PEER-REVIEWED PAPER

Energy efficient technologies in the German steel industry – low hanging fruits?

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Abstract
Energy efficiency has been recognized as the key short- to medium-run strategy to reduce CO_2 emissions and energy use in a cost-efficient way, in particular for energy-intensive industry sectors like steel production. A major option to increase energy efficiency in energy-intensive industries is the implementation of energy efficient technologies. Several studies estimate the potential of these technologies. Still little is known on their diffusion as well as on their impact on the overall energy intensity. Do energy efficient technologies diffuse as expected by diffusion theory? Do all energy efficient technologies follow more or less the same diffusion path? How does the diffusion of energy efficient technologies affect the overall energy use of the investigated industrial sector? And finally, to which extend can the energy use be reduced if all selected energy efficient technologies were diffused completely? In this paper we analyse the diffusion of four energy efficient technologies for the steel industry in Germany since their introduction. Since all technologies have been applied in the German steel industry for more than 30 years we would expect complete diffusion. We derived the diffusion rates based on data such as energy statistics, databases, press releases, annual reports and interviews. We only found complete diffusion for the oldest technologies of our selection. Newer technologies diffused quicker in the initial phase but then their diffusion slowed down. We number the impact of the diffusion of the single technologies on the primary energy use and we estimate by which amount the primary energy use could be reduced if all selected technologies were diffused completely. Furthermore we number the impact of the selected energy efficiency technologies on the energy efficiency improvements since their introduction. Finally, we shortly discuss technology specific market barriers and non-energy benefits.

Introduction
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 (e.g. IISI 1985, Poznaski 1983, Oster 1982). 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 (e.g. Tanaka et al. 2006).

This paper aims to study the diffusion of selected 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). We selected four 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 mainly belong 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), basic oxygen furnace gas recovery (BOFGR), and pulverized coal injection (PCI). We estimate the impact of the diffusion of these technologies on the primary energy use per ton 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 efficiency technologies in heavy industries and the impact on energy intensity. The paper is organized as follows. Section 2 provides a review of the literature on the diffusion of technologies and steel sector specific diffusion studies. The methodology and the results of the investigated technologies are presented in section 3 and 4. The final section provides conclusions.

Methodology

DIFFUSION RATES

We focus on proved and key energy efficiency technologies. We selected energy efficiency technologies (EET) exceeding a specific energy saving potential of 0.1 GJ/ t of product in order to detect an effect on the primary energy use per ton crude steel. The energy intensity of the steel industry often is expressed as energy use per ton crude steel. This approach does not distinguish between the two main steelmaking processes, i.e. BF/BOF and EAF steelmaking[1]. EAF steelmaking consumes only about one third 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 use[2].

For the diffusion rate of the selected EET we collected data on the national level, such as steel produced by CCM or coal input to blast furnaces. Whenever possible we triangulated the data using 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. 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 in the year k and the maximum diffusion (Equation 1):

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

where

$DR_i(k)$	diffusion rate of a technology i in the year k
$D_{i,k}$	diffusion of a technology i in the year k, e.g. average coal injection in BFs in the year k (PCI)
$D_{i,max}$	maximum diffusion of a technology i, e.g. 200 kg coal/thm (PCI).

Table 1 presents the methodology for constructing the diffusion rates of the selected EET.

IMPACT ON SPECIFIC ENERGY USE

We estimate the impact of the diffusion of the selected technologies on the primary energy use per ton crude steel.

First, we define the reference primary specific energy use per ton liquid steel ($EC_{Ref,prim}$) for the year 1960. We obtain a reference specific energy use ($EC_{Ref,prim}$) by using the specific primary energy use per ton crude steel in 1960, i.e. 29.43 GJ/t (Steelinstitute VDEh 2013). This value includes a diffusion of 7 % of EAF and 3 % of BOF steelmaking. Thus the reference specific primary energy use results as 30.9 GJ/t. This value includes assumed 4 GJ/tls for steelmaking and 1.9 GJ/tls for ingot casting. The energy use for iron making results as 25 GJ/tls which might be overestimated. Hence, in a sensitivity analysis we consider a minimum and medium reference energy use for a sensitivity analysis. The minimum references energy use is 20.9 GJ/tls which assumes only 15 GJ/tls for ironmaking. The medium reference energy use is assumed with 24.1 GJ/tls.

