)$	Maximum consumption of coal in blast furnaces per tonne crude steel in the year k
		i	PCI
CDQ, TRT (1991-2012)	$DR_i(k) = \frac{CAP_i(k)}{CAP_{i,max}(k)}$	$CAP_i(k)$	Blast furnace/coke oven capacity equipped with TRT/CDQ in the year k
		$CAP_{i,max}(k)$	Maximum capacity of blast furnaces/coke ovens which could be equipped with TRT/CDQ in the year k
		i	TRT, CDQ
TRT (1978-1990)	$DR_i(k) = \frac{P_{el,i}(k)}{P_{el,i,max}(k)}$	$P_{el,i}$	Specific electricity production by TRT
		$P_{el,i,max}(k)$	Maximum specific electricity production by TRT
		i	TRT

3.3.2 Primary energy consumption of EAF steelmaking route

The diffusion of EAF affects the specific energy consumption per tonne crude steel. Its impact depends on the specific energy consumption of the EAF steelmaking route, a reference energy consumption of primary steelmaking at the beginning of the investigated period, i.e. 1958 (section 3.3.5) and the efficiency of electricity production. Especially the last increased over the studied period. Thus for estimating the energy savings potential of the EAF steelmaking route we need to estimate its specific primary energy consumption from 1958 till today.

Fandrich et al. (2009) numbers the specific final electricity consumption of electric arc furnaces with 630 kWh/t in 1965. Kirschen et al. (2009) publish a specific final energy consumption including both electricity and fuels of 700 kWh/t. Thus, EAFs used approximately 70 kWh/t of fuels in 1965.

Statistisches Bundesamt (1991-2007) publishes electricity and fuel consumption in EAFs. According to this data source the specific electricity consumption was about 561 kWh/t and 554 kWh/t in 1991 and 2009, respectively. Fuel consumption ranged between 141 and 155 kWh/t in 1994 and 2009, respectively. Thus, the specific final energy consumption of EAFs was about 668 kWh/t in 1994 and 709 kWh/t in 2009.

For the year 2010, which still was characterized by the economic crisis, we assume a specific electricity consumption of 565 kWh/t and a specific fuel consumption of 265 kWh/t in EAFs. For the years 1958 to 1964 and for 2011 to 2012 we assume the same values as for 1965 and 2007, respectively. We assume a linear trend between the specific electricity consumption in 1965 and 1990. Furthermore, we assume a specific final energy consumption of 700 kWh for 1958 to 1980. The values for the specific final energy consumption from 1981 to 1990 are assumed to develop linear. The specific fuel consumption results as the difference between the specific final and the specific electricity consumption.

We assume the efficiency of electricity production with 29 % (1958) and 35 % (2012) (Rheinisch-Westfälisches Institut für Wirtschaftsforschung, 2010). We assume linear development for the years in between.

In order to estimate the primary energy consumption of the EAF steelmaking route we assume additional energy consumption for ingot casting (1.8 GJ/t), since the diffusion of CCM is modeled as a separate case. The specific primary energy consumption of the EAF steelmaking route $SEC_{EAF,prim}(k)$ in the year k is calculated according to (Eq. 3.2):

$$SEC_{EAF,prim}(k) = SEC_{EAF,fue}(k) + \frac{SEC_{EAF,el}(k)}{Eff_{el,pro}(k)} + SEC_{IC} \tag{3.2}$$

where

$SEC_{EAF,prim}(k)$	specific primary energy consumption of EAF steelmaking in year k,
$SEC_{EAF,fuel}(k)$	specific fuel energy consumption in EAFs in year k,
$SEC_{EAF,el}(k)$	specific electricity consumption in EAFs in year k,
$Eff_{el,pro}(k)$	efficiency of electricity production in year k,
SEC_{IC}	specific primary energy consumption for ingot casting.

Thus the primary specific energy consumption of EAFs ranged from 8.10 GJ/tls in (1958) to 6.10 GJ/t in 2012.

3.3.3 Energy saving potentials

In order to estimate the impact of the diffusion of the selected EET on the specific energy consumption (SEC) per tonne crude steel we assign energy saving potentials to each technology (ESP).

The energy saving potential of the EAF steelmaking route results as the difference between the reference energy consumption for primary steelmaking (REC) and the specific primary energy consumption of the EAF (secondary) steelmaking route (Eq. 3.3).

$$ESP_{EAF}(k) = REC - SEC_{EAF,prim}(k) \tag{3.3}$$

where

$ESP_{EAF}(k)$	energy saving potential of the EAF steelmaking route in the year k,
REC	reference primary energy consumption,
$SEC_{EAF,prim}(k)$	specific primary energy consumption of EAF steelmaking in year k.

The energy saving potential of the EAF steelmaking route is a function of time since we consider the efficiency improvement in electricity production as well as year specific electricity and fuel consumption of EAFs for the years 1990 (1994) to 2009.

The energy saving potential of BOF steelmaking results as the difference between the specific energy consumption for Thomas, Bessemer or Siemens-Martin steelmaking and the energy consumption of BOF steelmaking. The specific energy consumption for Thomas/Bessemer and Siemens-Martin steelmaking is roughly numbered with 5.0 GJ/t (International Energy Agency, 2007) while the BOF is assumed to provide a surplus

Table 3.2: Characteristics of the selected technologies.

Technology	**Type**	**Process**	**First introduction in Germany**	**Specific energy saving potential**	**Specific energy savings**
				GJ/t	**GJ/tls**
EAF route	PS	Steel	Mid 1950s	20.94 (1958) ... 22.94 (2012)$^{5)}$	20.94 (1958) ... 22.94 (2012)
BOF	RE	Steel	1958	5.30 GJ/tls$^{1),4),7)}$	5.30
CCM	RE	Steel	1964	1.73 GJ/tls$^{2),\ 4)}$	1.73
TRT	AO	Iron	1979	0.11 GJ/thm$^{2),8)}$	0.11
BOFGR	AO	Steel	1982	0.91 GJ/tls$^{2)}$	0.91
CDQ	AO	Coke	1984	1.46 GJ/t coke$^{2)}$	0.51$^{6)}$
PCI	PI	Iron	1986	0.85 GJ/thm$^{3),8)}$	0.82

1) International Energy Agency (2007).

2) Moya and Pardo (2013).

3) 1 t coal replaces 0.8 t of coke in BFs by PCI; 1 t coke needs 4.225 GJ of energy for its production (International Iron and Steel Institute, 1998).

4) The energy savings by BOF and CCM include the losses in these processes.

5) Energy consumption for the EAF steelmaking route includes energy consumption for ingot casting (1.863 GJ/tls) (Energy consumption ingot casting = energy consumption CCM (0.136 GJ/tls) (International Iron and Steel Institute, 1998)+ Energy saving CCM (1.727 GJ/tls) (Moya and Pardo, 2013)).

6) 0.36 t coke/thm (Heller, 2005).

7) Energy consumption Bessemer/Thomas/OHF steelmaking: 5.000 GJ/tls (International Energy Agency, 2007).
Energy consumption BOF: -0.296 GJ/tls (International Iron and Steel Institute, 1998).

8) 0.98 thm/tls (International Iron and Steel Institute, 1998).

PS	process substitution
RE	replacement
AO	add-on
PI	process intensification

of energy (0.297 GJ/t) (International Iron and Steel Institute, 1998). Thus the energy saving potential for BOF results as 5.30 GJ/t.

The energy saving potential of CCM is numbered by Moya and Pardo (2013) with 1.727 GJ/t. We assume that the production losses of the predecessor technology are included in this value.

The energy saving potential by TRT is numbered by Moya and Pardo (2013) with 0.108 GJ/thm. Assuming a hot metal ratio of 0.98 thm/tls (International Iron and Steel Institute, 1998) the specific primary energy saving potential of TRT results as 0.105 GJ/tls.

The energy saving potential for BOFGR is numbered by Moya and Pardo (2013) with 0.908 GJ/tls.

The energy saving potential of CDQ is numbered by Moya and Pardo (2013) with 1.46 GJ/t coke. Assuming a share of 0.36 t coke/thm (Heller, 2005) which has been achieved in Germany in e.g. 1998 to 1999 and 2004 to 2007 (Statistisches Bundesamt, 2007), the energy saving potential of CDQ results as 0.51 GJ/tls.

Finally, the energy saving potential of PCI is estimated. One tonne of coal replaces 0.8 t of coke in the blast furnace. One tonne of coke needs 4.23 GJ of energy for its production (International Iron and Steel Institute, 1998). Thus the energy saving potential of PCI results as 0.82 GJ/tls.

An overview on the selected technologies gives table 3.2.

3.3.4 Energy savings

The energy savings ES of a technology i in the year k are a function of the technology specific energy saving potential ESP_i, the diffusion rate $DR_i(k)$ and a technology specific adjustment factor $r_i(k)$ to refer the energy savings to the crude steel production.

We define the energy saving per tonne crude steel due to an EET i as (Eq. 3.4):

$$ES_i(k) = ESP_i(k) \cdot DR_i(k) \cdot r_i(k) \tag{3.4}$$

and

$$r_{EAF,CCM}(k) = 1; \tag{3.5}$$

$$r_{BOFGR,PCI,TRT,CDQ}(k) = \frac{P_{BOF}(k)}{\sum_j P_j(k)}; \tag{3.6}$$

$$r_{BOF}(k) = \frac{\sum_j P_j(k) - P_{EAF}(k)}{\sum_j P_j(k)}; \tag{3.7}$$

where

$ES_i(k)$	primary energy saving per tonne crude steel by technology i in year k,
$ESP_i(k)$	primary energy saving potential per tonne crude steel of technology i,
$DR_i(k)$	diffusion rate of a technology i in the year k,
$r_i(k)$	technology specific adjustment factor,
i	technology (BOF, EAF, CCM, TRT, CDQ, PCI),
$P_{BOF}(k)$	production of BOF steel in the year k,
$\sum_j P_j(k)$	production of steel by process j,
j	steelmaking process (Siemens-Martin, BOF, EAF)
$P_{EAF}(k)$	production of EAF-steel in the year k.

3.3.5 Reference energy consumption

We obtain the reference primary specific energy consumption REC by using the specific primary energy consumption per tonne crude steel in 1960, i.e. 29.43 GJ/t (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2013). This value includes a diffusion of 7 % of EAF and 3 % of BOF steelmaking. Thus the reference specific primary energy consumption results as 30.9 GJ/t (Eq. 3.8).

$$REC = SEC_{CS}(1960) - \sum_i ES_i(1960) = 30.9\ GJ/t \tag{3.8}$$

where

REC	reference primary energy consumption
$SEC_{CS}(1960)$	specific primary energy consumption per tonne crude steel in 1960
$\sum_i ES_i(1960)$	energy savings in 1960 due to all energy saving technologies i

3.3.6 Impact on specific energy consumption

We estimate the impact of the diffusion of the selected technologies on the primary energy consumption per tonne crude steel according to Eq. 3.9:

$$SEC(k) = REC + \sum_i ES_i(k) \tag{3.9}$$

where

$SEC(k)$	specific primary energy consumption per tonne crude steel in year k,
REC	reference primary energy consumption,
$\sum_i ES_i(k)$	energy savings in the year k due to all energy saving technologies i.

3.3.7 Remaining energy efficiency potential

We calculate the remaining energy efficiency potential $RESP$ for the year 2012. We assume as reference energy consumption the specific primary energy consumption per tonne crude steel for the year 2012 (i.e. 17.4 GJ/tls). Then, we estimate the remaining energy efficiency potential for the case that all investigated energy-efficient technologies increased their diffusion rate from the 2012 level to complete diffusion. The remaining energy efficiency potential for TRT, BOFGR, CDQ, and PCI is estimated as (Eq. 3.10):

$$RESP(2012) = \sum_i (1 - DR_i(2012)) \cdot ESP_i(2012) \cdot r_i(2012) \tag{3.10}$$

where

$RESP$	remaining energy efficiency potential due to an EET i,
$DR_i(2012)$	diffusion rate of a technology i in the year 2012,
$ESP_i(2012)$	energy saving potential of a technology i in the year 2012,
$r_i(2012)$	adjustment factor of a technology i in the year 2012,
i	TRT, BOFGR, CDQ, PCI.

3.4 Results

3.4.1 Diffusion of basic oxygen furnaces

The basic oxygen furnace (BOF) is the major innovation in the steel industry of the post-World War II period (Oster, 1982). The BOF replaced the open hearth furnace (OHF) or Siemens-Martin furnace. Molten iron is converted to steel by decreasing the carbon content from about 4 % to about 1 %. In OHF the reducing agent was preheated air, while in the BOF the air was replaced with oxygen. The BOF was invented in Austria in 1953 (Poznanski, 1983). Five years later, in 1958, the first BOFs were implemented in Germany (Poznanski, 1983).

The production share of the various steelmaking processes from 1950 until today is provided by Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2013). While the

BOF share has increased continuously, the share of OHF and Thomas-steelmaking has decreased. Thomas steelmaking faded out in 1977. In West Germany the last OHF was shut down in 1982, while in Eastern Germany OHFs were operated until 1993. The share of the EAF steelmaking route has continuously increased as well. The diffusion rate of BOFs is calculated by the annual production of BOF-steel divided by the total primary steel production in the same year.

In the first seven years BOFs diffused slowly and reached only an 8 %-diffusion (Fig. 3.1). However, in the following years the technology spread with an annual diffusion of about 4.6 % and reached complete diffusion in 1983 (Fig. 3.2). BOF reached a 10 % diffusion in the eighth year after its introduction. After 13 years its diffusion accounted for 50 %.

Poznanski (1983) compared the time-lag and diffusion speed of BOF among 21 countries including socialist countries and countries of Eastern Europe. He numbered the years that passed in a given country from when it had a 10 % share until it reached a 50 % share of BOF. For key steelmaking countries he found that Japan had the quickest increase in BOF, only taking five years to get from a 10 % to a 50 % diffusion (Austria and West Germany 6 years, U.S. 7 years, France 9 years, and Canada 17 years). At the time when his paper was published the Soviet Union had not yet reached a 40 % diffusion. Oster (1982) found a diffusion rate of the BOF for Japan and the U.S in 1968 of 73.3 % and 12.2 % respectively. Our results show that Germany had a BOF share of 37.1 % at that time. In 1980 Japan had a complete diffusion of BOF, while the U.S. and Germany had a BOF share of about 80 %.

3.4.2 Diffusion of continuous casting machines

Continuous casting machines (CCM) is said to be the second major innovation in the iron and steel industry in the post-World War II period (Oster, 1982). It replaced ingot casting where hot metal was first cast into ingots. For further processing into semi-finished products reheating is necessary. CCM directly produces semi-finished products from hot metal. This technology was first introduced in 1964 in Germany and is nowadays nearly fully diffused.

The production of steel by CCM is provided by Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2013). The diffusion rate is calculated as the share of steel produced by CCM of total crude steel production.

CCM diffused relatively slow in Germany (Fig. 3.1). It reached the 10 %-diffusion after eight years, and the 50 % diffusion after 18 years. No other technology which we investigated in this paper diffused slower during this period. After 26 years (i.e.

in 1989, Fig. 3.2) CCM achieved 90 % diffusion. Among the investigated technologies CCM is the second technology whose diffusion follows the expected s-shaped curve and reaches complete diffusion.

In general CCM diffused more slowly than the BOF. According to Poznanski (1983) it took Japan 14 years to increase the share of CCM from 10 % to 50 % (compared to France 19 years, West Germany 21 years, Austria 24 years, Canada 25 years). He explains the difference in the diffusion rates of BOF and CCM with the different complexity of those two technologies.

3.4.3 Diffusion of top-pressure recovery turbines

Top-pressure recovery turbines (TRT) are driven by the high pressure top gas from blast furnaces in order to generate electricity. TRT is a proven technology with little risk in installation and operation. Even if the turbine fails, the operation of the blast furnace is not affected since the top gas is then accommodated in the existing scrubber (ArcelorMittal, 2016). TRT can only be installed at blast furnaces with high top pressure. We assume that blast furnace exceeding a top pressure of 1.5 bar can be equipped with TRT. High pressure blast furnaces and TRT were introduced nearly simultaneously in Germany, i.e. at the beginning of the 1980s (Ameling, 2008). Low pressure blast furnaces cannot be updated to high pressure blast furnaces since they need different hot stoves, refractories and gas tubes. The diffusion of TRT is therefore closely related to the diffusion of high pressure blast furnaces or, in other words, to the replacement of old blast furnaces. Today nearly all blast furnaces in Germany have a high top pressure, though there are still two low pressure blast furnaces with little production capacity.

We used several types of information sources on the diffusion of TRT. For the years from its introduction in 1979 to 1990, Aichinger et al. (1991) provides the annual electricity production by TRT.

For the period from 1991 till today several sources were consulted. The database Plantfacts by the Stahlinstitut VDEh provides the number, working volume, top pressure and TRT equipment of all operating blast furnaces (Stahlinstitut VDEh, 2013). Reference lists by TRT suppliers mention the year of TRT implementation at the respective blast furnaces. Additional data was obtained from annual reports, press releases, and interviews with companies.

We constructed a timeline which presents in which year a blast furnace was shut down or when a blast furnace was newly built or reconstructed, listing all entries and exits of blast furnaces and the year a blast furnace was equipped with TRT, following the same method as Worrell and Biermans (2005).

The entity which determines the maximum of the diffusion changed due to two reasons. First, the number of blast furnaces has been reduced dramatically over the last three decades. In 1979 there were 84 blast furnaces while in 2012 only 15 were still working (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2013). The shut-down of blast furnaces without TRT increases the diffusion rate of TRT. Some uncertainties on the exact moment of shut-down persist. Second, the structure of the blast furnaces changed from low pressure to high pressure in the same period. In 1979 the majority of blast furnaces were low pressure blast furnaces. Already in 1991 80 % of the working volume belonged to high pressure blast furnaces while this number increased to 97 % in 2012. According to our definition of diffusion rates, the entity which determines the maximum diffusion of TRT would be equal to the amount of high pressure blast furnaces. Since both technologies – TRT and high pressure blast furnaces – were introduced at the same time, TRT diffusion would begin with complete diffusion and then decrease since more high pressure blast furnaces were built but were not equipped with TRT. With the fade-out of low pressure blast furnaces the entity slowly complies with our original definition. Keeping this in mind, we consider the determining entity to be equal to the working volume of all blast furnaces.

For the first twelve years the diffusion rate was based on data by Aichinger et al. (1991) who published the annual electricity production by TRT. The specific electricity production by TRT was estimated by the annual electricity production by TRT in Germany and the annual hot metal production. The maximum electricity generation was assumed to be 22 kWh/thm (Maier and Angerer, 1986). The diffusion is equal to the quotient of the specific electricity production and the maximum electricity production. For the following years we derived the diffusion rate by the quotient of blast furnace working volume equipped with TRT and the entire blast furnace working volume.

The diffusion rate for TRT in Germany rose quickly (Fig. 3.1). Four years after the first implementation 13 % of the blast furnace capacity was equipped with TRT, and already ten years after the first implementation its diffusion rate was 48 %. All other investigated technologies needed more time to reach a 50 %-diffusion. After another six years 70 % of German blast furnaces were equipped with TRT. Then the diffusion rate decreased continuously over 17 years to 58 % in 2011 (Fig. 3.2). Just in the very last reported year, i.e. 2012, the diffusion jumped to 65 %. Just in the beginning of 2013 a further blast furnace started operating with TRT. Hence, in 2010 there were six remaining blast furnaces in Germany which could apply TRT.

The increase of the diffusion of TRT in the first sixteen years originates from the implementation of TRT in blast furnaces as well as the shut-down of blast furnaces without TRT. The diffusion rate decreased since the year 17 of TRT implementation because blast furnaces with TRT were shut down as well. For instance, in 1991 twelve TRT were installed while in 2008 only seven blast furnaces were equipped with TRT. The last top pressure recovery turbine was erected with a newly built blast furnace in 1993. Between 1994 and 2011, i.e. 18 years, no TRT was installed in Germany, although five to six high pressure blast furnaces without TRT were in service. In 2012 TRT was implemented to one blast furnac, leaving five further high pressure blast furnaces without TRT.

In Japan and Korea all blast furnaces are equipped with TRT (Xu and Cang, 2010). According to Liu et al. (1996) China had a diffusion of TRT of 16 % in 1996. This number coincides with Okazaki and Yamaguchi (2011). On the further diffusion of TRT varying numbers have been published. For instance Hasanbeigi et al. (2011) put the diffusion of TRT in China in 2005 at 70 %. According to International Energy Agency (2007) China had a TRT diffusion of 50 % in 2004.

3.4.4 Diffusion of pulverized coal injection

The injection of pulverized coal (PCI) partly replaces coke consumption in the blast furnace. One kilogram of coal can replace about 0.8 kg of coke. Therefore, it does not reduce the energy consumption in the blast furnace itself but it reduces energy consumption for coke making. Since coke is needed to carry the weight in the blast furnace a minimum coke rate is needed. The amount of coal injected to the blast furnace depends on a set of factors such as coke properties, desired hot metal quality or type and condition of coal (Joint Research Center, 2012). In 2010 the highest PCI rate achieved in a single blast furnace in Germany was 177 kg/thm, which is also the highest PCI rate published for the German steel industry (Stahlinstitut VDEh 2005; 2007; 2008; 2009; 2010; 2011). In 2010 the national PCI average was 138 kg coal/thm (Stahlinstitut VDEh, 2011). Blast furnaces can be retrofitted with PCI. This technology is widely applied nowadays (Joint Research Center, 2012). In Germany PCI was first introduced in 1986.

Aichinger, Hoffmann and Seeger (1991) provide the specific coal consumption per tonne hot metal since its introduction in 1986 to 1989 (Aichinger et al., 1991). Statistisches Bundesamt (2007) published the coal consumption in blast furnaces from 1991 to 2001 and from 2004 to 2009. Stahlinstitut VDEh (2011) published the specific coal consumption for the years 2002 to 2010. His values differ to a maximum of 1 % from the values we derived, except for the year 2007 in which the difference accounts for 1.3 %. For the years 2002 and 2003 we use the PCI values by Stahlinstitut VDEh (2011). Despite the above mentioned factors which determine the PCI rate, Joint Research Center (2012) number the theoretical maximum coal injection rate at 270 kg/thm. Currently new or retrofitted blast furnaces are equipped with injection systems to reach an injection rate of 200 kg coal/thm and more (Joint Research Center, 2012). In order to respect the technical and economic viable use of PCI we assume a maximum PCI rate of 200 kg/thm. We define the diffusion as the quotient of the specific coal consumption and the maximum coal consumption. For the year 1990 we interpolate the diffusion rate.

The reports by the Steelinstitue VDEh also publish in which year PCI was installed at which location in Germany (Stahlinstitut VDEh 2005; 2007; 2008; 2009; 2010; 2011). In 2000 hot metal was produced at eight locations. In 2001 and 2002 two of these sites were closed. The remaining six locations are still operating. In 2000 PCI was used at three sites, while one of these was shut down in 2001. New PCI plants were installed in 2004 (at 3 blast furnaces at two sites) and in 2009 (at two blast furnaces at a single site). Hence, today, only one site in Germany does not apply PCI.

PCI reached a 30 %-diffusion after six years and a 52 %-diffusion after 20 years (Fig. 3.1). In 2009 the PCI diffusion dropped from 53 % to 46 %. This was caused by the drop in production due to the economic crisis. One year later in 2010 the PCI rate jumped to a 69 %-diffusion (Fig. 3.2).

According to Zhang and Wang (2008) the PCI-rate in China for key enterprises rose from 51 kg/thm in 1991 to 123 kg/thm in 2000. Guo and Fu (2010) numbers the PCI-rate for large and medium steel producers in China at 137 kg/thm in 2007. According to our definition of the maximum PCI-rate, it took Chinese key steel producers 9 years to increase the PCI diffusion from 34 % to 82 % and another 7 years to increase the diffusion to 91 %. International Energy Agency (2007) provides the annual PCI-rate for 2005 for several countries: South Korea has the highest PCI-rate with nearly 160 kg/thm, followed by China and South America (both about 140 kg/thm). Japan has a PCI-rate of about 130 kg/thm. Germany ranges only in seventh position with 100 kg/thm. Little PCI diffusion is reported for Russia, the U.S., and Ukraine (50, 42 and 0 kg/thm, respectively).

3.4.5 Diffusion of basic oxygen furnace gas recovery

Hot metal from the blast furnace contains about 4 % carbon. In the BOF steel is produced by reducing the carbon content of the hot metal. Oxygen is introduced to form carbon monoxide with the carbon of the liquid steel. The emerging BOF gas

(BOFG) contains carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and nitrogen (N_2). Its heating value is with 9 GJ/m^3(S.T.P) about one fourth of that of natural gas (Brauer, 1996). Per tonne crude steel 0.91 GJ of energy can be recovered (Moya and Pardo, 2013). Basic oxygen furnace gas recovery (BOFGR) is an add-on technology which collects the BOF gas. BOFs work in batch processes. The reaction which releases the converter gas is discontinuous. Indeed, within the first 30 % of the blowing time the amount of carbon monoxide in the gas increases. Within the last 25 % of the blowing time the carbon monoxide content decreases, since the carbon content of the hot metal has already been converted into carbon monoxide. Hence, heating values of converter gas varies depending on the hot metal ratio in the BOF. Secondly, the amount of converter gas which can be recovered from the BOFs can vary. Brauer (1996) estimates the converter gas production at 80 to 100 m^3(S.T.P.)/t crude steel. We assume that 90 m^3(S.T.P.) or 0.8 GJ of converter gas per tonne crude steel can be recovered. In Germany BOFGR was first introduced in 1982.

Aichinger et al. (1991) provide the annual BOFGR in volume from its introduction in 1982 to 1990. The same is published by the German Federal Statistical Office from 1993 to 2009 (Statistisches Bundesamt, 2007). The BOFGR for the years 1993 to 1995 differ from the values of 1990 and 1996 by 205 % and 153 % respectively. Since all other values of this timeline vary only incrementally from each other and since we could not identify a reason for these values, we assume a misallocation within the statistics for the respective years. Hence, we interpolate the values for the years from 1991 to 1995. The Steelinstitue VDEh provides data at which sites BOF gas is recovered (Stahlinstitut VDEh, 2013). In 2013 there were 21 BOFs with an annual capacity of 37.3 Mt located at 9 sites. At five sites, representing 63 % of the capacity share, BOFG is recovered, while at the remaining four sites BOFGR is not applied.

Our analysis shows that BOFGR diffused rapidly within the first eight years after its first implementation (Fig. 3.1). After six years it reached a 25 %-diffusion and after 14 years the diffusion rate was 50 %. Nowadays we find a 61 %-diffusion of BOFGR (Fig. 3.2).

International Energy Agency (2007) published the diffusion rate of BOFGR in China. According to their findings China had a 41 % diffusion in 2000 which increased to 89 % in 2003.

3.4.6 Diffusion of coke dry quenching

Coke dry quenching (CDQ) is one of the key EET for the steel industry (e.g. Okazaki and Yamaguchi, 2011). Moya and Pardo (2013) rate it to have the second largest energy

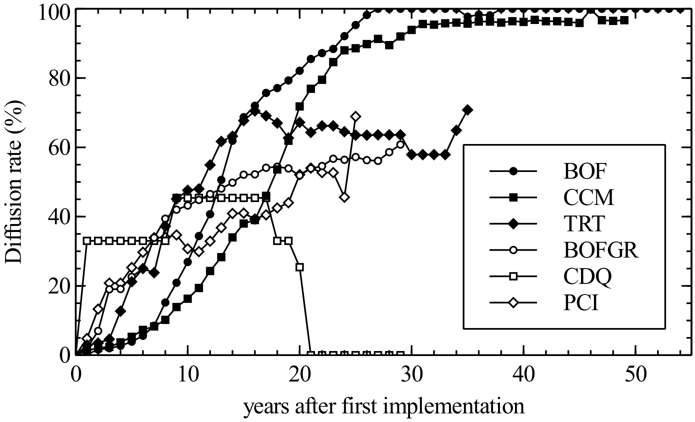

Figure 3.1: Diffusion rates of the selected technologies allocated by number of years after their first implementation.

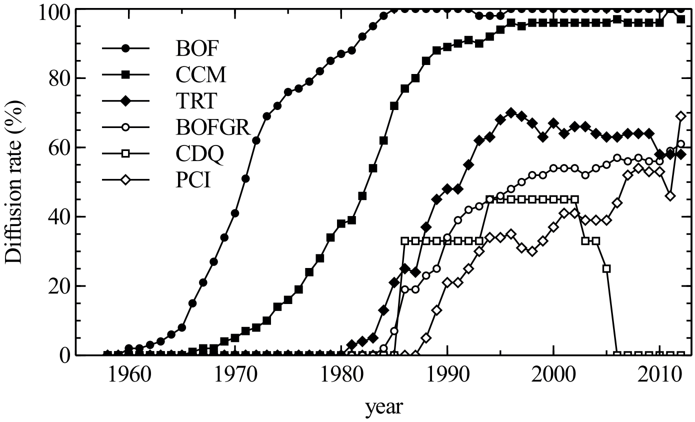

Figure 3.2: Diffusion rates of the selected technologies allocated by year of implementation.

saving potential within the European Union (EU27). In CDQ coke is cooled with gas instead of water. The sensible heat of the coke is transferred to the gas. The hot gas can be used for the production of steam and electricity. CDQ was originally developed in Switzerland in the 1920s. In the 1960s the technology was further advanced in Russia. Due to cold temperatures in Russia, CDQ is more favourable than wet quenching since it reduces the risk of ice formation (Bussmann et al., 1985). In the 1970s CDQ was further developed in Japan (Bussmann et al., 1985) to control dust emissions from coke making. Nowadays, China (to reduce water use) and Japan have high diffusion rates of CDQ, while this technology is little applied in e.g. the U.S. steel industry (International Energy Agency, 2007; U.S. Environmental Protection Agency, 2012).

Only two CDQ plants have ever been installed in Germany. The first was implemented to the coke oven August Thyssen in 1984 (Bussmann et al., 1985). This plant was shut down in 2003 (Kokerei August Thyssen, 2013). The second CDQ plant was applied to the new built coke oven Kaiserstuhl in 1992, which only ran for eight years. The steelworks was shut down in 2000 and so was the coke oven. In 2003 a new coke oven Schwelgern started. Originally it was approved with CDQ, but the operator ThyssenKrupp requested the substitution of the CDQ facility by a wet quenching plant. The local government approved this request (Landesumweltamt Nordrhein-Westfalen, 2000).

We collected data on capacity and the years in which the coke ovens were run in Germany since the introduction of CDQ in 1984. The diffusion rate results from the capacity equipped with CDQ divided by the total coke oven capacity in that same year.

CDQ was first introduced in 1984 and a second time in 1992. The first coke oven was closed in 2003, the latter in 2000. Hence, CDQ reached a maximum diffusion between 1992 and 2000 with 45 % (Fig. 3.2). After closing the coke oven Kaiserstuhl, the diffusion rate dropped to 33 %. In 2003 the coke oven August Thyssen was closed. Since then the diffusion rate of CDQ in Germany is 0 %.

In Japan CDQ was first introduced in the 1970s (6 plants). Major diffusion of CDQ took place in the 1980s and 1990s as another 19 and 13 units were built. Today, CDQ is completely diffused in Japan, and installed at 42 locations (Okazaki and Yamaguchi, 2011).

China's key iron and steel manufactures had a CDQ diffusion rate of 57 % in 2008 which increased to 80 % in 2010. Nevertheless, on a national level the diffusion rate of CDQ in 2008 and 2010 was only 18 % and 23 %, respectively (Huo et al., 2012). Okazaki and Yamaguchi (2011) find more than 130 CDQ plants in China, which reflect less than half of the Chinese coke oven plants. CDQ was first introduced with 4 plants

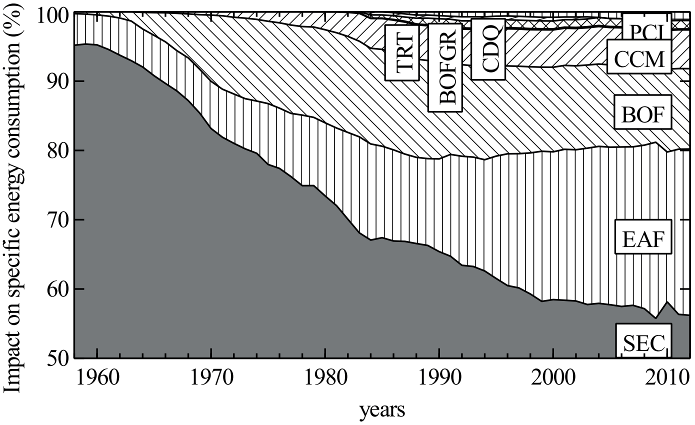

Figure 3.3: Impact of the selected technologies on the specific primary energy consumption per tonne crude steel from 1958 to 2012 in the German steel industry.

to China in the 1980s. In the 1990s another 12 plants were equipped with CDQ. But from 2000 onwards about 117 CDQ plants were installed. The major driver for this strong diffusion is government policies that promote CDQ to reduce water use in the 10th and 11th Five-Year-Plan.

3.4.7 Impact on energy use

Figure 3.3 shows the impact of the diffusion of the selected technologies on the primary energy consumption per tonne crude steel in the German steel industry between 1958 and 2010. According to our findings the specific energy consumption in 2012 is only 56 % of that in 1958, or 17.4 GJ/tls.

The Stahlinstitut VDEh publishes a SEC of 17.88 GJ/tls for 2012, which 2.9 % higher than our analysis indicates. Nevertheless, there is strong argument that our selection of technologies covers all major technologies which contributed to energy intensity changes in the German steel industry since the late 1950s.

The major reduction in the specific primary energy consumption is due to the EAF steelmaking route. This process reduced the SEC by 24 % compared to the reference energy consumption of 30.9 GJ/t. The second key technology which reduced the specific primary energy consumption is the BOF. In 2012 it contributed with 12 % to the reduction of the specific energy consumption per tonne crude steel compared to 1958. The third major technology is CCM. It contributed with 5.5 % to the decrease in energy consumption. These technologies are the oldest technologies of our selection. They were first introduced in the 1950s and 1960s.

The younger technologies, i.e. TRT, BOFGR , CDQ and PCI were introduced in the early or mid-1980s. CDQ was only applied in the period between 1984 and 2003 in Germany. At a maximum this technology contributed with 0.6 % to the decrease in the primary energy consumption per tonne crude steel compared to 1958. Both PCI and BOFGR reduced the specific energy consumption per tonne crude steel by the same amount, i.e. 1.2 % by 2012 compared to 1958. The impact of TRT on the specific energy consumption is rather small with 0.1 % in 2012 compared to 1958. Together, by 2012 these four technologies contributed with about 2.5 % to the reduction of the specific energy consumption compared to 1958.

Previously (Arens et al., 2012) we studied the development of the energy intensity of selected processes in the German steel industry between 1991 and 2007. We found that the total primary energy intensity declined by 0.4 %/year. Of this 75 %, or 0.3 %/year, was due to a structural change towards the EAF steelmaking route. Energy efficiency improvements accounted for about 25 % of the observed change in energy intensity, or 0.1 %/year. The specific net energy consumption of blast furnaces decreased due to increased top gas recovery by 0.2 %/year per tonne iron. In basic oxygen furnaces net energy consumption increased due to a 60 % decrease in BOFGR between 1993 and 2007. In EAFs and sinter plants the specific energy consumption remained constant or, respectively, even increased by 9 % between 1991 and 2007 per tonne sinter.

The outcome of this paper also supports that the main driver for energy intensity developments in the German steel industry between 1991 and 2007 was the increase in the production share of the EAF steelmaking route. The impact of BOF and CCM was comparably small since in 1991 they reached a 98 % and 90 % diffusion, respectively. The further diffusion of CCM from 90 % in 1991 to about 96 % in 2007 should have reduced the specific energy consumption by about 0.1 GJ/tls in the same period. In the used statistics, the energy consumption for CCM is assigned to steelmaking, i.e. BOFs and EAFs. In the previous paper we found altering energy intensities for BOFs between 1.0 GJ/tls and 1.2 GJ/tls. The primary energy consumption per tonne EAF-steel decreased from 1996 to 2003 from 6.4 to 5.9 GJ/t. But from 2003 onwards the energy intensity increased to the level of 1996, i.e. 6.4 GJ/t. In both processes the energy intensity varied more than the impact of the diffusion of CCM could have reduced the specific energy consumption. Hence, other factors such as scrap input in BOFs or scrap quality in EAFs might have offset the effect of increased use of CCM.

