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# Energy conservation measures for the German cement industry and their ability to compensate for rising energy-related production costs

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ABSTRACT

Cement is a bulk commodity that is correlated with the population growth. While the world-wide sales are continuously increasing, the demand for cement in Germany is stagnating. Nevertheless, cement production accounts for 3.8% of Germany's industrial final energy consumption and 2.9% of Germany's total $CO_2$ emissions in 2012. We assessed the energy conservation and $CO_2$ abatement potential of 21 identified measures by deriving fuel, electricity conservation and $CO_2$ abatement cost curves. In our bottom-up investigation, we account for the current efficiency of plants and use two different system boundaries: a process boundary for benchmarking measures and a facility boundary for calculating the total potential. We identified economical conservation and abatement potentials for the year 2013 of 4% for fuel, 0.7% for electricity and 3.4% fuel and process-related $CO_2$ emissions in relation to 2012. The results of the subsequent sensitivity analysis showed that electricity conservation measures in cement grinding can compensate for higher electricity prices in the amount of the German electricity tax. In contrast, the sector's energy-related productions costs showed a high sensitivity against rising $CO_2$ prices. Without radical process innovations such as low carbon cements, $CO_2$ prices until 2035 accounted in average for more than 40% of the gross value-added which indicates, according to the EU ETS directive, the carbon leakage risk of the cement sector.

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## 1. Introduction

Cement is with a world-wide annual production of 3.3 Gt a bulk commodity that is correlated with the population growth, as in consequence, new houses and infrastructure need to be built. Unsurprisingly, over 57% of the world production is accounted by China, while Europe holds a 5.7% share (Weiß et al., 2012). Germany in particular has with 1% an even smaller share of 1% with 32.5 Mt in 2012 (VDZ, 2013). Nevertheless, the production of clinker, an intermediate product for cement, is with 3300 MJ/t clinker and 0.816 t $CO_2$/t clinker, whereof 0.421 t $CO_2$/t clinker are process-related emissions, energy- and $CO_2$-intensive (Ecofys et al., 2009). In total, the cement industry is according to DESTATIS (2014) responsible for 3.8% of Germany's industry final energy consumption and 2.9% of Germany's total $CO_2$ emissions in 2012 (VDZ, 2013).

While carbon capture and storage (CCS) is an effective way to lower direct $CO_2$ emissions (Li et al., 2013), energy conservation can be a more cost-effective point of attack to lower fossil-fuel related $CO_2$ emissions. The importance of energy efficiency was accordingly identified by policy-makers (e.g. EIPPCB, 2009). As a consequence, policies, such as the 20–20–20 targets, which demand, among others, a reduction of the primary energy consumption of the industry by 19% until 2020, have been put in place. Besides, with energy costs accounting for 30–40% of total production costs, plant operators have been traditionally concerned with energy efficiency, but more from an economic point of view. In this context, we understand energy efficiency as the reduction of energy-related production costs, whereby external costs (e.g. air pollution, anthropogenic climate change) are included. Thus, energy conservation (EC), i.e. the reduction of the specific energy consumption, might lead to, but does not imply, an improvement in energy efficiency.

Since the two oil price shocks in the 1970s, EC cost curves (ECCC) and greenhouse gas (GHG) abatement cost curves are commonly used to disseminate the results of identified measure-specific potentials and their costs (Wächter, 2013). With publication of global GHG abatement cost curves by McKinsey (2009), this concept has