Second, we collected or derived specific energy savings potential of the selected technologies. We define the energy savings potential of EAF steelmaking as:

$$ES_{EAF,prim}(k) = EC_{Ref,prim} - EC_{EAF,final}(k)*Eff_{ElectrProd}(k)$$

where

$ESP_{EAF,prim}(k)$	primary energy saving per ton crude steel due to EAF steelmaking in the year k
$EC_{Ref,prim}$	reference primary energy use
$EC_{EAF,final}(k)$	final energy use of EAF steelmaking in the year k
$Eff_{ElectrProd}(k)$	efficiency of electricity production in the year k

Fandrich (2009) numbers the specific final electricity use of EAF steelmaking with 630 kWh/t in 1960.[3] For the years 1991 to 2009 we obtain the specific electricity use by StaBu (1991–2009) and by the Steelinstitute VDEh (2013a). For 1958–1964 and for 2010–2012 we assume the values of 1960 and 2009, respectively. Additional energy carriers are charged to the EAF as well mainly as injected carbon. The overall energy consumption for EAF steelmaking is about 700 kWh/t in final energy (Kirschen et al. 2009). Hence we assume, that while reducing the electricity use from the 1960s till today,

1. For a description of the two steelmaking processes, see e.g. Arens et al. (2012).

2. To our understanding EAF steelmaking is not an energy efficiency technology since it cannot completely replace primary steelmaking.

3. Fandrich (2009) numbers the specific electricity use for EAF steelmaking with 345 kWh/t in 2008. For the same year on the national level the specific electricity use is higher (539 kWh/t) (StaBu 1991-2009, Steelinstitute VDEh 2013a).

Table 1. Overview of the applied methodology to construct diffusion rates.

Energy efficient technology (EET)	Abbre-viation	Diffusion in a respective year [unit]	Maximum diffusion [unit]
Basic oxygen Furnace	BOF	Steel produced by BOF [t]	Crude steel production in the respective year excluding steel produced by EAF [t]
Continuous casting machines	CCM	Steel produced by CCM [t]	Crude steel production in the respective year [t]
Pulverised coal Injection	PCI	Coal use in blast furnaces [kg]/pig iron production [thm]	200 kg/thm
BOF gas recovery	BOFGR	BOFG production [m³(S.T.P.)]/oxygen steel production [t]	90 m³(S.T.P)/t
Electric Arc Furnace	EAF	Steel produced by EAF [t]	Crude steel production in the respective year [t]

the injection of carbon rises. Nevertheless, a reduction of the electricity demand reduces primary energy consumption. We assume the efficiency of electricity production with 29 % (1958) and 47 % (2012). Thus the primary specific energy use of EAF steelmaking ranges from 8.10 GJ/tls in (1958) to 4.80 GJ/t in 2012.

We define the energy saving per ton crude steel due to the diffusion of CCM and EAF as (Equation 2):

$$ES_i(k) = ESP_i * DR_{i,k}$$

where

$ES_i(k)$ primary energy saving per ton crude steel due to a technology *i* in the year *k*,

ESP_i primary energy saving potential per ton crude steel of a technology *i*,

$DR_{i,k}$ diffusion rate of a technology *i* in the year *k*

i CCM or EAF.

The energy saving due to the diffusion of PCI is defined as (Equation 3):

$$ES_{PCI}(k) = ESP_{PCI} \cdot DR_{PCI}(k) \cdot \frac{P_{BF}(k)}{\sum_j P_j(k)}$$

where

P_j production of crude steel by process *j*,

j Thomas-, Bessemer-, Siemens-Martin-, BOF-, and EAF-steelmaking.