Previously (Arens et al., 2012) we found a strong decrease in BOFGR between 1993 and 1996. The results of this paper suppose there are errors within the statistical data between 1993 and 1995, since the diffusion of BOFGR does not coincide with the results on BOFGR in that period of the previous paper.

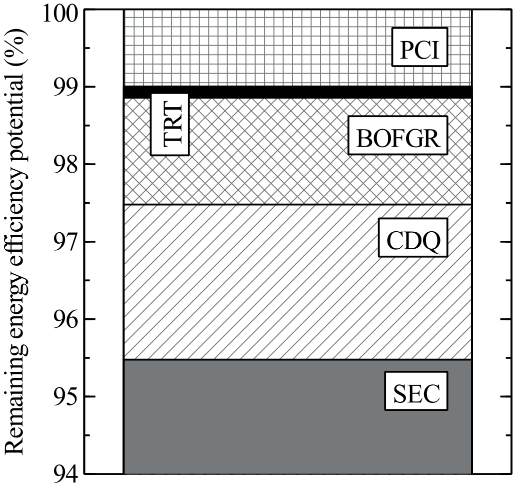

Figure 3.4: Remaining energy efficiency potential (2012) due to the further diffusion of the selected energy-efficient technologies.

3.4.8 Remaining energy efficiency potential

Full diffusion of PCI, CDQ, BOFGR and TRT could reduce the primary specific energy consumption in the German steel industry by 4.5 % (2012) (Fig. 3.4). The main potential with 2.0 % holds CDQ since it is currently not applied in the German steel industry. The further diffusion of BOFGR and PCI could reduce the primary energy intensity by another 1.4 % and 1.0 %, respectively. TRT holds a further energy efficiency potential of 0.1 %. The impact of further EET in the EAF steelmaking route, rolling and finishing is not included.

3.5 Conclusions, summary and outlook

This paper provides a detailed study of long-term trends of the diffusion of key energy-efficient technologies (EET) for a large steel producing country. In the past Germany has adopted technologies relatively rapidly, especially in terms of technologies which provide essential productivity benefits next to energy savings (e.g. BOF, CCM; see also Worrell et al., 2003). In contrast, CDQ, BOFGR and TRT have only minor productivity benefits. Hence, understanding the productivity benefits may be important to understand the rate of uptake for new technologies.

Nevertheless the implementation rates seem to have levelled off since the 1990s. The diffusion rates of TRT, PCI and BOFGR slowed down. After about 25 years they reached a diffusion rate roughly between 50 % and 60 % while after the same period BOF and CCM were nearly completely diffused. CDQ has been implemented in Germany but the last plant has been shut down in 2004.

The observed diffusion rates are affected by developments in the sector. New constructions – if there is growth – might increase the diffusion rates if the EET are implemented. Contractions might also increase the diffusion rates if plants without the EET are shut down. Still, not all new constructions apply the investigated EETs and plants which have the EETs implemented are shut down as well.

Our analysis shows that there is still room for further implementation of the investigated EET even though they were first introduced over 30 years ago. We find a further primary energy efficiency potential of 4.5 % for 2012. At the time writing three BFs could technically implement TRT, two BFs could apply PCI, six BOFs and five coke ovens are not equipped with BOFGR and CDQ, respectively.

Recently the diffusion of TRT increased rapidly in Germany. In both 2012 and 2013 one TRT was implemented at blast furnaces in Germany. For 2014 a further blast furnace is announced to be equipped with TRT. It is also reported that the last two BFs will adopt PCI in 2014.

Chapter 4

Drivers for and barriers to the diffusion of energy-efficient technologies – A plant-level analysis[3]

Abstract

The paper aims at explaining why large-scale energy intensive industries – here the German iron and steel industry – showed comparably slow uptake of energy-efficient technologies from the 1990s onwards as found in Arens and Worrell (2014). We analyse the underlying factors and investment/innovation behaviour of individual firms in the German iron and steel industry to better understand barriers and drivers for technological change. The paper gives insights on the decision making process on energy efficiency in firms and helps to understand how policy affects decision making. We use a mixed method approach. First, we analyse the diffusion of three energy-efficient technologies (EET) for primary steelmaking from their introduction until today (top-pressure recovery turbine, TRT; basic oxygen furnace gas recovery, BOFGR; and pulverised coal injection, PCI). We derive the uptake of these technologies both at the national and at the level of the individual firm. Second, we analyse the impact of drivers for and barriers on the decision making process of individual firms whether or not they want to implement these technologies. Economics and access to capital are the foremost barriers to the uptake of an EET. If the expected payback period exceeds a certain

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value or if the company lacks capital investments in EET seem not to happen. But even if an EET is economically viable and the company has access to capital investments in EET might not be realized. Policy induced prices might have strengthened the recent diffusion of TRT. We found indications that in a limited number of cases policy intervention was a driving factor. Technical risks and imperfect information are only marginal factors in our cases. Site specific factors seem to be important, as site specific factors shape the economics of the selected EET.

4.1 Introduction

Energy efficiency is regarded as a major means to reduce carbon dioxide emissions until the energy systems has been transformed to a sustainable system based on renewable energy carriers. However, e.g. Hirst and Brown (1990) found an untapped potential to improve energy efficiency although these measures were identified to be cost-effective. The energy efficiency gap thus describes the potential to implement energy-efficient technologies and the actual adoption of these technologies (Brunke et al., 2014).

Arens et al. (2012) analyzed the development of the energy intensity of selected processes of the steel industry in Germany between 1991 and 2007. Although the analysis covered a period of 17 years, energy efficiency improvements were surprisingly low. Arens and Worrell (2014) analysed the diffusion of key energy-efficient technologies (EETs) in the German steel industry to better understand the slow improvement rates. Technologies were introduced in two phases, i.e. in the earlier phase (around 1960) technologies diffused continuously and were completely implemented after about 30 years. However, technologies introduced during the second phase (around 1980) did not diffuse completely and further potential remains. The technologies diffused strongly in the initial phase but then, 10-15 years after their introduction, no further implementation took place. Only recently adoption has increased again.

4.1.1 Drivers and barriers

energy-efficient technologies (EETs) can be regarded as a particular case of innovations (Fleiter et al., 2012a). There is a wide range of literature on the diffusion of innovations. Rogers (2003) describes the s-shaped diffusion process. He categorized the adopters as innovators (those that take up innovative technologies first), early adopters (those that take up a technology when proven), and those that implement it once the technology is more widespread (i.e. early majority, late majority, and laggards). This process of uptake may partly explain the energy efficiency gap, which is defined as the difference between the economic viable level of energy efficiency and the actual level (e.g. Brunke et al., 2014; Backlund et al., 2012; Levine et al., 1995). Drivers are factors that accelerate the uptake of energy efficiency measures, while barriers are all factors that impede the adoption of cost-effective energy saving measures (Fleiter et al., 2011). Nevertheless, Sutherland (1991; 1996) argued that the energy-saving potential is only profitable from a superficial point of view and that many barriers can be traced back to rational economic behavior, e.g. transaction costs and other factors. Yet, many of the barriers can be addressed or even mitigated by policies.

Different taxonomies of drivers and barriers have been developed, although most refer back to the taxonomy of Sorrell et al. (2000) (Brunke et al., 2014). They derived a taxonomy of barriers combining findings from orthodox economics, transaction cost economics and behavioral economics. The six classes of barriers are: risk, imperfect information, hidden costs, access to capital, split incentives, and bounded rationality. According to Cagno et al. (2013) the taxonomy of Sorrell et al. (2000) lacks accuracy and is incomplete. They suggest a novel, more sophisticated taxonomy, which distinguishes the origin of the barrier, i.e. either internal or external with respect to the firm. They also classify the actor or area affected by the barrier (e.g. market, government/politics, behavioral, economic), arriving at a taxonomy encompassing 33 barriers.

This analysis bases the drivers and barriers on the taxonomy of Sorrell et al. (2000) complemented by the findings of Cagno et al. (2013) and Brunke et al. (2014) (Tab. 4.1). Since original drivers can become barriers, drivers and barriers may overlap. Hence, this study unifies drivers and barriers as diffusion factors. Economics are self-evidently a key driver or barrier towards the diffusion of EET. Depending on the scope of the studies, economics of an EET are considered as a driver or not. Especially newer studies seem to focus on cost-effective EET (e.g. Okazaki and Yamaguchi, 2011; Thollander et al., 2007; Thollander and Ottosson, 2008; Trianni et al., 2013). In contrast Harris et al. (2000) highlight low rates of return and long pay-back periods as key barriers. Other studies address economics from different perspectives. Fleiter et al. (2012b) name high investment costs and non-profitability as key barriers to the diffusion of EETs in small and medium sized enterprises (SMEs) in Germany. Sardianou (2008) finds bureaucratic procedures for financial support too difficult, i.e. the measure does not meet the companies' economic requirements without governmental support.

The role of policy induced energy price components on the economics of energy-efficient technologies has rarely been quantified. Rosenberg et al. (2011) studied the impact of tax exemptions and levy reductions on the German industry of four energy policies (i.e. the Environmental Tax Reform, the Combined Heat and Power Act, the EU Emission Trading Scheme, and the Renewable Energy Act). They found that these exemptions

Table 4.1: Considered diffusion factors for the selected energy-efficient technologies (based on Sorrell et al., 2000; Cagno et al., 2013; Brunke et al., 2014).

Origin	**Area**	**Diffusion factors**
External	Markets	Economics incl. policy induced energy prices
		Imperfect information
	Government	Liberalized electricity market
		Policy intervention
Internal	Economic	Access to capital
		Technical risk
	Organizational/behavioural	Management practices

and reductions of energy prices in Germany reduce the incentive for manufacturing industries to invest in energy efficiency measures. Furthermore, they conclude that polices and their exemptions create significant differences in energy costs among companies, especially in large scale and electricity-intensive industries.

In the taxonomy of barriers by Sorrell et al. (2000) imperfect information is recognized as a key barrier towards the diffusion of EETs. For instance, energy audits aim to overcome these information related barriers. Imperfect information is a barrier in SMEs, which do not employ an energy manager. Large and energy-intensive companies – like steel mills – are assumed to have access to relevant information on key energy-efficient technologies.

In 1998, Germany liberalized its electricity market thereby accomplishing a European directive. Market liberalization intended to benefit customers (Lise and Kruseman, 2008). However, Newbery (2001; 2002) argues that benefits can be offset if regulation is insufficient. Pollitt (2012) found that generally electricity prices did not decrease demonstrably through market liberalization, contrary to expectations. Instead, electricity prices increased due to rising commodity prices, unwinding subsidies, and reduced rates of technological progress, in part due to rising environmental concerns around power generation. In Germany, industrial electricity prices dropped after liberalization from March 1998 till March 2000 (Ziesing et al., 2001). Thollander et al. (2005) assumed that industrial electricity prices will rise in Sweden due to market liberalization.

Environmental protection agencies permit the erection of large industrial plants thereby controlling environmental requirements. They control the environmental impact of the plants. In Germany this kind of policy intervention is backed up by a strong law; i.e. the Federal Control of Pollution Act that implemented the European Industrial Emissions Directive (2010/75/EU). The Federal Control of Pollution Act includes a paragraph on the efficient use of energy for plants (BImSchG §5/4, Bundesministerium für Justiz und Verbraucherschutz, 2014c). So far, no studies have investigated the impact of this law on energy efficiency developments in the German industry.

Access to capital is regarded as a major barrier. Thollander et al. (2007) evaluated a Swedish energy efficiency programme for SMEs, and found that after a low priority for energy issues, access to capital is a major barrier towards energy efficiency improvement. Trianni and Cagno (2012) investigated 128 non-energy intensive small and medium sized enterprises in northern Italy, and identified access to capital as the most important barrier towards energy efficiency.

Another pillar of Sorrell's taxonomy is risk (Sorrell et al., 2000), distinguishing external risks, business risks, and technical risks (Brunke et al., 2014). Brunke et al. (2014) emphasize technical risks like production failures and production interruptions as a key barrier.

In summary, there is a wide range of studies on drivers for, barriers to and policy for the diffusion of EETs. Still, the factors affecting diffusion on the level of firms and plants have received little attention. Little is known about the decision making process at site and company level, as well as site specific constraints towards the up-take of EETs.

4.1.2 Research aim

This paper aims to shed some light on the reasons why key energy-efficient technologies diffused discontinuously as shown in Arens and Worrell (2014) in the German steel industry, seemingly opposed to diffusion theory (e.g. Rogers, 2003). This study focuses on currently running sites. The studied period also covers the time before German reunification. However, only one site on the territory of former German Democratic Republic is part of this study (i.e. Eisenhüttenstadt). Its analysis considers these historical facts. The selected technologies are applied major energy-efficient technologies with a remaining diffusion potential (see Arens and Worrell, 2014). It aims to find explanations for the observed diffusion patterns, and why some plants still have not implemented these – at least to competitors – cost effective technologies. The analysis gives insights on the decision making process of firms helping to understand how poli-

Table 4.2: Overview on the methods.

Step	Method	Aim
1.	– Analysis of reference lists by plant manufactures	Diffusion of EET on the national level
2.	– Establishing a timeline with relevant plants of the German steel sites/companies (1980-2015) – Indicating in which year a plant has been equipped with an EET	Diffusion of EET on the site/company level
3.	– Calculating average years passed till an EET was implemented at a plant (site average)	Innovator behaviour of single sites/companies
4.	– Tracking end-user energy prices for industry (Germany, 1980-2014) – Tracking policy induced energy price components – Estimating payback periods as a function of energy prices – Estimating at which payback periods companies invested in an EET	Impact of energy prices on the implementation of EET
5.	– Literature review – Interviews – Qualitative description of the findings	Impact of further drivers and barriers

cies can act on them. National trends (Arens and Worrell, 2014) are broke down to that of individual firms and plants focusing on key energy-efficient technologies for primary steelmaking that are currently applied and have a further diffusion potential (Arens and Worrell, 2014), i.e. top pressure recovery turbine (TRT), basic oxygen furnace gas recovery (BOFGR) and pulverized coal injection (PCI). These technologies are either applied to the blast furnace or the basic oxygen furnace. A detailed description of steelmaking processes can be found in e.g. Arens et al. (2012).

Section 4.2 describes the methods. Section 4.3 investigates the diffusion of the selected technologies both on the national and on the site level. Section 4.4 studies the impact of drivers and barriers on the diffusion of the selected technologies, followed by the conclusions.

4.2 Methods

The analysis is based on five steps (Tab. 4.2). First data obtained from reference lists by plant manufacturers is analysed and cross-checked with reports by the Stahlinstitut VDEh (2005-2010) and interviews (step 1). The findings are shown in a timeline in which year a certain EET was implemented in Germany. Then a timeline of all current German integrated steel sites is established including the start up of blast furnaces (BF) and basic oxygen furnaces (BOF) as well as the year of implementation of the selected EET since 1980 (Stahlinstitut VDEh, 2013) (step 2). Data is cross-checked with other sources and interviews. Also it is indicated in which year an EET was available on the market but was yet not implemented to a certain plant, showing whether individual sites behave similarly or not.

In order to compare the behaviour of single sites or companies the average number of years are calculated which passed till an EET was implemented (Eq. 4.1) (step 3).

$$Av_j(m) = \frac{\sum NY(m)}{NT_j} \tag{4.1}$$

where

$Av_j(m)$	average years which passed till an EET was implemented at site j,
$NY(m)$	number of years passed before an EET was implemented at plant m,
NT_j	maximum number of EETs which can be implemented at site j.

The development of the energy prices for the German industry from the late 1960s until today is tracked, acknowledging that time series over such a long time include uncertainties (step 4). We chose the development of energy prices on the industrial level due to the lack of more specific energy prices for individual industrial branches (e.g. Eurostat: Electricity prices for industrial consumers). The analysis of the energy prices starts about 10 years earlier than the commercialisation of the selected EET to review the firms' decision making process. Furthermore, we include the impact of two major policy induced energy price components on the payback period of the selected EET, i.e. the European Emission Trading Scheme (ETS) and the German Renewable Act (EEG).

Energy prices are collected from several federal, international and non-profit organisations (App. A, Tab. A.1). Following the German Energy Tax Act (Bundesministerium für Justiz und Verbraucherschutz, 2014a) that exempts iron and steelmaking, the impact of taxes for solid fuels is neglected. Neither transportation costs for coal, coke, and coking coal are considered.

The prices are deflated using a BIP-Deflator for the year 2005 (Statistisches Bundesamt, 2013, own calculations). Then prices are converted to Euro_{2005}/MWh using conversion factors (App. A, Tab. A.1).

The period from the late 1980s till early 2000 is characterised by relatively low energy prices (Fig. 4.1).

The first phase of the European Emission Trading Scheme (ETS) started in 2005 (Verein der Kohlenimporteure, 2004-2014). Under the ETS selected sectors, including iron- and steelmaking companies, receive free allowances up to the benchmark (BMU 2006). Furthermore, within the third trading period (2013-2020) a compensation for an increasing electricity price due to ETS is introduced for selected sectors, including iron and steelmaking (Deutsche Emissionshandelsstelle, 2015). In our analysis we refer to the costs

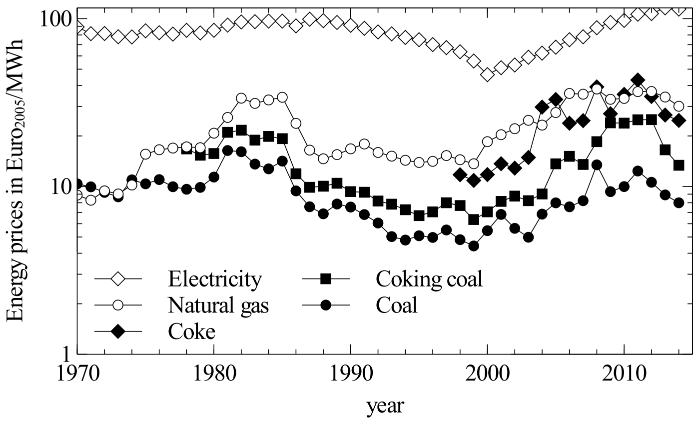

Figure 4.1: Energy prices in the German industry (sources: Tab. A.1).

of ETS without any free allowances, or compensations, to evaluate the companies' decision making processes, as these represent opportunity costs if any allowances can be sold. The impact of the ETS has decreased since the economic crisis in 2008/2009 (Fig. 4.2). The net results of both are summarized in table 4.3 excluding free allowances and compensation.

Germany charges a levy for the support of renewable energies empowered by the German Renewable Act (Erneuerbare-Energien-Gesetz; EEG) (Bundesministerium für Justiz und Verbraucherschutz, 2014b) since 2003. The levy was 0.41 eurocent/kWh of electricity in 2003, and has since evolved to one of the key electricity price components (2013: 5.23 eurocent/kWh; 2014: 6.24; 2015: 6.17; Fig. 4.3). Reductions are given to companies with a high ratio of electricity costs to gross value added (Rosenberg et al., 2011) and that face international competition (special equalization scheme) (Bundesministerium für Justiz und Verbraucherschutz, 2014b). While electric steel mills are mostly privileged, integrated steel mills in general do not fulfill the requirements for privileging (Bundesamt für Wirtschaft und Ausfuhrkontrollen, 2014b). Nevertheless, the overall impact of the EEG on integrated steel mills is rather low, since they produce the majority of the consumed electricity in on-site power plants fed with top gases, which are excluded from the levy.

While the impact of the EEG on the energy prices increased since its introduction, the impact of the ETS lowered (Tab. 4.3).

Payback periods are calculated as explained in Appendix B. They show the impact of the selected policy induced energy prices (EEG, ETS) (Tab. 4.4). Since BOFGR and

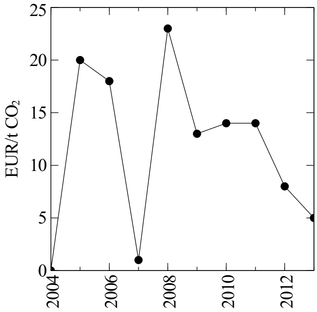

Figure 4.2: CO_2 price under the EU-ETS (Verein der Kohlenimporteure, 2004-2014).

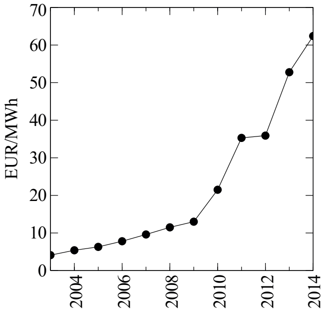

Figure 4.3: Levy under the EEG (Bundesministerium für Wirtschaft und Energie, 2015).

PCI save natural gas and coke, respectively, the economics of these technologies are not affected by the EEG. The economics of TRT are subject to both, ETS and EEG.

Since this study is mainly ex-post, past firms' assumptions on future energy prices can hardly be derived from the present. However, a limited number of interviewees stated that companies expected increasing electricity prices. Nevertheless, it hardly can be determined a) in which period they expected increasing electricity prices, b) for which period they expected increasing prices, or c) by which amount they expected prices to increase. Hence, this analysis does not consider firms' assumptions on future developments of energy prices.

Investment, operation, and maintenance costs are kept ceteris paribus. All costs are converted to Euro_{2005}. Interest rates are not included. The calculations of the payback periods are explained in detail in Appendix B.

The uptake of the selected energy-efficient technologies (EETs) in the German iron and steel industry has been rather quick during the 1980s but slow in the 1990s (Arens and Worrell, 2014). Since the mid-2000s these technologies are again being implemented, but some plants still possess a potential to adopt these technologies (Tab. 4.5). In step 5 we try to understand the drivers for the recent uptake and the barriers on a plant specific level. We analysed those cases in detail which either have implemented an EET recently, i.e. since 2009, or which still could implemented one. In total these are 10 cases (Tab. 4.5).

Next to literature research in step 5 also interviews with stakeholders are conducted, e.g. staff at the companies, plant manufacturers and governmental institutions. Confidentiality to all interviewees was assured. Interviewees were typically contacted by

Table 4.3: Impact of EEG and ETS on the energy price in Germany.

eurocent$^{1)}$/kWh	**2003**	**2005**	**2013**	
	EEG	**ETS**	**EEG**	**ETS**
Electricity$^{2)}$	0.410	1.214	5.227	0.298
Coal / coke / coking coal$^{3)}$	-	0.678	-	0.170
Natural gas$^{4)}$	-	0.404	-	0.101

1) Nominal.
2) 0.559 t CO_2 /MWh.
3) 0.339 t CO_2 /MWh.
4) 0.202 t CO_2 /MWh.

Table 4.4: Cases for the estimation of the payback period of the selected energy-efficient technologies.

Case	**BOFGR, PCI**	**TRT**
(a)	including ETS	including ETS, including EEG
(b)	excluding ETS	excluding ETS, including EEG
(c)	-	excluding ETS, excluding EEG

phone. Sometimes the interview was held directly. In other cases, the interviewees requested advanced information via e-mail. Then either the interview was held on a later appointment, or the interview was passed on to a more appropriate person. In total about 40 persons were consulted.

Case specific interview guidelines were prepared based on Gläser and Laudel (2010). After a short introduction, open questions were asked. In case of a recent implementation of an EET two main questions were raised: Why have the EET been implemented recently? Why have the EET not been implemented earlier? In the case that the plant has not implemented the technology yet the basic question was: Why has the EET not been implemented yet? Depending on the answers, more detailed queries were raised, checking the impact of possible drivers and barriers (Tab. 4.1). Additionally site specific issues were raised such as the financial situation of the firm, earlier adoption of the same technology or other EETs, other investments, plants at the site, site specific production processes, and commitment of the management.

Notes were taken manually. The notes were transcribed subsequently. If necessary, follow-up questions were raised via e-mail or by an additional phone call. The content of the interviews was analysed qualitatively according to Gläser and Laudel (2010). The interviews were scanned for relevant information that helps to shed light on why after

Table 4.5: Recently implemented energy-efficient technologies and plants which have not (yet) implemented them (Germany, 2014).

Implemented	**TRT**	**PCI**	**BOFGR**
recently[1)]	Hamborn 8 (2013) Salzgitter B (2012) Eisenhütt. 5A (2014)	Salzgitter A+B (2014)	Bremen (2009)
not yet	HKM A+ B Bremen 3	-	HKM Dillingen Ruhrort

1) since 2009.

a period of nearly no uptake, recently EETs were implemented again as well as why some plants still have not agreed on investing in these technologies. Thus, the decision whether information is relevant or not is based on the included factors (Tab. 4.1). But relevant information is also considered even if it does not apply to the structure of those factors. The relevant information is extracted from the interviews and is allocated by factor. The extracted information is analysed and interpreted.

4.3 Diffusion of energy-efficient technologies

4.3.1 Technology description

Top-pressure recovery turbines (TRT) are driven by the high-pressure top gas from blast furnaces generating electricity. TRT is a proven technology with little risk involved for installation and operation. TRT can only be installed at blast furnaces with high top pressure. Today, there are only three high-pressure and two low pressure blast furnaces with little production capacity in Germany without TRT (Arens and Worrell, 2014). In Germany TRT was first introduced in about 1978 (Arens and Worrell, 2014).

Basic oxygen furnace gas recovery (BOFGR) is an add-on technology which collects the BOF gas (BOFG). The heating value of BOFG varies depending on the hot metal ratio in the BOF. Also, the recoverable amount of converter gas varies (Brauer, 1996). In Germany BOFGR was first introduced in 1982 (Arens and Worrell, 2014).

Pulverized coal injection (PCI) partly replaces coke consumption in the blast furnace. One kilogram of coal can replace about 0.8 kg of coke. It does not reduce energy consumption in the blast furnace itself but reduces energy consumption for coke making. Since coke is a structural element needed to carry the weight in the blast furnace a

Table 4.6: Diffusion of TRT, PCI and BOFGR on the national level. **Still running plants** in bold letters; *shut down plants* in italics (sources: reference lists by plant manufactures, interviews).

year	TRT	PCI	BOFGR
1977	*Ruhrort 6*		
1978 – 1980			
1981			*Rheinhausen*
1982	**Salzgitter A + Schwelgern 1**		*Georgsmarinenhütte*
1983			**Bruckhausen**
1984	*Hamborn 4*		*Peine* + **Eisenhüttenstadt**
1985	**Dillingen 5**	*Hamborn 4*	**Völklingen**
1986	**Dillingen 4**	**Dillingen 3+4+5** + *Hamborn 6*	**Salzgitter**
1987		*Rheinhausen 1+2* + *Ruhrort 6* + **Schwelgern 1**	**Beeckerwerth**
1988	*Rheinhausen*		
1989	*Westfalenhütte 4+7*	*Westfalenhütte 4+7*	
1990	**Bremen 2 + Hamborn 9**		
1991		**Hamborn 9**	
1992			
1993	**Schwelgern 2**	**Schwelgern 2**	
1994 – 2003			
2004		**Eisenhüttenstadt 5A + Bremen 2**	
2005			
2006		**Bremen 3**	
2007		**Eisenhüttenstadt 1 + HKM A+B**	
2008		**Hamborn 8**	
2009			**Bremen**
2010			
2011			
2012	**Salzgitter B**		
2013	**Hamborn 8**		
2014	**Eisenhüttenstadt 5A**	**Salzgitter A+B**	

minimum coke rate is needed. The amount of coal injected into the blast furnace depends on a set of factors such as coke properties, desired hot metal quality or type and the condition of the coal (Joint Research Center, 2012). In 2010, the highest PCI rate in Germany achieved in a single blast furnace was 177 kg/thm while the national average was 138 kg coal/thm (Stahlinstitut VDEh, 2011). Blast furnaces can be retrofitted with PCI. This technology is widely applied nowadays. It was first introduced in Germany in 1986 (Arens and Worrell, 2014).

4.3.2 Diffusion on the national level

The selected EETs diffused quickly in the initial phase after their introduction to Germany (Tab. 4.6). During the first ten years (seven years for BOFGR) the EETs were implemented at a new site at least every two years. This was followed by a period in which none of the selected EETs were installed (1994-2003). From 1998 to 2008, no BOFGR has been adopted. Only in 2009 one site was equipped with BOFGR. Since then, again no company has invested in BOFGR. A similar observation is made with

TRT and PCI. Between 1994 and 2012, i.e. for 18 years no TRT was installed in Germany. Since then two TRTs have been implemented and a third blast furnace will be equipped with TRT. Its start-up is expected for mid 2015 (Stahleisen, 2013). PCI was not installed in Germany between 1994 and 2003. A period of five years followed in which five sites invested in PCI. In 2014 the last site adopted PCI.

This analysis shows phases with high and low diffusion of the selected EET hence it can be assumed that there are national level drivers and barriers that shape the diffusion of EET in the German steel industry.

4.3.3 Diffusion on the site and company level

Sites and companies seem to vary a lot in their attitude towards the uptake of the selected technologies (Tab. 4.7). While some sites implemented the selected technologies shortly after they had been introduced (Schwelgern/Beeckerwerth, Hamborn/Bruckhausen), other sites adopted these technologies only many years later, if at all. Interestingly some sites implemented an EET at one furnace, but equipped a second furnace only many years later with the same – but proven – technology (TRT at Salzgitter), or did not install it at a second furnace (TRT at Bremen). In some cases a site took up an EET quickly, but it is very slow to adopt a different technology (Rogesa/Dillingen, Eisenhüttenstadt). Some sites seem to be very slow in adopting the selected EETs (HKM).

According to our analysis the quickest site is Schwelgern/Beeckerwerth by ThyssenKrupp Steel that is located in a densely populated area. On average only 1.6 years passed before one of the selected EETs was implemented at this site. Hamborn/Bruckhausen also belongs to ThyssenKrupp Steel Europe and quickly adopted the selected EETs. In 2007 they built a new blast furnace that they directly equipped with PCI. Interestingly TRT was not directly implemented in the newly built blast furnace, but only in 2013. Eight out of the first nine implementations of PCI took place at sites belonging to firms that are considered as predecessors of the current ThyssenKrupp group. The same accounts for BOFGR.

The second quickest site (i.e. Völklingen) and the slowest site (i.e. Ruhrort) only produce steel, not hot metal. The site of Völklingen implemented BOFGR in 1986 when the site was just closing its blast furnaces. The blast furnace gas was replaced by BOFG (Marion, 2009). Ruhrort was one of the first sites implementing a waste heat boiler in its BOF in Germany. In 1994 the blast furnaces were shut down (ArcelorMittal, 2014). The site has not implemented BOFGR yet.

Table 4.7: Diffusion of TRT, BOFGR, and PCI on the site level in Germany (source: Stahlinstitut VDEh 2013; reference lists by plant manufactures, interviews).

			1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Schwelgern/ Beeckerwerth [ThyssenKrupp]	BF1	TRT														T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI														P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	BF2	TRT	O	O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							O	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	BOF	BOFGR			O	O	O	O	O	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Hamborn/ Bruckhausen [ThyssenKrupp]	BF1	TRT																												O	O	O	O	O	O	T	T	T
		PCI																												P	P	P	P	P	P	P	P	P
	BF2	TRT	O	O	O	O	O	O	O	O	O	O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							O	O	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	BOF	BOFGR			O	O	O	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
HKM	BF1	TRT		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P
	BF2	TRT	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P
Salzgitter	BF1	TRT														O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	T	T	T	T
		PCI														O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P
	BF2	TRT	O	O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P
	BOF	BOFGR			O	O	O	O	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Rogesa/ Dillingen	BF1	TRT						O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	BF2	TRT	O	O	O	O	O	O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	BOF	BOFGR			O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Völklingen	BOF	BOFGR			O	O	O	O	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Bremen [ArcelorMittal since 2002]	BF1	TRT	O	O	O	O	O	O	O	O	O	O	O	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
		PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P
	BF 2	TRT	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P	P
	BOF	BOFGR			O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	B	B	B	B	B	B	B
Eisenhütten-stadt [ArcelorMittal since 2002]	BF1	TRT																		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	T
		PCI																		O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P
	BF2	PCI							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P	P	P	P	P	P	P	P	P
	BOF	BOFGR					B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Ruhrort*	BOF	BOFGR			O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

*[ArcelorMittal since 2005]

plant runs | O: EET available and plant runs | T: TRT installed | P: PCI installed | B: BOFGR installed

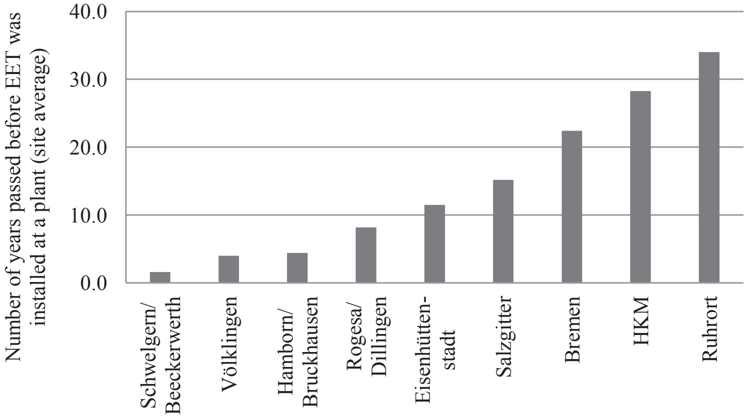

Figure 4.4: Number of years passed before an energy-efficient technology was installed at a plant (site average).

The site that was the second most slowly in implementing the selected EETs is HKM, which is also situated in the same densely populated area as ThyssenKrupp and Ruhrort. This site does not possess rolling mills (i.e. large electricity consumer within integrated steel mills), which might be a site specific constraint to implementing EETs. HKM does not (yet) use TRT and BOFGR and implemented PCI (only) in about 2007.

The third slowest site is ArcelorMittal Bremen, which implemented TRT at one blast furnace in 1990, PCI in 2004 and 2006 and BOFGR only in 2009. A second high pressure blast furnace does not possess TRT yet.

In the middle range there are the sites of Dillingen/Rogesa, Eisenhüttenstadt, and Salzgitter. The first two sites implemented BOFGR quickly, while BOFGR is still not applied at Dillingen. Additionally, Salzgitter was one of the first companies to install TRT at one blast furnace though it equipped its second blast furnace with TRT a remarkable 30 years later (i.e. 2012). Dillingen/Rogesa adopted PCI and TRT early. The implementation of TRT at Eisenhüttenstadt (formerly located in the German Democratic Republic) and PCI at Salzgitter can be considered to have happened rather slowly.

The findings suggest that the adoption of EET depends to some extent on the companies' attitude towards new technologies and energy efficiency. ThyssenKrupp was initially very quick to implement the selected technologies, though the recent implementation of TRT at Hamborn 8 might not be considered as quick. It is also notable that the three sites belonging to ArcelorMittal are among the five slowest sites according to this analysis. Nevertheless, we cannot find proof that the management practices

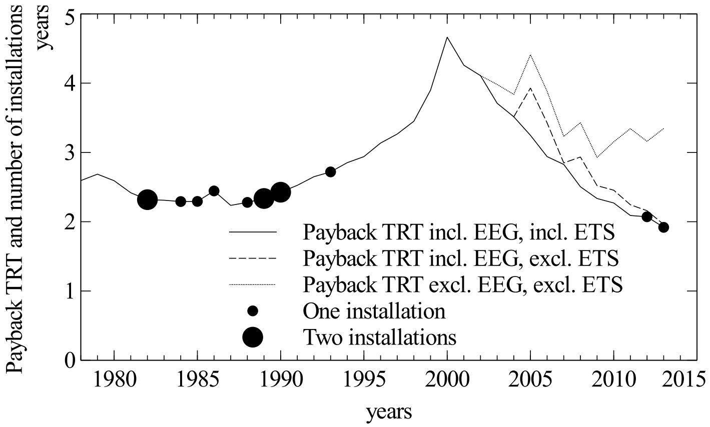

Figure 4.5: Payback periods for top-pressure recovery turbines in the German iron and steel industry as function of the end-user electricity price, levy for renewable energies under the EEG and a price for CO_2 under the EU-ETS.

towards innovation and energy efficiency is responsible for the observations. Barriers such as economics and access to capital could explain the behaviour as well.

This analysis only provides partial insights into a section of the German steel industry. The results indicate that there are site or company specific factors driving the diffusion of EET besides national level drivers and barriers.