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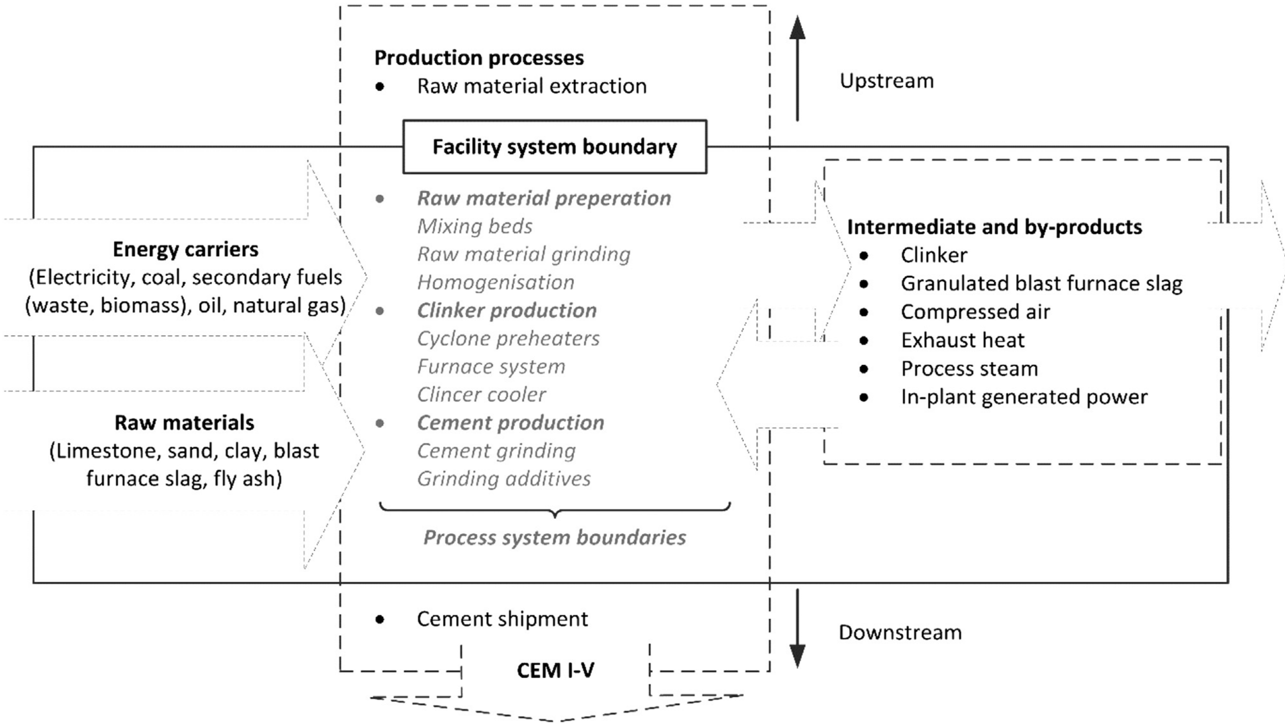


**Fig. 1.** Typical production processes of an integrated cement facility and the system boundaries respected in the investigation. The process system boundaries (in grey italic font) cover each of the production processes and the respective energy conservation measure. They are used for benchmarking measures. The facility boundary covers the raw material preparation, clinker and cement production processes. It is used to calculate the total energy conservation potential.

reached a wide public and is increasingly used to inform policy-makers (Vogt-Schilb and Hallegatte, 2013). The ranking of EC and abatement measures according to their cost-effectiveness gives policy-makers a least cost pathway to fulfil certain reduction targets. Using technological EC or $CO_2$ abatement (CA) measures in a bottom-up approach is one common method to develop ECCC or $CO_2$ abatement cost curves (CACC) (Wächter, 2013). For the production of cement, ECCCs and CACCs have been developed for China (Hasanbeigi et al., 2013b), India (Morrow et al., 2013), Thailand (Hasanbeigi et al., 2010a,b), USA (Sathaye et al., 2010) and on a global level for GHG abatements of 21 selected world regions (McKinsey, 2009). Detailed knowledge of available and prospective EC measures is needed for the development of cost curves. Madlool et al. (2013) reviews previous studies on EC and CA technologies applicable to the cement industry. Benhelal et al. (2013) provides a good overview of CA potentials of recent studies. We add three selected recent case studies to these two reviews: First, Feiz et al. (2014) researched with the cooperation of the company CEMEX (see Table 2) ways to improve the $CO_2$ performance of cement and present a framework for assessing CA measures including corresponding results for CEMEX. Second, Castañón et al. (2014) performed a case study at a cement plant in Spain with the aim to achieve ECs and CAs via optimisation of the production process. Third, Xi et al. (2013) quantified the co-benefits and abatement costs for 18 CA measures.

The aim of this paper is to determine the cost-effective EC potential for the production of cement in Germany with the help of ECCCs and to investigate its sensitivity and its impact towards energy-related production costs. Therefore, we identify 21 EC measures and apply them to German cement plants individually to derive EC potentials. We use a plant-specific bottom-up approach which is explained in Section 2. The measure-specific electricity, fossil fuel and $CO_2$ conservation and abatement potentials are displayed in ECCCs and CACCs in Section 3. Subsequently, we perform a sensitivity analysis of the cost-effective EC and CA potentials as well as the energy-related production costs in the period 2013–2035 with varying interest rates, electricity and $CO_2$ prices.