The energy saving due to the diffusion of BOF is defined as (Equation 4):

$$ES_{BOF}(k) = ESP_{BOF} \cdot \frac{P_{BOF}(k)}{\sum_j P_j(k)}$$

Finally, the energy saving per tonne crude steel due to the diffusion of BOFGR is defined as (Equation 5):

$$ES_{BOFGR}(k) = ESP_{BOFGR} \cdot DR_{BOFGR}(k) \cdot \frac{P_{BOF}(k)}{\sum_j P_j(k)}$$

An overview of the selected technologies gives Table 2.[4]

4. Note 3 in Table 2. Personal communication. H.-B. Lüngen, Steelinstitute VDEh. Heidelberg/Düsseldorf: July 26th 2013.

REMAINING ENERGY EFFICIENCY POTENTIAL

We calculate the remaining energy efficiency potential for the year 2012. We assume as reference energy use the specific primary energy use per ton crude steel for the year 2012 (i.e. 18.1 GJ/tls for the maximum reference energy use in 1960). In the sensitivity analysis we also calculate the remaining energy efficiency potential for the minimum and medium reference energy use in 1960. We estimate the remaining energy efficiency potential for the case that all investigated energy efficiency technologies increased their diffusion rate from the 2012 level to complete diffusion. The remaining energy efficiency potential for BOFGR and PCI is estimated as (Equation 6):

$$REP_i = (1 - \mathrm{DR_i}) \cdot \mathrm{ESP_i} \cdot \frac{\mathrm{P_{BF}}}{\sum_j P_j}$$

where

REP_i remaining energy efficiency potential due to an EET *i*,

i *BOFGR* and *PCI.*

Results

DIFFUSION OF BASIC OXYGEN FURNACES (BOF)

The 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 air is replaced with oxygen. The BOF was invented in Austria in 1953. 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 the Steelinstitute VDEh (2013a). 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 the last OHFs were operated until 1993. The share of EAF has continuously increased as well. The diffusion rate is calculated by the annual production of oxygen 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 (Figure 1). However, in the following

Table 2. Characteristics of the selected technologies.

Energy efficient technology	Abbre-viation	Type	Process / plant type	First introduction in Germany	Specific energy saving potential (GJ/t product)	Specific primary energy savings (GJ/tls)
Basic oxygen furnace	BOF	Replace-ment	Steel making	1958	4.30 GJ/tls[1)4)6)]	4.30
Continuous casting machines	CCM	Replace-ment	Steel making	1964	1.73 GJ/ tls[2), 4)]	1.73
Pulverised coal injection	PCI	Process Intens.	Iron making	1986	0.85 GJ/thm[3)7)]	0.82
BOF gas recovery	BOFGR	Add on	Steel making	1982	0.91 GJ/tls[2)]	0.91
Electric arc furnace	EAF	Process substitution	Steel making	Mid 1950s	13.06 (1958) ... 19.89 (2012) GJ/tls[5)]	13.06 (1958) ... 19.89 (2012)

1) IEA 2007.

2) Moya 2013.

3) 1 t coal replaces 0.8 t of coke in the blast furnace by PCI; 1 t coke needs 4.225 GJ of energy for its production (IISI 1998).

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

5) Energy use for EAF steelmaking includes energy use for ingot casting (1.863 GJ/tls) (Energy use ingot casting = Energy use CCM [0.136 GJ/tls] [IISI 1998] + Energy saving CCM [1.727 GJ/tls] [Moya and Pardo, 2013]).

6) Energy use Bessemer/Thomas steelmaking (4.000 GJ/tls) (IEA 2007). Energy use BOF -0.296 GJ/tls (IISI 1998).

7) 0.98 thm/tls (IISI 1998).

years the technology spread with an annual diffusion of about 4.6 % and reached complete diffusion in 1983 (Figure 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 reached a 40 % diffusion yet. 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 %.

DIFFUSION OF CONTINUOUS CASTING MACHINES (CCM)

CCM is said to be the second major innovation 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 was necessary. CCM directly produces semi-finished products from hot metal. This technology was first introduced in 1964 in Germany and is nowadays nearly completely diffused.

The production of steel by CCM is provided by the Steelinstitute VDEh (2013a). The diffusion rate is calculated as the share of steel produced by CCM of total crude steel production.

CCM diffused relatively slow in Germany (Figure 1). It reached the 10 %-diffusion after eight years, and the 50 % diffusion after 18 years. No other technology which we investigate in this paper diffused slower during this period. After 26 years (i.e. in 1989, Figure 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 slower than the BOF. According to Poznanski[5] (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.