The average years which passed before a site/company adopted an EET cover a broad range (Fig. 4.4). The value differs from 1.6 years (Schwelgern/Beeckerwerth) to (more than) 34 years (Ruhrort). The distribution has a linear to parabolic shape.

4.4 Findings on drivers and barriers

4.4.1 Economics

Economics are a key driver for the diffusion of EETs. The diffusion of the selected EETs rarely happened at payback periods above three years (Fig. 4.5-4.7). Moreover, the low energy prices in the late 1980s until the mid 2000s seem to have stopped the diffusion of the EETs in that period. It seems that the strong increase in energy prices from 2000 onwards helped to further diffuse the technologies.

Even without considering free allocations, the EU ETS affect fairly the economics of the selected technologies. Only for the period of 2005 to 2008, the EU-ETS reduced the

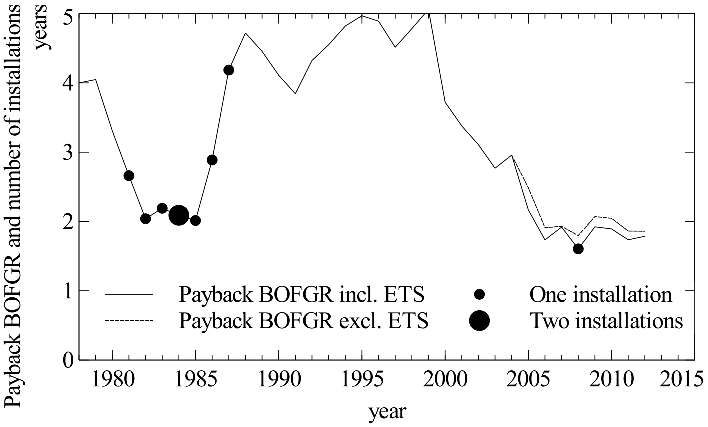

Figure 4.6: Payback periods for basic oxygen furnace gas recovery in the German iron and steel industry as function of the end-user natural gas price and the price for CO_2 under the EU-ETS.

payback period of the selected EETs by about 10 to 14 %. The biggest impact was on TRT when the EU-ETS reduced the payback period by 17 % in 2005. Since 2009 the impact of the EU-ETS on the reduction of the payback period has been far below 10 % for all selected technologies. Although the current impact of the EU-ETS is limited, the interviewees acknowledged the importance of how the EU-ETS might develop.

The analysis indicates that the levy for the support of renewable energies (EEG) shaped the economics of TRT (Fig. 4.5). It is assumed that integrated steel mills pay an electricity price which equals the average electricity price of the German industry. Integrated steel mills in general are not excluded from EEG. Hence, the average electricity price of the German industry is taken as an estimation of the electricity price of integrated steel mills. The payback period of an investment in TRT in 2012 would nearly double from 2.0 years with EEG to 3.4 years without EEG.

According to these findings economics seem to play a key role in the diffusion of EETs. However, economics alone cannot explain why some companies do not invest in an EET while other companies do.

4.4.2 Access to capital

Access to capital is also a key barrier, mentioned both in literature (e.g. Thollander et al., 2007; Rohdin and Thollander, 2006; Trianni and Cagno, 2012; Apeaning and Thollander, 2013) and by the interviewees. Good and bad economic prospects on the

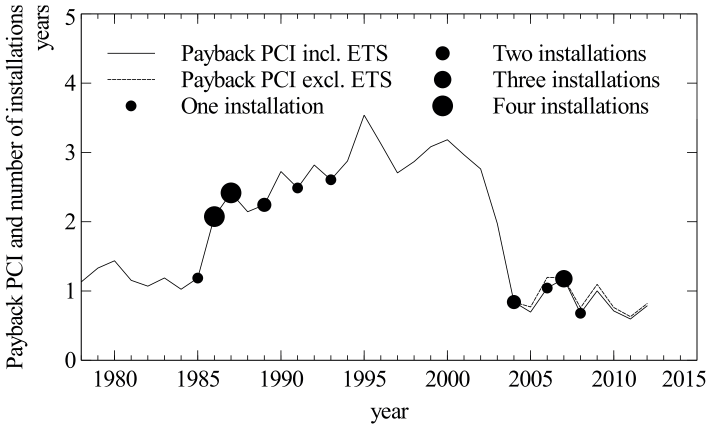

Figure 4.7: Payback periods for pulverized coal injection in the German iron and steel industry as function of the end-user coal price and the price for CO_2 under the EU-ETS.

national or global level and as for the company determine how easily or not a company can access capital. The firm has to decide which investments are more important to secure the companies' competiveness. For example, several interviewees stated that limited access to capital is a strong reason why blast furnace Bremen 3 is not yet equipped with TRT. The site of Bremen was insolvent in 1993. In recent years they have made several investments (ArcelorMittal Bremen, 2014). Additionally, the owner company of the site of Bremen, i.e. ArcelorMittal, has currently bad financial ratings (Reuters, 2012) and has therefore more limited access to capital. Finally, blast furnace Bremen 3 is the smallest high-pressure blast furnace in Germany. The smaller the blast furnace is, the smaller the TRT, and the investment may be less economically viable.

While access to capital seems to be a barrier for the implementation of TRT at Bremen 3, it seems to be a driver for the investment in BOFGR at Bremen in 2009. Until then the released BOFG was flared. The BOFGR only met the firms' economic requirements in the early 1980s and from the mid-2000s onwards (Fig. 4.6). Once a firm missed the first window of opportunity, it was unlikely to invest in BOFGR between the mid-1980s and mid-2000s. The BOF at Bremen is the last one in a German integrated steel mill which was equipped with BOFGR.

The blast furnace Eisenhüttenstadt 5A will be equipped with TRT in 2015, which can be considered as late. Eisenhüttenstadt is located in the territory of the former German Democratic Republic, that reunified in 1991. From 1990 onwards the site was run by EKO Stahl AG, and was acquired by Arcelor in 2002. Interviewees claim that the site of Eisenhüttenstadt has evolved into one of the most competitive sites of the ArcelorMittal Group in Germany or even Europe, which may explain the current investment in the TRT. Furthermore, the local energy supplier co-financed the investment (Stahleisen, 2013). ArcelorMittal is actively looking for investors in TRT at their sites (ArcelorMittal, 2016).

4.4.3 Lack of information and technological risk

Lack of information does not seem to be a barrier to the diffusion of the selected technologies. Without exception, all interviewees knew the technologies and reported that the company every once in a while estimates the economics.

Only in two cases technological risk was mentioned as a strong barrier to the diffusion of the selected EET. An interviewee of ArcelorMittal Ruhrort stressed the danger of carbon monoxide which is part of BOFG and its leakage. He put forward that at another site two workers had died of carbon monoxide. The interviewee is responsible for security, and therefore does not promote the implementation of BOFGR. Second, an interviewee of HKM stressed the risk of retrofitting TRT to the blast furnaces at the site.

According to our finding risks are considered when analysing the economics, but in none of the cases risks surpassed good economics in decision making.

4.4.4 Liberalized electricity market

Salzgitter was one of the first companies to implement TRT in Germany (1982). It runs another high pressure blast furnace which was equipped with TRT only in 2012, i.e. 30 years later. When Salzgitter B was erected in 1994, it was not equipped with TRT, while the same year the new blast furnace Schwelgern 2 (1993) of ThyssenKrupp was. One member of the company said that during times of state controlled electricity markets Salzgitter held a contract with the electricity supplier in which it agreed to refrain to build a TRT to retain a high level of purchased power. In return low electricity prices were assured. After liberalizing the German electricity market in 1998, the firm assessed the economics, and the recent increase in power prices led to the erection of a TRT at Salzgitter B in 2012.

4.4.5 Policy intervention

Germany is a federal state which shares responsibilities between the governmental and the federal level. Permissions for the construction of new industrial plants are allocated to the responsibility of the *Länder* which might even empower hierarchic lower institutions with the permission process. The case of TRT at Hamborn 8 seems to have been impacted by policy intervention. Several members of ThyssenKrupp claim that the blast furnace would not have been equipped with TRT if the company had not faced pressure from the local government. The local government officer in charge stated that his institution applies a law that requires large industrial plants to be run energy efficiently (BImSchG §5/4, Bundesministerium für Justiz und Verbraucherschutz, 2014c). He stated that companies have to illustrate the energy efficiency of the plant, while the local government itself collects information on energy-efficient technologies. The local government might find more options to increase energy efficiency than the company plans to include. The local government generally approves the application with additional requirements, e.g. the implementation of energy-efficient technologies which are (a) appropriate, (b) necessary, and (c) adequate to use energy efficiently. energy-efficient technologies (e.g. TRT) are self-evidently appropriate to save energy, are necessary since the law asks to use energy efficiently, and are adequate if they are economically viable. The last is given when competitive companies in reasonable economic conditions are already applying this technology. Though there are some indications that environmental permitting agencies such as the local government of Duisburg may play a role in the diffusion of energy-efficient technologies, we did not find any further proof that this happened in other regions of Germany (*Länder*) as well. Few plant suppliers mentioned policy intervention for the case of TRT at Salzgitter B. However, the respective governmental institutions strongly deny any influence.

In summary, we found some indication for policy intervention on the diffusion of energy-efficient technologies in the German iron and steel industry, though only in a single case and with differing views from the regulator and company side. It seems that different environmental permitting agencies have different approaches towards the implementation of energy-efficient technologies.

4.4.6 Site specific constraints

Site specific factors have been described to some extent by Sutherland (1991; 1996), though not by Sorrell et al. (2000), Cagno et al. (2013) and Brunke et al. (2014). In this analysis four out of five cases that have not implemented a selected EET yet (Tab. 4.5) put forward site specific constraints as a key barrier. The four cases belong to three sites. The cases are TRT and BOFGR at HKM as well as BOFGR at Ruhrort and Dillingen. All three sites are not complete integrated steelworks. One site has no rolling capacity (HKM), a second only a rolling capacity of about 50 % of its hot metal production (Dillingen) and the third has steelmaking and rolling but no iron production (Ruhrort).

The implementation of TRT at HKM seems to be restrained by site specific constraint that HKM has no rolling and thus a lower electricity demand than integrated steelworks including rolling. Rolling is one of the key electricity and fuel consumers in an integrated steel plant. If an integrated steel plant does not possess rolling mills, its electricity and gas demand is lower. If it then was to produce electricity with TRT or recover BOFG, the company would either have to sell the energy or to find other onsite uses.

Additionally, currently market power prices are low in Germany while consumer prices are high, particularly due to the EEG reallocation charge. Since HKM does not have any further electricity demand, the price of electricity produced with TRT at HKM would have to compete with power plants. As an interviewee stated, the company consistently evaluates the economic viability of TRT at its blast furnaces. So far, the implementation would not meet the companies' economic requirements. The implementation of TRT at HKM is foreseen when the blast furnaces are re-built.

The recovery of BOFG at Dillingen seems to be held back by the site specific constrain that its blast furnace capacity is about twice as big as its rolling capacity. Hence, the amount of blast furnace gas covers already to a large extent the energy demand for heating in rolling. The economics of BOFG recovery seems to depend largely on whether a company can reduce its natural gas consumption or not.

The site of Ruhrort seems to abstain from implementing BOFGR since this site does not possess ironmaking facilities, but only two BOFs and rolling. It was one of the first BOFs in Germany that was equipped with a waste heat boiler, so the BOFG is burned to boil water. The steam is used for both on-site purposes such as vacuum-degassing and is sold to another steel plant. The pipes for the transport of the steam to the other steelwork were renewed in 2004 at times of comparably low energy prices. The interviewee stated that the company considers BOFGR once in a while but that so far it has not turned out to meet the firms' economic requirements. Since the site has recovered parts of the off-gas energy, invested in the pipes, and has a contract with the other company, possible additional proceeds by BOFGR would not compensate for the opportunity costs.

4.5 Conclusions

Policy can shape the uptake of EETs but so far its impact is limited. The strong increase of the levy for the support of renewable energies (EEG) seems to have led to a further diffusion of one TRT since about 2012. Furthermore, we found indications that one TRT has been erected partly due to the application of an existing law on energy efficiency in industry by a local government. The introduction of the European Emission Trading System in 2005 has had only marginal effects on the diffusion of the selected EETs.

Economics matter. The results indicate that investment rarely happened at payback periods exceeding about three years. Increasing coke prices led to the strong uptake of PCI from 2004 onwards. A better economic outlook of a company also strengthens the uptake of EET.

Site specific constraints seem to be the key barrier to a further diffusion of the selected EETs in Germany since they impact their economics. A second strong barrier seems to be access to capital, i.e. the economic situation of the company. In one case the formerly state regulated electricity market seemed to have hindered the implementation of a TRT. Risk and lack of information were not identified as barriers to the diffusion of the selected EETs.

Our analysis shows that there are still few plants that could implement the selected EETs in Germany, but that mainly site specific constraints lower the economics of the technologies. Lessons learnt from this paper might be applied to other market economies with a similar share of primary to secondary steel production. The selected technologies were introduced about 30 years ago, so the remaining diffusion potential should be limited in most countries.

A significant increase in the price of CO_2 within the EU-ETS (in the case of Germany) or the introduction of a strong emission trading system in other countries would most likely lead to a further diffusion of the selected technologies. However, the energy efficiency potential seems to be limited. Reducing CO_2 emissions in the iron and steel industry requires new technologies (e.g. strip casting, breakthrough technologies) or carbon capture and storage.

It should be elaborated to which extend the CO_2 emissions in the steel industries of selected countries could be reduced considering different technological pathways. This would also help to design future policy including targets within emission trading systems.

Chapter 5

Alternative emerging ironmaking technologies[4]

Abstract

Iron and steel manufacturing is among the most energy-intensive industries. Ironmaking accounts for the major share of total energy use in steel production in integrated steel mills that use blast furnaces and basic oxygen furnace. Although studies from around the world have identified a wide range of energy-efficient technologies applicable to the ironmaking process that have already been commercialized, information is limited and/or scattered regarding alternative emerging or advanced energyefficiency and low-carbon technologies that are not yet fully commercialized. This paper consolidates available information on twelve alternative emerging ironmaking technologies, with the intent of providing a well-structured database of information on these technologies for engineers, researchers, investors, steel companies, policy makers, and other interested parties. For each technology included, we provide information on energy savings and environmental and other benefits, costs, and commercialization status. All the alternative emerging ironmaking technologies eliminate energy-intensive coke production. Corex process, Finex process, and coal-based HYL process are very promising alternative emerging ironmaking technologies because they are already commercialized, but they have very low adoption rate in the steel industry worldwide.

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5.1 Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, use of coal as the primary fuel for iron and steel production means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. The iron and steel industry accounts for approximately 27 % of CO_2 emissions from the global manufacturing sector (International Energy Agency, 2007).

Annual world steel demand is expected to grow from approximately 1,410 Mt of crude steel in 2010 (U.S. Geological Survey, 2012) to approximately 2,200 Mt in 2050 (Bellevrat and Menanteau, 2008). The bulk of this growth will take place in China, India, and other developing countries in Asia (Bellevrat and Menanteau, 2008). This significant increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions.

Studies have documented the potential for the worldwide iron and steel industry to save energy by adopting commercially available energy efficient technologies and measures (International Energy Agency, 2007; Hasanbeigi et al., 2012; Worrell et al., 2003). However, in view of the projected continuing increase in absolute steel production, future reductions (e.g. by 2030 or 2050) in absolute energy use and CO_2 emissions will require innovation beyond technologies that are available today. New developments will likely include alternative ironmaking processes that can economically reduce energy use and CO_2 emissions. Deployment of these new technologies in the market will be critical to the industry's climate change mitigation strategies for the mid and long term. It should be noted that the technology adoption in regions around the world is driven by economic viability, raw materials availability, energy type used and energy cost as well as regulatory regime.

Many studies from around the world have identified sector-specific (Worrell et al., 2010; American Iron and Steel Institute, 2010; Asia Pacific Partnership on Clean Development and Climate, 2010; Joint Research Center, 2012; U.S. Environmental Protection Agency, 2012) and cross-cutting (U.S. Department of Energy, 2016) energy-efficient technologies for the iron and steel industry that are already commercially available. However, information is limited and not easily accessible regarding emerging or advanced energy-efficient- and low-carbon technologies for the industry that have not yet been commercialized. Since ironmaking consumes highest share of the energy in the steel production from iron ore, this paper consolidates the available information on alternative emerging ironmaking technologies to assist engineers, researchers, investors, iron and steel companies, policy makers, and other interested parties. The paper aims to contribute to energy efficiency, CO_2 and other air pollutants emissions reduction and sustainability in the steel industry by filling the gap in the information.

The information presented in this paper is collected from publically available sources and covers the main alternative emerging ironmaking technologies; however, the list of emerging technologies addressed is not exhaustive.

The paper uses a uniform structure to present information about each of the twelve technologies covered. First, we describe the technology, including background, theory, pros and cons, barriers and challenges, and case studies if available. Next, we present the energy, environmental, and other benefits of the technology as well as cost information if available. Finally, we identify the commercialization status of each technology. The commercialization status of each technology is as of the writing of this paper and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: The technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

The purpose of this paper is solely informational. Many emerging technologies are proprietary and/or the manufacturers who are developing a new technology are the primary sources of information about it. Thus, in some cases, we identify a company that is the source of a technology so that readers can obtain more information about the company and product. Because the nature of emerging technologies is continual and often rapid change, the information presented in this paper is also subject to change.

5.2 Description of iron and steel production

Iron ore is chemically reduced to produce steel by one of these three process routes: blast furnace (BF)/basic oxygen furnace (BOF), smelting reduction, or direct reduction (Joint Research Center, 2012). Steel is also produced by direct melting of scrap in an electric arc furnace (EAF). Each of these processes are briefly explained in the section below.

BF/BOF and EAF production are the most common today. In 2010, BF/BOF production accounted for approximately 65 % of the steel manufactured worldwide, and EAF production accounted for approximately 30 % (World Steel Association, 2011). Iron and steel can be produced at separate facilities or in an integrated steel mill, where the iron ore is reduced into hot metal or DRI (direct reduced iron) and then processed into steel at the same site.

Ironmaking production processes

Figure 5.1 is a simplified flow diagram of steel production using BF/BOF, EAF, and direct reduction. The following subsections describe the main production steps. Since the focus of this paper is ironmaking, in this section we only briefly describe three ironmaking processes, i.e. the blast furnace, direct reduction, and smelting reduction processes.

Blast furnace

A blast furnace is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide gas. The heat melts the charge, and the carbon monoxide removes the oxygen from the iron ore, producing hot metal. Hot metal is a solution of molten iron at approximately 1,480°C, which contains 4 % carbon and some silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically tapped from the furnace into transfer cars and transported to the BOF where it is refined into steel.

The blast furnace is the most energy-intensive step in the BF/BOF steelmaking process, generating large quantities of CO_2 (American Iron and Steel Institute, 2010). Energetics gives a range of energy use of 13.0 to 14.1 GJ/thm (Energetics, 2004).

Direct reduction

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, and reducing agents. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, 92.6 % of direct reduction worldwide was based on natural gas and took place in shaft furnaces, retorts, and fluidized bed reactors. The metallization rate of the end product, called direct reduced iron (DRI) or *sponge iron*, ranges from 85 % to 95 % (often even higher).

In 2008, 68.5 Mt of DRI was produced worldwide, using primarily Midrex technology (58.2 %). The Midrex process typically consists of four stages: 1) reduction, 2) reforming, 3) heat recovery, and 4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 % fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and carbon monoxide (International Energy Agency, 2010). The iron is then formed into briquettes, and heat from the process is recovered.

Smelting reduction

Smelting reduction iron is an alternative to the blast furnace, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products coke and sinter. Smelting reduction aims to use coal and iron fines. Several processes are under development; some have been commercially proven (Corex, Finex, ITmk3), others are under demonstration (e.g. Hismelt).

Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage – similar to DRI – is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and carbon monoxide rich hot gas that can be further oxidized to generate additional heat to smelt the iron.

Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting (International Energy Agency, 2010). Commercial smelting reduction is still dominated by first-generation processes, notably the Corex process developed in Germany and Austria (International Energy Agency, 2010).

CO_2 impact of iron and steel production

Iron and steel production generates CO_2 emissions as 1) process emissions, in which raw materials and combustion both may contribute to CO_2 emissions; 2) emissions from combustion sources alone; and 3) indirect emissions from consumption of electricity

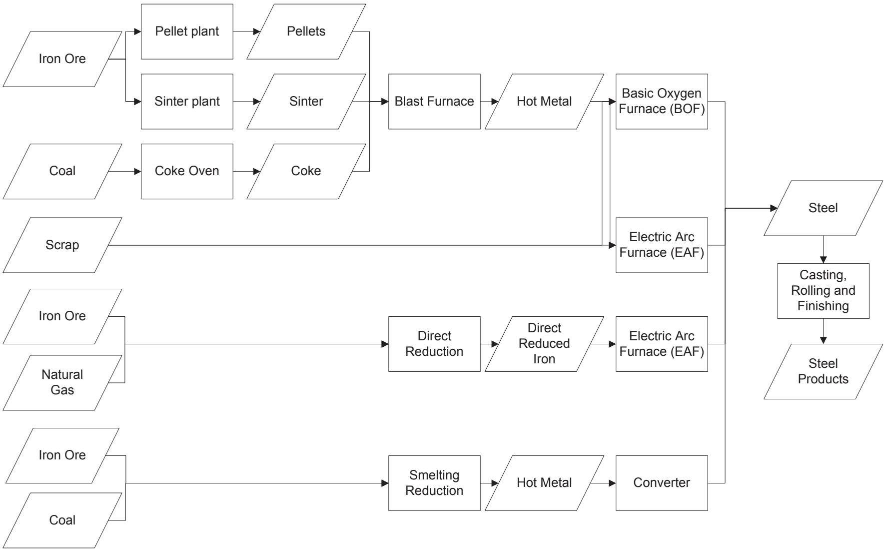

Figure 5.1: Flow diagram of steel production.

(primarily in EAFs and in finishing operations such as rolling mills at both integrated steel plants and EAF plants) (U.S. Environmental Protection Agency, 2012).

The major process units at iron and steel facilities where raw materials, usually in combination with fuel combustion, contribute to CO_2 emissions include the sinter plant, non-recovery coke oven battery combustion stack, coke pushing, blast furnace exhaust, BOF exhaust, and EAF exhaust (U.S. Environmental Protection Agency, 2012). The primary combustion sources of CO_2 include: byproduct recovery coke oven battery combustion stack, blast furnace stove, boiler, process heater, reheat furnace, flame-suppression system, annealing furnace, flare; ladle reheater, and other miscellaneous (U.S. Environmental Protection Agency, 2012).

Total CO_2 emissions of a typical integrated steel plant are equal to about 1.8 t CO_2/t rolled coil, of which 1.7 t CO_2/t rolled coil is associated with coal use, and the other 0.1 t CO_2/t rolled coil is related to lime use (Birat, 2010).

5.3 Alternative emerging ironmaking technologies

The subsections below describe the following alternative ironmaking processes that reduce energy use and carbon emissions: the Corex process, the Finex process, Tecnored, ITmk3, the paired straight hearth furnace, the coal-based HYL process, the coal-based

Midrex process, molten oxide electrolysis, suspension hydrogen reduction, fine ore reduction in a circulating fluidized bed, charging carbon composite agglomerates, use of biomass and waste oxides, and the cyclone converter furnace.

5.3.1 Corex

Corex is an industrially and commercially proven smelt reduction process that allows for production of hot metal directly from iron ore and non-coking coal. The process was developed to industrial scale by Siemens VAI, now Primetals. Corex differs from blast furnace production in using non-coking coal as reducing agent and energy source. In addition, iron ore can be directly charged to the process in form of lump ore, pellets, and sinter (Siemens VAI, 2007).

The Corex process is a two-stage direct smelting process, consisting of: 1) a melter-gasifier, which melts the DRI and gasifies the coal; and 2) a DRI shaft furnace mounted above melter-gasifier, which reduces lump ore or pellets to DRI by reducing gas from the melter-gasifier. The shaft furnace is a modified Midrex DRI counter-current reactor without a cooling zone in which lump ore or/and pellets are reduced to approximately 85-% metallization. The hot DRI at a temperature of approximately 800 °C is discharged from the shaft furnace by means of horizontal screw conveyors, to the charging pipes of the melter-gasifier.

The reducing gas enters the bottom of metallization zone. The fresh reducing gas from the melter-gasifier enters the shaft furnace at approximately 800 °C and then exits from the furnace top at about 450 °C. The melter-gasifier, which completes the reduction and melting of the DRI, consists of a fluidized bed chamber resting on liquid slag and a hot metal bath. Coarse coal is charged to the top of melter-gasifier and charred in the fluidized bed. Oxygen is injected via tuyeres around the circumference of the melter-gasifier. This forms a raceway in which the oxygen reacts with charred coal to form carbon monoxide.

For optimum energy efficiency and economics, the process requires the following auxiliaries: 1) CO_2 stripping of the shaft top gas, which enables better utilization of the process gas (after CO_2 stripping, the rich reducing gas could be recirculated to the shaft furnace); and 2) In most cases, co-generation of the export gas, required because of the high calorific value of the gas. 3) An additional DRI shaft furnace could be also installed to utilize the off gas and to produce an amount of DRI equivalent to the hot metal from the melter-gasifier (Asia Pacific Partnership on Clean Development and Climate, 2010).

Some of the limitations of the Corex process are (Agrawal and Mathur, 2011):

- It can't use ore fines directly
- There are restrictions on non-coking coal (volatile matter of carbonaceous material to be maintained at around 25 %
- Net export gas should be utilised very economically, otherwise the process becomes un-viable.

There are five commercial Corex units in operation in China, Korea, India, and South Africa (Siemens VAI, 2007). The following benefits are reported for Corex compared to a conventional blast furnace (Asia Pacific Partnership on Clean Development and Climate, 2010; Siemens VAI, 2007):

- No need for coking coal and coke
- Fuel savings of 18 % and oxygen consumption reduction of 13 % (reported for a low-export gas system demonstration in India)
- Approximately 20 % lower CO_2 emissions per tonne of product
- Approximately 30 % lower mono-nitrogen oxides emissions per tonne of product
- No volatile organic compound emissions; significantly lower sulfur osxides emissions
- Fuel rate significantly reduced by circulation of the shaft furnace top gas back to the shaft furnace
- Reduced investment and operation costs
- Lower slag production (18 % slag production reduction reported in a low-export gas system demonstration in India).

Commercial status: Commercial with very low adoption rate.

5.3.2 Finex

The Finex smelting-reduction process, developed by Siemens VAI and the Korean steel producer Posco, is based on the direct use of non-coking coal and fine ore. The major difference between the Corex and Finex processes is that the Finex process can directly use sinter feed iron ore (up to 0.012 m) (Siemens VAI, 2007), without agglomeration.

The Finex core plant consists of a melter-gasifier and a series of successive fluidized bed reactors that form a counter-flow system in which ore fines are reduced in three or four stages to DRI. The upper reactor stage serves primarily as a preheating stage. In the succeeding stages, the iron ore is progressively reduced to fine DRI. The fine DRI is then compacted and charged in the form of hot compacted iron into the melter-gasifier. The charged hot compacted iron is subsequently reduced to metallic iron and melted. The heat needed for the metallurgical reduction and melting is supplied by coal gasification with oxygen. The reduction gas, also produced by the coal gasification, is passed through the fluidized bed reactors. The Finex export gas is a highly valuable product and can be further used for DRI or hot briquetted iron production, electric energy generation, or heating. The hot metal and slag produced in the melter-gasifier is frequently tapped from the hearth, as is also done in blast furnace or Corex operation (Siemens VAI, 2007).

Currently the Corex plant at Posco is part of the Finex demonstration, with an annual hot metal capacity of 0.9 Mt/year. Based on good results at the Finex demonstration plant, Posco decided in 2004 to construct a 1.5-Mt/year industrial Finex plant at Posco Pohang Works, Korea which was commissioned in 2007 (Siemens VAI, 2007). Posco orderd a third Finex plant with a capacity of 2 Mt/year from Siemens VAI in 2011. Its commission was scheduled for 2013 (Siemens, 2011).

The following benefits are reported for Corex compared to blast furnace production (Asia Pacific Partnership on Clean Development and Climate, 2010; Siemens VAI, 2007):

- No need for pelletizing, sintering, or agglomeration of iron-bearing materials
- Allows use of fine concentrates
- Capital cost claimed to be 20 % lower than for blast furnace, and production cost 15 % lower
- Lower emissions because of lower energy consumption and no need for coke making
- Direct utilization of non-coking coal
- High valuable export gas for a wide range of applications in metallurgical processes and energy production
- Production of hot metal with quality similar to that produced in a blast furnace

Commercial status: Commercial with very low adoption rate.

5.3.3 Tecnored

The Tecnored process uses agglomerated pellets or briquettes containing iron ore fines and low-cost coals. Within the furnace, the pellets or briquettes are reduced to hot metal. Hot blast and other solid reductants are injected into the furnace as well. The furnace' shaft height is only two to three meters and therefore much smaller than typical blast furnaces (Danieli Corus, nd).

The Tecnored process starts with preparation of self-reducing pellets or briquettes, which are made from iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines are mixed and agglomerated into pellets or briquettes. After a drying process, the pellets/briquettes are fed from the top to the Tecnored furnaces. Additional lump coal and hot blast are injected into the furnace as well. The top gas is cleaned. Some of the top gas is re-fed as cold blast to the furnace. Preheated top gas is either fed as hot blast to the furnace or is used for the drying of the self-reducing pellets/briquettes. Surplus top gas is exported, for example to co-generation system or to replace fuels in other processes. Hot metal and slag are tapped at the bottom of the furnace (Danieli Corus, nd).

The Tecnored process can use low-cost materials (e.g., low grade iron ore fines, low-cost fuels). Its smaller design means it requires less power and less pressure within the furnace. It achieves full metallization (up to 99 %). The process takes just 0.5 h compared to a typical blast furnace process, which takes up to 8 hours (MiningWeekly, 2011). However, this technology needs further development, and its capacity is smaller than typical blast furnaces. A Vale Tecnored pilot plant reportedly started operating in 2011 in Brazil. The capacity of the test facility was intended to be 75,000 t with an increase to 0.3 Mt planned (The International Resource Journal, 2011).

The following benefits are reported for the Tecnored process compared to conventional blast furnace production (Danieli Corus, nd; Lockwood, 2000):

- Eliminates the need to use coke and sintering facilities, thereby reducing construction costs, energy use, pollutants, and CO_2 emissions.
- Lower power and pressure requirements because of smaller size of furnace
- Uses low-cost iron ore fines and low-cost fuels
- Achieves full metallization (up to 99 %).

Commercial Status: Pilot stage

5.3.4 ITmk3 ironmaking process

In almost all direct reduction ironmaking technologies that use a rotary hearth furnace (RHF), the RHF reduces iron ore to about 80 %. A secondary smelting facility removes the remaining other material (gangue) from the ore. The DRI produced is usually taken to an EAF for final reduction and gangue removal. However, ITmk3 technology uses the RHF as a stand-alone unit that produces gangue-free metal eliminating the need for a secondary smelting process (Fruehan, 2004a). The ITmk3 process uses low-grade iron ore and coal to produce iron nuggets with an iron content is about 96 to 97 % (Kobelco, 2010). The mixing, agglomeration, and feeding steps are the same as in the production of DRI or blast furnaces, but the RHF is operated differently. In the last zone of the RHF, the temperature is raised, which melts the reduced iron ore and enables it to separate easily from the gangue. The result is a nugget containing iron and carbon with almost no oxygen or slag (Ishikawa et al., 2008). This technology was demonstrated in a commercial scale demonstration plant co-funded by the U.S. DOE in 2006. This technology achieves reduction, melting, and slag removal in only about 0.15 h (U.S. Department of Energy, 2010).

Kobe Steel, a Japanese steel company, developed and licensed the ITmk3 technology for production of nuggets. Mesabi Nugget, LCC, a joint venture between Steel Dynamics and Kobe Steel, began producing pig iron nuggets using ITmk3 technology in January 2010. The plant has the capacity to produce 0.5 Mt of nuggets per year. Mesabi Nugget produces iron nuggets principally as feedstock for EAF steelmaking (Kikuchi et al., 2011). Kobe Steel and SAIL (India's largest steel producing company) have signed an agreement to build the second ITmk3 plant with the capacity of 0.5 Mt in India (SAIL, 2012).

Mesabi Nugget claims the following benefits for the ITmk3 technology compared to conventional steelmaking (Kikuchi et al., 2011):

- Lower capital and operation costs; no coke oven is required
- 30 % energy savings over integrated steelmaking, 10 % over EAF fed by DRI
- Utilization of all chemical energy of coal; no gas exported from the system
- Reduced NOx, sulfur oxide (SOx), and particulate matter emissions
- Reduction, melting, and slag removal in only 0.15 h
- Reduction of iron oxide (FeO) to <2 %, minimizing attack to refractories

Commercial Status: Demonstration stage

5.3.5 Paired straight hearth furnace

The paired straight hearth (PSH) furnace is charged with cold-bonded self-reducing pellets composed of iron oxide and coal. When the pellets are heated, the iron oxide is chemically reduced to produce a 95-% metallized pellet suitable for use in steelmaking in an EAF. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal. As the pellets are heated on the hearth, carbon monoxide gas is evolved and combusted above the pellet bed to drive the process.

The bed of conventional RHFs is only two to three pellets high whereas the PSH furnace has a bed height of eight pellets (approximately 120 mm). The PSH furnace off gases are fully combusted to raise the temperature above the bed to 1,600 °C. Reoxidation is prevented by the CO-rich gases rising through the bed. The PSH furnace technology is significantly more productive while using less energy than conventional furnaces (American Iron and Steel Institute, 2010). The initial research program, funded by the DOE/AISI TR Program, was completed in 2002.

In 2006, DOE/AISI, through its TR Program, commissioned an engineering study by a well-known furnace builder to verify the feasibility and costs of building a PSH furnace. The study concluded that it is feasible to design, build, and continuously operate a PSH furnace to produce 46,000 t per year of DRI at 95-% metallization for a cost of USD 16,729,000. A detailed design and validation study to evaluate raw material flexibility was then initiated, and this study is scheduled to be completed in 2013. A demonstration-scale PSH furnace planned after that study is complete. The PSH furnace may be coupled to a smelter to provide a viable replacement for blast furnace and BOF steelmaking.

Technology integration issues related to materials handling, furnace and waste treatment control systems, pellet quality, multi-layer bed stability, DRI quality, material throughput, process economics, long-term furnace performance, reliability, and stability are some of the barriers and uncertainties about this technology that need to be addressed (U.S. Department of Energy, 2011). The most likely point of initial entry for PSH furnaces into the mainstream market is integrated steelmaking facilities that might be looking for an alternative source of hot metal. This could include producers of coil, slab, long, or specialty steel products (U.S. Department of Energy, 2011).

The following benefits are reported for PSH furnace ironmaking compared to blast furnace ironmaking (Asia Pacific Partnership on Clean Development and Climate, 2010; U.S. Department of Energy, 2011):

- Higher-productivity smelting operations when used as a pre-reducer with a smelter, to the degree that the combined process is a suitable replacement for a blast furnace/coke oven
- 30 % less energy at lower capital cost compared to blast furnace ironmaking
- One-third fewer total CO_2 emissions per t of hot metal produced
- No coke oven is required.
- Coal used without requiring gasification
- For EAF operations, reduced energy intensity because of availability of hot metal on site (reduced power consumption, tap-to-tap time)
- Reduced costs (no cokemaking process needed, high-volatility coals can be used)
- Can use high-volatility coals to produce DRI pellets from virgin iron ores and steelmaking waste products, an important advantage given the scarcity of high-quality raw material

Commercial Status: Development stage

5.3.6 Coal-based HYL process – A syngas-based DRI plant

The HYL process, by Tenova HYL, is designed to directly reduce iron ores using reducing gases in a solid-gas moving bed reactor. Oxygen is removed from the iron ores by chemical reactions based on hydrogen and carbon monoxide to produce highly metallized DRI (Tenova and Danieli, nd).