## 2. Method

### 2.1. The process and facility system boundaries

The definition of the system boundary has an important impact on the results. Comparison of studies addressing energy efficiency in the iron and steel industry (Siitonen et al., 2010) and in the aluminium industry (Liu and Müller, 2012) unveiled significant differing results regarding energy- and $CO_2$-equivalent intensities which can be, to some extent, explained by the use of different system boundaries. We therefore define our system boundaries in this section (see Fig. 1).

The smallest boundary is the process boundary. It covers the inputs and outputs of the respective process. The process level is

**Table 1**
Comparison of our number and capacity of plants for clinker production in Germany in 2012 (IER, see also Table 2) with the numbers of the German cement association (VDZ, 2013).

| Type | Number | | Daily capacity [t/d] | |
|---|---|---|---|---|
| | VDZ | IER | VDZ | IER |
| Kilns with cyclone preheaters | 39 | 38 | 100,460 | 89,500 |
| Kiln with grate preheater | 6 | 6 | 5050 | 7050 |
| Total | 45 | 44 | 105,510 | 96,550 |
| | | | Average daily capacity [t/d] | |
| Kilns with cyclone preheaters | | | 2355 | 2355 |
| Kiln with grate preheater | | | 917 | 1175 |

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**Table 2**
Selected data of the 49 cement facilities in Germany in 2013. Together with Table 3, the parameters give input for the calculation of energy conservations and the associated costs which are elaborated in Section 2.3.[a]