DIFFUSION OF PULVERIZED COAL INJECTION (PCI)

The injection of pulverized coal partly replaces coke use in the blast furnace. One kilogram of coal can replace about 0.8 kg of coke[6]. Therefore, it does not reduce the energy use in the blast furnace itself but it reduces energy use 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 (BAT 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 (Aichinger 2005 and 2007, Ghenda 2008–2011). In 2010 the national PCI average was 138 kg coal/thm (Ghenda 2011). Blast furnaces can be retrofitted with PCI. This technology is widely applied nowadays (BAT 2012). In Germany PCI was first introduced in 1986.

Aichinger (1991) provides the specific coal use per ton hot metal since its introduction in 1986 to 1989. The German Federal Statistical Office published the coal use in blast furnaces from 1991 to 2001 and from 2004 to 2009 (StaBu 1991–2009).

5. Poznanski (1993) publishes a slower diffusion of CC for West Germany, though his results on BOF coincide with our findings on BOF diffusion.

6. Personal communication. H.-B. Lüngen, Steelinstitute VDEh. Heidelberg/Düsseldorf: July, 26th 2013.

Ghenda (2011) published the specific coal use 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 Ghenda (2011). Despite the above mentioned factors which determine the PCI rate, BAT (2012) numbers 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 (BAT 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 use and the maximum coal use. For the year 1990 we interpolate the diffusion rate.

The reports by the Steelinstitute VDEh also publish in which year PCI was installed at which location in Germany (Aichinger 2005 and 2007, Ghenda 2008–2011). In 2000 pig iron 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 sites 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 (Figure 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 (Figure 2).

According to Zhang (2008) the PCI-rate in China for key enterprises rose from 51 kg/thm in 1991 to 123 kg/thm in 2000. Guo (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 %. IEA (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).

DIFFUSION OF BASIC OXYGEN FURNACE GAS RECOVERY (BOFGR)

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 about 9 GJ/m³(S.T.P.) about one fourth of that of natural gas (Brauer 1996). Per ton crude steel 0.91 GJ of energy can be recovered (Moya et al. 2013). 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 m³(S.T.P.)/t crude steel. We assume that 90 m³(S.T.P.) or 0.8 GJ of converter gas per ton crude steel can be recovered. In Germany BOFGR was first introduced in 1982.

Aichinger (1991) provides 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 (StaBu 1991–2009). 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 Steelinstitute VDEh provides data at which sites BOF Gas is recovered (Steelinstitute 2013b). 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 (Figure 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 (Figure 2).

IEA (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.

IMPACT ON ENERGY USE

Figure 3 shows the impact of the diffusion of the selected technologies on the primary energy use per ton crude steel in the German steel industry between 1958 and 2012. According to our findings the specific energy use in 2012 has been reduced by 36 % compared to 1958 due to the diffusion of the selected technologies (i.e. EAF, CCM, BOF, BOFGR, and PCI) (from 29.9 to 19.1 GJ/tls).

The Steelinstitute VDEh (2013a) publishes a SEC of 17.9 GJ/tls for 2012, which is 6.5 % lower than our analysis indicates. Thus the selection of our technologies explains 93.5 % of the efficiency improvements in the German steel industry between the late 1950s and 2012.

The major reduction in the specific primary energy use is the EAF. This process reduced the SEC by 21 % compared to the reference energy use of 30.9 GJ/t. The second key technology which reduced the specific primary energy use is the BOF. In 2012 it contributed with 9 % to the reduction of the specific energy use per ton crude steel compared to 1958. The third major technology is CCM. It contributed with 6 % to the decrease in energy use. These technologies are the oldest technologies of our selection. They were first introduced in the 1950s and 1960s.

BOFGR[7] and PCI[8] were introduced in the early or mid-1980s. Both PCI and BOFGR reduced the specific energy use per ton crude steel by the same amount, i.e. 1.2 % by 2012 com-