The original HYL technology used natural gas, but Tenova HYL has built a new coal-based HYL technology (also known as Energiron HYL technology) by adding a coal gasification technology to HYL. The reactor and its peripheral systems and the principles of operation for the coal-based HYL process are same as for the gas-based HYL process in which oxide material is fed from the top and is reduced by a counter-current flow of hydrogen and carbon monoxide containing gas. Because this process does not use natural gas, a lower-carbon-content product (around 0.4 %) is expected. Similar to the gas-based HYL process, in the coal-based process, the furnace top gas is cooled and cleaned, and its CO_2 is removed and then recycled into a reducing gas circuit. Reducing gas is produced in a coal gasifier that can process practically any kind of carbon-bearing material. Coal and oxygen are injected into the gasifier, and almost all carbon in the coal is gasified. The gas is dust laden and includes CO_2 and water as well as other impurities. It is cleaned and cooled in a series of cyclones and water, CO_2, and sulfur are removed. Because the HYL reactor is designed to work with high content hydrogen reducing gas, and the gas from the gasifier contains considerable amounts of CO, a gas shift reactor is required to convert carbon monoxide into hydrogen by the reaction (Eq. 5.1):

$$CO + H_2O \rightarrow CO_2 + H_2. \tag{5.1}$$

The shift reactor is installed before the CO_2 removal system. The temperature and pressure of the gas are then regulated before injection into the reactor (Asia Pacific Partnership on Clean Development and Climate, 2010).

Danieli and Tenova HYL will build four units, each 2.75 Mt/year coal-based HYL plant for Jindal Steel and Power Limited in India. The Syngas plant will provide reducing gas for the DR plant as well as power generation facilities (Steel Times International, 2011).

Tenova HYL claims the following benefits for coal-based HYL compared to blast furnace production (Asia Pacific Partnership on Clean Development and Climate, 2010; Tenova HYL, 2008):

- No need for coking coal and coke
- No need for natural gas
- Allows usage of low-quality coals
- Production of hot DRI that could be charged to EAF with significant energy savings

Commercial status: Commercial with very low adoption rate

5.3.7 Coal-based Midrex process

The Midrex direct reduction process uses a natural-gas-based shaft furnace process that converts iron oxides (pellets or lump ore) into DRI. The Midrex direct reduction technology has evolved during the past four decades from plant capacities of just 150,000 t/year to capacities now approaching 2 Mt/year (Siemens VAI, 2007). This process currently produces 60 % of the world's DRI annually (Midrex, 2013). However, because not all regions have abundant, inexpensive natural gas, another direct reduction alternative is needed. An alternative option is the MXCOL process, which uses synthetic gas (syngas) made from coal in combination with a Midrex direct reduction plant. Syngas options include a coal gasifier, coke oven gas, or BOF gas. The big advantage of coal gasification is that lower-grade, inexpensive domestic coals can be used to produce a high-quality reducing gas for the Midrex shaft furnace (Midrex, 2011).

The coal-based MXCOL/Midrex reactor and auxiliary systems are the same as those for a gas-based Midrex plant. In the MXCOL process, the cold syngas is depressurized to about 3 bar in a turbo expander, which generates electricity. The low-pressure syngas is mixed with recycled gas to produce the required reducing gas. The mixed gas is then heated to more than 900 °C and enters the shaft furnace where it reacts with the iron oxide to produce DRI. The spent reducing gas (top gas) exiting the shaft furnace is scrubbed and cooled, then passed through a CO_2 removal system, which reduces the CO_2 content to 2 to 3 % or less. This ensures that the mixed reducing gas (syngas from the gasification plant and recycled top gas from the Midrex plant) has an acceptably high reductant (hydrogen+CO) to oxidant (water+ CO_2) ratio for efficient iron oxide reduction. The CO_2 removal system will also remove the sulfur gases contained in the recycled top gas. The recycling of the top gas makes MXCOL a very efficient process. Very pure CO_2 is recovered from the gasifier cleaning and conditioning plant and the CO_2 removal system in the Midrex plant. These streams could be sequestered or sold for enhanced oil recovery or use in a petrochemical or other operation (Midrex, 2011).

Jindal Steel and Power Limited in India has contracted with Midrex Technologies for a 1.8 Mt/year MXCOL plant, the world's first coal gasifier-based Midrex plant (Midrex, 2011).

Midrex Technologies claims the ffollowing benefits for coal-based Midrex compared to blast furnace production (Midrex, 2011):

- Can use any coal gasification technology (The additional cost of coal gasification should be taken into account.)
- Fixed-bed or fluidized-bed gasifier able to readily use the low-rank, high-ash domestic coals in India and China
- Potential to use coal syngas from other sources such as coke oven gas or BOF gas
- Uses the well-proven Midrex direct reduction process; can readily use domestic iron oxides as feed material.
- Produces DRI with quality comparable to that produced by natural gas-based Midrex plants
- The DRI can be hot charged into a nearby EAF to significantly reduce the EAF electricity requirement and increase productivity
- No coke, coke ovens, or sinter plant required
- Lower specific capital cost than an integrated steel works

- Lower air emissions than an integrated steel works
- Ability to capture high-purity CO_2 for sequestering or injecting into oil and gas fields

Commercial status: Demonstration stage

5.3.8 Fine ore reduction in circulating and bubbling fluidized beds

Both Circored and Circofer are fine ore reduction processes. Circored is gas-based, and Circofer is coal-based. Both use a proven two-stage configuration, combining a circulating fluidized bed with a bubbling fluidized bed. Both are direct reduction processes utilizing iron ore fines directly to decrease DRI or HBI production costs by avoiding an expensive agglomeration step. The Circored process uses hydrogen as reductant.

The first Circored plant, designed to produce 0.5 Mt/year of HBI, was commissioned in Trinidad in 1999. In the Circofer process, coal is used as reductant. The Circofer pilot plant at Outotec's research and development center in Frankfurt, Germany, has a capacity of 5 tonnes per day ore fines and has demonstrated the basic principle of the process (Outotec, 2007, 2015).

In the Circofer process, coal and ore are fed into two fluid beds. The first is a circulating fluidized bed where the coal is charred, and the ore is 50-% metallized. The second is a bubbling fluidized bed where final reduction using the char is achieved. Productivity is limited because of required high retention times in the bubbling fluidized bed. In the proposed combined process for Circofer only the circulating fluidized bed would be used to produce char and a 50-% metallized product which would be fed into a smelter. Smelting using char could achieve 80-% post combustion, and final reduction is very rapid (Fruehan, 2004a).

The Circofer process operates at reduction temperatures of approximately 950 °C in a closed gas circuit without producing export gas. One possible application of Circofer is as a single-stage pre-reduction step for the HIsmelt process. It is claimed that this leads to a significant increase in the throughput of the HIsmelt process (Outotec, 2007).

The following benefits are reported for Circored and Circofer technology compared to blast furnace production(Outotec, 2007, 2015):

- No iron ore agglomeration required
- Reduced energy use and CO_2 emissions because sintering process eliminated

- If Circofer added to the HIsmelt process, a claimed significant increase in the throughput of the HIsmelt process

Commercial Status: Circored: Demonstration stage; Circofer: Pilot stage

5.3.9 Cyclone converter furnace

In primary iron making, about one-fifth of the energy consumed is used for coke making and sintering. Smelting reduction processes avoid this energy use because they make iron directly from iron ore and coal, omitting the need for coke ovens and sinter plants. The cyclone converter furnace consists of a cyclone for pre-reduction of the iron ore; the cyclone is mounted on a converter-type vessel in which the iron ore is then reduced to iron (Beer et al., 1998). The iron ore is pre-reduced and melted in the cyclone at the top of the furnace. From there, the molten iron ore falls into the lower part of the vessel where reduction is completed. Granular coal as well as oxygen are introduced in the lower part of vessel. Combining the pre-reduction unit and the final reduction unit avoids heating losses that occur when these two components are separated.

The cyclone converter furnace was the first smelting reduction process that combined pre-reduction and final combustion in one vessel (Beer et al., 1998). Currently, its development is included within the HIsarna process (van der Steel et al., 2013)

A 20 t/hour test facility for the melting cyclone was built and successfully operated in 1994. The converter has not yet been tested on a pilot scale (Beer et al., 1998). The cyclone has been implemented in a HIsarna pilot plant which was tested in 2011 (van der Steel et al., 2013).

The following benefits can be achieved by use of the cyclone converter furnace (Joint Research Center, 2012; Beer et al., 1998):

- Estimated specific energy consumption of 13 to 14 GJ/t hot metal as compared to about 16.1 GJ/thm for the conventional blast furnace production (including coke making and sintering)
- Lower investment costs because the cyclone converter furnace is simple compared to other smelting reduction processes
- Total production costs estimated to be lower than those of blast furnace

Commercial Status: Pilot stage

5.3.10 Molten oxide electrolysis

Electrolysis of iron ore or molten oxide electrolysis (MOE) is an emerging process. The DOE/ AISI TR program funded an initial research and development project at MIT (Cambridge, MA USA) which was successfully completed in 2007. A similar technology is currently being studied in the Ulcos program. This process would allow the transformation of iron ore into metal and gaseous oxygen (O_2) using only electrical energy. Producing iron by electrolysis would eliminate the need for coke ovens and the reactors used for reducing the iron ore, such as blast furnaces, and thereby eliminate the CO_2 created by these production methods. Although no iron is currently produced industrially by electrolysis, electrolysis is a well-established technique developed at the industrial scale for production of aluminum, zinc, and nickel (Ulcos, 2012).

MOE is an extreme form of molten salt electrolysis, a technology that has been used to produce tonnage metal – aluminum, magnesium, lithium, sodium, and the rare-earth metals – for more than 100 years. MOE is different from other molten salt electrolytic technologies because it uses carbon-free anodes, which facilitates the production of oxygen gas at the anode. MOE is totally carbon-free, producing only oxygen, and no carbon monoxide or CO_2, an environmental advantage compared to conventional technology. Even including the CO_2 emissions from electricity generation related to the process, MOE ranks lowest among breakthrough technologies in terms of CO_2 emissions per unit metal product (Sadoway, nd).

The most promising options for electrolysis are Ulcowin, also called electrowinning, and iron ore Ulcolysis (similar to the MIT process). Both technologies have already been demonstrated at a small scale, through the research carried out during Ulcos Phase I.

In the Ulcolysis process, iron ore is dissolved in a molten oxide mixture at 1,600 °C. This electrolyte medium can sustain a temperature above the melting point of iron metal. The anode, made of a material inert in relation to the oxide mixture, is dipped in this solution. An electric current flows between this anode and a liquid iron pool that is connected to the circuit to act as the cathode. Oxygen evolves as a gas at the anode, and iron is produced as a liquid metal at the cathode. The development of Ulcowin is, however, more advanced. A proposal has been made to further test Ulcowin through additional scaling up of the process. A prototype plant has been proposed that could produce 5 kg/day (Ulcos, 2012).

In contrast to a conventional integrated steel mill, which requires coke ovens, blast furnaces, and BOFs, an electrolytic cell reduces iron ore concentrates and produces molten steel in a single unit. Therefore, MOE is expected to have much lower capital costs than a conventional plant. The CO_2 reduction potential is large, depending upon the MOE plant's electricity source. An analysis by Birat in the 1990s estimated 1,750 kg CO_2/t liquid steel from benchmark blast furnace technology compared to 345 kg CO_2/t liquid steel from MOE. This analysis assumed 90 g CO_2/kWh for electric power generation and 3,500 kWh/t of molten steel in the electrolytic cell (American Iron and Steel Institute, 2010).

AISI is funding Massachusetts Institute of Technology to develop and validate scale-up parameters for the design, construction, and operation of a pre-pilot-scale, self-heating MOE cell with a capacity of 4,000 amperes. This cell would operate continuously and produce iron at the rate of about 72 kg/day. If fitted with an inert anode, it could produce about 32 kg of oxygen gas per day. Long-term operation of this cell will provide the data required to design the first-generation industrial-scale cell and develop a detailed cost model to assess the commercial viability of the process (American Iron and Steel Institute, 2010).

The following benefits are reported for MOE compared to blast furnace production (American Iron and Steel Institute, 2010; Ulcos, 2012):

- Significantly lower CO_2 emissions
- Likely significant capital cost savings
- Lower level of air pollutant emissions (coke making, BF, and BOF are omitted)

Commercial Status: Research/Development stage

5.3.11 Suspension hydrogen reduction of iron oxide concentrate

Hydrogen is currently cost prohibitive as a reducing agent or fuel. Large quantities of inexpensive hydrogen may become available in the future based on worldwide research and development work. Hydrogen produces only water vapor and no other gaseous byproducts when used as a reducing agent or fuel (U.S. Department of Energy, 2007).

Hydrogen flash smelting would use, as a smelting vessel, a suspension or flash-type furnace similar to those used in the copper industry. Iron ore concentrates would be sprayed directly into the furnace chamber. Three reductants are suitable for this type of vessel: hydrogen, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics. The high temperature and lack of contact between the iron ore particles in suspension furnaces eliminates sticking and fusion of the particles (American Iron and Steel Institute, 2010).

Detailed material and energy balances conducted by University of Utah in an earlier research and development project with the support of the DOE/AISI TR Program show that the proposed technology using any of the three possible reductants/fuels could use approximately 38 % less energy than a blast furnace. This savings results largely from eliminating coke making and the iron ore pelletizing and sintering steps. If hydrogen is used, this new technology will generate only 4 % of the CO_2 produced in the blast furnace process; when natural gas or coal is used, CO_2 emissions are 39 % and 69 %, respectively, of those from a blast furnace.

Because the residence time in a suspension furnace is only a few seconds, studies were performed to establish that full reduction could be achieved in such a short time. Kinetic studies of the reduction of iron oxide concentrates (about 30 micrometer size) as a function of temperature and gas composition showed that 90 to 99 % reduction is possible within a few seconds at temperatures of 1,300 °C or higher. This was verified by larger bench-scale testing, proving that complete ore reduction is achieved in the residence time typical of industrial-size suspension vessels (American Iron and Steel Institute, 2010).

Conventional blast furnace-based steelmaking processes use carbon monoxide gas to remove oxygen in iron ore. However, the molecules of carbon monoxide gas are large enough that it is difficult for them to penetrate iron ore. By contrast, the much smaller molecules of hydrogen gas can easily penetrate into iron ore. The penetration rate of hydrogen into iron is five times as great as that of carbon monoxide, so hydrogen can rapidly reduce iron ore in a conventional blast furnace (Japan Iron and Steel Federation, 2011).

Hydrogen reduction could be a part of an overall continuous direct steelmaking process, in which case the product from this process would be collected in its molten or solid state (e.g., reduced iron pellets or briquettes) (U.S. Department of Energy, 2007).

Based on the success of the earlier project conducted by University of Utah, AISI had initiated a subsequent Phase II-project where a larger-scale bench reactor vessel was fabricated (American Iron and Steel Institute, 2010). In 2012, a USD 7.1 million award was given by the U.S. DOE to AISI/University of Utah to perform tests to determine the best vessel configuration and reductant to be used in a future industrial pilot plant.

The following benefits are reported for hydrogen flash smelting compared to BF production (American Iron and Steel Institute, 2010):

- Reduction or elimination of CO_2 generation in the ironmaking process
- Reduction of iron oxide waste

- Reduction in energy consumption; University of Utah earlier research and development study showed potential energy savings of 7.4 GJ/t hot metal (more than 50 % of conventional BF energy use)

Commercial Status: Research/Development stage

5.3.12 Ironmaking using biomass and waste oxides

Ironmaking is the most energy-consuming and therefore CO_2-intensive step in the steel industry. Replacing fossil fuels (e.g. coal) with biomass or waste oxide would reduce both energy use and CO_2 emissions. A project funded by the DOE/AISI TR program conducted preliminary research on an ironmaking process using wood charcoal in ore waste pellets (composite pellets) in a RHF.

A number of processes are already under development that use composite pellets of ore or waste oxides and a carbonaceous material, such as coal or coke, which are reduced in the solid state using a rotary hearth or similar type of furnace. The product of these processes is too high in gangue and sulfur to be used effectively in the EAF. If biomass is used instead, the metal will be low in sulfur, so further processing in an EAF or a BOF should be possible. It is expected that the reduced iron ore using biomass in composite pellets would contain low percentages of gangue as well (American Iron and Steel Institute, 2010, 2002).

The process combines a rotary hearth furnace (RHF) and a smelter such as the AISI or direct iron smelting reduction (DIOS) to produce hot metal using wood charcoal in composite pellets. In the RHF the reduction of the iron ore is limited to approximately 70 to 80 % metallization. The pre-reduced material is then fed into the smelter for final reduction and gangue separation, yielding hot metal. Compared to conventional processes, this process increases RHF productivity and avoids high energy consumption for full metallization in the smelter (Fruehan, 2004b).

So far, no pilot plants have been built, and only computer models have been developed. A computational model predicts productivity gains as high as 50 % from replacing coal with wood charcoal in the composite pellets (Fruehan, 2004b). AISI claims the following benefits from using biomass and waste oxides in ironmaking compared to conventional BF production (American Iron and Steel Institute, 2002; Fruehan, 2004b):

- Reduction of more than 90 % in greenhouse gas emissions
- Significant decrease in capital and operating costs
- Increased productivity of the rotary hearth furnace

- Increased recycling of waste oxides in steelmaking

Commercial Status: Research stage

5.4 Comparison of ironmaking technologies

Table 5.1 shows a comparison of some of the aspects for different ironmaking technologies explained in this paper with the conventional ironmaking in blast furnace. Corex Process, Finex Process, and Coal-Based HYL Process are very promising alternative emerging ironmaking technologies because they are already commercially proven and are commercialized but they have very low adoption rate in the steel industry worldwide. All the alternative emerging ironmaking technologies eliminate energy-intensive coke production (Tab. 5.1).

5.5 Conclusions

This paper describes twelve alternative emerging energy-efficient- and CO_2 emissions reduction ironmaking technologies for the steel industry. The information presented for each technology was collected from various sources, including manufacturers. All the emerging technologies presented in this paper are alternatives to conventional production of iron. It is likely that no single technology will be the best or only solution but instead that a portfolio of technologies should be developed and deployed to address the increasing energy use and CO_2 emissions of the iron and steel industry.

As can be seen from the information presented in this paper, most of the technologies have not been commercialized yet. Therefore, further research is needed to improve and optimized these technologies in order to make them commercial. In addition, for some technologies, there was not much information available except from the technology developer. Conducting independent studies and validation on the fundamentals, development, and operation of these emerging technologies can be helpful to private and public sectors as well as academia.

Shifting away from conventional processes and products will require a number of developments including: education of producers and consumers; new standards; aggressive research and development to address the issues and barriers confronting emerging technologies; government support and funding for development and deployment of emerging technologies; rules to address the intellectual property issues related to dissemination of new technologies; and financial incentives (e.g., through carbon trading mechanisms)

Table 5.1: Comparison of analysed ironmaking technologies.

	Reducing agent and energy source				**Form of iron ore that can be used**				**Use of Oxygen**	**Coal gasification**	**Commercialization**
	NC-coal$^{j)}$	**coke**	**NG**$^{a)}$	**Other**	**Sinter**	**Pellets**	**Lump ore**	**Fine ore**			
BF*		x			x	x					Commercial
Corex	x				x	x	x		x		Commercial$^{i)}$
Finex	x							x	x		Commercial$^{i)}$
Technored	x					x$^{b)}$		x$^{b)}$			Pilot
ITmk3	x					x$^{c)}$		x$^{c)}$			Demonstration
PSHF$^{k)}$	x					x$^{d)}$		x$^{d)}$			Development
HYL$^{o)}$	x					x	x			x	Commercial$^{i)}$
Midrex$^{o)}$	x					x	x		x	x	Demonstration
Cirored	x$^{e)}$		x$^{e)}$					x			Demonstration
Ciroder	x$^{e)}$		x$^{e)}$					x			Pilot
CCF$^{l)}$	x					x	x		x		Pilot
MOE$^{m)}$				x$^{f)}$		x	x				R&D
SH2R$^{n)}$			x$^{g)}$	x$^{g)}$			x	x		x	R&D
Biomass				x$^{h)}$		x$^{h)}$					R&D

*) Reference

a) NG: natural gas

b) Pellets or briquettes used in Tecnored process are made from low-grade iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines which are mixed and agglomerated into pellets or briquettes.

c) Low grade ores are beneficiated, and the resulting fines (with more than 62 % Fe content) are pelletized and used.

d) Cold-bonded self-reducing pellets composed of iron oxide and coal. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal.

e) Circored is gas-based (hydrogen as reductant), and Circofer is coal-based.

f) Only electricity is used.

g) Three reductants are suitable for this process: hydrogen, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics.

h) This process uses wood charcoal in ore waste pellets (composite pellets) in a RHF.

i) Commercial with very low adoption rate.

j) NC-coal: non-coking coal.

k) PSHF: Paired straight hearth furnace.

l) CCF: Cyclone converter furnace.

m) MOE: molten oxide electrolysis.

n) SH2R: Suspension hydrogen reduction of iron oxide Concentrate.

o) coal-based

to make emerging low-carbon technologies, which might have a higher initial costs, competitive with the conventional processes and products. It should be noted that the purpose of this paper is solely informational.

Chapter 6

Pathways to a low-carbon iron and steel industry[5]

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 iron and steel industry would have to reduce its carbon dioxide emissions from about 60 million metric tonnes currently to 28 to 34 million metric tonnes 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

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[5] The chapter has been published as Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi A., Qi, Zh. (2016). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2015.12.097.

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 will take decades to develop and introduce, there should be a second focus on incremental CO_2 reductions in the short to medium term.

6.1 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, 2016, 2014; Bundesministerium für Wirtschaft und Energie, 2016a). 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 will 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 (Bundesministerium für Wirtschaft und Energie, 2010). This study assumes targets set as equal proportional reductions (flat targets) for all sectors (Tab. 6.1), since no more specific targets have been set so far. Further significant improvements and reductions in CO_2 emissions by best available technologies seem to

Table 6.1: Estimated CO_2 emission reduction targets for the German iron and steel industry according to current policy if targets have to be met equally across sectors (sources: European Council, 2014; Bundesministerium für Wirtschaft und Energie, 2010; Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

		1990	**2005**	**Target 2030**
				Mt CO_2
Specific CO_2 emissions	t CO_2/tcs	1.59	1.35	-
Crude steel production	Mt	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

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. Dixon et al., 2013; World Steel Association, 2009a; 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) (Santos, 2014).

Here, the German iron and 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 iron and 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 iron and 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 iron and 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 (2015) 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 iron and 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 ironmaking 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 iron and steel industry will meet future climate targets.

Section 6.2 gives a short introduction to the German iron and steel industry. Section 6.3 describes the model, and section 6.4 shows the structural parameters that shape energy intensity and CO_2 emissions in the steel industry. Section 6.5 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 6.6, 6.7 and 6.8.

6.2 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.

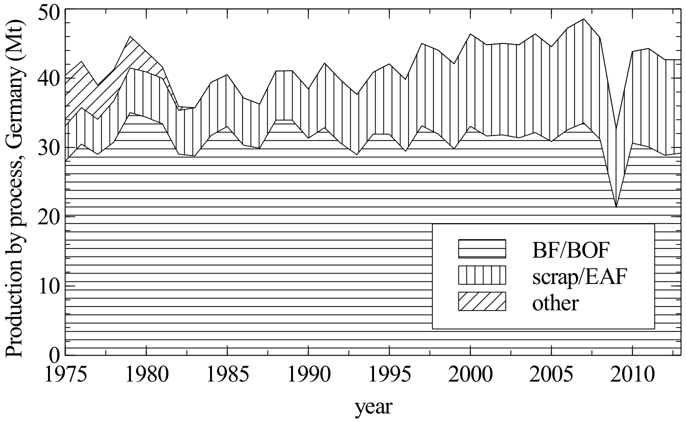

Figure 6.1: Annual steel production by BF/BOF, scrap/EAF and other processes in Germany (source: Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

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, 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, 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. 6.1). 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 to 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.

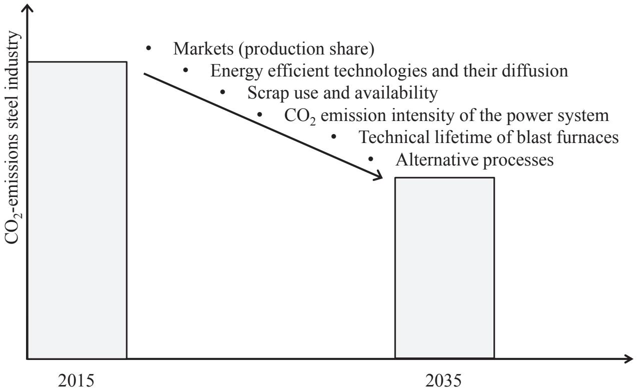

Figure 6.2: Parameters for estimating current and future CO_2 emissions in the German iron and steel industry.

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; 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; 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 iron and 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.

6.3 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.

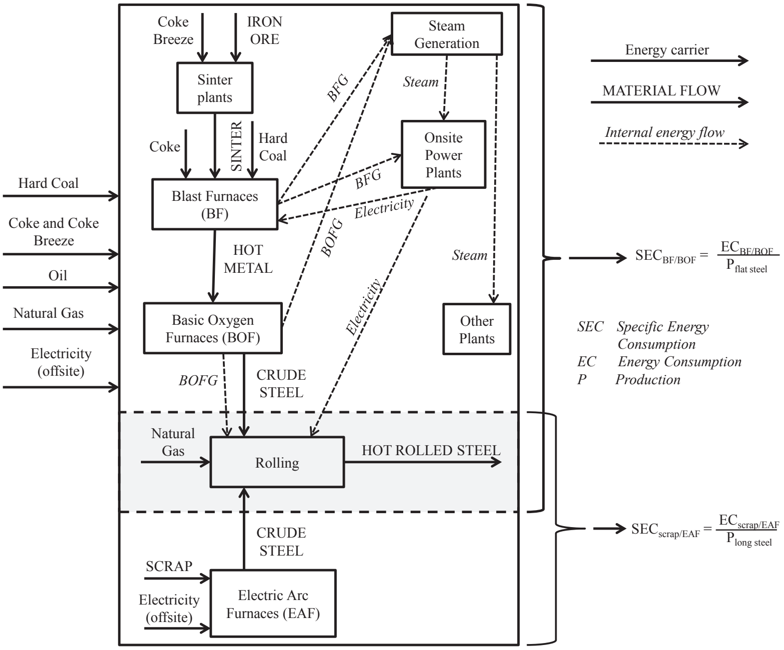

Figure 6.3: Boundary settings to estimate the specific energy consumption in BF/BOF and scrap/EAF steelmaking in Germany.

Several structural factors shape the future energy consumption and CO_2 emissions of the steel industry (Fig. 6.2). 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.

6.3.1 Key mathematical equations

The specific energy consumption from BF/BOF and scrap/EAF steelmaking is affected by the diffusion of energy-efficient technologies (Eq. 6.1).

$$SEC_{i+1,j,k}\left[\frac{GJ}{t}\right] = SEC_{i,j,k}\left[\frac{GJ}{t}\right] - \sum_{l}\left(ESP_{k,l}\left[\frac{GJ}{t}\right]\cdot\left(DR_{i+1,l} - DR_{i,l}\right)\right) \tag{6.1}$$

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 (Eq. 6.2, 6.3).

$$EC_{DE,i}\,[GJ] = \sum_{j}\sum_{k} SEC_{i,j,k}\left[\frac{GJ}{t}\right]\cdot P_{i,j}[t] \tag{6.2}$$

$$TCE_{DE,i}[t\ CO_2] = \sum_{i}\sum_{k} SEC_{i,j,k}\left[\frac{GJ}{t}\right]\cdot P_{i,j}[t]\cdot CEF_{i,k}\left[\frac{t\ CO_2}{GJ}\right] \tag{6.3}$$

where

$EC_{DE,i}$	total energy consumption of the German iron and steel industry in the year i,
P	production,
$TCE_{DE,i}$	total CO_2 emissions of the German iron and steel industry in the year i,
CEF	CO_2 emission factor.

6.3.2 Model input parameters

The model estimates the future energy consumption and CO_2 emissions of the German iron and 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.

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 iron and 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 iron and 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. 6.3). Energy consumption in energy units is calculated by applying heating values and the energy required to supply the energy carriers (Tab. 6.2).

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.

Table 6.2: Assumed lower heating values, energy required to derive the energy carriers and CO_2 emission factors per energy carrier (sources: Umweltbundesamt and Deutsche Emissionshandelsstelle, 2012; Umweltbundesamt, 2016; Statistisches Bundesamt, 2009; Stahlinstitut VDEh, 2011, own calculations).

Energy carrier	**Unit**	**Value**	**Unit**	**Value**
Hard coal	GJ/t	29.31	kg CO_2/GJ	95
Coke	GJ/t	28.42	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, 2011)	GJ/1000 kWh	10.34	kg CO_2/kWh	0.570

Table 6.3: Assumed primary energy consumption per metric tonne of final product for each process (sources: Wirtschaftsvereinigung Stahl, 2011; Worrell et al., 2008; Meijer, 2013, own calculations).

	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	4.04	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
SR (Hisarna)	11.86	0.00	0.36	1.37	0.57	92	1349.0

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. 6.3). 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. 6.3. 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.

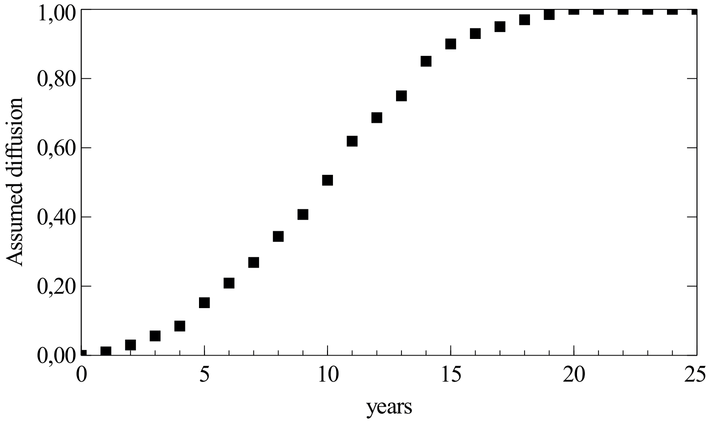

Figure 6.4: Assumed diffusion rate for energy-efficient technologies.

Specific energy consumption is converted into CO_2 emissions by applying CO_2 emission factors (Tab. 6.2). Tab. 6.3 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 to 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) (Tab. 6.3).

The energy consumption of the smelt reduction technology Hisarna is assumed to be 80 % of current BF/BOF steelmaking (Meijer, 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 (Tab. 6.3).

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 6.4.4. 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 three years instead of after five years (Fig. 6.4).

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

Production pathway definition

Four production pathways are developed for the German iron and steel industry to show the impact of varying production levels and processes on CO_2 emissions and energy consumption (Tab. 6.4). The resulting production pathways are discussed in section 6.5.1.

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. 6.1), 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 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 iron and steel industry currently supplies high quality steel markets and that therefore the German iron and 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 to 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 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 iron and 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 iron and 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 iron and 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 ironmaking technology is implemented.

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

Table 6.4: Parameters of future production pathways.

Parameter	**Pathway**			
	0	**1**	**2**	**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; SR
BF capacity utilization rate	95 %	95 %	92 %	95 %
Ratio BF/BOF steel and hot metal	1.07	1.07	1.07	1.07
Shut down BF capacity is replaced by …	new BF capacity	scrap/EAF capacity	scrap/EAF capacity	2015-2030: scrap/EAF capacity; new BF capacity 2030-2035: 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.			

Table 6.5: Future scrap availability in Germany (assumed scrap availability growth rate of 0.9 %/year; Boston Consulting Group, 2013).

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

* estimated.

Table 6.6: Assumed specific scrap consumption in primary and secondary steelmaking (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 2014).

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

6.4 Structural parameters that determine energy intensity and CO_2 emissions

The energy consumption and CO_2 emissions of the German iron and 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 ironmaking process.

6.4.1 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 iron and 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 iron and 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 Eq. 6.4:

$$SC_{av,2012} = SC_{cons,2012} + SC_{net,exp,2012}; SC_{net,exp,2012} > 0 \tag{6.4}$$

Table 6.7: Assumed CO_2 emission grid factor for the German electricity grid (Umweltbundesamt, 2016; Öko-Institut and Fraunhofer ISI, 2015).

		2011	**2020***	**2030***	**2040***
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

* estimated.

where

$SC_{\mathrm{av},2012}$	scrap availabilty in 2012 in Germany,
$SC_{\mathrm{cons},2012}$	scrap consumption in 2012 in Germany,
$SC_{\mathrm{net,exp},2012}$	net scrap export in 2012 in Germany.

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 Stahlinstitut 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 (Tab. 6.5). The impact of much bigger scrap availability (e.g. Pauliuk et al., 2013) is tested in a sensitivity analysis (Chapter 6.6). All production pathways assume constant scrap consumption for primary and secondary steelmaking (Tab. 6.6). Furthermore, the model is constructed to not exceed the amount of scrap actually available in any year for each production pathway.

6.4.2 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 to 2035 based on Öko-Institut and Fraunhofer ISI (2015) and the scenario that includes all policies enforced by October 2012 (Aktuelle-Maßnahmen-Szenario, AMS, Tab. 6.7).

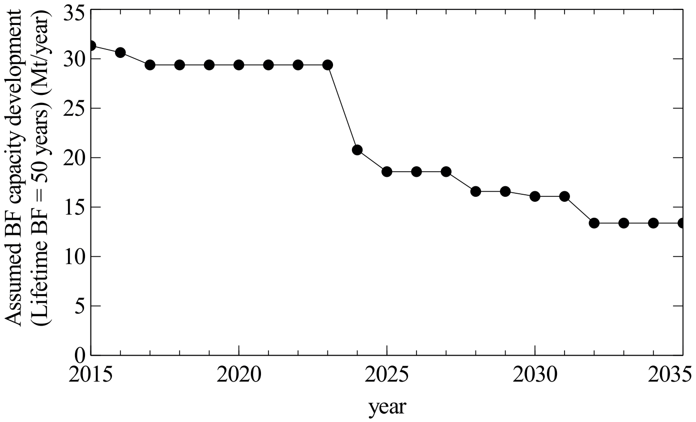

Figure 6.5: Blast furnace capacity in Germany 2015-2035, considering a technical lifetime of 50 years (source: Stahlinstitut VDEh, 2013, own calculations).

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.

6.4.3 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 (Stahlinstitut VDEh, 2013). The database encompasses 16 blast furnaces. A database of Stahlinstitut 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, since much blast furnace capacity was errected in the 1970s (Fig. 6.5).

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).

Table 6.8: Characteristics of the selected energy-efficient technologies (sources: Moya and Pardo, 2013; Brunke and Blesl, 2014; Worrell et al., 2008; Okazaki and Yamaguchi, 2011).

		Maximum reduction potential						Diffusion		Max. Diff.
		Hard coal	Coke	Oil	Natural gas	Oxygen	Electricity (offsite)			
Process	Name	GJ/tcs	GJ/tcs	GJ/tcs	GJ/tcs	GJ/tcs	kWh/tcs	2011	2014	-
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

6.4.4 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 (Tab. 6.8).

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

6.5 Results

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

6.5.1 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. 6.6-a).

Pathway 1 shows the results for a constant production level but a shift to scrap/EAF and DRI/EAF steelmaking (Fig. 6.6-b). 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. 6.6-c). BF/BOF capacity gradually phases out, while the remaining steel production capacity is provided by scrap/EAF steelmaking.

Pathway 3 represents increasing production (Fig. 6.6-d). 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 up-take of the smelt reduction technology from 2030 onwards.

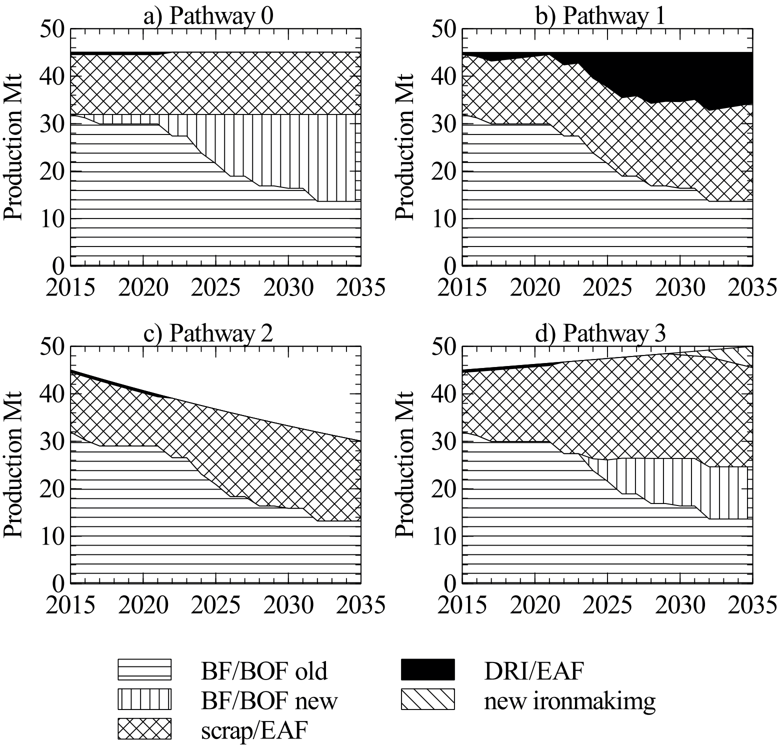

Figure 6.6: Resulting production pathways for the German iron and steel industry by process for a) and b) constant, c) decreasing, and d) increasing crude steel production.