| No. | General information | | | | | Raw material preparation | | Clinker production |
|---|---|---|---|---|---|---|---|---|
| | Company | Facility/ Location | Integrated production? | Clinker production [kt/y] | Cement production [kt/y] | Vertical roller mill (roll), ball mill | Last major renewal of subsection | Rotary kiln [number] |
| 1 | CEMEX OstZement GmbH | Rüdersdorf | yes | 2000 | 2400 | roll | 1990 | 3 |
| 2 | CEMEX WestZement GmbH | Beckum | yes | 850 | 800 | roll | 1990 | 1 |
| 3 | Dyckerhoff AG | Lengerich | yes | 1200 | 1800 | roll | 2001 | 1 |
| 4 | Dyckerhoff AG | Göllheim | yes | 850 | 800 | ball | 1981[d] | 2 |
| 5 | Dyckerhoff AG | Geseke | yes | 370 | 370 | ball | 2004 | 1 |
| 6 | Dyckerhoff AG | Amöneburg | yes | 200 | 280 | roll | 2005 | 1 |
| 7 | Dyckerhoff AG | Deuna | yes | 1040[c] | 1300 | ball | 1992 | 4 |
| 8 | HeidelbergCement AG | Schelklingen | yes | 726[c] | 1400 | ball | 1990 | 0 |
| 9 | HeidelbergCement AG | Ennigerloh-Nord | yes | 1000 | 1200 | ball | 2000 | 1 |
| 10 | HeidelbergCement AG | Geseke | yes | 800 | 1200 | ball | 1996 | 1 |
| 11 | HeidelbergCement AG | Burglengenfeld | yes | 800 | 1100 | roll | 1974 | 2 |
| 12 | HeidelbergCement AG | Lengfurt | yes | 835 | 1000 | roll | 1981[d] | 1 |
| 13 | HeidelbergCement AG | Hannover | yes | 720[c] | 900 | roll | 1979 | 1 |
| 14 | HeidelbergCement AG | Leimen | yes | 500[c] | 800 | roll | 1994 | 0 |
| 15 | HeidelbergCement AG | Paderborn | yes | 296[c] | 370 | roll | 1981[d] | 1 |
| 16 | Holcim (Deutschland) AG | Höver | yes | 800 | 1800 | roll | 1981[d] | 1 |
| 17 | Holcim (Deutschland) AG | Lägerdorf | yes | 1308 | 1600 | ball | 2002 | 1 |
| 18 | Holcim (Süddeutschland) AG | Dotternhausen | yes | 622 | 780 | roll | 1981[d] | 1 |
| 19 | Lafarge Zement Karsdorf GmbH | Karsdorf | yes | 1520[c] | 1900 | roll | 1981[d] | 2 |
| 20 | Lafarge Zement Wössingen GmbH | Wössingen | yes | 640[c] | 800 | ball | 2009 | 1 |
| 21 | Märker Zement GmbH | Harburg | yes | 800[c] | 1000 | roll | 1981[d] | 1 |
| 22 | Phoenix Zementwerke | Beckum | yes | 400[c] | 500 | ball | 1981[d] | 1 |
| 23 | Portland-zementwerk “Wotan” H. Schneider KG | Üxheim-Ahütte | yes | 350 | 350 | ball | 2000 | 1 |
| 24 | Portland-Zementwerk Wittekind | Erwitte | yes | 800[c] | 1000 | ball | 1981[d] | 1 |
| 25 | Portland-Zementwerke Gebr. Seibel GmbH & Co. KG | Erwitte | yes | 440 | 550 | ball | 1981[d] | 0 |
| 26 | Schwenk Zement KG | Karlstadt | yes | 960[c] | 1200 | roll + ball | 2010 | 1 |
| 27 | Schwenk Zement KG | Allmendingen | yes | 800 | 1000 | roll | 2014 | 1 |
| 28 | Schwenk Zement KG | Mergelstetten | yes | 800[c] | 1000 | roll | 1981[d] | 1 |
| 29 | Schwenk Zement KG | Bernburg | yes | 1000 | 860 | roll | 1990 | 1 |
| 30 | Solnhofer Portland-Zementwerke GmbH & Co. KG | Solnhofen | yes | 420[c] | 420 | roll | 1981[d] | 1 |
| 31 | Spenner Zement GmbH & Co KG, | Erwitte | yes | 825 | 1000 | roll | 1980 | 2 |
| 32 | Südbayer. Portland-Zementwerk Gebr. Wiesböck & Co. GmbH | Rohrdorf | yes | 800 | 1000 | roll | 2006 | 1 |
| 33 | Zement- und Kalkwerke Otterbein GmbH & Co. KG | Großenlüder | yes | 160[c] | 200 | ball | 1980 | 1 |
| 34 | Zementwerk Seibel und Söhne oHg | Erwitte | yes | 480 | 600 | ball | 1995 | 0 |
| 35 | CEMEX HüttenZement GmbH | Dortmund | no | – | 750 | – | – | – |
| 36 | CEMEX OstZement GmbH | Eisenhüttenstadt | no | – | 750 | – | – | – |
| 37 | CEMEX WestZement GmbH | Schwelgern | no | – | 1000 | – | – | – |
| 38 | Dornburger zement GmbH & Co. KG | Dornburg | no | – | 500 | – | – | – |
| 39 | Dyckerhoff AG | Neuss | no | – | 700 | – | – | – |
| 40 | Dyckerhoff AG | Neuwied | no | – | 300 | – | – | – |
| 41 | HeidelbergCement AG | Mainz | no | – | 1400 | – | – | – |
| 42 | HeidelbergCement AG | Königs-Wusterhausen | no | – | 1200 | – | – | – |
| 43 | Holcim (Deutschland) AG | Bremen | no | – | 300 | – | – | – |
| 44 | Holcim (Deutschland) AG | Lübeck | no | – | 100 | – | – | – |
| 45 | Holcim (Deutschland) AG | Rostock | no | – | 100 | – | – | – |
| 46 | Lafarge Zemnt GmbH | Sötenich | no | – | 500 | – | – | – |
| 47 | Märker Zement GmbH | Lauffen | no | – | 300 | – | – | – |
| 48 | Sebald Zement GmbH | Pommelsbrunn | no | – | 300 | – | – | – |
| 49 | Zementwerk Berlin GmbH & Co. KG | Berlin | no | – | 300 | – | – | – |
| **Total** | | | | **26,112** | **41,780** | | **39** | **12** |

[a] The data from case studies and personal communications is confidential. Thus, this table displays data that was collected from published sources. For this, up to twelve, and four in average, sources were needed to obtain the required information for each facility. Sources consist of publications from companies like environment reports (e.g. Holcim, 2013), articles from national (e.g. Winkelhage, 2007), regional newspaper (e.g. Krogmeier, 2012) and public notices according to the German Federal Pollution Control Act (BImSchG), (e.g. Bezirksregierung Arnsberg, 2011). We like to note that due to the amount (over 100 unique sources) and the fact that these sources are in German, we refrained from listing them.