7. Due to the lack of data we assume the same diffusion rate for BOFGR for 2011–2012 as in 2010.

8. Same accounts for PCI.

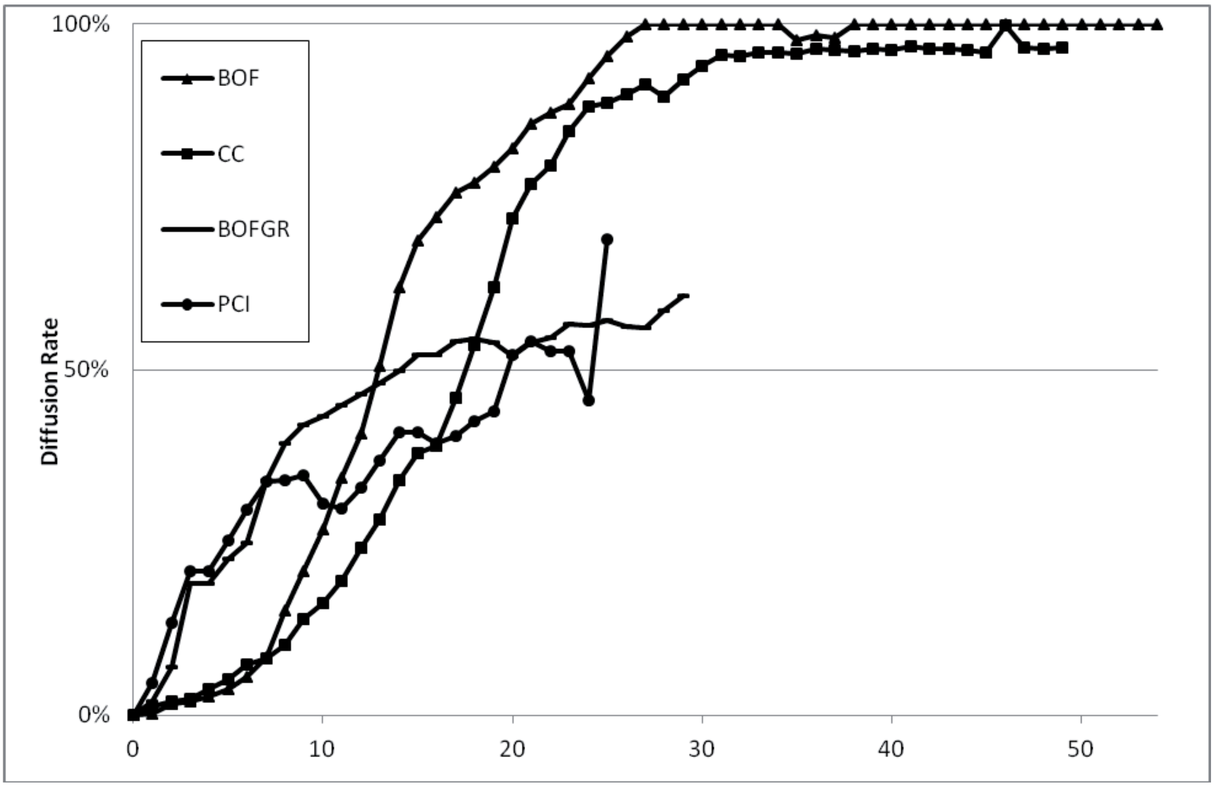

Figure 1. Diffusion rates of the selected technologies allocated by years after their first implementation.