6.5.2 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 2035 than in 2011, Fig. 6.7-a), while energy savings in secondary steelmaking could be more significant (21 % lower in 2035 than in 2011, Fig. 6.7-b). 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 3 but 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; pathway 3: 535 PJ) (Fig. 6.11). 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. 6.8 a-d). Introducing DRI (pathway 1; Fig. 6.8-b) 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. 6.8-d increased production, new ironmaking technology) implies a shift from coke to coal from 2030 onwards due to the replacement of blast furnaces with smelt reduction technology.

6.5.3 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. 6.12, 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.

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

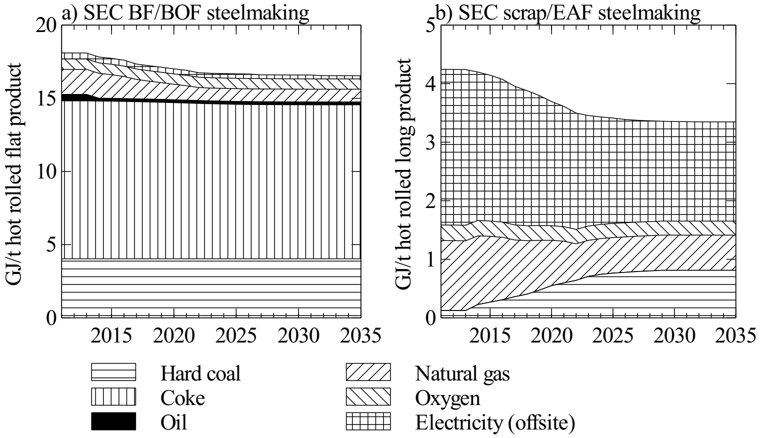

Figure 6.7: Specific energy consumption of a) BF/BOF and b) scrap/EAF steelmaking in Germany, considering the diffusion of energy-efficient technologies.

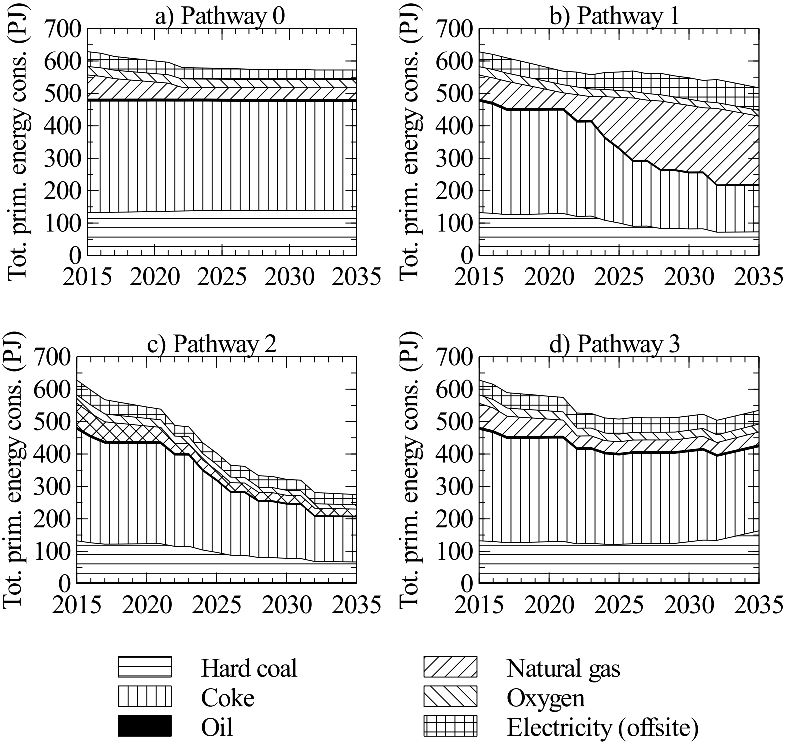

Figure 6.8: Primary energy consumption in the German iron and steel industry by energy carrier and pathway; a) and b) constant, c) decreasing, and d) increasing crude steel production.

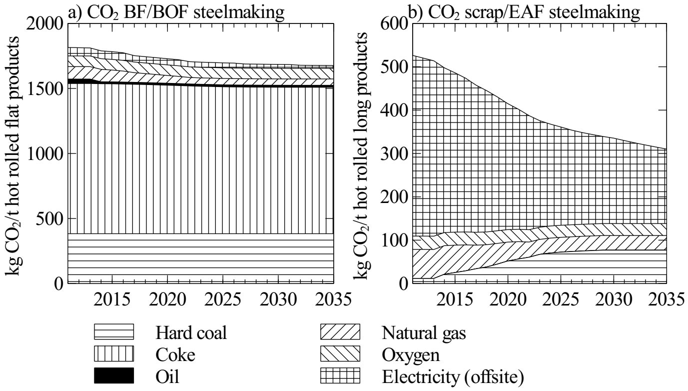

Figure 6.9: Specific CO_2 emissions in the German iron and steel industry, a) BF/BOF, and b) scrap/EAF steelmaking and considering the diffusion of energy-efficient technologies and the CO_2 emission factor of the public electricity grid.

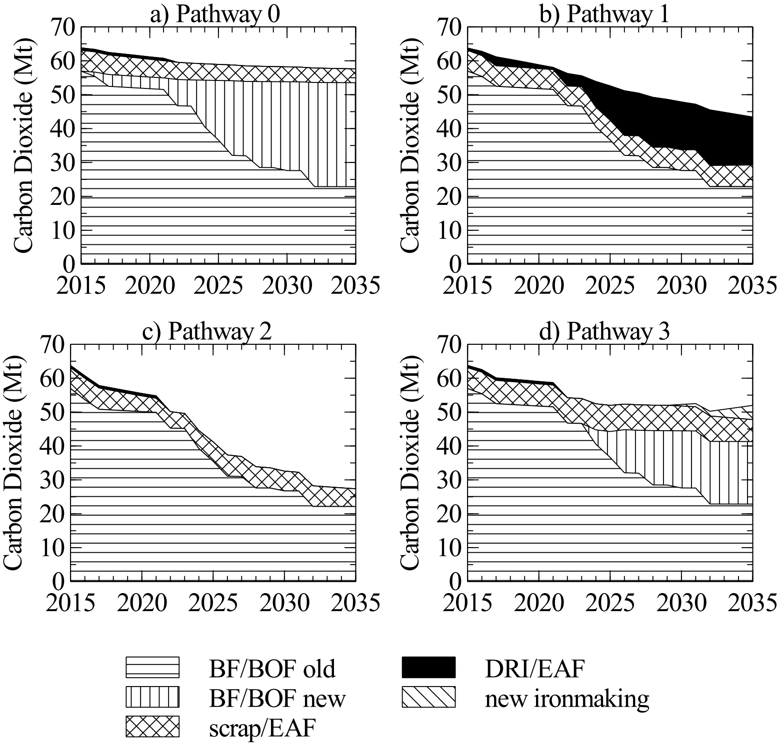

Figure 6.10: CO_2 emissions by process and pathway in the German iron and steel industry; a) + b) constant, c) decreasing, and d) increasing crude steel production.

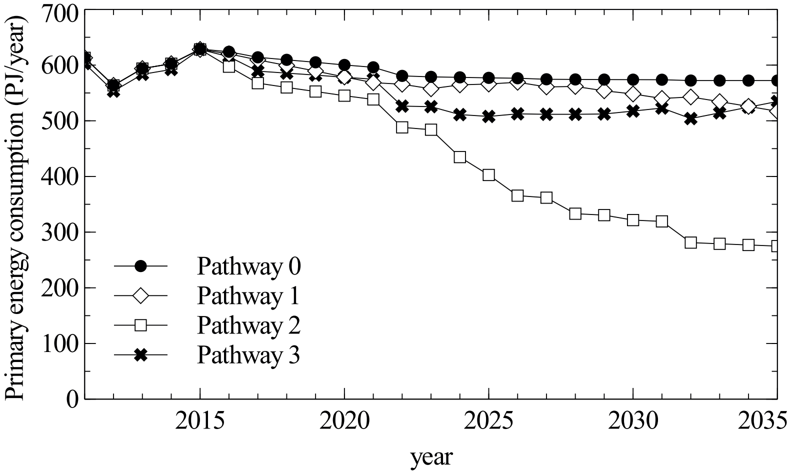

Figure 6.11: Primary energy consumption by production pathway in Germany.

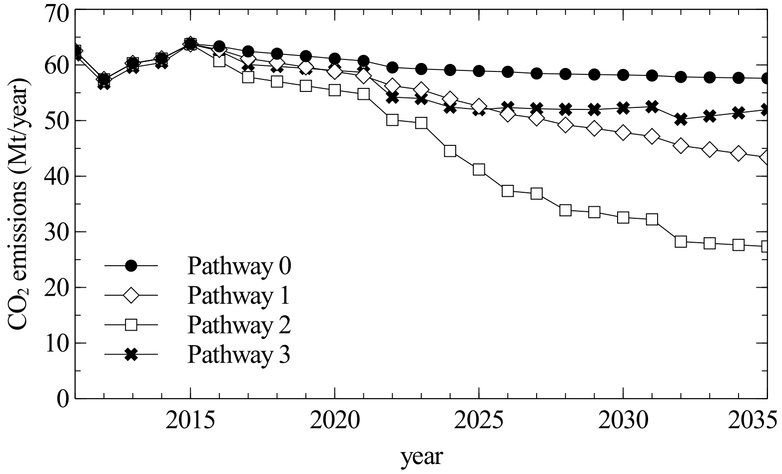

Figure 6.12: CO_2 emissions by pathway in the German iron and steel industry.

Table 6.9: Fulfillment of CO_2 emission reduction targets in 2030 by pathway.

Pathway	**Est. CO_2 emis. in 2030**	**Est. CO_2 emis./ European target**	**Est. CO_2 emis./ German target**
	Mt	%	%
0	58.1	169	211
1	47.6	139	173
2	32.4	95	118
3	52.0	153	190

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 iron and 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. 6.10-a). 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. 6.10-b). Moreover, total steel production can even be increased with decreasing CO_2 emissions (pathway 3; 14 % lower in 2035 than in 2014, Fig. 6.10-d).

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. 6.10-c). 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 iron and steel industry's current customers' demand for high quality steel.

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 (Tab. 6.9). German energy policy's targets are not reached by any pathway (Bundesregierung, 2010). If the German iron and 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. 6.9-a).

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. 6.9-b). 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.

6.6 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.

Table 6.10: Comparison of the CO_2 emissions of the German iron and steel industry of the results from this study 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**	**SpecificCO_2 emissions**	**Total CO_2 emissions (calculated)**	**Pathway results/ data by Stahlinstitut VDEh**
	Mt	Mtcs	t CO_2/tcs	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

6.6.1 Estimation of CO_2 emissions

Data on the specific CO_2 emissions per metric tonne crude steel for the German iron and steel industry in 2011 to 2013 are provided by the Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (2014). Our analysis slightly overestimates the CO_2 emissions of the German iron and steel industry in 2011 and 2013 but mirrors the reported CO_2 emissions in 2012 (Tab. 6.10).

6.6.2 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 (Tab. 6.11).

Pathway 1 has the largest amount of scrap/EAF steelmaking in 2035 (20.6 Mt). However, CO_2 emissions of the German iron and 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*) (Tab. 6.11). This shows the dominant influence of BF/BOF steelmaking on the CO_2 emissions of the German iron and steel industry.

Table 6.11: Variation of CO_2 intensity of the power system for pathway 1.

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

Table 6.12: Variation of the lifetime of blast furnaces for pathway 2.

		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 6.13: Variation of scrap availability for pathway 3.

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

6.6.3 Variation of technical lifetimes of blast furnaces

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 (Tab. 6.12).

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

6.6.4 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 iron and steel industry would be 19 % lower in pathway 3* (Tab. 6.13).

6.7 Discussion

One main goal of this study was to find a production pathway of the German iron and 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 recycling 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 iron and 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 (2015), 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.

6.8 Conclusions

The analyses of future CO_2 emissions by the German iron and 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 iron and 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.

Chapter 7

Summary and Conclusions

7.1 Introduction

The decarbonisation of industry and especially of the iron and steel industry is key to mitigating the impacts of climate change. Energy intensity in iron and steel making declined steeply from the 1950s to the 1990s, but this industry still accounts for about 6.5 % of global anthropogenic CO_2 emissions (Basson, 2012). The technical potentials to further reduce energy use in steel making are limited. But further emission reductions have to be made to transform this sector into a low-carbon industry.

The iron and steel industry is of special interest because it depends on fossil fuels, not only for heating purposes, but also as a chemical reducing agent. Thus its key energy carrier (i.e. coal) cannot be replaced by any (renewable) heat source. Substituting of fossil fuels in iron and steelmaking requires new technological concepts.

Carbon capture and storage is often discussed as an option to reduce CO_2 emissions in iron and steelmaking (e.g. International Energy Agency, 2009). The European Ulcos project is one project developing carbon capture and storage for the iron and steel industry. It aims to cut CO_2 emissions from the steel industry by 50% (Ulcos, 2016). However, carbon capture and storage is an uncertain option for several reasons including acceptance issues and delayed progress in announced projects. Since new technological concepts for low CO_2 steelmaking and carbon capture and storage will only be available in the future, energy efficiency is the main short- to medium-term option to reduce CO_2 emissions to a minimum.

Companies are generally interested in improving energy efficiency to save energy costs. This is why energy efficiency typically improves over time. However, energy intensity, which is typically used as an indicator for energy efficiency, varies between countries and companies showing that there are factors that accelerate (drivers) or impede (barriers) energy efficiency improvements. An in-depth understanding of energy intensity trends in iron and steelmaking is necessary to design effective policies that aim to transform the manufacturing sector into a low-carbon industry.

This thesis presents a detailed study of the German iron and steel industry, which is taken as one example for an average iron and steel industry with regard to its past achievements in energy intensity and its future options to cut CO_2 emissions drastically until 2035.

The approach focuses on (Fig. 1.4):

a. the assessment and understanding of past trends in energy intensity, and

b. the assessment of future options to reduce CO_2 emissions.

The main research question of this thesis is:

How can technological change lead to energy efficiency and CO_2 reduction in the German iron and steel industry?

The main issue is addressed in five groups of sub-questions:

1. How did energy intensity change on the process level in the German iron and steel industry between 1991 and 2007? What impact did these process level changes have on the energy intensity of the German iron and steel industry as a whole?
2. What are the diffusion rates of key energy-efficient technologies in the German iron and steel industry? What impact do they have on energy intensity development of the total German iron and steel industry? What is their remaining energy efficiency potential?
3. What are drivers for and barriers to the implementation of key energy-efficient technologies in the German iron and steel industry?
4. Which are the promising low-carbon ironmaking technologies in research and development or at an early stage of commercialization?
5. How does technological change impact the energy consumption and CO_2 emissions of the German steel industry until 2035 considering the findings from chapters 2 to 5?

Chapter 2 assesses energy intensity trends by process from 1991 to 2007 and estimates the impact of an increasing share of secondary steelmaking on the specific energy consumption per tonne crude steel. The diffusion rates of key energy-efficient technologies are derived since their introduction and the impact of these technologies on energy intensity in the iron and steel industry is estimated in chapter 3. The remaining energy saving potential is also determined. Chapter 4 describes recent developments in energy intensity and assesses the impact of energy prices on the adoption of energy-efficient technologies. The diffusion of energy-efficient technologies is also derived on the national level and on the plant level. The main drivers for and barriers to diffusion are assessed for selected cases. Chapter 5 reviews and rates emerging alternative ironmaking technologies. Finally, in chapter 6 production pathways are constructed including several variables that drive CO_2 emissions in order to estimate which pathway leads to strong CO_2 reduction.

7.2 Assessing and understanding past trends

How did energy intensity change on the process level in the German iron and steel industry between 1991 and 2007? What impact did these process level changes have on the energy intensity of the German iron and steel industry as a whole?

Assessing past energy intensity trends provides insights into what has been achieved so far and the probability of trends continouing autonomously. Assessing the energy intensity trends of several processes additionally reveals whether remaining energy efficiency potentials are spread equally across processes.

While previous studies (e.g. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, 2010) assessed energy intensity developments for the steel industry as a whole, this section analyses energy intensity developments on the process level. It thus reveals how much the increasing share of secondary steelmaking has reduced the energy intensity of the total steel industry compared to improvements in energy efficiency.

The section evaluates energy consumption data provided by the German Federal Statistical Office (Statistisches Bundesamt, 1991-2007). The energy consumption for key iron and steelmaking processes on the national level is reported annually by energy carrier. Production values are assigned to each reported process step based on data provided by Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh (1991-2007). Energy consumption given in physical units is converted into energy units using lower heating values. The results concerning the energy intensity development per process are presented as the development of the specific energy consumption per process by energy carriers from 1991 to 2007. The impact of an increasing share of secondary steelmaking on the energy intensity of the total German iron and steel industry is shown as well.

Energy intensity on the process level did not decrease significantly between 1991 and 2007, except in rolling. Decreasing energy intensity in the total iron and steel industry (i.e. primary and secondary steel production unified) was to a large extent driven by an increasing share of secondary steelmaking. Between 1991 and 2004 the specific energy consumption per tonne crude steel decreased annually by 0.3 %, of which 75% or 0.2 % can be attributed to the increase in secondary steelmaking.

Energy input to the blast furnace actually increased from 2000 onwards, but the net energy consumption decreased continuously when considering the production of top gases from 12.50 GJ per tonne hot metal in 1991 to 12.00 GJ/thm in 2007, equalling an improvement of 0.2 % per year.

The energy intensity values of sinter plants increased between 1991 and 1998 and between 2002 and 2006. Energy intensity peaked in 1998 at 2.28 GJ/t sinter, which is 0.26 GJ/t sinter or 12 % higher than in 1991.

The energy intensity in electric arc furnaces varied only slightly over the studied period. Taking 1994 as the reference, the specific energy consumption varies between 2 % (e.g. in 1996, 2004 and 2007) and -2 % (in 1998). No real improvements in the energy efficiency of electric steel works in Germany were found in the studied period.

Rolling was the only process group for which the identified trend in energy intensity was as expected: A continuous decrease in energy intensity was found of about 1.4 %/year. However, in the studied period, the production share of cold rolled steel to hot rolled steel decreased from 35.0 % in 1994 to 31.4 % in 2007. Such a decrease could partially explain the identified energy intensity development.

To sum up, the energy intensity improvements in the German iron and steel industry between 1991 and 2007 are far behind the expected continuous energy efficiency improvements due to technological progress, diffusion of best available technologies, retiring of older plants, and improved energy management. The studied period covers almost two decades which can be characterised as a period with no major progress in energy efficiency.

The study is limited to the development of the specific energy consumption, so cannot provide any findings on factors shaping energy consumption in iron and steelmaking. Throughout the research, companies and associations claimed that they did improve their processes during this period. However, other factors such as raw material quality might have outweighed improvements in energy efficiency.

What are the diffusion rates of key energy-efficient technologies in the German iron and steel industry? What impact do they have on energy intensity development of the total German iron and steel industry? What is their remaining energy efficiency potential?

While previous studies focussed on explaining the diffusion process (e.g. Oster, 1982; Poznanski, 1983), this section tracks the diffusion rates of key energy-efficient technologies in the German iron and steel industry and assesses their impact on energy intensity of the total German iron and steel industry.

The section provides an in-depth analysis of the diffusion of six key energy-efficient technologies for the iron and steel industry in Germany using national and plant level data. A period of 60 years is covered. The impact is shown of these technologies on energy intensity development in the total German iron and steel industry. Based on these diffusion rates, the remaining energy efficiency potential is estimated assuming that all the technologies were diffused completely.

Technologies that were introduced in the 1950s to 1960s diffused slower in their initial phase but reached complete diffusion within about 20 to 25 years (i.e. basic oxygen furnace and continuous casting machines). Technologies introduced around 1980 were adopted more rapidly at the beginning but their diffusion levelled off after about 10 years, i.e. from about 1990 onwards. These technologies include top-pressure recovery turbines, pulverized coal injection, basic oxygen furnace gas recovery, and coke dry quenching. Even 20 to 25 years after their introduction, none of these technologies had a diffusion rate above 70 %. One technology (i.e. coke dry quenching) is no longer in use.

This section also shows the impact of technological change on the specific energy consumption per tonne crude steel. In addition to the six selected energy-efficient technologies, secondary steelmaking is also included in the estimation. Secondary steelmaking had the largest impact by far on the reduction of the specific energy consumption per tonne crude steel between 1958 and 2012 with about 21 %. The technologies introduced in the 1950s to 1960s, namely the basic oxygen furnace and continuous casting also contributed significantly to the energy consumption reduction per tonne crude steel, i.e. with about 12 % and 6 %, respectively.

The four technologies that were introduced around 1980 only contributed with about 4 % in total to the reduction of the specific energy consumption. The total reduction in the specific energy consumption per tonne crude steel due to the selected technologies (including secondary steelmaking) amounted to about 43 % from 1958 to 2012.

Aichinger and Steffen report a 40 % reduction of the specific primary energy consumption per tonne crude steel in the German iron and steel industry between 1959 and 2004 (Aichinger and Steffen, 2006). Thus these energy-efficient technologies and secondary steelmaking seem to be the key drivers for the reduction of the specific energy consumption in the German iron and steel industry over the past decades.

Finally, the energy saving potentials of the four energy-efficient technologies were estimated. Since it is currently not applied in Germany, coke dry quenching is the technology with the greatest energy saving potential with 2.0 % of the specific primary energy consumption. Basic oxygen furnace gas recovery and pulverized coal injection would reduce the specific primary energy consumption per tonne crude steel by 1.4 % and 1.0 %, respectively. The impact of a further diffusion of top-pressure recovery turbines would be limited to only 0.1 %.

The energy efficiency trends in the German steel industry over the past five decades seem to be largely driven by three technologies (i.e. secondary steelmaking, basic oxygen furnace, and continuous casting). The remaining potential of the selected energy-efficient technologies is limited to about 4.5 %.

What are the drivers for and barriers to the implementation of key energy-efficient technologies in the German iron and steel industry?

This section aims at explaining the identified energy intensity trends in the German iron and steel industry between 1991 and 2007 (Chap. 2) as well as the derived diffusion rates of key energy-efficient technologies in the German iron and steel industry since their introduction (Chap. 3).

Studies on drivers for and barriers to the diffusion of energy-efficient technologies in the European or German iron and steel industry are typically based on an economic assessment of these technologies (e.g. Brunke and Blesl, 2014; Moya and Pardo, 2013). Drivers for and barriers to the diffusion of energy-efficient technologies in the iron and steel industry of selected countries have been studied (e.g. Brunke et al., 2014). This section tracked the diffusion of key energy-efficient technologies in the German iron and steel industry, assessed past payback periods considering historical energy prices, and analyses the drivers and barriers on the plant level using an interview approach. Answers were identified that help to explain why energy-efficient technologies were implemented at one plant while other plants remain without these technologies.

A mixed-method approach is used. First, data is evaluated from plant manufacturers on the implementation of the selected energy-efficient technologies at German iron and steel works. These technologies are basic oxygen furnace gas recovery, top-pressure recovery turbines, and pulverized coal injection. Second, a timeline is drawn for the respective German iron and steel works (i.e. blast furnaces and basic oxygen furnaces). Only still operating works are included in the study. Third, the average number of years is calculated which passed until a site adopted an energy-efficient technology. Fourth, the price history is reconstructed of relevant energy carriers for the German industry. Policy-induced energy price components are evaluated as well. Based on this data, energy price-dependent payback periods are calculated for each energy-efficient technology referring to an assumed reference plant (Fig. 4.5-4.7). Additionally, it is indicated in which year (and over which payback period) an energy-efficient technology was implemented. Ten cases are selected to identify the drivers for and barriers to the uptake of energy-efficient technologies on plant level using literature research and conducting interviews with experts. The interviews are analysed qualitatively.

From 1993 to 2004, i.e. over 12 years, there was no uptake of any of the selected technologies. Top-pressure recovery turbines were implemented from 1982 to 1993 and again from 2012 onwards, i.e. after a period of 20 years with zero diffusion. Pulverized coal injection diffused strongly between 1985 and 1993, and between 2004 and 2008 and again in 2014. The recovery of basic oxygen furnace gas was adopted from 1981 to 1987 and then once again in 2009.

Different sites or companies show different behaviour towards the implementation of new technologies. The average number of years until a site adopts a new technology ranges between 1.6 years and more than 34 years. The above mentioned analyses on the national level and the company level indicate that there are factors on each level, e.g. energy prices, legislation on the national level and site-specific factors on the company level, that drive the adoption of energy-efficient technologies.

There was a period of low energy prices between the mid-1980s and the year 2000. The payback period of the selected technologies was estimated as a function of the annual energy prices from the introduction of the selected technologies until 2014. Companies generally only decide to invest in energy-efficient technologies if a certain payback period is achieved, which turns out to be just under three years according to the findings of this section.

Economics can therefore explain why companies invest in energy-efficient technologies. But economics cannot explain why some companies do not invest, even if short payback periods are given, at least compared to their competitors.

Evaluating the adoption of the selected technologies reveals that site-specific constraints (e.g. not being a completely integrated steelworks) and access to capital were the two main barriers to the diffusion of energy-efficient technologies. Both also shape the economics of energy-efficient technologies. The introduction of the levy for renewable energies seems to have enabled the adoption of top-pressure recovery turbines from 2012 onwards, since integrated steelworks typically did not profit from the levy exemption, the so-called special equalization scheme. Policy intervention might have induced the implementation of one top-pressure recovery turbine.

7.3 Assessing future options to reduce CO_2 emissions

What are the promising low-carbon ironmaking technologies in research and development or at the early stage of commercialization?

This section provides an updated review of emerging energy-efficient and low carbon ironmaking technologies. Earlier studies include e.g. Martin et al. (2000) and de Beer et al. (1998). Other studies include reviews of energy-efficient technologies (e.g. Moya and Pardo, 2013; Brunke and Blesl, 2014). This section reviews twelve alternative ironmaking technologies under research and development or at an early commercialization stage. Information was collected from publicly available sources and provides details about the technology, its benefits and its commercial status. The main technologies are covered, but the list does not claim to be exhaustive.

Similar to current primary steelmaking, eight of the 12 technologies still depend on coal for the key energy input. Compared to current blast furnaces, these technologies omit energy-intensive coke-, sinter-, and/or pellet-making. Coal is still used to provide the energy for ironmaking. CO_2 reductions are therefore limited to about 20 % compared to current ironmaking in blast furnaces. Three of these technologies are commercially available but show only low adoption rates (i.e. Corex, Finex, coal-based HYL).

Four technologies use alternative energy sources. Biomass-based ironmaking is discussed as an alternative to coal-based ironmaking, especially in countries with abundant biomass sources (e.g. Scandinavian countries, Brazil). Research and development activities are also recorded for central European countries and the United States of America. In Brazil, biomass is already being commercially used in steelmaking (IBA Brazilian Tree Industry, 2016). However, the substitution of coal by biomass is limited by its availability and to some extent also by quality issues.

Electricity from renewable sources could substitute coal in ironmaking and greatly reduce CO_2 emissions. The electrolysis of iron ore is thus a promising option for a low carbon iron and steel industry. However, this technology is still at the early stage of research and development and commercialization is not expected before 2040.

Flash smelting of iron ore is one option to replace coal by hydrogen in ironmaking (Suspension hydrogen reduction of iron ore concentrate). Like the electrolysis of iron ore, this technology is still at an early research and development stage.

Hydrogen is being explored as a low CO_2 energy carrier for industrial applications (Energiepark Mainz, 2016). If hydrogen became available for large-scale industrial processes, ironmaking based on hydrogen would be an option to produce low carbon steel. Circored is one technology that reduces iron ore to iron using hydrogen. It proved its applicability in Trinidad in the 1990s at a scale of 500,000 tonnes of hot briquetted iron per year.

How does technological change impact the energy consumption and CO_2 emissions of the German steel industry until 2035 considering the findings from chapters 2 to 5?

Previous studies assessing the future energy consumption and CO_2 emissions of the German iron and steel industry either focus on the long term (Fischedick et al., 2014) or assume constant production levels (Brunke and Blesl, 2014). Other studies focus on different steelmaking countries (e.g. Kuramochi, 2015). This section provides an outlook of the energy consumption and CO_2 emissions of the German iron and steel industry until 2035 considering different production values as well as various process technologies. Results from the previous chapters 2 to 5 are included.

This section constructs four production pathways for future iron and steelmaking in Germany and estimates the probability of each achieving the climate targets set for 2035 if imposed as equal proportional targets. The pathways assume that currently operated blast furnaces are not phased out before they reach the end of their technical lifetime (i.e. 50 years). Future scrap availability is assessed and sets the limits for secondary steelmaking. The specific energy consumption of primary and secondary steelmaking decreases according to an assumed diffusion rate for energy-efficient technologies. Furthermore alternative steelmaking routes are included in the study (i.e. direct reduction based on natural gas, and the new ironmaking technology HIsarna that is assumed to be available from 2030 onwards). CO_2 emissions of the iron and steel industry are also shaped by the CO_2 emissions of the German electricity mix. Since the German government plans to expand the generation of electricity from renewable sources, the CO_2 intensity of German electricity is assumed to decrease.

This section finds that the current European climate target for the German iron and steel industry for 2030, if set as an equal proportional target, will only be achieved by a pathway with decreasing production and no replacement of blast furnaces. The current German climate target will not be achieved by any pathway. The dominance of primary steelmaking in the CO_2 emissions of the total iron and steel industry is stressed. The section also shows that current production levels cannot be maintainded by increasing of secondary steelmaking due to insufficient scrap availabilty.

A fuel switch from coal to natural gas (i.e. the replacement of blast furnaces with natural gas based direct reduction) will not help to meet current climate targets. The CO_2 emission savings potential from natural gas based direct reduction is not sufficient to meet current climate targets.

Current technologies under research and development will not be ready on time to help achieve the climate targets for 2030. Greatly increased renewable electricity generation has only a limited impact on the CO_2 emissions of the steel industry in every production pathway.

7.4 General conclusions

Conclusion 1: The German iron and steel industry is not on track to reduce its CO_2 emissions in line with the current climate targets for 2030, if these are set as equal proportional targets.

The German iron and steel industry is very unlikely to reach the current European and German climate targets for 2030 – if set as equal proportional targets (Tab. 6.9). These targets could only be achieved if primary steelmaking production were to decrease strongly by no longer replacing blast furnaces at the end of their technical lifetime from today onwards. Then, in 2030, primary steelmaking would have dropped to half of today's primary steelmaking production and secondary steelmaking would have to increase, especially since carbon capture and sequestration technology were not applied.

Additionally, total crude steel production would have to drop below the lowest production level of the past four decades (Fig. 6.10-c). The currently remaining potential to increase energy efficiency and reduce CO_2 emissions is low (Chap. 3) and technologies under research and development will not be ready on time (Chap. 5).

Conclusion 2: The German iron and steel industry has not undertaken special efforts to increase energy efficiency and reduce CO_2 emissions.

The reported progress in the energy intensity development of the total German iron and steel industry can mainly be traced back to a production shift towards more secondary steelmaking (Fig. 2.12). Energy intensity values on the process level were fairly constant between 1991 and 2007 (e.g. Fig. 2.10) or only showed slight improvements (e.g. Fig. 2.6). The reduction in the specific energy consumption since the 1950s can largely be explained by the diffusion of three technologies (i.e. the electric arc furnace steelmaking route, continuous casting, and the basic oxygen furnace) (Chap. 3).

Companies only agreed to invest in energy-efficient technologies if these pay off within two to three years (Chap. 4), even though payback periods can be considered a measure of risk rather than profitability. In addition, companies invest in production facilities that they assume will run for several decades, but do not invest in an additional energy-efficient technology in the same plant if its payback period exceeds the requested two to three years.

Conclusion 3: The German iron and steel industry has barely been affected by policies aiming to increase energy efficiency and reduce CO_2 emissions.

The voluntary agreement between German industry and the German government to protect the climate was in place throughout the studied period of chapter 2. German industry agreed to undertake *special efforts* to reduce its specific CO_2 emissions by 22 % in 2012 compared to 1990. The results from chapter 2 do not reveal any exceptional action by the German iron and steel industry between 1991 and 2007 to reduce its fossil fuel consumption. Instead, the set goal seems to be largely – and autonomously – achieved by an increasing share of secondary steelmaking. This finding is supported e.g. by Flues et al. (2015).

The impacts of the European Emission Trading Scheme have been cushioned by allocating free emission allowances to energy-intensive industries in global competition, including the iron and steel industry (European Commission, 2016c).

Finally, article §5/4 of the German Federal law on combating pollution (BImSchG) asks the owners of large industrial plants to run these energy efficiently. This law has not been specified in any directive, and is typically not applied (Chap. 4).

Conclusion 4: The Association of European steel companies including the German iron and steel industry does not propose any pathway towards low carbon iron- and steelmaking except for carbon capture and storage.

In its low carbon roadmap 2050, the European iron and steel industry represented by Eurofer, focuses on policies that support its current steelmaking processes. Steel is stressed as a mitigating enabler that helps reduce CO_2 emissions in several sectors, most notably in the energy and transport sector.

Although low-carbon alternatives to coal like electricity and hydrogen from renewables are discussed, carbon capture and storage is the only technology included that could lead to large CO_2 reductions in the iron and steel industry. Explicit policies to transform this industry into a low-carbon one are not proposed (Eurofer, 2013).

7.5 Recommendations for future research

This section gives an overview of pathways towards low-carbon energy-intensive industries based on the results from chapters 1 to 6 and additional literature.

Besides shutting down the production facilities of energy-intensive industries, there are only two ways to drastically reduce their CO_2 emissions. The first is to capture CO_2 emissions from off-gases before these are released into the atmosphere and store the CO_2 underground. This is called carbon capture and storage or CCS. CCS does not prevent the production of anthropogenic CO_2, but does prevent it contributing to the greenhouse gas effect as long as it remains in its underground storage.

Since the CO_2 concentration in off-gases from industrial plants is typically too low to capture CO_2, new processes need to be developed to apply CCS here. Developing new processes for large-scale industries is time intensive; typically, it takes decades to scale up from laboratory to commercial plants that produce several million tonnes per year. In addition, the diffusion of new large-scale industrial plants is slow because large industrial facilities normally are run for several decades before they are replaced.

In the discussions surrounding the European Low-Carbon Roadmap 2050, fossil fuel industries emphasized CCS as a sustainable and cost-effective way to reduce greenhouse gas emissions (European Commission, 2011). However, when taking a closer look at the low carbon roadmaps of European energy-intensive industries, it becomes clear that CCS is viewed more guardedly. The European cement industry stresses that CCS is only realistic if the transport infrastructure and storage sites of CO_2 are suitable and approved – an issue that remains unresolved and beyond the scope of responsibility of the cement industry. Even if the costs for CCS decline in the future, the European cement industry believes that investment and operating costs will still be substantial (The European Cement Association, 2013). The European chemical industry only sees CCS as an economically viable option if it is adopted by many sectors worldwide (The European Chemical Industry Council, 2013). The European pulp and paper industry even favours supporting other breakthrough technologies than CCS (Confederation of European Paper Industries, 2011).

While CCS addresses the carbon-intensive *output* of industries, the second option considers substituting carbon-intensive *input* materials by low-carbon alternatives.

Carbon-intensive input materials to energy-intensive industries are typically fossil fuel-based energy carriers, but also include raw materials such as limestone in cement production or steelmaking. Adapting industry to low-carbon feedstocks requires sector- or even process-specific solutions.