[b] The European standard (EN 197-1) for common cement, lists 27 different cement types into five groups (CEM I–CEM V). In general, the higher the class the more clinker is substituted. For instance CEM III cements have a clinker percentage by mass from 64 to 5%. CEM IV and CEM V have a low share on the total production (<7% in the EU-25) and require tailored grinding processes (EIPPCB, 2010). Therefore, we focused on the cement types CEM I–CEM III.

[c] Despite thorough research, we couldn't obtained the specific value which is therefore estimated. The estimation takes the average and total values of the top-down information from VDZ (2013) into account. Where necessary, we assumed on the basis of VDZ (2013) an average clinker/cement factor of 73%.

[d] Despite thorough research, we couldn't obtained the specific value and estimated it.

| Clinker production | | | | | | | Cement production | | |
|---|---|---|---|---|---|---|---|---|---|
| Shaft kilns [number] | Lepol kilns [number] | Grate, satellite (satel) and other cooler | Precalciner | Cyclone preheater stages [number] | Share of secondary fuels in fuel mix [%] | Last major renewal of subsection | Types of cement [CEM I, CEM II, CEM III][b] | Vertical mill (vert), ball mill | Last major renewal of subsection |
| 0 | 0 | grate | yes | 5 | 73 | 2008 | I–III | vert + ball | 1992 |
| 0 | 0 | grate | no | 4 | 77 | 1990 | I–III | vert + ball | 1997 |
| 0 | 0 | grate | yes | 5 | 42 | 2001 | I–III | vert + ball | 1992 |
| 0 | 0 | grate | no | 4 | 57 | 2005 | I–III | vert + ball | 1991 |
| 0 | 0 | grate | yes | 4 | 68 | 2004 | I,II | ball | 1981[d] |
| 0 | 0 | grate | no | 3 | 53 | 2002 | I–III | ball | 1981[d] |
| 0 | 0 | grate | yes | 4 | 50 | 1992 | I–III | vert + ball | 2001 |
| 0 | 2 | satel | – | – | 60 | 1999 | I, II | ball | 1998 |
| 0 | 0 | satel | – | 4 | 70 | 2000 | I–III | ball | 1991 |
| 0 | 0 | other | – | 4 | 0 | 1996[d] | I | vert + ball | 2004 |
| 0 | 0 | grate | yes | 4 | 60 | 1974 | I–III | ball | 1979 |
| 0 | 0 | grate | yes | 4 | 70 | 1993 | I–III | ball | 1979 |
| 0 | 0 | grate | yes | 4 | 60 | 1997 | I–III | ball | 1992 |
| 0 | 2 | grate | – | – | 52 | 1972 | I–III | vert + ball | 1999 |
| 0 | 0 | other | – | – | 70[c] | 1996[d] | I, II | ball | 1981[d] |
| 0 | 0 | grate | yes | 4 | 70 | 2008 | I–III | ball | 1996 |
| 0 | 0 | grate | yes | 4 | 70 | 1994 | I–III | ball | 1981[d] |
| 0 | 0 | grate | yes | 5 | 40 | 1995 | I, II | ball | 1970[d] |
| 0 | 0 | grate | no | 4 | 80 | 1981[d] | I–III | vert + ball | 1978 |
| 0 | 0 | grate | yes[d] | 5 | 60 | 2009 | I–III | vert + ball | 1985 |
| 0 | 0 | satel | – | 4 | 60 | 1998 | I, II | vert + ball | 1995 |
| 0 | 0 | grate | nein | 4 | 60[c] | 1964 | II, III | ball | 1969 |
| 0 | 0 | grate | yes | 4 | 40[c] | 1996 | I–III | ball | 1998 |
| 10 | 0 | grate | yes | 5 | 60 | 1996[d] | I–III | ball | 2006 |
| 0 | 1 | grate | yes | – | 0 | 1995 | I–III | vert + ball | 1989 |
| 0 | 0 | grate | no | 4 | 10 | 1969 | II | vert + ball | 1989 |
| 0 | 0 | grate | yes | 4 | 96 | 2011 | I–III | ball | 1982[d] |
| 0 | 0 | grate | yes[d] | 6[d] | 95 | 2010 | I, II | ball | 1982[d] |
| 0 | 0 | grate | Yes | 6 | 60[c] | 1990 | I, II | vert + ball | 2001 |
| 0 | 0 | grate | Yes | 4 | 60[c] | 1981[d] | I–III | ball | 1990[d] |
| 0 | 0 | grate | yes | – | 46 | 2007 | I–III | ball | 1999 |
| 0 | 0 | grate | yes | 4 | 90 | 1981[d] | I, II | ball | 1969[d] |
| 2 | 0 | grate | no | – | 60 | 2007 | I–III | ball | 2009 |
| 0 | 1 | other | – | – | 60[c] | 1995 | I–III | ball | 1981[d] |
| – | – | – | – | – | – | – | III | ball | 1979 |
| – | – | – | – | – | – | – | III | ball | 2008 |
| – | – | – | – | – | – | – | III | vert + ball | 1981[d] |
| – | – | – | – | – | – | – | I–III | vert + ball | 1995[d] |
| – | – | – | – | – | – | – | III | vert + ball | 2010[d] |
| – | – | – | – | – | – | – | I–III | vert + ball | 2004 |
| – | – | – | – | – | – | – | II, III | ball | 2009 |
| – | – | – | – | – | – | – | I–III | vert + ball | 1990 |
| – | – | – | – | – | – | – | III | ball | 1985 |
| – | – | – | – | – | – | – | I–III | vert + ball | 1981[d] |
| – | – | – | – | – | – | – | I, II | ball | 1980[d] |
| – | – | – | – | – | – | – | III | vert + ball | 1981 |
| – | – | – | – | – | – | – | II, III | vert + ball | 1981 |
| – | – | – | – | – | – | – | II | ball | 2010 |
| – | – | – | – | – | – | – | I–III | ball | 2010 |
| **6** | | | | | | | | | |