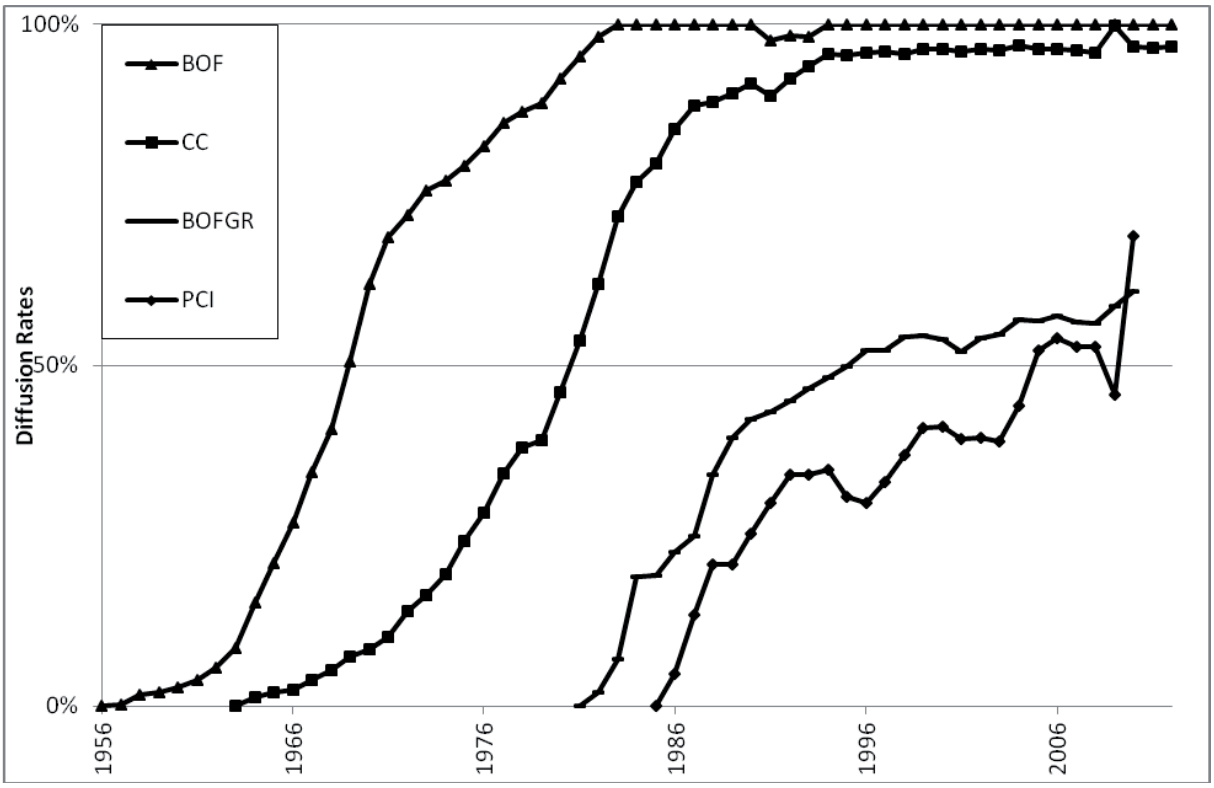

Figure 2. Diffusion rate of the selected technologies allocated by the year of their implementation.