Electricity from renewables will be a cornerstone of low-carbon economies. Thus producing more electricity from renewables helps to make processes that rely on electricity to become low-carbon ones. Electrolysis is currently the dominant process for primary aluminium making. In contrast, electrolysis for ironmaking is still at an early stage of research and is only considered a promising technology in a fully decarbonised electricity scenario (Eurofer, 2013). In pulp and paper making, about two thirds of the total CO_2 reduction potential until 2030 is attributed to the decarbonisation of the power sector (Confederation of European Paper Industries, 2011).

The use of biomass, solar or geothermal heat in industrial processes is currently very limited (section 1.3.1). More attention is being paid to the conversion of excess electricity from renewables into other products, called *power-to-X*. *Power-to-heat* allows the consumption of heat from renewable electricity. Current devices are designed as hybrids that can still use fossil fuels if no excess renewable power is available. Other ways to utilise excess renewable electricity include *power-to-liquid*, or *power-to-chemicals*. The production of hydrogen from renewable electricity (*power-to-gas*) is being tested in several demonstration plants (section 1.3.1). Hydrogen is a promising low carbon option for the iron and steel industry that is starting to be explored in Sweden and Austria (Eurofer, 2013; Neuberg, 2016). In contrast to other industrial processes, ironmaking based on hydrogen is a commercially available process.

All the outlined options to drastically reduce CO_2 emissions from energy-intensive industries are currently limited, either by their availability (e.g. biomass) or maturity (e.g. power-to-X). Thus strategies have to be enhanced that aim to use the current feedstocks containing carbon more efficiently.

Energy efficiency can still be improved in energy-intensive sectors (The European Cement Association, 2013; Confederation of European Paper Industries, 2011; Eurofer, 2013; The European Chemical Industry Council, 2013). New concepts for heat recovery are being developed. Heat recovery from blast furnace slag or hot slabs is being explored in pilot plants. New processes such as belt casting technologies promise to cut energy consumption by omitting reheating processes. Some energy-efficient technologies have not yet reached complete diffusion. Coke dry quenching, for instance, is widely applied in Japan, but is not used in Europe.

Internal energy flows might need to be re-thought. When electricity generation is fuel-based then the production of electricity from carbon-intensive off-gases in the steel industry is an energy-efficient measure. But if electricity is generated from renewables, then carbon-intensive off-gases could be used to substitute further fuel input, e.g. through the production of direct reduced iron with coke-oven gas, thus substituting natural gas or coal consumption.

Cross-sectoral energy cooperations offer a so far mostly untapped energy-efficiency potential. Energy-rich off-gases from one industrial sector can serve as the input to another sector. For instance, hydrogen- and carbon monoxide-rich off-gases from the steel industry could serve as input to the chemical industry.

Carbon capture and usage also connects different sectors. Captured CO_2 can be used as an input to other industries, e.g. for the production of algae as biomass that can be used as a fuel (The European Cement Association, 2013).

Recycling energy-intensive products strongly decreases the energy consumption of selected sectors including iron and steelmaking (Eurofer, 2013). However, recycling in this sector is limited by the quality and availability of scrap. Primary production will only become less important once sufficient primary materials have been produced that can be recycled with qualities similar to primary products. Other energy-intensive sectors also stress the importance of recycling (The European Chemical Industry Council, 2013; The European Cement Association, 2013; Confederation of European Paper Industries, 2011).

Material efficiency reduces waste along production processes or provides a similar benefit with less material, e.g. light-weight steel grades that reduce the weight of automobiles or high-strength concrete that reduces the volume of concrete needed to create a specific structure (Eurofer, 2013; The European Cement Association, 2013).

Finally, low-carbon products could replace carbon-intensive products, such as cement, steel or aluminium. Products from the forest fibre industry could substitute carbon-intensive products, e.g. in construction, packaging, as fuels or chemicals (Confederation of European Paper Industries, 2011). Assessing this potential requires life-cycle analyses and the identification and development of suitable alternatives to carbon-intensive products.

7.6 Policy recommendations

The section above gave an overview of promising fields of research on transforming energy-intensive industries into low-carbon industries. This section suggests further steps towards a low-carbon industry which should be supported by policies.

Industry- and process-specific CO_2 reduction potentials should be assessed in detail. Evaluating past developments in energy and CO_2 intensity provides insights on how much has been achieved and whether it is probable that trends will proceed autonomously. Identifying the factors shaping energy efficiency improvements and CO_2 reductions helps to understand why companies may be cautious about further CO_2 reductions.

Based on the specific findings, a systems approach should identify industry and cross-sectoral approaches to reduce CO_2.

Financing is a key issue when developing and deploying large-scale industrial plants because this is capital-intensive and often harbours risks. It should be assessed to which extent companies can receive financial support while complying with current state-aid legislation.

The current policies aiming to increase energy efficiency and reduce CO_2 emissions do not seem to have been very effective. They need to be improved or new policies should be introduced.

The European Emission Trading Scheme is perceived as the major policy for a low-carbon economy. It could have more impact on energy efficiency improvements and CO_2 reductions once the price for CO_2 increases, e.g. by back-loading and/or further cutting free allowances. The envisioned enhanced reduction of free allowances after 2020 is likely to put additional pressure on energy-intensive industries. If there is no global price on the emission of CO_2, it must be ensured that companies in global competition are protected from the severe effects of carbon leakage. The revenue from selling CO_2 allowances should be increased and redirected to the research, development and demonstration of low-carbon industrial processes similar to the NER-300 and NER-400 reserves.

For German industry, there is already a law that asks the operators of large-scale industrial plants to run these energy-efficiently (Article §5/4 of the German federal law on combating pollution, Chap. 4). However, this law has not been detailed by any directive and is typically not applied. It should be evaluated whether and how this law can be enforced.

Hydrogen seems to offer a promising low-carbon option at least in ironmaking. Ironmaking based on hydrogen is a commerically available technology. Research needs to be conducted on the hydrogen supply from renewable energies.

Samenvatting

Inleiding

Het koolstofvrij maken van de industrie en in het bijzonder de ijzer- en staalindustrie vormt de sleutel tot het verminderen van de effecten van de klimaatverandering. De energie-intensiteit van de ijzer- en staalproductie nam gedurende de jaren '50 tot en met '90 sterk af, maar deze industrie vertegenwoordigt nog steeds ongeveer 6,5 % van de globale antropogene CO_2-emissies (Basson, 2012). Het technische potentieel voor het verder reduceren van het energieverbruik in de staalproductie is beperkt, maar verdere uitstootverminderingen dienen te worden gerealiseerd om deze sector in een koolstofarme te transformeren.

De ijzer- en staalindustrie is van bijzonder belang omdat zij afhankelijk is van fossiele brandstoffen, niet alleen voor verwarmingsdoeleinden, maar ook als chemisch reductiemiddel. Haar belangrijkste energiebron (d.w.z. kolen) kan daarom niet worden vervangen door andere (hernieuwbare) hittebronnen. Het vervangen van fossiele brandstoffen bij de productie van ijzer en staal vereist nieuwe technologische concepten.

De koolstofafvang en -opslag wordt vaak besproken als een optie voor het reduceren van CO_2-emissies bij het produceren van ijzer en staal (bijv. Internationaal Energieagentschap, 2009). Het Europese Ulcos-project is gericht op het ontwikkelen van de koolstofafvang en -opslag voor de ijzer- en staalindustrie. Het doel van dit project bestaat uit het reduceren van de CO_2-uitstoot van de staalindustrie met 50 % (Ulcos, 2016). De afvang en opslag van koolstof is echter om verschillende redenen een onzekere optie, onder andere vanwege goedkeuringskwesties en een vertraging in de voortgang van aangekondigde projecten. Daar nieuwe technologische concepten voor een staalproductie met lage CO_2-uitstoot en koolstofafvang en -opslag alleen in de toekomst beschikbaar zullen zijn, vormt energie-efficiëntie op korte- en middellange termijn de enige optie voor het tot een minimum reduceren van de CO_2-uitstoot.

Ondernemingen zijn doorgaans geïnteresseerd in het verbeteren van hun energie-efficiëntie, om op energiekosten te besparen. Dit is de reden waarom de energie-efficiëntie normaliter op termijn verbetert. De energie-intensiteit echter, die doorgaans wordt gebruikt als indicator voor de energie-efficiëntie, varieert tussen landen en ondernemingen en toont aan dat er factoren bestaan die verbeteringen in energie-efficiëntie versnellen (drijvende factoren) of belemmeren (remmende factoren). Een grondig begrip van de energie-intensiteitstrends in de ijzer- en staalproductie is noodzakelijk voor het bepalen van effectieve beleidsmaatregelenlijnen die erop gericht zijn, de productiesector in een koolstofarme industrie te transformeren.

Deze dissertatie presenteert een gedetailleerde studie van de Duitse ijzer- en staalindustrie, die als een voorbeeld voor een gemiddelde ijzer- en staalindustrie wordt gebruikt voor wat betreft in het verleden behaalde resultaten op het gebied van de energie-intensiteit, en haar toekomstige opties voor het drastisch reduceren van CO_2-uitstoot tot het jaar 2035. De benadering concentreert zich op (afbeelding 7.2):

a. het beoordelen en begrijpen van energie-intensiteitstrends in het verleden en

b. het beoordelen van toekomstige opties voor het reduceren van CO_2-emissies.

De belangrijkste onderzoeksvraag van deze dissertatie is:

Hoe kan technologische verandering leiden tot energie-efficiëntie en de reductie van CO_2 in de Duitse ijzer- en staalindustrie?

De hoofdkwestie wordt behandeld met behulp van vijf groepen met onderliggende vragen:

1. Hoe veranderde energie-intensiteit op procesniveau in de Duitse ijzer- en staalindustrie tussen 1991 en 2007? Welke impact hadden deze veranderingen op procesniveau op de energie-intensiteit van de Duitse ijzer- en staalindustrie als geheel?
2. Wat zijn de diffusiesnelheden van de belangrijkste energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie? Welke impact hebben deze op de ontwikkeling van de energie-intensiteit van de Duitse ijzer- en staalindustrie als geheel? Wat is hun resterende energie-intensiteitspotentieel?
3. Wat zijn de drijvende en remmende factoren voor de implementatie van belangrijke energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie?
4. Wat zijn de veelbelovende koolstofarme ijzerproductietechnologieën die worden onderzocht of ontwikkeld of zich in een vroegtijdige fase van commercialisering bevinden?
5. Hoe beïnvloedt technologische verandering het energieverbruik en CO_2-emissies in de Duitse staalindustrie tot 2035, uitgaand van de bevindingen in de hoofdstukken 2-5?

In hoofdstuk 2 worden de energie-intensiteitstrends per proces van 1991 tot 2007 geëvalueerd en de impact geschat van een stijgend aandeel van secundaire staalproductie op het specifieke energieverbruik per ton ruwstaal. De diffusiesnelheden van de belangrijkste energie-efficiënte technologieën worden bepaald sinds hun introductie en de impact van deze technologieën op de energie-intensiteit in de ijzer- en staalindustrie wordt in hoofdstuk 3 ingeschat. Ook het restpotentieel voor energiebesparing wordt bepaald. Hoofdstuk 4 beschrijft recente ontwikkelingen op het gebied van energie-intensiteit en beoordeelt de invloed van energieprijzen op de introductie van energie-efficiënte technologieën. Ook de diffusie van energie-efficiënte technologieën wordt zowel op nationaal- als ook op installatieniveau bepaald. De belangrijkste drijvende en remmende factoren voor de diffusie worden aan de hand van geselecteerde gevallen onderzocht. Hoofdstuk 5 geeft een overzicht en evaluatie van alternatieve ijzerproductietechnologieën. Ten slotte worden on hoofdstuk 6 productietrajecten geconstrueerd die meerdere variabelen afdekken, die bepalend zijn voor CO_2-emissies om zodanig tot een inschatting te komen van welk traject een sterke CO_2-reductie met zich meebrengt.

Beoordelen en begrijpen van trends uit het verleden in de Duitse ijzer- en staalindustrie

Hoe heeft zich de energie-intensiteit op procesniveau in de Duitse ijzer- en staalindustrie tussen 1991 en 2007 ontwikkeld? Welke invloed hadden deze veranderingen op procesniveau op de algehele energie-intensiteit van de Duitse ijzer- en staalindustrie?

De analyse van trends uit het verleden in energie-intensiteit geeft een inzicht in wat men tot dusver heeft bereikt en hoe waarschijnlijk het is dat zich deze trends zich autonoom zullen voortzetten. Het onderzoek op het gebied van de energie-intensiteit op procesniveau geeft bovendien aan of het efficiëntiepotentieel gelijkmatig over de processen is verdeeld.

Terwijl eerdere studies op dit gebied (bijv. Rheinisch-Westfälisches Institut für Wissenschaftsforschung, 2010) energie-intensiteitsontwikkelingen voor de gehele staalindustrie onderzochten, worden in dit onderdeel de ontwikkelingen op het gebied van energie-intensiteit op procesniveau onderzocht. Op deze wijze wordt duidelijk in hoeverre het toenemende aandeel van de secundaire staalproductie heeft geleid tot een afname van de energie-intensiteit van de staalindustrie als geheel, vergeleken met verbeteringen in energie-efficiëntie.

In dit onderdeel worden gegevens van het Duitse federale bureau voor de statistiek over het energieverbruik geëvalueerd (Statistisches Bundesamt, 1991-2007). Het energieverbruik voor belangrijke ijzer- en staalproductieprocessen op nationaal niveau wordt jaarlijks per energiebron gerapporteerd. Er worden productievolumes aan elk gerapporteerd proces toegewezen op basis van gegevens van de Duitse staalvereniging en het staalinstituut VDEh (1991-2007). Het energieverbruik dat in fysieke eenheden wordt weergegeven, wordt met behulp van de laagste verwarmingswaarden in energie-eenheden omgerekend. De resultaten voor de ontwikkeling van de energie-intensiteit per proces worden gepresenteerd als de ontwikkeling van het specifieke energieverbruik per proces en per energiebron van 1991 tot 2007. De invloed van een stijgend aandeel van secundaire staalproductie op de energie-intensiteit van de Duitse ijzer- en staalindustrie als geheel wordt eveneens weergegeven.

Van 1991 tot 2007 heeft zich de energie-intensiteit op procesniveau niet essentieel verbeterd, met uitzondering van walsprocessen. Een afname van de energie-intensiteit van de ijzer- en staalindustrie als geheel (d.w.z. primaire- én secundaire staalproductie) is grotendeels te danken aan een stijgend aandeel van de secundaire staalproductie. Tussen 1991 en 2004 is het specifieke energieverbruik per ton ruwstaal jaarlijks met 0,3 % afgenomen, waarvan 0,2 % kan worden herleid tot de secundaire staalproductie.

Het energieverbruik van hoogovens steeg vanaf 2000, maar het netto-energieverbruik daalde doorlopend, uitgaand van een productie van topgassen van 12,50 GJ per ton vloeibaar ruwijzer in 1991, tot 12,00 GJ/ton vloeibaar ruwijzer in 2007, hetgeen overeenkomt met een verbetering van 0,2 % per jaar.

De energie-intensiteitswaarden van sinterinstallaties steeg tussen 1991 en 1998 en tussen 2002 en 2006. De energie-intensiteit bereikte in 1998 een piekwaarde van 2,28 GJ/t sinter, hetgeen 0,26 GJ/t sinter, oftewel 12 % hoger lag dan in 1991. De energie-intensiteit van elektrische vlamboogovens varieerde slechts licht gedurende de periode van de studie. Uitgaand van 1994 als referentiejaar, varieerde het specifieke energieverbruik van 2 % (bijv. in 1996, 2004 en 2007) tot -2 % (in 1998). Er werden gedurende de periode van de studie geen daadwerkelijke verbeteringen in de energie-efficiëntie van elektrische staalfabrieken in Duitsland vastgesteld.

Het walsen van staal vormde de enige procesgroep waarvoor de geïdentificeerde trend in energie-intensiteit overeenkwam met de verwachte: wij stelden een doorlopende afname in energie-intensiteit van ongeveer 1,4 % per jaar vast. Gedurende de periode van de studie vond echter een afname van 35,0 % in 1994 tot 31,4 % in 2007 in het productie-aandeel van koudgewalst ten opzichte van warmgewalst staal plaats. Een dergelijke afname kan een gedeeltelijke verklaring voor de geïdentificeerde ontwikkeling van de energie-intensiteit bieden.

Samenvattend blijven de verbeteringen in energie-intensiteit in de Duitse ijzer- en staalindustrie tussen 1991 en 2007 ver achter de verwachte doorlopende verbeteringen in de energie-intensiteit, ten gevolge van technologische vooruitgang, diffusie van de beste beschikbare technologieën, het ontmantelen van oudere installaties en het verbeteren van het energiebeheer. De periode van de studie beslaat nagenoeg twee decennia, die kunnen worden gekenmerkt als een periode zonder noemenswaardige vooruitgang op het gebied van energie-efficiëntie. De studie beperkte zich tot de ontwikkeling van het specifieke energieverbruik en kan dus geen bevindingen leveren die betrekking hebben tot factoren die invloed hadden op het energieverbruik bij de productie van ijzer en staal. Tijdens het onderzoek beweerden ondernemingen en verenigingen echter dat zij gedurende deze periode hun processen wel degelijk verbeterden. Andere factoren zoals grondstofkwaliteit kunnen echter van groter belang zijn geweest voor verbeteringen in energie-efficiëntie.

Wat zijn de diffusiesnelheden van de belangrijkste energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie? Welke impact hebben deze op de ontwikkeling van energie-intensiteit van de gehele Duitse ijzer- en staalindustrie? Wat is hun restpotentieel met betrekking tot de energie-efficiëntie?

Terwijl eerdere studies zich concentreerden op het verklaren van het diffusieproces (bijv. Oster, 1982; Poznanski, 1983), verdiept zich dit onderdeel in de diffusiesnelheden van belangrijke energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie en wordt hun impact op de energie-intensiteit van de Duitse ijzer- en staalindustrie als geheel bepaald.

Dit onderdeel biedt, gebruik makend van gegevens op nationaal- en installatieniveau, een diepgaande analyse van de diffusie van zes belangrijkste energie-efficiënte technologieën in de ijzer- en staalindustrie in Duitsland. Er wordt een periode van 60 jaar besproken. De impact van deze technologieën op de ontwikkeling van de energie-intensiteit binnen de Duitse ijzer- en staalindustrie als geheel wordt weergegeven. Op basis van de diffusiesnelheden wordt het restpotentieel voor de energie-efficiëntie geschat, ervan uitgaand dat alle technologieën volledig werden verspreid.

Technologieën die in de jaren 1950-1960 werden geïntroduceerd, werden in hun initiële fase gekenmerkt door een langzamere diffusie, maar bereikten binnen 20-25 jaar een complete diffusie (oxystaalovens en continugietinstallaties). Technologieën die rond 1980 werden geïntroduceerd, werden in het begin sneller overgenomen, maar hun diffusie kwam na ongeveer 10 jaar tot stilstand, vanaf ongeveer 1990. Deze technologieën omvatten topdrukturbines, poederkoolinjectie, gasrecuperatie van oxystaalovens en het droogblussen van coke. Zelfs 20-25 jaar na hun introductie heeft geen van deze technologieën een diffusiesnelheid van meer dan 70 % bereikt. Een van de technologieën (droogblussen van cokes) is niet langer in gebruik.

In dit onderdeel wordt ook de impact van technologische veranderingen op het specifieke energieverbruik per ton ruwstaal weergegeven. Buiten de zes geselecteerde energie-efficiënte technologieën wordt de secundaire staalproductie ook opgenomen in de schatting. De secundaire staalproductie heeft met ongeveer 21 % tot heden verreweg de grootste impact gehad op de vermindering van het specifieke energieverbruik per ton ruwstaal tussen 1958 en 2012. De technologieën die in de jaren 1950 en '60 werden geïntroduceerd, namelijk die van de oxystaalovens en continugietinstallaties, droegen ook aanzienlijk bij tot de reductie van het energieverbruik per ton ruwstaal, namelijk met respectievelijk ongeveer 12 % en 6 %. De vier technologieën die rond 1980 werden geïntroduceerd, droegen in totaal slechts met ongeveer 4 % bij aan de vermindering van het specifieke energieverbruik. De totale reductie in specifiek energieverbruik per ton ruwstaal dankzij de geselecteerde technologieën (inclusief de secundaire staalproductie), bedroeg tussen 1958 en 2012 ongeveer 43 %. Aichinger en Steffen rapporteren een reductie van het specifieke primaire energieverbruik per ton ruwstaal van 40 % in de Duitse ijzer- en staalindustrie tussen 1959 en 2004 (Aichinger en Steffen, 2006). Zodoende lijken deze energie-efficiënte technologieën en de secundaire staalproductie gedurende de afgelopen decennia de belangrijkste drijfkrachten voor de reductie van het specifieke energieverbruik in de Duitse ijzer- en staalindustrie.

Ten slotte werd het energiebesparingspotentieel van de vier energie-efficiënte technologieën geschat. Omdat het momenteel in Duitsland niet wordt aangewend, vormt het droogblussen van cokes met 2 % van het specifieke primaire energieverbruik de technologie met het grootste energiebesparingspotentieel. Gasrecuperatie van oxystaalovens en poederkoolinjectie zou voor een reductie van het specifieke primaire energieverbruik per ton ruwstaal van respectievelijk 1,4 % en 1,0 % zorgen. De impact van een verdere diffusie van topdrukrecuperatieturbines zou beperkt blijven tot slechts 0,1 %.

De energie-efficiëntietrends in de Duitse ijzer- en staalindustrie gedurende de laatste vijf decennia lijken voornamelijk te worden gedreven door drie technologieën (secundaire staalproductie, oxystaalovens en continugieten). Het restpotentieel van de geselecteerde energie-efficiënte technologieën blijft beperkt tot ongeveer 4,5 %.

Wat zijn de drijvende en remmende factoren voor de implementatie van belangrijke energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie?

Dit onderdeel richt zich op het verklaren van geïdentificeerde energie-intensiteitstrends in de Duitse ijzer- en staalindustrie tussen 1991 en 2007 (hoofdstuk 2) en de afgeleide diffusiesnelheden van belangrijke energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie sinds hun introductie (hoofdstuk 3).

Studies over drijvende en remmende factoren voor de diffusie van energie-efficiënte technologieën in de Europese of Duitse ijzer- en staalindustrie zijn doorgaans gebaseerd op een economische beoordeling van deze technologieën (bijv. Brunke en Blesl, 2014; Moya en Pardo, 2013). Er werden studies uitgevoerd op het gebied van drijvende- en remmende factoren voor de diffusie van energie-efficiënte technologieën in de ijzer- en staalindustrie van geselecteerde landen (bijv. Brunke et al, 2014). Dit onderdeel verdiept zich in de diffusie van belangrijke energie-efficiënte technologieën in de Duitse ijzer- en staalindustrie, evalueert terugverdientijden uit het verleden op basis van historische energieprijzen en analyseert de drijvende en remmende factoren op installatieniveau, gebruik makend van een interviewmethode. Er werden antwoorden geïdentificeerd die bijdroegen tot het verklaren van het feit dat energie-efficiënte technologieën in bepaalde installaties wel werden geïmplementeerd, terwijl deze niet in andere installaties werden geïntroduceerd.

Er werd gebruik gemaakt van een gecombineerde benadering. Eerst werden gegevens van producenten over de implementatie van de geselecteerde energie-efficiënte technologieën in de Duitse ijzer- en staalfabrieken geëvalueerd. Deze technologieën omvatten de gasrecuperatie van oxystaalovens, topdrukrecuperatieturbines en poederkoolinjectie. Als tweede stap werd een tijdslijn opgesteld voor de betreffende Duitse ijzer- en staalfabrieken (d.w.z. hoogovens en oxystaalovens). Er werden uitsluitend fabrieken in de studie opgenomen die nog operationeel zijn. Als derde stap werd het gemiddelde aantal jaren berekend, dat verstreek totdat een fabriek de energie-efficiënte technologie introduceerde. De vierde stap bestond uit het reconstrueren van de voor de Duitse industrie relevante energiebronnen. Ook door beleidsmaatregelen aangespoorde energieprijscomponenten werden geëvalueerd. Op basis van deze gegevens werden voor elke energie-efficiënte technologie energieprijsafhankelijke terugverdientijden berekend, verwijzend naar een als referentiepunt gebruikte fabriek. Bovendien werd aangegeven in welk jaar (en met welke terugverdientijd) een energie-efficiënte technologie werd geïmplementeerd. Er werden tien gevallen geselecteerd voor het identificeren van drijvende en remmende factoren voor de opname van energie-efficiënte technologieën op installatieniveau, gebruik makend van literatuuronderzoek en interviews met deskundigen. De interviews werden op kwaliteit geanalyseerd.

Van 1993 tot 2004, d.w.z. over een periode van 12 jaar, vond er geen opname van de geselecteerde technologieën plaats. Topdrukrecuperatieturbines werden tussen 1982 en 1993 en opnieuw vanaf 2012 geïmplementeerd, d.w.z. na een periode van 20 jaar zonder diffusie. Poederkoolinjectie kende tussen 1985 en 1993, 2004 en 2008 en opnieuw in 2014 een sterke diffusie. De gasrecuperatie van oxystaalovens werd van 1981 tot 1987 en opnieuw in 2009 geïntroduceerd.

Verschillende fabrieken of ondernemingen vertonen verschillende gedragingen op het gebied van de implementatie van nieuwe technologieën. Het gemiddelde aantal jaren voordat een fabriek een nieuwe technologie overneemt, ligt tussen 1,6 tot meer dan 34 jaar. De voornoemde analyse op nationaal- en ondernemingsniveau geeft aan dat er op elk niveau factoren bestaan, bijv. energieprijzen, wetgeving op nationaal niveau en fabrieksspecifieke factoren op ondernemingsniveau, die de invoering van energie-efficiënte technologieën bepalen.

De periode tussen het midden van de jaren 1980 en het jaar 2000 werd gekenmerkt door lage energieprijzen. De terugverdientijd van de geselecteerde technologieën werd geschat als een functie van de jaarlijkse energieprijzen vanaf de introductie van de geselecteerde technologieën tot 2014. Ondernemingen gaan doorgaans uitsluitend over tot het investeren in energie-efficiënte technologieën wanneer een bepaalde terugverdientijd wordt bereikt, die volgens de bevindingen in dit onderdeel iets minder dan drie jaar blijkt te bedragen.

Economische factoren kunnen daarom verklaren, waarom ondernemingen in energie-efficiënte technologieën investeren. Economische factoren kunnen echter niet verklaren waarom sommige ondernemingen niet investeren, zelfs niet wanneer de terugverdientijden kort zijn, tenminste in vergelijking met hun concurrenten.

Een evaluatie van de invoering van geselecteerde technologieën toont aan dat de fabrieksspecifieke beperkingen (bijv. voor niet geheel geïntegreerde staalbedrijven) en de toegang tot kapitaal de twee voornaamste remmende factoren voor de diffusie van energie-efficiënte technologieën vormden. Beiden bepalen bovendien de economische aspecten voor energie-efficiënte technologieën. De introductie van de heffing op hernieuwbare energieën lijkt de invoering van topdrukrecuperatieturbines vanaf 2012 te hebben mogelijk gemaakt, daar geïntegreerde staalfabrieken doorgaans geen voordeel genoten van de vrijstelling van de heffing, het zogenaamde vereveningsstelsel. Beleidsinterventie kan hebben geleid tot het implementeren van één topdrukrecuperatieturbine.

Evalueren van toekomstige opties voor het reduceren van CO_2-emissies in de Duitse ijzer- en staalindustrie

Wat zijn de veelbelovende koolstofarme ijzerproductietechnologieën die worden onderzocht of ontwikkeld of zich in een vroegtijdige fase van commercialisering bevinden?

Dit onderdeel biedt een bijgewerkte behandeling van opkomende energie-efficiënte en koolstofarme technologieën voor de vervaardiging van ijzer. Eerdere studies omvatten bijv. Martin et al. (2000) en de Beer et al. (1998). Andere studies bevatten evaluaties van energie-efficiënte technologieën (bijv. Moya en Pardo, 2013; Brunke en Blesl, 2014).

Dit onderdeel presenteert een beoordeling van de twaalf alternatieve technologieën voor de vervaardiging van ijzer, die momenteel worden onderzocht en ontwikkeld, of die zich in een vroegtijdige fase van commercialisering bevinden. Er werd informatie verzameld van openbaar beschikbare bronnen en er worden details geleverd over de technologie, haar voordelen en haar commerciële status. De belangrijkste technologieën worden behandeld, maar de lijst maakt geen aanspraak op volledigheid. Soortgelijk aan wat geldt voor de huidige staalproductie, zijn acht van de 12 technologieën nog steeds afhankelijk van kool als belangrijkste energiebron. Vergeleken met de huidige hoogovens, omvatten deze technologieën geen energie-intensieve cokes-, sinter- en/of pelletsproductie. Kool wordt nog steeds gebruikt als energiebron voor de ijzerproductie. CO_2-reducties worden hierdoor beperkt tot ongeveer 20 % ten opzichte van die van de ijzerproductie met behulp van hoogovens. Drie van deze technologieën zijn commercieel beschikbaar, maar worden slechts in beperkte mate overgenomen (Corex, Finex, kolen-gebaseerd HYL).

Vier van de technologieën maken gebruik van alternatieve energiebronnen. Biomassa-gebaseerde ijzerproductie wordt als alternatief voor koolgebaseerde ijzerproductie besproken, in het bijzonder in landen met een overvloed aan biomassabronnen (bijv. Scandinavische landen, Brazilië). Ook inspanningen op het gebied van onderzoek en ontwikkeling in Midden-Europese landen en de Verenigde Staten van Amerika worden vastgelegd. In Brazilië wordt biomassa reeds commercieel gebruikt voor het vervaardigen van staal (IBA Brazilian Tree Industry, 2016). De vervanging van kool door biomassa blijft echter beperkt om redenen van beschikbaarheid en, tot op zekere hoogte, kwaliteitsproblemen.

Elektriciteit uit hernieuwbare bronnen zou een vervanging kunnen vormen voor kool in de vervaardiging van ijzer, en de uitstoot van CO_2 aanzienlijk kunnen terugdringen. De elektrolyse van ijzererts vormt derhalve een veelbelovende optie voor een koolstofarme ijzer- en staalindustrie. Deze technologie bevindt zich echter nog steeds in een vroegtijdige fase van onderzoek en ontwikkeling, en commercialisering wordt niet voor 2040 verwacht.

Het flash-smelten van ijzererts vormt een optie voor het vervangen van kool door waterstof voor de productie van ijzer (suspensie waterstofreductie van ijzerertsconcentraat). Net als de elektrolyse van ijzererts, bevindt deze technologie zich nog steeds in een vroegtijdige fase van onderzoek en ontwikkeling.

Waterstof wordt verkend als een koolstofarme energiebron voor industriële toepassingen (Energiepark Mainz, 2016). Wanneer waterstof beschikbaar zou worden voor grootschalige industriële processen, zou waterstofgebaseerde ijzerproductie een optie kunnen vormen voor de productie van koolstofarm staal. Circored is een technologie die ijzererts met behulp van waterstof reduceert tot ijzer. In de jaren 1990 heeft zij haar toepasbaarheid in Trinidad bewezen, met een volume van 500.000 ton heetgebriketteerd ijzer per jaar.

Hoe beïnvloedt technologische verandering het energieverbruik en CO_2-emissies in de Duitse staalindustrie tot 2035, uitgaand van de bevindingen in de hoofdstukken 2-5?

Eerdere studies die het toekomstige energieverbruik en CO_2-uitstoot van de Duitse ijzer- en staalindustrie evalueerden, concentreerden zich ofwel op de lange termijn (Fischedick et al., 2014), ofwel gingen uit van constante productieniveaus (Brunke en Blesl, 2014). Andere studies richtten zich op andere staalproducerende landen (bijv. Kuramochi, 2015). Dit onderdeel biedt een inzicht in het energieverbruik en de CO_2-uitstoot van de Duitse ijzer- en staalindustrie tot 2035, uitgaand van verschillende productiewaarden en procestechnologieën. Ook de resultaten uit hoofdstuk 2-5 werden opgenomen.

In dit onderdeel worden vier productietrajecten voor de toekomstige ijzer- en staalproductie in Duitsland geconstrueerd en wordt een inschatting gemaakt voor de waarschijnlijkheid waarmee elk traject zal voldoen aan de klimaatdoelstellingen voor 2035, indien deze in de vorm van gelijke proportionele doelen worden opgelegd. Deze trajecten gaan ervan uit, dat er geen uitfasering van de momenteel operationele hoogovens zal plaatsvinden voordat zij het einde van hun technische levensduur (50 jaar) bereiken. De toekomstige beschikbaarheid van schroot wordt vastgesteld en bepaalt de limieten voor de productie van secundair staal. Het specifieke energieverbruik van de primaire en secundaire staalproductie neemt af als gevolg van een aangenomen diffusiesnelheid voor energie-efficiënte technologieën. Bovendien worden alternatieve staalproductiemethoden in de studie opgenomen (directe reductie op basis van natuurgassen en de nieuwe technologie voor het vervaardigen van ijzer, HIsarna, waarvan wordt aangenomen dat deze vanaf 2030 beschikbaar zal zijn). CO_2-emissies van de ijzer- en staalindustrie worden ook beïnvloed door de CO_2-emissies van de Duitse elektriciteitsmix. Daar de Duitse regering van plan is, de generatie van elektriciteit uit hernieuwbare bronnen uit te bouwen, wordt ervan uitgegaan dat de CO_2-intensiteit van de Duitse elektriciteit zal afnemen.

In dit onderdeel wordt bevonden dat het huidige Europese klimaatdoel voor de Duitse ijzer- en staalindustrie voor 2035, wanneer het wordt opgelegd als gelijk proportioneel doel, alleen zal worden bereikt middels een traject met een afnemende productie en geen vervanging van hoogovens. Het huidige Duitse klimaatdoel zal met geen enkel traject worden behaald. De dominantie van de Duitse primaire staalproductie in de totale ijzer- en staalindustrie wordt benadrukt. In dit onderdeel wordt eveneens aangetoond, dat huidige productieniveaus niet kunnen worden aangehouden door middel van een verhoging van de secundaire staalproductie, vanwege een te lage beschikbaarheid van schroot.

Een overgang van kool naar natuurgassen als brandstof (d.w.z. de vervanging van hoogovens door op natuurgassen gebaseerde directe reductie) draagt niet bij tot het behalen van de huidige klimaatdoelen. Het potentieel voor het terugdringen reductie van CO_2-emissies door op natuurgassen gebaseerde directe reductie is niet voldoende voor het behalen van de huidige klimaatdoelen.

Technologieën die momenteel worden onderzocht en ontwikkeld, zullen niet op tijd gereed zijn voor het behalen van de klimaatdoelen voor 2030. Een sterke verhoging van de generatie van hernieuwbare elektriciteit heeft in alle productietrajecten slechts een beperkte impact op de CO_2-uitstoot van de staalindustrie.

Algemene conclusies

Conclusie 1: het reduceren van CO_2-emissies door de Duitse ijzer- en staalindustrie volgens de huidige klimaatdoelen voor 2030 verloopt wanneer deze als gelijke proportionele doelen worden toegepast, niet volgens plan.

Het is zeer onwaarschijnlijk dat de Duitse ijzer- en staalindustrie de huidige Europese en Duitse klimaatdoelen voor 2030 bereikt – indien deze als gelijke proportionele doelen worden toegepast (tab. 6.9). Deze doelen kunnen alleen worden bereikt wanneer de primaire staalproductie sterk afneemt doordat hoogovens vanaf heden niet meer aan het einde van hun technische levensduur worden vervangen. In dat geval zou de primaire staalproductie in 2030 zijn afgenomen met de helft van de huidige primaire staalproductie en zou de secundaire staalproductie moeten stijgen, met name wanneer de technologie voor CO_2-afvang en -opslag niet zouden worden aangewend.

Bovendien zou de totale ruwstaalproductie moeten dalen tot onder het laagste productieniveau van de afgelopen vier decennia (afb. 6.10-c). Het huidige restpotentieel voor het verhogen van de energie-efficiëntie en het reduceren van CO_2-emissies is klein (hoofdstuk 3) en technologieën die zich in de onderzoeks- en ontwikkelingsfase bevinden, zullen niet op tijd gereed worden (hoofdstuk 5).