suitable for benchmarking individual EC measures. However, the sum of the measures-specific EC potential does not reflect the situation of the whole plant. For instance, measures that utilise the same heat source influence each other, as heat used by one measure will not be available for a second measure. These interactions can only be taken into account by an additional boundary: the facility boundary. We use this boundary to derive the total EC and CA potential of the German cement industry.

### 2.2. Data collection

Obtaining high detailed plant-specific data such as type, capacity, year of construction and modernisation is challenging. To the current knowledge of the authors, there is no commercial database for German cement plants available that provides the same high-level of detail and quality than for instance the PLANT-FACTs database of the Steel Institute VDEh (2011). Existing

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databases like the Global Database from the International Cement Review magazine provided only incomplete and often outdated data for German plants (see Cemnet, 2007). We therefore use a two-step approach for the data collection. By analogy with the PLANTFACTs database, we collected data on the cement companies and their plants from German trade journals like "ZKG International" (e.g. Bracht, 2011). Despite our efforts, the journals alone could not provide all the information, so we additionally consulted publications from companies like environment reports (e.g. Holcim, 2013) and articles from national (e.g. Winkelhage, 2007) and regional newspaper (e.g. Krogmeier, 2012). Within the German Federal Pollution Control Act (BImSchG), substantial modification of the plant needs to be approved and the public needs to be informed. Thus, public notices provide further detailed data (e.g. Bezirksregierung Arnsberg, 2011). The obtained data is enhanced and checked for consistency in the second step by three cases studies and personal communications with plant manufactures and operators. The data captured in the second step is confidential. Table 2 therefore displays only selected parameters of the 49 cement facilities in Germany from the first step.

The acquired data was compared to the aggregated number and capacity of plants published by the German cement association VDZ (2013). It is appealing that our data covers 1 kiln less and that the total capacity is 6% lower than of the VDZ data (see Table 1). Inconsistence conversion factors might be one explanation for the lower capacity. The performance of kilns is usually given in t/d. For conversion annual capacity to daily capacity, we assumed, in line with Weiß et al. (2012), 330 production days per year. VDZ usually assumes 320 days or less per year. Still, considering that Achternbosch and Bräutigam (2000) found a similar divergence in their study on German clinker capacities, plus, that the average daily capacity of our data is in line VDZ, we assume that the acquired data is sufficient for the investigation.