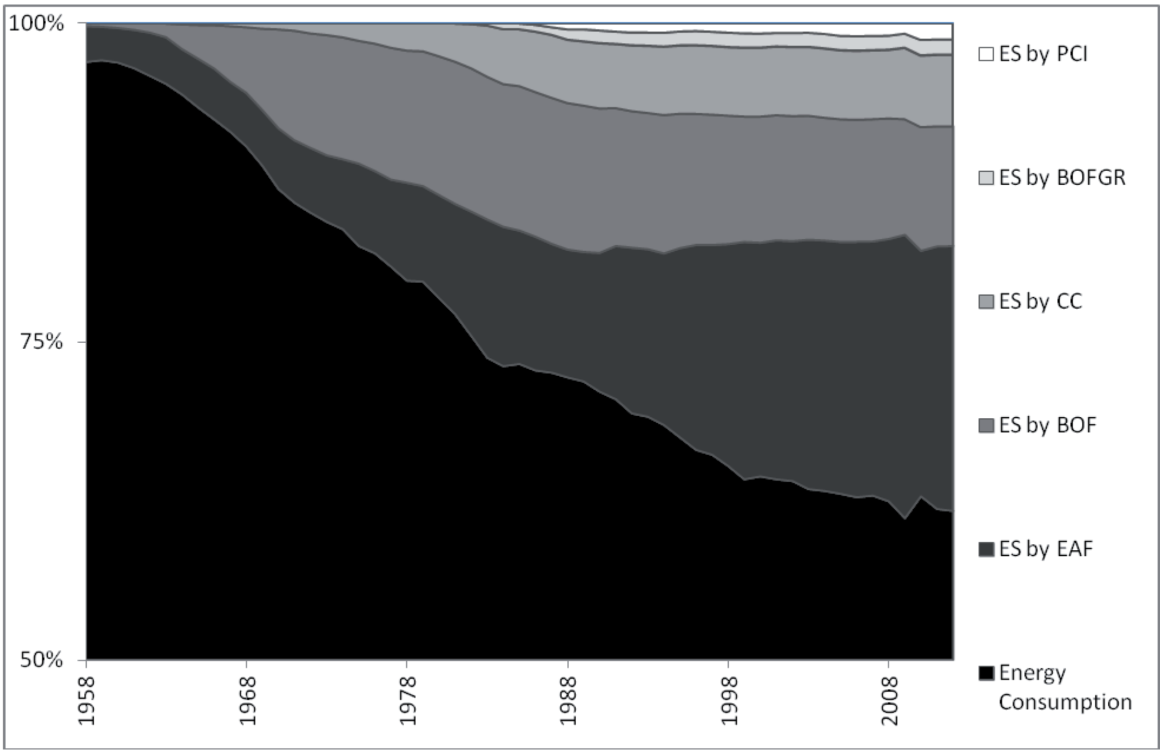

Figure 3. Impact of the selected technologies on the specific primary energy use per ton crude steel from 1958 to 2012 in the German steel industry. The reference specific energy use per ton crude steel in 1958 is assumed with 30.9 GJ/tls (excluding rolling and finishing). The figure shows to which extends the diffusion of the selected technologies reduce the specific energy use. According to our findings the specific energy use has been reduced by the selected technologies by 36 % from 1958 to 2012.

pared to 1958. Together, by 2012 these two technologies contributed with about 2.5 % to the reduction of the specific energy use compared to 1958.

REMAINING ENERGY EFFICIENCY POTENTIAL
Full diffusion of PCI and BOFGR could reduce the primary specific energy use in the German steel industry by 2.1 % (2012) (Figure 4). The further diffusion of BOFGR and PCI could reduce the primary energy intensity by another 1.2 % and 0.9 %, respectively. The impact of energy efficiency improvements in EAF-production, rolling and finishing is not included.

MARKET BARRIERS
What hinders the selected EET to diffuse completely? Certainly energy prices play a key role. Still, we need to consider other factors to explain the observed diffusion rates.

Our results indicate that PCI diffusion is mainly driven by coal, coke and oil prices. Many PCI plants were implemented after the second oil crises when energy prices were high. In the 1990s and 2000s PCI has been installed further blast furnaces. The increase of PCI diffusion coincides with a period with rising coal and oil prices in Germany.

Site specific factors seem to play an important role as well. Mainly sites which have a demand for the recovered energy invest in BOFGR.

NON-ENERGY BENEFITS
Certainly productivity benefits push EET into the market. BOF and CCM provide essential productivity benefits and they – although comparably slow – diffused constantly to complete penetration. BOFGR is an end-of-pipe technology which does not improve the production process. PCI substitutes reducing agents and does not provide essential productivity benefits.

SENSITIVITY ANALYSIS
Table 3 shows the sensitivity analysis for the variation of the reference primary specific energy use in 1960. The maximum reference value is obtained by Steelinstitute VDEh (2013a). The minimum reference value assumes 15 GJ/tls for iron making, 4 GJ/tls for steelmaking and 1.9 GJ/tls for ingot casting. The impact of the diffusion BOFG and PCI on the reduction of the specific energy use ranges from 2–4 %.

Table 4 shows the remaining energy efficiency potential based on the resulting specific energy use in 2012. The specific primary energy use per ton liquid steel ranges from 19.1 GJ/tls to 11.8 GJ/tls. Thus the remaining energy saving potential for BOFGR and PCI is between 2.1–3.3 % according to our analysis.

Conclusions, Summary and Outlook
This paper provides a detailed study of long-term trends of the diffusion of selected energy efficiency 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, BOFGR and PCI have only minor productivity benefits. Hence, understanding the productivity benefits may be important to understand the rate of uptake for new technologies.