Conclusie 2: de Duitse ijzer- en staalindustrie heeft niet voldoende ondernomen voor een verhoging van de energie-efficiëntie en een reductie van CO_2-emissies.

De gerapporteerde vooruitgang in de ontwikkeling van de energie-intensiteit van de Duitse ijzer- en staalindustrie als geheel kan voornamelijk worden herleid tot een verschuiving in de productie naar de vervaardiging van secundair staal (afb. 2.12). Tussen 1991 en 2007 waren energie-intensiteitswaarden op procesniveau tamelijk constant (afb. 2.10) of vertoonden slechts lichte verbeteringen (afb. 2.6).

De afname in het specifieke energieverbruik sinds de jaren 1950 kan voornamelijk worden verklaard door de diffusie van drie technologieën (het staalproductietraject van de vlamboogovens, continugieterij en oxystaalovens) (hoofdstuk 3).

Ondernemingen waren uitsluitend bereid tot het investeren in energie-efficiënte technologieën wanneer deze investeringen binnen twee tot drie jaar konden worden terugverdiend (hoofdstuk 4), ook al kunnen terugverdientijden als een risico- in plaats van rentabiliteitsmaatstaf worden beschouwd. Bovendien investeren ondernemingen in productiefaciliteiten waarvan zij verwachten dat zij meerdere decennia operationeel zullen zijn, maar investeren voor dezelfde fabriek niet in een aanvullende energie-efficiënte technologie, wanneer de terugverdientijd niet overeenkomt met de nagestreefde twee tot drie jaar.

Conclusie 3: de Duitse ijzer- en staalindustrie heeft nagenoeg geen gevolgen ondervonden van de beleidsmaatregelen die zijn gericht op het verhogen van de energie-intensiteit en het reduceren van CO_2-emissies.

De vrijwillige overeenkomst tussen de Duitse industrie en de Duitse regering tot het beschermen van het klimaat was gedurende de gehele periode van de studie voor hoofdstuk 2 van kracht. De Duitse industrie had zich bereid verklaard, speciale inspanningen te bezigen om haar specifieke CO_2-emissies in 2012 in vergelijking tot 1990 met 22 % te reduceren. De resultaten uit hoofdstuk 2 onthullen tussen 1991 en 2007 geen uitzonderlijke acties van de Duitse ijzer- en staalindustrie voor het reduceren van het fossiele brandstofverbruik. In plaats daarvan lijkt het alsof het gestelde doel grotendeels – en autonoom – wordt bereikt door een verhoging van het aandeel van de secundaire staalproductie. Deze bevinding wordt ondersteund door bijv. Flues et al. (2015).

De effecten van de Europese regeling voor de handel in emissierechten worden opgevangen door het toewijzen van gratis emissierechten aan energie-intensieve industrieën die een wereldwijde concurrentiepositie bezitten, inclusief de ijzer- en staalindustrie (Europese Commissie, 2016c).

Ten slotte worden eigenaars van grote industriële installaties in §5/4 van de Duitse federale wet op de bestrijding van vervuiling (BImSchG) verzocht, deze op energie-efficiënte wijze te bedrijven. Deze wet werd in geen enkele richtlijn gespecificeerd en wordt doorgaans niet toegepast (hoofdstuk 4).

Conclusie 4: De vereniging van Europese staalbedrijven, inclusief de Duitse ijzer- en staalindustrie, stelt buiten de CO_2-afvang en -opslag geen trajecten voor koolstofarme ijzer- en staalproductie voor.

In haar stappenplan voor een lage koolstofuitstoot voor 2050 concentreert de Europese ijzer- en staalindustrie, vertegenwoordigd door Eurofer, zich op beleidsmaatregelen die haar huidige staalproductieprocessen ondersteunt. De temperende sleutelrol van staal voor het reduceren van CO_2-emissies in diverse sectoren, in het bijzonder de energie- en transportsector, wordt benadrukt.

Hoewel koolstofarme alternatieven voor kool, zoals elektriciteit en waterstof uit hernieuwbare bronnen worden besproken, vormt de CO_2-afvang en -opslag hierbij de enige technologie die zou kunnen leiden tot grote CO_2-reducties in de ijzer- en staalindustrie. Expliciete beleidsmaatregelen voor het transformeren van deze industrie in een koolstofarme worden niet voorgesteld (Eurofer, 2013).

Aanbevelingen voor toekomstig onderzoek

Dit onderdeel bevat een overzicht van trajecten voor het bereiken van koolstofarme energie-intensieve industrieën, gebaseerd op de resultaten uit hoofdstuk 1-6 en aanvullende literatuur.

Naast het sluiten van productiefaciliteiten van energie-intensieve industrieën, bestaan er slechts twee wijzen voor de drastische reductie van CO_2-emissies. De eerste bestaat uit het afvangen van CO_2-emissies van afgassen voordat deze de atmosfeer bereiken en het ondergronds opslaan van CO_2. Dit wordt CO_2-afvang en opslag ofwel CCS genoemd. CCS voorkomt niet de productie van antropogeen CO_2, maar voorkomt dat het bijdraagt aan het broeikasgaseffect, zolang het ondergronds blijft opgeslagen.

Daar de CO_2-concentratie in afgassen van industriële installaties doorgaans te laag is voor het afvangen van CO_2, dienen nieuwe processen te worden ontwikkeld om CCS hier toe te kunnen passen. Het ontwikkelen van nieuwe processen voor grootschalige industrieën is tijdsintensief. Doorgaans vergt het opschalen van laboratorium tot commerciële installatie, die meerdere tonnen per jaar produceert, decennia. Bovendien verloopt de diffusie van nieuwe grootschalige industriële installaties langzaam omdat grote industriële faciliteiten normaliter gedurende meerdere decennia worden bedreven, voordat zij worden vervangen.

Bij de discussies omtrent het Europese stappenplan voor een lage koolstofuitstoot in 2050, hebben op fossiele brandstoffen gebaseerde industrieën de rol van CCS als zijnde een duurzame en kostenefficiënte wijze voor het reduceren van broeikasgasemissies benadrukt (Europese Commissie, 2011). Uit nader onderzoek van de stappenplannen voor een lage koolstofuitstoot voor Europese energie-intensieve industrieën blijkt echter dat behoedzamer met het onderwerp CCS wordt omgegaan. De Europese cementindustrie benadrukt dat CCS alleen realistisch is indien de transportinfrastructuur en opslaglocaties voor CO_2 geschikt en goedgekeurd zijn – een probleem dat onopgelost blijft en buiten het verantwoordelijkheidsbereik van de cementindustrie valt. Zelfs wanneer de kosten voor CCS in de toekomst zouden afnemen, is de Europese cementindustrie van mening dat investerings- en operationele kosten aanzienlijk zullen blijven (Europese cementvereniging, Cembureau, 2013). De Europese chemische industrie ziet CCS alleen dan als een economisch levensvatbare optie, wanneer het wereldwijd in vele sectoren wordt geïntroduceerd (Europese raad van de chemische nijverheid, 2013). De Europese pulp- en papierindustrie heeft een voorkeur voor het ondersteunen van andere doorbraaktechnologieën dan CCS (Europese vereniging van papier- en pulpproducerende bedrijven, 2011).

Terwijl CCS zich op de koolstofintensieve output van industrieën richt, overweegt de tweede optie de vervanging van koolstofintensieve invoermaterialen door koolstofarme alternatieven. Koolstofintensieve invoermaterialen voor energie-intensieve industrieën bestaan doorgaans uit op fossiele brandstoffen gebaseerde energiebronnen, maar omvatten ook grondstoffen zoals kalksteen voor de productie van cement of staal. Het aanpassen van de industrie op koolstofarme grondstoffen vereist sector- of zelfs processpecifieke oplossingen.

Elektriciteit uit hernieuwbare bronnen zal de hoeksteen gaan vormen van koolstofarme economieën. Derhalve helpt het produceren van meer energie uit hernieuwbare bronnen, elektriciteitsafhankelijke processen in koolstofarme processen te transformeren. Elektrolyse vormt momenteel het dominante proces voor de primaire aluminiumproductie. Elektrolyse voor het vervaardigen van ijzer bevindt zich daarentegen in een vroegtijdige fase van onderzoek en wordt alleen in een volledig koolstofneutraal elektriciteitsscenario als veelbelovende technologie beschouwd (Eurofer, 2013). Bij de pulp- en papierproductie wordt ongeveer twee-derde van het totale CO_2-reductiepotentieel tot 2030 herleid tot het ontkolen van de energiesector (Europese vereniging van papier- en pulpproducerende bedrijven, 2011).

Het gebruik van biomassa, zonne- of geothermale warmte voor industriële processen is momenteel zeer beperkt (onderdeel 1.3.1). Er wordt meer aandacht geschonken aan de conversie van energie-overschotten uit hernieuwbare bronnen in andere producten, het zogenaamde power-to-X. Power-to-heat maakt de consumptie van warmte uit hernieuwbare bronnen mogelijk. Actuele apparaten worden ontworpen als hybriden, die nog steeds gebruik kunnen maken van fossiele brandstoffen wanneer er geen overschot aan hernieuwbare energie beschikbaar is. Andere manieren voor het gebruiken van overschotten aan hernieuwbare energie omvatten power-to-liquid of power-to-chemicals. De productie van waterstof uit hernieuwbare elektriciteit (power-to-gas) wordt in verschillende demonstratie-installaties getest (onderdeel 1.3.1). Waterstof vormt een veelbelovende koolstofarme optie voor de ijzer- en staalindustrie, die men nu in Zweden en Oostenrijk verkent (Eurofer, 2013; Neuberg, 2016). In tegenstelling tot andere industriële processen, vormt de waterstofgebaseerde ijzerproductie een commercieel beschikbaar proces.

Alle beschreven opties voor het drastisch reduceren van CO_2-emissies van energie-intensieve industrieën zijn op dit moment beperkt, ofwel ten gevolge van hun beschikbaarheid (bijv. biomassa) of wegens hun mate van ontwikkeling (bijv. power-to-X). Er dienen derhalve strategieën te worden uitgewerkt, die zich richten op het efficiënter gebruik maken van actueel beschikbare, koolstofhoudende grondstoffen.

De energie-efficiëntie kan in energie-intensieve sectoren nog steeds worden verbeterd (Europese cementvereniging, 2013; Europese Vereniging van papier- en pulpproducerende bedrijven, 2011; Eurofer, 2013; Europese raad van de chemische nijverheid, 2013). Er worden nieuwe concepten voor de terugwinning van warmte ontwikkeld. De warmteterugwinning van hoogovenslakken of hete plakken wordt in proefinstallaties onderzocht. Nieuwe processen zoals bandgiettechnologieën beloven het energieverbruik te reduceren doordat heropwarmingsprocessen worden overgeslagen. Een aantal energie-efficiënte technologieën hebben nog geen complete diffusie bereikt. Het droogblussen van cokes, bijvoorbeeld, wordt in Japan op grote schaal toegepast, maar in Europa niet gebruikt.

Interne energiestromen dienen wellicht opnieuw te worden vormgegeven. Wanneer het genereren van elektriciteit brandstofgebaseerd is, vormt de productie van elektriciteit uit koolstofintensieve afgassen in de staalindustrie een energie-efficiënte maatregel. Wordt de elektriciteit echter met hernieuwbare bronnen gegenereerd, dan kunnen de koolstofintensieve afgassen worden gebruikt als vervanging voor verdere brandstofinput, bijv. door middel van de productie van direct gereduceerd ijzer met behulp van cokesovengas, waardoor het verbruik van natuurgas of kool wordt vermeden.

Sectoroverschrijdende samenwerkingen op het gebied van energie bieden een tot dusver grotendeels onaangeroerd energie-efficiëntiepotentieel. Energierijke afgassen uit de ene industriële sector kunnen in een andere worden gebruikt als gebruiksmaterialen. Water stof- en koolmonoxiderijke afgassen uit de staalindustrie kunnen bijvoorbeeld in de chemische industrie worden gebruikt.

CO_2-afvang en opslag zorgen ook voor een verbinding tussen sectoren. Afgevangen CO_2 kan worden gebruikt in andere industrieën, bijvoorbeeld voor de productie van algen als biomassa, die als brandstof kan worden gebruikt (Europese cementvereniging, 2013).

Recycling van energie-intensieve producten zorgt voor een sterke afname van het energieverbruik in geselecteerde sectoren, inclusief de ijzer- en staalindustrie (Eurofer, 2013). Recycling in deze sector blijft echter beperkt vanwege de kwaliteit en beschikbaarheid van schroot. Primaire productie wordt alleen dan minder belangrijk wanneer er voldoende primaire materialen zijn geproduceerd, die kunnen worden hergebruikt met een kwaliteit die soortgelijk is aan die van primaire producten. Andere energie-intensieve sectoren leggen ook de nadruk op het belang van recycling (Europese raad van chemische bedrijven, 2013; Europese cementvereniging, 2013; Europese vereniging van papier- en pulpproducerende bedrijven, 2011).

Materiaalefficiëntie reduceert het afval van productieprocessen of biedt een soortgelijk voordeel met minder materiaal, bijv. lichtgewicht staalkwaliteiten die het gewicht van auto's reduceren, of sterk beton dat wordt gebruikt voor de constructie van specifieke gebouwen (Eurofer, 2013; Europese cementvereniging, 2013).

Ten slotte kunnen koolstofarme producten koolstofintensieve, zoals cement, staal of aluminium vervangen. Producten uit de houtvezelindustrie kunnen koolstofintensieve producten vervangen, bijv. in de bouw- en verpakkingssector, als brandstoffen of chemicaliën (Europese vereniging van papier- en pulpproducerendebedrijven, 2011). Het bepalen van dit potentieel vereist levenscyclusanalyses en het identificeren en ontwikkelen van geschikte alternatieven voor koolstofintensieve producten.

Beleidsaanbevelingen

Het voorafgaande onderdeel gaf een overzicht van veelbelovende gebieden van onderzoek met betrekking tot het transformeren van energie-intensieve- in koolstofarme industrieën. In dit onderdeel worden verdere stappen voor een koolstofarme industrie voorgesteld, die dienen te worden ondersteund door beleidsmaatregelen.

Industrie- en processpecifieke CO_2-reductiepotentiëlen dienen in detail te worden geëvalueerd. Het evalueren van ontwikkelingen op het gebied van energie- en CO_2-intensiteit in het verleden bieden een inzicht in hoeveel werd bereikt en of het waarschijnlijk is dat trends zich op autonome wijze voortzetten. Het identificeren van factoren die van invloed zijn op de verbetering van de energie-efficiëntie en CO_2-reducties dragen bij tot het begrijpen van de reden waarom ondernemingen voorzichtig kunnen zijn als het gaat om verdere CO_2-reducties.

Gebaseerd op de specifieke bevindingen, dient een systeembenadering de industrie- en sectoroverschrijdende benaderingen voor het reduceren van CO_2 te identificeren.

Financiering vormt een centraal onderwerp voor het ontwikkelen en inzetten van grootschalige industriële installaties, daar deze kapitaalintensief zijn en vaak risico's herbergen. Men dient te bepalen in hoeverre ondernemingen financiële ondersteuning kunnen verkrijgen, terwijl zij aan de wetgeving op het gebied van staatssteun blijven voldoen.

De huidige beleidsmaatregelen die zich richten op het verhogen van de energie-efficiëntie en het reduceren van CO_2-emissies lijken niet bijzonder effectief te zijn geweest. Zij dienen te worden verbeterd, of er dienen nieuwe beleidsmaatregelen te worden geïntroduceerd.

De Europese regeling voor de handel in emissierechten wordt beschouwd als een belangrijke beleidsmaatregel voor een koolstofarme economie. Zij kan een grotere invloed op energie-efficiëntieverbeteringen en CO_2-reducties hebben wanneer de prijs voor CO_2 stijgt, bijv. door middel van het uitstellen van steun en/of het terugdringen van gratis rechten. De voorgestelde versterking van de reductie van gratis rechten na 2020 zal waarschijnlijk voor aanvullende druk op energie-intensieve industrieën zorgen. Indien er wereldwijd geen prijs voor de uitstoot van CO_2 wordt bepaald, dient te worden gewaarborgd dat ondernemingen in een globale concurrentiepositie worden beschermd tegen de ernstige gevolgen van koolstoflekkage. De opbrengsten uit de verkoop van CO_2-rechten dienen te worden verhoogd en omgeleid naar onderzoek, ontwikkeling en demonstratie van koolstofarme industriële processen en van een vergelijkbaar niveau te zijn als die voor NER-300- en NER-400-reserves.

Voor de Duitse industrie bestaat er reeds een wet waarin exploitanten van grootschalige industriële installaties wordt opgedragen, deze op energie-efficiënte wijze te bedrijven (§5/4 van de Duitse federale wet op de bestrijding van vervuiling, hoofdstuk 4). Deze wet is echter nog niet middels richtlijnen in detail uitgewerkt en wordt doorgaans niet toegepast. Men zou moeten evalueren of en op welke wijze deze wet kan worden opgelegd.

Waterstof lijkt in ieder geval voor de ijzerproductie een veelbelovende koolstofarme optie te vormen. De vervaardiging van ijzer op basis van waterstof vormt een commercieel beschikbare technologie. Waterstoftoevoer op basis van hernieuwbare energiebronnen dient te worden onderzocht.

Zusammenfassung

Einführung

Die Senkung der industriellen CO_2-Emissionen, insbesondere die der Stahlindustrie, ist bei der Eindämmung der Auswirkungen des Klimawandels von zentraler Bedeutung. Die Stahlindustrie hat ihre Energieintensität in der Zeit von den 1950er- bis in die 1990er-Jahre deutlich reduziert. Dennoch ist sie für etwa 6,5 % der weltweiten anthropogenen CO_2-Emissionen verantwortlich (Basson, 2012). Gerade weil die derzeitigen Reduktionspotenziale begrenzt sind, ist es notwendig, weitere Anstrengungen zu unternehmen, um diese Industrie in eine CO_2-arme Industrie zu verwandeln.

Die Stahlindustrie ist im besonderen Maße von fossilen Energieträgern abhängig, da sie diese nicht nur zur Erzeugung von Wärme, sondern auch als chemisches Reduktionsmittel nutzt. Ihr Hauptenergieträger Kohle kann somit nicht durch eine beliebige Wärmequelle ersetzt werden. Daher erfordert die Substitution von Kohle in der Stahlindustrie neue technologische Konzepte.

Die Abscheidung und unterirdische Speicherung von CO_2 (Carbon Capture and Storage, CCS) wird als eine Möglichkeit angesehen, die CO_2-Emissionen in der Eisen- und Stahlindustrie zu senken (e.g. International Energy Agency, 2009). Das europäische Ulcos-Projekt hat eine Verringerung des durch die Stahlindustrie verursachten CO_2-Ausstoßes in die Atmosphäre um 50 % zum Ziel (Ulcos, 2016). Allerdings wird der Durchbruch von CCS durch Akzeptanzprobleme sowie Verzögerungen bei der Entwicklung der entsprechenden Technologien erschwert. Die Verringerung von CO_2 in der Atmosphäre mithilfe von CCS bleibt also vorerst ein Zukunftsszenario. Bis dahin ist Energieeffizienz die zentrale Maßnahme, um CO_2-Emissionen auf ein Minimum zu senken.

Für Unternehmen ist eine verbesserte Energieeffizienz generell von Interesse, da sie damit Kosten einsparen können. Die Energieeffizienz von Unternehmen verbessert sich also typischerweise von Jahr zu Jahr. Dennoch variiert die Energieintensität, die als Indikator für Energieeffizienz gilt, zwischen einzelnen Ländern und Unternehmen. Es gibt also Faktoren, die Energieeffizienzverbesserungen fördern oder hemmen können. Nur ein grundlegendes Verständnis der Energieverbrauchsentwicklung in der Eisen- und Stahlindustrie ermöglicht es, politische Maßnahmen zu konzipieren, die diese Industrie in eine kohlenstoffarme Industrie überführen.

Diese Arbeit legt eine grundlegende Analyse der Eisen- und Stahlindustrie in Deutschland vor. Sie soll sowohl bezüglich der bisher erreichten Einsparungen als auch im Hinblick auf zukünftige Reduktionsmöglichkeiten im Zeitraum bis zum Jahr 2035 ein Beispiel für typische Stahlindustrien in westlichen Ländern sein.

Die Vorgehensweise beinhaltet:

a. das Verständnis und die Beurteilung bisher erreichter Verbesserungen der Energieintensität, und

b. die Bewertung zukünftiger Möglichkeiten zur Senkung der CO_2-Emissionen.

Daraus ergibt sich für diese Arbeit folgende Forschungsfrage:

Wie kann der technologische Wandel in der Eisen- und Stahlindustrie in Deutschland dazu beitragen, die Energieeffizienz zu verbessern und die CO_2-Emissionen zu senken?

Davon leiten sich fünf Unterfragen ab:

1. Wie hat sich die Energieintensität in der deutschen Eisen- und Stahlindustrie im Zeitraum zwischen 1991 und 2007 auf Prozessebene entwickelt? Welchen Einfluss hatte diese Entwicklung auf die Energieintensität in der deutschen Eisen- und Stahlindustrie als Ganzes?

2. Wie hoch sind die Diffusionsraten wesentlicher Energieeffizienztechnologien in der Eisen- und Stahlindustrie in Deutschland? Wie haben sie die Energieintensität der gesamten Eisen- und Stahlindustrie in Deutschland beeinflusst? Welches restliche Effizienzpotenzial bieten sie noch?

3. Was sind fördernde und hemmende Faktoren für die Implementierung wesentlicher Energieeffizienztechnologien in der Eisen- und Stahlindustrie in Deutschland?

4. Welche vielversprechenden CO_2-armen Technologien zur Eisenerzeugung befinden sich in Forschung und Entwicklung oder im frühen Stadium der Kommerzialisierung?

5. In welchem Maße ist die Beeinflussung des Energieverbrauchs und der CO_2-Emissionen in der deutschen Eisen- und Stahlindustrie durch den technologischen Wandel bis zum Jahr 2035 zu erwarten, wenn man die Ergebnisse der Kapitel 2 bis 5 dieser Arbeit berücksichtigt?

Kapitel 2 analysiert die Entwicklungen der Energieintensität auf Prozessebene in der deutschen Eisen- und Stahlindustrie von 1991 bis 2007, dabei wird der Einfluss des steigenden Anteils von Sekundärstahl an der gesamten Stahlproduktion auf die Energieintensität der Stahlindustrie untersucht. In Kapitel 3 werden die Diffusionsraten wesentlicher Energieeffizienztechnologien seit ihrer Einführung bestimmt. Darüber hinaus wird eine Einschätzung ihres Einflusses auf die Veränderung der Energieintensität in der Stahlindustrie sowie ihres verbleibenden Effizienzpotenzials vorgenommen. Kapitel 4 beschreibt die jüngsten Entwicklungen der Energieintensität in der deutschen Eisen- und Stahlindustrie und bestimmt den Einfluss der Energiepreise auf diese Entwicklungen. Die Diffusion von Effizienztechnologien wird sowohl auf nationaler als auch auf Standortebene erfasst. Fördernde und hemmende Faktoren für die Diffusion von Effizienztechnologien werden anhand ausgewählter Fälle untersucht. Kapitel 5 gibt einen Überblick über alternative Eisenherstellungsverfahren und bewertet diese mithilfe verschiedener Kriterien. Am Ende der Dissertation wird ein Modell aufgezeigt. Es skizziert Technologiepfade, mithilfe derer eine drastische Senkung der Emissionen möglich ist (Kapitel 6).

Wie hat sich die Energieintensität in der Eisen- und Stahlindustrie Deutschlands im Zeitraum zwischen 1991 und 2007 auf Prozessebene entwickelt? Welchen Einfluss hatte diese Entwicklung auf die Energieintensität in der deutschen Eisen- und Stahlindustrie als Ganzes?

Die Analyse vergangener Entwicklungen bei der Energieintensität gibt Aufschluss darüber, in welchem Maße etwas erreicht wurde und wie wahrscheinlich diese Entwicklungen in der Zukunft bestehen bleiben werden. Die Untersuchung der Energieintensität auf Prozessebene gibt Aufschluss darüber, ob Effizienzpotenziale gleichmäßig über die Prozesse verteilt sind.

Frühere Arbeiten untersuchten Energieintensitätsentwicklungen in der Regel für die Stahlindustrie als Ganzes (z.B. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, 2010). Diese Forschungsfrage zielt darauf ab, Energieintensitäten auf Prozessebene zu analysieren. Der Einfluss des steigenden Anteils an Recyclingstahl auf die Energieintensität der Stahlindustrie als Ganzes wird bestimmt und mit den Verbesserungen durch Energieeffizienzmaßnahmen verglichen.

Die Eisen- und Stahlstatistik von 1991 bis 2007 des Statistischen Bundesamtes wurde ausgewertet (Statistisches Bundesamt, 1991-2007). Durch diese Daten erhält man Angaben über den jährlichen Verbrauch verschiedener Energieträger auf Prozessebene. Den Prozessen werden Produktionsmengen zugewiesen (Wirtschaftsvereinigung Stahl and Stahlinstitut VDEh, 1991-2007). Der Energieverbrauch ist in physikalischen Einheiten angegeben, die mittels unterer Heizwerte in Energieeinheiten umgerechnet werden. Die so erhaltenen Energieintensitäten pro Prozess im Zeitraum von 1991 bis 2007 werden graphisch dargestellt. Der Einfluss des steigenden Anteils an Recyclingstahl auf die Energieintensität der Eisen- und Stahlindustrie als Ganzes wird ebenfalls als Graphik angezeigt.

Die Energieintensität auf Prozessebene hat sich im Zeitraum von 1991 bis 2007 nicht wesentlich verbessert. Nur Walzprozesse stellten eine Ausnahme dar. Die Verbesserung der Energieintensität der gesamten Eisen- und Stahlindustrie ist zum großen Teil auf die Erhöhung der Sekundärstahlproduktion zurückzuführen. Zwischen 1991 und 2007 hat sich der spezifische Energieverbrauch je Tonne Rohstahl um 0,3 % pro Jahr verbessert. Zwei Drittel davon sind auf die Erhöhung der Sekundärstahlproduktion zurückzuführen, Effizienzmaßnahmen trugen dagegen zu einer jährlichen Verbesserung der Energieintensität um nur 0,1 % bei.

Der spezifische Energieeinsatz in die Hochöfen stieg ab dem Jahr 2000. Der Bruttoenergieverbrauch der Hochöfen hingegen sank durch eine erhöhte Nutzung von Kuppelgasen von 12,5 GJ pro Tonne Roheisen im Jahr 1991 auf 12,0 GJ/t 2007. Dies entspricht einer jährlichen Verbesserung um 0,2 %.

In Sinteranlagen stieg der durchschnittliche Energieverbrauch in den Jahren von 1991 bis 1998 an, dasselbe gilt für den Zeitraum von 2002 bis 2006. Der höchste Energieverbrauchswert wurde 1998 mit 2,28 GJ/t Sinter erzielt, er lag damit also 0,26 GJ/t oder 12% über dem Wert von 1991.

Die Energieintensität in Elektro-Lichtbogenöfen änderte sich über den betrachteten Zeitraum hinweg kaum. Im Vergleich zu 1994 variierte die Energieintensität zwischen +2 % (z.B. 1996, 2004 und 2007) und -2 % (1998). Auf Basis der Analysen konnten keine wesentlichen Verbesserungen in Elektro-Lichtbogenöfen erkannt werden.

Walzprozesse stellten die einzige Prozessgruppe dar, bei der die Entwicklungen der Energieintensität deutliche Verbesserungen zeigten. Pro Jahr reduzierte sich der spezifische Energieverbrauch kontinuierlich um etwa 1,4 %. Allerdings können nicht nur Verbesserungen der Energieeffizienz, sondern auch andere Faktoren der Grund für diese Entwicklung sein. So sank beispielsweise der Anteil von kaltgewalztem Stahl gegenüber warmgewalzten Stahl von 35,0 % (1994) auf 31,4 % (2007).

Aufgrund des technischen Fortschritts, der Diffusion von Effizienztechnologien, des Abschaltens veralteter Anlagen und vermehrten Energiemanagements steigt die Energieeffizienz in der Regel kontinuierlich. Allerdings blieben die Verbesserungen in der

Energieintensität in der deutschen Eisen- und Stahlindustrie zwischen 1991 und 2007 weit hinter den Erwartungen zurück. Der Zeitraum der Untersuchungen umfasst fast zwei Jahrzehnte, die aufgrund der Ergebnisse als eine Periode charakterisiert werden kann, innerhalb derer kaum Verbesserungen stattfanden.

Die Analyse beschränkt sich auf die Entwicklungen des spezifischen Energieverbrauchs. Daher können im Rahmen dieser Arbeit keine Aussagen über weitere Faktoren getroffen werden. Im Verlauf der Untersuchungen haben sowohl Verbände als auch Unternehmen bekräftigt, dass sie ihre Prozesse sehr wohl verbessert hätten. Allerdings würden andere Faktoren, wie zum Beispiel eine sinkende Rohstoffqualität dem entgegenlaufen.

Wie hoch sind die Diffusionsraten wesentlicher Energieeffizienztechnologien in der deutschen Eisen- und Stahlindustrie? Auf welche Weise haben sie die Energieintensität der gesamten Eisen- und Stahlindustrie in Deutschland beeinflusst? Was bieten sie an verbleibendem Effizienzpotenzial?

Frühere Studien konzentrierten sich auf die Erklärung des Diffusionsprozesses (z.B. Oster, 1982; Poznanski, 1983). Die vorliegende Arbeit leitet Diffusionsraten von wesentlichen Effizienztechnologien her und bestimmt ihren Einfluss auf Energieeffizienzentwicklungen in der deutschen Eisen- und Stahlindustrie.

Die Diffusion von sechs Energieeffizienztechnologien in der deutschen Eisen- und Stahlindustrie wird anhand nationaler und auf Standortebene erhobener Daten über einen Zeitraum von 60 Jahren hinweg analysiert. Der Einfluss der Technologien auf die Entwicklung der Energieintensität der Eisen- und Stahlindustrie als Ganzes wird aufgezeigt. Auf der Grundlage der hergeleiteten Diffusionsraten wird das verbleibende Effizienzpotenzial bestimmt.

Effizienztechnologien, die in den 1950er- und 1960er-Jahren eingeführt wurden (LD-Konverter, Stranggießen), verbreiteten sich zu Beginn zwar langsamer als Technologien, die um 1980 auf den Markt kamen (Gichtgasentspannungsturbine, Kohlenstaubeinblasen, Konvertergasrückgewinnung, Kokstrockenkühlung), dafür erreichten sie schneller die Marktsättigung. Keine der letztgenannten Technologien hatte 20 bis 25 Jahre nach ihrer Einführung eine Diffusion von über 70 %. Die Kokstrockenkühlung wird in Deutschland sogar nicht mehr angewendet.

Der technologische Wandel beeinflusst die Energieintensität in der Eisen- und Stahlindustrie. Um den Einfluss zu quantifizieren, wurde zusätzlich zu den sechs Effizienztechnologien auch die Sekundärstahlerzeugung betrachtet. Diese hatte mit einer Reduktion des spezifischen Energieverbrauchs von 21 % in den Jahren zwischen 1958 und 2012 den weitaus größten Einfluss auf die Energieintensität in der Eisen- und Stahlindustrie. Die Effizienztechnologien, die in den 1950er- und 1960er-Jahren eingeführt wurden, also LD-Konverter und Stranggießen, trugen mit 12 % und 6 % ebenfalls wesentlich zu einer verringerten Energieintensität bei. Die vier Technologien, die um 1980 in den Markt kamen, trugen mit lediglich 4 % dazu bei.

Die betrachteten Technologien, inklusive der Sekundärstahlerzeugung, reduzierten den Energieverbrauch je Tonne Rohstahl in den Jahren von 1958 bis 2012 laut der durchgeführten Analysen um 43 %. Aichinger und Steffen (2006) berichten für den Zeitraum von 1959 bis 2004 von einer 40 %-igen Reduktion des spezifischen Energieverbrauchs je Tonne Rohstahl in der deutschen Eisen- und Stahlindustrie. Es liegt somit die Vermutung nahe, dass die untersuchten Effizienztechnologien und die Einführung der Sekundärstahlerzeugung die wesentlichen Faktoren sind, die zu einer verbesserten Energieeffizienz beigetragen haben.

Das verbleibende Energieeffizienzpotenzial der vier Technologien, die den Markt noch nicht vollständig durchdrungen haben, wurde untersucht. Da die Kokstrockenkühlung derzeit nicht angewendet wird, birgt sie mit einer Verringerung von 2 % des spezifischen Primärenergieverbrauchs das größte Potenzial der untersuchten Technologien. Die Konvertergasrückgewinnung und das Kohlenstaubeinblasen bieten weitere Potenziale von 1,4 % und 1,0 % (Stand 2012). Der Einfluss der weiteren Verbreitung von Gichtgasentspannungsturbinen liegt bei geringen 0,1 %.

Die Energieeffizienzentwicklung der deutschen Eisen- und Stahlindustrie in den vergangen fünf Jahrzehnten scheint im Wesentlichen durch die Diffusion von nur drei Technologien getrieben worden zu sein, und zwar durch die der Sekundärstahlerzeugung, des LD-Konverters und der Stranggießverfahren. Das verbleibende Potenzial liegt bei 4,5 %, einschließlich der Kokstrockenkühlung.

Was sind fördernde und hemmende Faktoren für die Implementierung von wesentlichen Energieeffizienztechnologien in der deutschen Eisen- und Stahlindustrie?

Kapitel 4 erläutert sowohl die in Kapitel 2 festgestellten Entwicklungen der Energieintensität der Eisen- und Stahlindustrie zwischen 1991 und 2007 als auch die in Kapitel 3 behandelten Diffusionsraten.

Arbeiten zu den fördernden und hemmenden Faktoren für die Diffusion von Effizienztechnologien in der europäischen oder deutschen Eisen- und Stahlindustrie gründen in der Regel auf Betrachtungen zur Wirtschaftlichkeit (z.B. Moya und Pardo, 2013;

Brunke und Blesl, 2014). Fördernde und hemmende Faktoren für die Diffusion von Energieeffizienztechnologien in der Eisen- und Stahlindustrie wurden für ausgewählte Länder untersucht (z.B. Brunke et al., 2014).

Kapitel 4 analysiert die Diffusion wesentlicher Energieeffizienztechnologien für die Eisen- und Stahlindustrie in Deutschland. Es ermittelt auf der Basis historischer Energiepreise Amortisationszeiten und untersucht fördernde und hemmende Faktoren auf Anlagenebene für diese Technologien, u. a. mittels Interviews. Es konnten Antworten auf die Frage gefunden werden, warum Energieeffizienztechnologien an bestimmten Anlagen installiert wurden, während andere Anlagen noch immer nicht mit diesen Technologien ausgestattet sind.

Der Ansatz verknüpft verschiedene Methoden miteinander (Mixed-Methods-Ansatz). Zunächst wurden Referenzlisten von Anlagenbauern über die untersuchten Technologien zusammengestellt und ausgewertet. Die untersuchten Technologien sind die Konvertergasrückgewinnung, Gichtgasentspannungsturbinen und Kohlenstaubeinblasen. Im nächsten Schritt wurde ein Zeitstrahl für die untersuchten Standorte und deren Anlagen (Hochöfen und LD-Konverter) erstellt. Dabei wurden nur Anlagen und Standorte berücksichtigt, die derzeit noch in Betrieb sind. Drittens wurde die durchschnittliche Anzahl der Jahre berechnetet, die vergehen, bevor ein Standort eine neu auf dem Markt verfügbare Effizienztechnologie implementiert. Im vierten Schritt wurde die Entwicklung von historischen Energiepreisen für die deutsche Industrie hergeleitet, dabei wurden politisch induzierte Preiskomponenten ebenfalls berücksichtigt. Es wurden mit Hilfe von angenommenen Referenzanlagen energiepreisabhängige Amortisationszeiten berechnet und dargestellt. Es wurde verdeutlicht, in welchem Jahr bzw. bei welcher Amortisationszeit eine Energieeffizienztechnologie an einer Anlage installiert wurde. Zehn Fälle wurden im Rahmen einer Fallstudie ausgewählt, um fördernde und hemmende Faktoren für die Diffusion von Effizienztechnologien zu identifizieren. Dazu wurden auch eine Literaturrecherche und Experteninterviews durchgeführt, Letztere wurden qualitativ ausgewertet.