In terms of EC measures, we collected in a first step information from international literature (e.g. Hasanbeigi et al., 2013b; Madlool et al., 2013; Sathaye et al., 2010) and compared them to literature with focus on Europe (e.g. CSI/ECRA, 2009; EIPPCB, 2010) and on Germany (e.g. Schlomann et al., 2011). In a second step, the obtained measures were discussed with experts from Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT) as well with plant manufactures (e.g. Gebr. Pfeiffer SE, ThyssenKrupp Resource Technologies GmbH, Aumund Fördertechnik GmbH) and operators during the ZKG International "Technical Excursion 2013" in Wiesbaden, Germany. The complete list of measures with references can be found in Table 3.

For the economic perspective, prices of energy carriers and $CO_2$ emissions need to be defined so that ECs can be monetarily quantified. Carbon and fossil-fuel prices are based on Fleiter et al. (2012). Retail price for electricity depend on a considerable extent on national taxes, polices, and on the annual electricity consumption. Seefeld and Claaßen (2011) give a good estimate of the retail electricity prices for energy-intensive industries in Germany for the period 2013–2020. We used internal model-generated estimations of the spot market price development (see Blesl et al., 2010) to extent the electricity prices of Seefeld and Claaßen (2011) to the remaining years till 2035. Fig. 2 displays the price developments from 2013 to 2035 in the base scenario (see Fig. 12 for the price developments of the sensitivity analysis).

Secondary fuels represent a special form of energy carrier, because they are characterised by their composition of waste materials. We distinguish between the biomass and the non-biomass component of secondary fuels for two reasons: First, the utilisation of biomass is under increasing competition and we assume that, although the share of secondary fuel will continue to rise in the fuel mix, the total amount of biomass in the fuel mix remains constant. Second, biomass that fulfils the sustainability requirement of EC (2012) is accounted as $CO_2$-neutral in the EU Emission Trading Scheme (EU ETS) and, thus, has additional cost advantages. It is noteworthy that, in contrast to the European Commission and this article, the German cement association (VDZ) accounts also non-biomass types of secondary fuels as $CO_2$-neutral.

### 2.3. Calculation of energy conservation cost curves

First, we identified EC measures as they lay the foundation for the plant-specific parameters in the industry analysis. Together with the result of the parameter analysis which defined the price developments (see Fig. 2) and interest rates, plant-specific ECs and costs can be calculated separately. On this basis, ECCCs on process level can be derived (see Fig. 4). To calculate the total EC potential, the system boundary is extended to cover the whole facility (see Fig. 1) so that competing measures are excluded. Following the approach of the neoclassical theory – individuals maximise utility and firms maximise profits – the measure with the highest net present value (NPV) is applied. With the help of the ECCC on facility level, the cost-effective EC potential can be obtained. On this basis, the sensitivity of the cost-effective EC potential against varying electricity, $CO_2$ prices and interest rates is analysed and the effects on the energy-related production costs in the period 2013–2035 are quantified. This approach was developed during the investigation of EC potentials in the German iron and steel industry and is elaborated in Brunke and Blesl (2014).

#### 2.3.1. Calculation of the energy conservation potential

The energy conservation potential $EC_{k,i}$ for a measure $k$ is calculated for each plant $i$ individually. In a first step, the respective requirements for the applicability of measure $k$ to plant $i$ are checked. These requirements are:

- Measure $k$ is not applied to plant $i$ yet.
- Plant $i$ condition status is operational.
- Plant $i$ will not be shut down within the next three years.
- Plant $i$ fulfils the measure-specific technological requirements (see Table 3).

If all four requirements are fulfilled, energy conservations $EC_{k,i}$ of measure $k$ at plant $i$ are determined by the product of the specific fuel $FlC_k$ and electricity conservations $ElC_k$ and the annual capacity $Cap_i$

$$EC_{k,i} = ((FlC_k + ElC_k) \times Cap_i). \quad (1)$$

$Cap_i$ refers to the capacity of the respective subsection namely raw material preparation, clinker and cement production (see Table 2). $FlC_k$ and $ElC_k$ in the preparation of raw material subsection are referenced to the production of one tonne of clinker (see Table 3). In case of measures with plant-related specific ECs, $EC_{k,i}$ constitutes of the difference between the measure-specific utilisation value $X_{BAT,k}$ (e.g. share of secondary fuels in the fuel mix) of the best available technology (BAT) and the current utilisation value $X_{i,k}$ of plant $i$ multiplied by the ECs and the annual capacity $Cap_i$ of plant $i$

$$EC_{k,i} = \left(\left(X_{BAT,k} - X_{k,i}\right) \times (FlC_k + ElC_k) \times Cap_i\right). \quad (2)$$