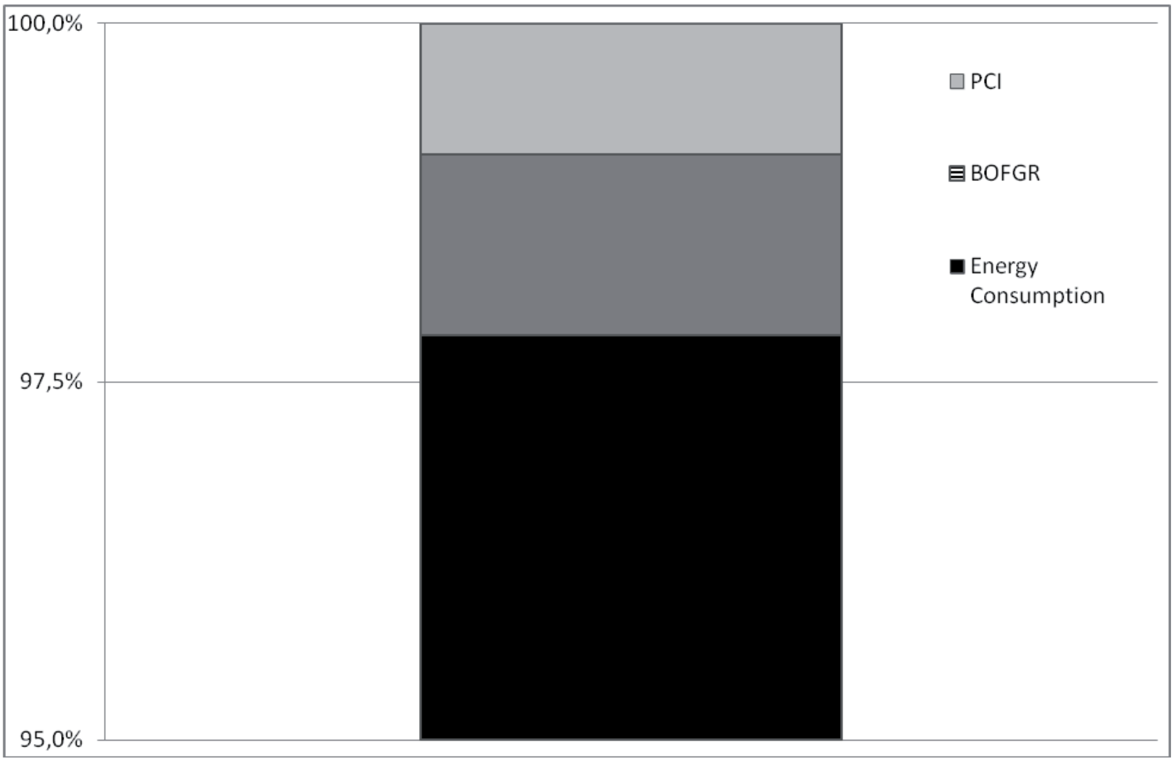

Figure 4. Remaining energy efficiency potential (2012) due to the further diffusion of the selected EET. The specific primary energy per ton crude steel could be reduced by 2.1 % if the selected technologies reached complete diffusion (1.2 % BOFGR, 0.9 % PCI).

Table 3. Sensitivity analysis – reference specific primary energy use.

	Reduction of the specific primary energy consumption per ton crude steel by EET						
Assumed reference specific energy consumption in 1960	EAF	BOF	CC	BOFGR	PCI	Sum EAF, BOF, and CCM	Sum BOFGR and PCI
[GJ/t]	[–]	[–]	[–]	[–]	[–]	[–]	[–]
20,9	15 %	14 %	8 %	2 %	2 %	37 %	4 %
24,1	18 %	12 %	7 %	2 %	2 %	37 %	3 %
30,9	21 %	9 %	6 %	1 %	1 %	36 %	2 %

Table 4. Sensitivity analysis – specific primary energy use and remaining energy saving potentials.

	Remaining energy saving potential by EET		
Resulting specific primary energy use in 2012	BOFGR	PCI	Sum remaining energy saving potential
[GJ/t]	[–]	[–]	[–]
11.8	1.9 %	1.4 %	3.3 %
14.5	1.6 %	1.1 %	2.7 %
19.1	1.2 %	0.9 %	2.1 %

Nevertheless the implementation rates seem to have levelled off since the 1990s. The diffusion rates of 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.

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 EET and plants which have the EET 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 2.1 % for 2012. At the time writing 2 BFs at one single site could apply PCI and 6 BOFs at two sites are not equipped with BOFGR. It is reported that the last 2 BFs will adopt PCI in 2014.

Abbreviations

BOF	basic oxygen furnace
BOFG	BOF gas
BOFGR	BOF gas recovery
CCM	continuous casting machines
EAF	electric arc furnace
EC	energy use
EET	energy efficient technology
ES	energy saving
GJ	giga joule
m^3(S.T.P.)	cubic meter at standard temperature and pressure
OHF	open hearth furnace
PCI	pulverized coal injection
thm	ton hot metal
tls	ton liquid steel

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