In der Zeit von 1993 bis 2004, also über eine Zeitspanne von 12 Jahren hinweg, wurde keine der betrachteten Technologien an einer Anlage in Deutschland installiert. Gichtgasentspannungsturbinen wurden im Zeitraum von 1982 bis 1993 eingebaut und nochmals ab 2012, d.h. nach einem Zeitraum von 20 Jahren. Kohlenstaubeinblasen hatte zwischen 1985 und 1993 sowie in den Jahren 2004, 2008 und 2014 eine starke Verbreitung. Die Konvertergasrückgewinnung wurde von 1981 und 1987 an verschiedenen Anlagen eingebaut und darüber hinaus noch ein Mal im Jahr 2009.

Die einzelnen Standorte oder Unternehmen zeigen gegenüber der Aufnahme von neuen Technologien unterschiedliches Verhalten. Im Durchschnitt verstrichen zwischen 1,6 und über 34 Jahre, bevor ein Standort eine neu auf den Markt gekommene Technologie implementierte. Daraus wird geschlossen, dass es sowohl fördernde und hemmende Faktoren auf nationaler Ebene (z.B. Energiepreise, Gesetze) als auch standortspezifische Faktoren gibt, die die Diffusion von Energieeffizienztechnologien beeinflussen.

Von Mitte der 1980er-Jahre bis zum Jahr 2000 waren die Energiepreise verhältnismäßig niedrig. Für die untersuchten Energieeffizienztechnologien wurden die Amortisationszeiten in Abhängigkeit von den Energiepreise ab der Einführung der Technologie bis 2014 ermittelt. Es zeigte sich, dass Unternehmen nur in eine Energieeffizienztechnologie investieren, wenn die Amortisationszeit einen gewissen Zeitraum nicht überschreitet; anhand der durchgeführten Analysen liegt die tolerierte Amortisationszeit bei höchstens drei Jahren.

Die Wirtschaftlichkeit von Energieeffizienztechnologien kann somit erklären, warum Unternehmen in diese Technologien investieren. Allerdings investieren manche Unternehmen auch in Phasen mit geringen Amortisationszeiten nicht in diese Technologien.

Die Analyse der Umstände, unter denen Unternehmen Energieeffizienztechnologien aufnehmen, lässt darauf schließen, dass standortspezifische Beschränkungen (z.B. das Fehlen von Produktionsschritten, wie dem Walzen oder der Roheisenerzeugung) und der mangelnde Zugang zu Kapital die zwei größten Hemmnisse sind; diese haben auch Einfluss auf die Wirtschaftlichkeit der Technologien.

Die Einführung der Erneuerbaren-Energien-Umlage scheint die Implementierung von Gichtgasentspannungsturbinen ab 2012 gefördert zu haben, da integrierte Hüttenwerke in der Regel nicht durch die Besondere Ausgleichsregelung entlastet wurden.

Möglicherweise hat die Einflussnahme vonseiten der Behörden dazu geführt, dass eine Gichtgasentspannungsturbine installiert wurde.

Was sind vielversprechende CO_2-arme Technologien der Eisenerzeugung, die sich in der Forschung und Entwicklung oder im frühen Stadium der Kommerzialisierung befinden?

Dieser Abschnitt gibt einen aktualisierten Überblick über neue Energieeffizienztechnologien und CO_2-arme Eisenherstellungsverfahren. Frühere Studien sind z.B. Martin et al. (2000) oder de Beer et al. (1998). Andere Veröffentlichungen geben einen Überblick über Energieeffizienztechnologien (z.B. Moya und Pardo, 2013; Brunke und Blesl, 2014).

Es wurden zwölf alternative Eisenherstellungstechnologien im Forschungs- und Entwicklungsphase oder im frühen Stadium der Kommerzialisierung untersucht. Die Informationen wurden aus öffentlich zugänglichen Quellen gewonnen und im Anschluss ausgewertet. Das Kapitel gibt einen Überblick über die Technologien und Prozesse, über deren CO_2-Reduktionspotenzial und über den Entwicklungsstand. Die wesentlichen Technologien sind erfasst, aber die Liste erhebt keinen Anspruch auf Vollständigkeit.

Wie die derzeitige Primärstahlerzeugung auch, beruhen acht der zwölf untersuchten Technologien auf dem Einsatz von Kohle als Hauptenergieträger. Im Vergleich zum derzeitigen Hochofen verzichten diese Technologien auf Koks, Sinter und/oder Pellets. Dennoch bleibt Kohle der wesentliche Energielieferant für die Eisenerzeugung. Damit bleibt das CO_2-Reduktionspotenzial auf etwa 20 % im Vergleich zu der Eisen- und Stahlerzeugung über die Hochofenroute begrenzt. Drei dieser Technologien sind kommerziell verfügbar, zeigen aber nur eine geringe Verbreitung (Corex, Finex, kohlebasiertes HYL).

Vier Technologien nutzen alternative Energiequellen. Die Nutzung von Biomasse stellt eine Alternative zur Eisen- und Stahlherstellung auf Kohlebasis dar, besonders in Ländern mit großen Ressourcen an Biomasse (z.B. Skandinavien und Brasilien); aber auch in Mitteleuropa und in den USA beschäftigen sich Forschung und Entwicklung aktiv mit diesem Thema. In Brasilien wird Biomasse bereits kommerziell in der Eisen- und Stahlherstellung eingesetzt (IBA Brazilian Tree Industry, 2016). Die Nutzung von Biomasse als Energieträger bleibt jedoch im Allgemeinen aufgrund der Verfügbarkeit und teilweise auch aus Qualitätsgründen begrenzt.

Strom aus erneuerbaren Energien könnte Kohle in der Eisen- und Stahlindustrie ersetzen und somit die CO_2-Emissionen drastisch senken. Die Elektrolyse von Eisenerz ist demnach eine vielversprechende Option für eine kohlenstoffarme Eisen- und Stahlindustrie. Allerdings befindet sich diese Technologie noch im sehr frühen Entwicklungsstadium, und ihr Markteintritt wird nicht vor 2040 erwartet.

Mit dem Schwebeschmelzverfahren könnte Wasserstoff bei der Eisenerzreduktion als Reduktionsmittel fungieren und Kohle ersetzen. Wie auch die Elektrolyse von Eisenerz befindet sich dieses Verfahren noch in einem frühen Entwicklungsstadium.

Derzeit wird Wasserstoff als kohlenstoffarmer Energieträger für industrielle Anwendungen erforscht, zum Beispiel im Energiepark Mainz (Energiepark Mainz, 2016). Wenn Wasserstoff für großindustrielle Anwendungen zur Verfügung stünde, dann wäre die Eisenerzeugung mit Wasserstoff eine Option, um CO_2-arm Eisen und Stahl zu erzeugen. Circored ist beispielsweise eine Direktreduktion für Eisenerz auf der Basis von Wasserstoff, die in Trinidad in den 1990er Jahren mit einer Kapazität von 500.000 Tonnen in Betrieb war.

Wie beeinflusst technologischer Wandel den Energieverbrauch und die CO_2-Emissionen der Eisen- und Stahlindustrie in Deutschland bis 2035, wenn man die Ergebnisse aus Kapitel 2 bis 5 berücksichtigt?

Frühere Studien zur Beurteilung des zukünftigen Energieverbrauchs und der CO_2-Emissionen in der Eisen- und Stahlindustrie betrachteten entweder einen längeren Zeitraum (Fischedick et al., 2014) oder nahmen konstante Produktion an (Brunke und Blesl, 2014). Andere Studien untersuchten weitere Länder (e.g. Kuramochi, 2015).

Unter Beachtung verschiedener Produktions- und Prozesspfade unternimmt Kapitel 6 eine Einschätzung des zukünftigen Energieverbrauchs und der CO_2-Emissionen der deutschen Eisen- und Stahlindustrie bis 2035. Zudem fließen die Ergebnisse aus den Kapiteln 2 bis 5 in die Analyse ein.

Vier Produktionspfade, die mögliche Entwicklungen bis zum Jahr 2035 darstellen, werden skizziert. Gleichzeitig wird die Frage untersucht, in welchem Maße die einzelnen Pfade die derzeitig gesetzten Klimaziele für 2030 erreichen können, wenn diese Ziele gleichmäßig auf alle Sektoren herunter gebrochen werden. Der Skizzierung der Produktionspfade liegt die Annahme zugrunde, dass derzeitige Hochöfen nicht vor Ende ihrer technischen Lebensdauer von geschätzten 50 Jahren außer Betrieb genommen werden. Die Produktionsmenge von Sekundärstahl wird durch die Verfügbarkeit von Schrott begrenzt; diese wiederum ergibt sich aus einem Schätzwert. Der spezifische Energieverbrauch bei der Primär- und Sekundärstahlerzeugung nimmt mit einer angenommenen Diffusionsrate für ausgewählte Energieeffizienztechnologien ab. Weiterhin werden sowohl die Direktreduktion auf Erdgasbasis als auch das Schmelzreduktionsverfahren Hisarna als alternative Stahlherstellungsverfahren berücksichtigt. Es wird angenommen, dass Hisarna ab 2030 kommerziell verfügbar sein wird. Die CO_2-Emissionen der Eisen- und Stahlindustrie werden under anderem von der CO_2-Intensität des deutschen Strommixes mitbestimmt. Da die deutsche Regierung plant, den Anteil erneuerbarer Energien an der Stromproduktion langfristig zu erhöhen, wird eine abnehmende CO_2-Intensität des Strommixes angenommen.

Nach den Ergebnissen von Kapitel 6 kann die Eisen- und Stahlindustrie in Deutschland das derzeitig gesetzte Europäische Klimaschutzziel für 2030 – sofern es auf alle Sektoren gleich verteilt wird – nur erreichen, wenn die Produktion von Eisen und Stahl insgesamt deutlich sinkt und die energieintensiven Hochöfen auslaufen. Das derzeitig geltende deutsche Klimaschutzziel für 2030 – ebenfalls gleichmäßig auf alle Sektoren verteilt – wird von keinem der entwickelten Produktionspfade erreicht. Die Ergebnisse verdeutlichen, dass die CO_2-Emissionen der Eisen- und Stahlindustrie in ganz besonderem Maße von den Emissionen der Hochöfen getrieben werden. Es wird auch deutlich, dass das derzeitige Produktionsniveau nur mit der Produktion durch die Hochöfen gehalten werden kann. Die Verfügbarkeit von Schrott reicht derzeit nämlich nicht aus, um die Hochofenroute zu ersetzen.

Die Substitution von Kohle durch Erdgas – also eine Substitution der Hochöfen durch Direktreduktionsanlagen auf Erdgasbasis – ist ebenfalls nicht ausreichend, um die derzeitigen Klimaschutzziele zu errreichen. Das CO_2-Einsparungspotenzial von Erdgas gegenüber Kohle ist dafür nicht ausreicend.

Es zeigt sich auch, dass CO_2-ärmere Stahlherstellungsverfahren, die sich derzeit in der Entwicklungsphase befinden, nicht rechtzeitig zur Verfügung stehen, um die CO_2-Emissionen der Eisen- und Stahlindustrie derart zu senken, dass die derzeitigen Klimaschutzziele erreicht werden können.

Eine starke Erhöhung des Anteils erneuerbarer Energien am Strommix hat auf die CO_2-Emissionen der Stahlindustrie nur begrenzt Einfluss, da die CO_2-Emissionen des Hochofens in allen Produktionspfaden dominieren.

Schlussfolgerungen

Schlussfolgerung 1: Die deutsche Eisen- und Stahlindustrie ist nicht auf dem Weg dahin, ihre CO_2-Emissionen so zu reduzieren, dass sie die derzeitigen Klimaschutzziele für 2030 erreicht, sofern diese Ziele gleichmäßig für alle Sektoren gelten.

Die Ergebnisse dieser Arbeit führen zu dem Schluss, dass die Eisen- und Stahlindustrie in Deutschland die derzeit geltenden Klimaschutzziele für 2030 sehr wahrscheinlich nicht erreichen wird, sofern diese Ziele gleichmäßig für alle Sektoren gelten (Tab. 6.9). Die Ziele könnten nur erreicht werden, wenn die Primärstahlerzeugung drastisch gesenkt würde, indem Hochöfen am Ende ihrer technischen Lebensdauer, die mit 50 Jahren veranschlagt wird, nicht wieder ersetzt werden. Dann würde sich die Primärstahlerzeugung bis 2030 im Vergleich zu heute halbieren und die Erzeugung von Sekundärstahl müsste ausgeweitet werden, insbesondere deswegen, da auch CCS bis dahin nicht in ausreichendem Maße zur Verfügung stehen wird. Zusätzlich läge die Rohstahlerzeugung dann unter dem niedrigsten Wert der letzten vier Jahrzehnte (Fig. 6.10-c).

Das derzeitige CO_2-Reduktionspotenzial ist gering (Kapitel 3), und alternative Technologien, die sich derzeit im Forschungs- und Entwicklungsstadium befinden, werden nicht rechtzeitig verfügbar sein, um die derzeitigen Klimaschutzziele zu erreichen (Kapitel 5).

Schlussfolgerung 2: Die Eisen- und Stahlindustrie in Deutschland hat keine besonderen Anstrengungen zur Erhöhung der Energieeffizienz und zur Senkung der CO_2-Emissionen unternommen.

Der Rückgang der Energieintensität in der Eisen- und Stahlindustrie im Zeitraum von 1991 bis 2007 kann im Wesentlichen auf eine verhältnismäßige Erhöhung der Sekundärstahlerzeugung zurückgeführt werden (Abb. 2.12). Die Energieintensität auf Prozessebene blieb nämlich im gleichen Zeitraum in den meisten Fällen konstant (z.B. Abb. 2.10) oder zeigte nur leichte Verbesserungen (z.B. Abb. 2.6).

Der Rückgang des spezifischen Energieverbrauchs in der Eisen- und Stahlindustrie seit den 1950er-Jahren kann zum großen Teil durch die Diffusion dreier Technologien erklärt werden, und zwar der Sekundärstahlerzeugung, dem Stranggießen und dem LD-Konverter (Kapitel 3).

Unternehmen stimmen einer Investition in Energieeffizienztechnologien in der Regel nur dann zu, wenn die Amortisationszeit unter zwei bis drei Jahren liegt, auch wenn davon ausgegangen werden muss, dass diese Technologien deutlich über diesen Zeitraum hinaus in Betrieb sein werden (Kapitel 4).

Schlussfolgerung 3: Politikmaßnahmen, die auf die Erhöhung der Energieeffizienz oder auf die Reduktion der CO_2-Emissionen abzielten, hatten auf die Eisen- und Stahlindustrie in Deutschland nur einen geringen Einfluss.

Die Selbstverpflichtung der deutschen Wirtschaft und der Bundesregierung zum Schutz des Klimas war während des untersuchten Zeitraums von Kapitel 2 in Kraft. Die deutsche Industrie sagte zu, sich in besonderem Maße zu engagieren, um die spezifischen CO_2-Emissionen ihrer jeweiligen Branche zwischen 1990 und 2012 um 22 % zu reduzieren (Deutsche Wirtschaft und Regierung der Bundesrepublik Deutschland, 2000).

Die Ergebnisse von Kapitel 2 legen nahe, dass die Eisen- und Stahlindustrie zwischen 1991 und 2007 keine besondere Maßnahmen ergriffen hat, um den Einsatz fossiler Energieträger zu senken. Das Ziel ist vermutlich zum großen Teil durch den sich ohnehin erhöhenden Anteil der Sekundärstahlerzeugung erreicht worden. Diese Vermutung wird z.B. durch Flues et al. (2015) gestützt.

Die Auswirkungen des Europäischen Emissionshandels auf energieintensive Industrien im internationalen Wettbewerb wurden durch die freie Zuteilung von Emissionszertifikaten begrenzt. Darunter fiel auch die Eisen- und Stahlindustrie (European Commission, 2016c).

Das Bundesimmissionsschutzgesetz Artikel §5/4 fordert, dass die Betreiber von genehmigungspflichtigen Anlagen diese energieeffizient betreiben. Dieses Gesetz wurde bisher nicht durch eine Rechtsverordnung spezifiziert, so dass es in der Regel keine Anwendung findet (Kapitel 4).

Schlussfolgerung 4: Der europäische Eisen- und Stahlverband Eurofer zeigt in seiner Low-Carbon-Roadmap 2050 mit Ausnahme von CCS keinen Pfad auf, der eine CO_2-arme Eisen- und Stahlindustrie ermöglichen würde.

Der Schwerpunkt der oben genannten Low-Carbon-Roadmap 2050 liegt auf Politikmaßnahmen, die die derzeitigen Eisen- und Stahlherstellungsprozesse fördern. Die Bedeutung, die Stahl insbesondere im Energie- und Transportsektor für CO_2-arme Technologien in Form von beispielsweise Windkrafträdern oder Leichtbaustählen hat, wird hervorgehoben.

Auch wenn CO_2-arme Alternativen zur derzeitigen Stahlherstellung, wie z.B. Strom oder Wasserstoff aus erneuerbaren Energien, genannt werden, so ist doch CCS die einzige Technologie, der im Bericht ein signifikantes CO_2-Reduktionspotenzial zugesprochen wird. Politikmaßnahmen, die diese Industrie in eine CO_2-arme Industrie transformieren können, werden nicht genannt (Eurofer, 2013).

Ausblick

Die Kapitel 1 bis 6 sowie zusätzliche Literatur sind die Grundlage für diesen Abschnitt, der einen Überblick über die Optionen zur Überführung energieintensiver in CO_2-arme Industrien gibt.

Neben der Schließung von Produktionsstätten energieintensiver Industrien gibt es zwei weitere Strategien, deren CO_2-Emissionen drastisch zu reduzieren. Die erste Möglichkeit ist das Auffangen von CO_2 aus industriellen Abgasen, bevor sie in die Atmosphäre eintreten, und ihre unterirdische Speicherung. Dieses Konzept wird *Carbon capture and storage* oder CCS genannt. CCS verhindert nicht die Erzeugung von anthropogenem CO_2, unterbindet aber die Freisetzung seines Treibhausgaspotenzials, solange es im Untergrund verbleibt.

Die CO_2-Konzentrationen in den Abgasen industrieller Prozesse reichen typischerweise nicht aus, um CCS anzuwenden. Zur Nutzung von CCS als Technologie müssen also neue Prozesse entwickelt werden, was sich bei großskaligen Anlagen in der Regel über Jahrzehnte hinweg zieht.

Bei den Anhörungen zur europäischen Low-Carbon-Roadmap 2050 befürworteten Vertreter fossil basierter Industrien CCS als eine angemessene und kostengünstige Technologie zur Senkung von CO_2-Emissionen (European Commission, 2011). Wirft man einen genaueren Blick auf die Low-Carbon-Roadmaps der energieintensiven Industrien Europas fällt jedoch auf, dass CCS differenzierter bewertet wird. Die europäische Zementindustrie hebt hervor, dass CCS nur realistisch ist, wenn die Infrastruktur für CO_2-Transport und -Speicherung geeignet und geprüft ist – etwas, das derzeit noch ungelöst ist und zudem nicht in der Verantwortung der Zementindustrie liegt. Auch im Falle zukünftig sinkender CCS-Kosten ist die Europäische Zementindustrie davon überzeugt, dass die Investitionen und die laufenden Kosten für CCS die Kosten der Zementproduktion substantiell erhöhen werden (The European Cement Association, 2013). Die Europäische Chemieindustrie betrachtet CCS nur dann als kosteneffiziente Option, wenn CCS in mehreren Sektoren und weltweit angewendet wird (The European Chemical Industry Council, 2013). Die Europäische Papierindustrie befürwortet anstelle der Förderung von CCS gar die Unterstützung anderer Breakthrough-Technologien (Confederation of European Paper Industries, 2011).

Während CCS eine Maßnahme im Hinblick auf den kohlenstoffintensiven industriellen *Output* darstellt, beinhaltet das zweite Bündel an Maßnahmen die Substitution des kohlenstoffintensiven *Input*. Dies sind typischerweise fossile Energieträger, aber auch kohlenstoffintensive Rohstoffe, wie Kalk in der Zement- und Stahlherstellung. Die Anpassung der Industrie an kohlenstoffarme Ausgangsmaterialien erfordert sektor- oder gar prozessspezifische Lösungen.

Strom aus erneuerbaren Energien wird eine Hauptsäule der kohlenstoffarmen Volkswirtschaften sein. Der Ausbau erneuerbarer Energien zur Stromerzeugung hilft dabei, die CO_2-Intensität strombasierter Prozesse zu senken. Elektrolyse ist beispielsweise derzeit das dominante Verfahren zur Herstellung von Primäraluminium. Die Elektrolyse von Eisenerz hingegen befindet sich im frühen Forschungs- und Entwicklungsstadium (Eurofer, 2013). In der Papierindustrie basieren etwa zwei Drittel der bis 2030 erwarteten CO_2-Einsparungen auf dem Ausbau erneuerbarer Energien im Stromsektor (Confederation of European Paper Industries, 2011).

Der industrielle Einsatz von Biomasse, solarer Wärme oder Geothermie ist derzeit sehr begrenzt (Abschnitt 1.3.1). Mehr Beachtung findet die Umwandlung von Überschussstrom aus erneuerbaren Energien in andere Produkte, das sogenannte *Power-to-X*. *Power-to-heat* ermöglicht die Erzeugung und Nutzung von Wärme aus Überschussstrom von erneuerbaren Energien. Die Herstellung von Wasserstoff mit Strom aus erneuerbaren Energien (*power-to-gas*) wird in verschiedenen Demonstrationsanlagen getestet (Abschnitt 1.3.1). Wasserstoff ist eine vielversprechende kohlenstofffreie

Option für die Eisen- und Stahlindustrie, deren Umsetzbarkeit derzeit in Schweden und Österreich geprüft wird (Eurofer, 2013; Neuberg, 2016). Im Gegensatz zu anderen Industrieprozessen ist die Erzeugung von Eisenschwamm mit Wasserstoff eine verfügbare Technologie.

Alle aufgezeigten Optionen zur drastischen Senkung der CO_2-Emissionen aus energieintensiven Industrien sind derzeit begrenzt – entweder durch ihre Verfügbarkeit (z.B. Biomasse) oder durch ihre Reife (z.B. power-to-X). Daher sollten zum jetzigem Zeitpunkt auch Strategien verfolgt werden, die den aktuellen fossilen Energieeinsatz besser ausnutzen.

In den energieintensiven Industrien gibt es durchaus weitere Energieeffizienzpotenziale (The European Cement Association, 2013; Confederation of European Paper Industries, 2011; Eurofer, 2013; The European Chemical Industry Council, 2013). So werden beispielsweise in der Abwärmenutzung neue Konzepte entwickelt. Dazu wird die Abwärmenutzung von Hochofenschlacke oder von heißen Brammen in Pilotprojekten untersucht. Neue Prozesse wie das Bandgießen versprechen einen geringeren Energieverbrauch durch das Wegfallen von Wiedererwärmvorgängen. Einige Energieeffizienztechnologien sind noch nicht vollständig verbreitet. Die Kokstrockenkühlung zum Beispiel ist in Japan weit verbreitet, in Europa allerdings wird sie derzeit nicht genutzt.

Werksinterne Energieflüsse sollten angesichts des steigenden Anteils von Erneuerbaren an der Stromproduktion überdacht werden. Wenn die Stromproduktion auf fossilen Energieträgern basiert, dann ist es eine Effizienzmaßnahme, gasförmige Abfallprodukte zu verstromen. Bei einer Stromversorgung allerdings, die zum großen Teil auf Erneuerbaren basiert, sollten energiereiche Abgase als fossile Energieträger wiederverwendet werden, beispielsweise durch die Erzeugung von direkt reduziertem Eisen mittels Koksofengas.

Sektorübergreifende Energieverbünde beinhalten ein bisher kaum erschlossenes Energieeffizienzpotenzial. Energiereiche Abgase aus einem Sektor könnten als Eingangsstoff für einen anderen Sektor dienen. So könnten z.B. wasserstoff- und kohlenmonoxidreiche Abgase der Stahlindustrie als Energieträger für die Chemieindustrie verwendet werden.

Auch CCS verknüpft unterschiedliche Sektoren miteinander. Aufgefangenes CO_2 kann als Einsatzmaterial z.B. bei der Produktion von Algen als Biomasse verwendet werden (The European Cement Association, 2013).

Das Recycling energieintensiver Produkte ist eine wesentliche Maßnahme zur Minderung des Energieverbrauchs, z.B. auch in der Eisen- und Stahlindustrie (Eurofer, 2013). Allerdings ist das Recycling von Stahl durch Qualitätsanforderungen und die Verfügbarkeit von Schrott begrenzt. Die Primärerzeugung von energieintensiven Produkten, also die Erzeugung auf Basis von Rohstoffen, wird erst dann an Bedeutung verlieren, wenn genügend Primärmaterial für das Recycling zur Verfügung steht und zudem das recycelte Material ein Qualitätsniveau erreicht, das dem der Primärmaterialien gleichkommt. Auch andere energieintensive Sektoren unterstreichen die Bedeutung von Recycling (The European Chemical Industry Council, 2013; The European Cement Association, 2013; Confederation of European Paper Industries, 2011).

Materialeffizienz verringert Abfall entlang des Produktionsprozesses oder stellt einen gleichen Nutzen mit weniger Material bereit. Leichtbaustähle reduzieren das Gewicht von Fahrzeugen und hochfester Zement ermöglicht die Herstellung ähnlicher Strukturen mit weniger Material (Eurofer, 2013; The European Cement Association, 2013).

Schießlich könnten kohlenstoffarme Produkte kohlenstoffintensive Produkte wie z.B. Zement, Stahl oder Aluminium ersetzen. Wertstoffe aus der holzverarbeitenden Industrie könnten kohlenstoffintensive Produkte ersetzen. Anwendungen könnten z.B. in der Bauwirtschaft, Verpackungsindustrie oder als Brennstoffe und Chemikalien liegen (Confederation of European Paper Industries, 2011). Um dieses Potenzial abzuschätzen, benötigt man ein Life-Cycle-Assessment und die Identifikation und Entwicklung solcher Alternativen.

Politikempfehlungen

Industrie- und prozessspezifische CO_2-Reduktionspotenziale sollten im Detail identifiziert werden. Die Untersuchung der Energieintensitätsentwicklungen der letzten Jahre ermöglicht Einblicke, wie viel und in welchem Maße bisher Verbesserungen erzielt wurden, und mit welcher Tendenz diese Entwicklungen sich in der Zukunft vermutlich fortschreiben. Einblicke in fördernde und hemmende Faktoren in Energieeffizienzverbesserungen und CO_2-Reduktionen helfen dabei, ein Verständnis für die Zurückhaltung von Unternehmen im Hinblick auf weitere CO_2-Reduktionen zu entwickeln.

Auf diesen spezifischen Ergebnissen sollte ein Systemansatz weitere industriespezifische und sektorübergreifende Ansätze für CO_2-Reduktionen entwickeln.

Die Finanzierung von Pilot- und Demonstrationsanlagen stellt häufig ein Hindernis dar, da großskalierte industrielle Anlagen kapitalintensiv sind und ihre Entwicklung risikoreich ist. Es sollte untersucht werden, in welchem Maße Unternehmen eine finanzielle Unterstützung erhalten können, ohne mit bestehenden Subventionsregeln in Konflikt zu geraten.

Die derzeitige Energie- und Klimapolitik scheint Entwicklungen in der industriellen Energieeffizienz nur in geringem Maße zu beeinflussen. Vor diesem Hintergrund scheint eine Überarbeitung der entsprechenden Gesetze sinnvoll.

Der Europäische Emissionshandel ist die zentrale Politikmaßnahme zur Senkung der CO_2-Emissionen in allen Bereichen. Sein Einfluss würde stärker, sobald der Preis für die Emissionszertifikate steigt, z.B. durch Backloading und/oder eine geringere Zuteilung von freien Zertifikaten. Die bereits vorgesehene Reduktion der freien Zertifikate nach 2020 wird die Produktionskosten für die energieintensive Industrie erhöhen. Falls es bis dahin keinen globalen Preis für CO_2-Emissionen gibt, sollten energieintensive Unternehmen im internationalen Wettbewerb vor Carbon Leakage geschützt werden.

Die Erlöse aus dem Verkauf der CO_2-Zertifikate sollten verstärkt in Maßnahmen fließen, die die Forschung, Entwicklung und Demonstration von CO_2-armen industriellen Prozesstechnologien fördern, wie z.B. die NER-300- oder die NER-400-Reserve.

Artikel §5/4 des Bundesimmissionsschutzgesetzes verpflichtet die Industrie in Deutschland bereits dazu, ihre genehmigungspflichtigen Anlagen energieeffizient zu betreiben (Kapitel 4). Da dieses Gesetz durch keine Rechtsverordnung spezifiziert wurde, wird es im Regelfall nicht angewendet. Die Möglichkeit, das Gesetz durch eine Verordnung zu stärken, sollte in Betracht gezogen werden.

Wasserstoff wird derzeit als eine Option für einen CO_2-armen Energieträger angesehen und könnte eine Möglichkeit sein, Eisen CO_2-arm zu erzeugen. Die Eisenerzeugung auf Wasserstoffbasis ist eine bereits verfügbare Technologie, bei der jedoch noch offen ist, wie die Versorgung mit Wasserstoff aus erneuerbaren Energien dargestellt werden kann.

Appendix A

Data sources for the construction of energy prices 1970-2014

Table A.1: Data sources for the construction of the timeline of energy prices for the German industry.

Energy carrier	Period	Details I	Details II	Original unit	Conversion factor	Source
Coal	1970-2014	Imported to Germany	Cross-border price	EUR/t SKE	8.141 MWh/ t SKE	Bundesamt für Wirtschaft und Ausfuhrkontrollen (1970-2014a)
Coking Coal	1978-1998	Industry, Germany	Cross-border price	EUR/t	6.978 MWh/t	International Energy Agency (1978-2014a)
	1998-2014	Imported to Germany	Cross-border price	EUR/t	6.978 MWh/t	Verein der deutschen Kohlenimporteure (2004-2015)
Coke from hard coal[1)]	1998-2014	Imported to Germany	Cross-border price	EUR/t	6.978 MWh/t	Verein der deutschen Kohlenimporteure (2004-2015)
Natural Gas	1978-2014	Industry, Germany	Energy end use price	ct/cbm	8.816 MWh/ 1000 cbm	Bundesministerium für Wirtschaft und Energie (1978-2014)
	1970-1977	Industry, Germany	Energy end use price	EUR/MWh	-	International Energy Agency (1978-2014a)
Electricity	1970-2009	Industry, Germany	Energy end use price	EUR/MWh	-	Bundesministerium für Wirtschaft und Energie (1970-2014)
	1978-2012	Industry, Germany	Energy end use price	EUR/MWh	-	International Energy Agency (1978-2014a)
	2008-2014	Industry, Germany	Energy end use price	ct/kWh	-	Statistisches Bundesamt (2016)

1) Since coke prices are only available from 1998 onwards, we estimate the coke prices from 1978-1997. Prices for coking coal are available from 1978 onwards. The ratio between the price of coke and coking coal varied between 1.5 and 1.7 in the years 1998-2003. In 2004-2005, the ratio was extraordinarily high (3.3, 2.4), while in the year of the economic crisis 2009 the ratio was extremely low (1.1). Thus we assume an average ratio of the price between coke and coking coal of 1.6 for the years from 1978-1997.

Appendix B

Calculation of payback periods

The payback periods are calculated according to Eq. B.1.

$$PB_{i,t}(k) = \frac{I_i}{P_{i,t}(k) - C_i(k)} \tag{B.1}$$

where

PB	payback period,
I	investment,
P	annual return due to technology i,
C	annual operation and maintenance costs,
i	technology,
t	case (Tab. 4.4),
k	year.

The proceeds for top-pressure recovery turbines are assumed to equal the market value of generated electricity. This assumes that the company purchases electricity from the public grid and that by applying a top-pressure recovery turbine the company can

Table B.1: Assumptions on the selected energy-efficient technologies.

		TRT	**BOFGR**	**PCI**
Capacity	Mio t/year	2.0	3.0	2.0
Investment	Mio EUR_{2012}	15	50	55
Operation and maintenance costs	EUR_{2012}/year	150,000	150,000	100,000
Energy saving/recovery	kWh/t	30	222	290 1)
CO_2 saving	kg CO_2/t	17 2)	45	180

1.) $SC_{CK,OP}$ = 0.49 t/thm; $SC_{CK,WP}$ = 0.30 t/thm; $SC_{CL,WP}$ = 0.18 t/thm; HV_{coal}= 697.8 kWh/t; HV_{coke}= 798.7 kWh/t

2.) 559 kg CO_2/MWh in 2013 (UBA 2014a) reduce its electricity consumption from the public grid. Later we will see that not all steel companies in Germany fulfill this assumption and that top-pressure recovery turbines in some cases does not compete with the electricity price from the public grid but with the price for onsite electricity generation. Hence the electricity prices for case (b) and (c) are (Eq. B.2 and B.3):

$$PC_{EL,b}(k) = PC_{EL,a}(k) - SE_{CO_2,EL}(k) \cdot PC_{CO_2}(k) \tag{B.2}$$

$$PC_{EL,c}(k) = PC_{EL,a}(k) - SE_{CO_2,EL}(k) \cdot PC_{CO_2}(k) - EEG(k) \tag{B.3}$$

where

PC	price,
EL	electricity,
SE	specific emissions,
CO_2	carbon dioxide,
EEG	levy for renewable energies,
k	year,
a, b	case (Tab. 4.4).

For basic oxygen furnace gas recovery we assume that the recovered basic oygen furnace gas reduces the consumption of natural gas and that in case of the European Emission Trading Systems costs for the CO_2-emissions of that amount of natural gas are saved.

Estimating the economic benefits of pulverized coal injection we follow the approach of Schott et al. (2012). Coke is partly replaced by coal in the blast furnace. Differences between the coke and coal price lead to economic benefits. CO_2 emission reductions are calculated by accounting coal consumption both in coke ovens and blast furnaces. We assume that one ton of coke is produced from 1.3 tons of coal (Schott et al., 2012). Table B.1 lists further assumptions. The calculations of the proceeds of the respective technologies are given below (Eq. B.4 - B.8).

$$P_{TRT,t}(k) = SP_{EL,TRT} \cdot PC_{EL,t}(k) \cdot CP_{BF} \tag{B.4}$$

$$P_{BOFGR,a}(k) = SR_{BOFGR} \cdot PC_{NG}(k) \cdot CP_{BOF} \tag{B.5}$$

$$P_{BOFGR,b}(k) = SR_{BOFG} \cdot [PC_{NG}(k) + SE_{CO_2,NG} \cdot PC_{CO_2}(k)] \cdot CP_{BOF} \tag{B.6}$$

$$P_{PCI,a} = \Big(SC_{CK,OP}\cdot PC_{CK}(k) - [(SC_{CK,WP}\cdot PC_{CK}(k) + SC_{CL,WP}\cdot PC_{CL}(k)]\Big)\cdot CP_{BF} \tag{B.7}$$

$$P_{PCI,b} = P_{PCI,a} + [SC_{CK,OP}\cdot Q - (SC_{CK,WP}\cdot Q + SC_{CL,WP})\cdot SE_{CO_2,CL}\cdot PC_{CO_2}(k)]\cdot CP_{BF} \tag{B.8}$$

where

P_i	annual return due to technology *i*,
–	
SP	specific production,
SR	specific recovery,
SE	specific emissions,
SC	specific consumption,
PC	price,
CP	capacity,
Q	input factor coke oven: coke/coal (1.6) (Schott et al., 2012)
–	
BF	blast furnace
BOF	basic oxygen furnace
BOFG	basic oxygen furnace gas
CK	coke
CL	coal
CO_2	carbon dioxide
EL	electricity
NG	natural gas
OP	without pulverized coal injection
WP	with pulverized coal injection
–	
k	year
t	case a, b, or c (Tab. 4.4)
a, b, c	cases (Tab. 4.4)

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Curriculum Vitae

Marlene Arens has a degree in mechanical engineering from the Technical University of Dresden, Germany. She joined the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, Germany, in 2008. In 2010, she began writing her doctorate thesis under the guidance of Ernst Worrell from Utrecht University, Netherlands. She spent three months in 2014 as a visiting scientist at the Lawrence Berkeley National Laboratory, USA, in the International Energy Analysis Group. Her research focus is energy efficiency and CO_2 reductions in industry.