The three measures to which (2) applies are elaborated in the following. German cement works use secondary fuels like tires, industrial and commercial waste to substitute fossil fuels for primarily economic reasons since 25 years. In 2013, the share of secondary fuels

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**Table 3**
Energy conservations and costs for measures applicable to the cement industry in Germany in 2013. Together with Table 2, the parameters give input to the calculation of energy conserva[illegible] and the associated costs which are elaborated in Section 2.3.

| ID | Name | Electricity conservations [MJ/t product] | Fuel conservations [MJ/t product] | $CO_2$ abatements [kg $CO_2$/t product][c] | Capital expenditure [$EUR_{2013}$/t capacity] | Operational expenditure [$EUR_{2013}$/t product][d] | Technical lifetime [y] | Coupling factor (see Table 4) | Requirements for application[e] | Competing measures | Number of plants in 2013 to which the measure is applicable [# plants of# total plants] | [illegible] clinker/[illegible]ent capacity [illegible]2013 to which measure is applicable [kt/y] | Sources[i] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw material preparation | | | | | | | | | | | | | |
| RAW2 | Replacing a ball mill with vertical roller mill | 39.60 | 0 | 0.00 | 14.95 | 0.00 | 20 | 0 | Ball mill raw material grinding | | 16 of 34 | 15,203 | (Hasanbeigi et al., 2013b) |
| RAW3 | Replacing pneumatic with mechanical transport system[b] | 11.27 | 0 | 0.00 | 8.55 | 0.00 | 20 | 0.2 | Pneumatic transport systems | | 16 of 34 | 14,853 | (Hasanbeigi et al., 2013b; Weber, 2010) |
| RAW4 | Gravity-type homogenising silo[b] | 9.58 | 0 | 0.00 | 3.00 | 0.00 | 25 | 0 | Pneumatic homogenising silos | | 18 of 34 | 16,272 | (Hasanbeigi et al., 2013b; VDZ, 2013; Worrell and Galitsky, 2008) |
| Clinker production | | | | | | | | | | | | | |
| KLIN1 | Changing from Lepol kilns to kilns with cyclone preheater and precalciner | 18.00 | 900 | 80.00 | 85.00 | 0.00 | 40 | 0 | Grate preheater & capacity > 1000 t/y | KLIN11 (NEW1) | 4 of 6 | 2800 | (CSI/ECRA, 2009; Harder, 2010a) |
| KLIN2 | Retrofitting of precalciner | 0.00 | 430 | 16.27 | 23.21 | 0.00 | 40 | 0.5 | Cyclone preheaters & no precalciner & FUEL1 | KLIN4 KLIN11 (NEW1) | 21 of 39 | 17,025 | (Hasanbeigi et al., 2013b; Worrell and Galitsky, 2008) |
| KLIN3 | Retrofitting of cyclones with lower pressure drop[b] | 9.36 | 0 | 0.00 | 3.68 | 0.00 | 20 | 0.2 | If cyclone type is not available: construction year < 1995 | KLIN7 KLIN11 (NEW1) | 17 of 39 | 14,938 | (CSI/ECRA, 2009) |
| KLIN4 | Changing from rotary or satellite cooler to modern grate coolers | −12.60 | 200 | 7.57 | 8.75 | 0.00 | 20 | 0.2 | Capacity > 200 kt/y & KLIN2 | KLIN2 KLIN11 (NEW1) | 5 of 39 | 4300 | (CSI/ECRA, 2009; Hammerich, 2009; Harder, 2011) |
| KLIN5 | Modernisation of grate coolers[b] | 0.00 | 25.1 | 0.95 | 0.75 | 0.00 | 20 | 0 | If cooler type is unknown: construction year < 2000 & capacity > 1000 kt/y | KLIN11 (NEW1) | 4 of 39 | 4300 | (CSI/ECRA, 2009; EIPPCB, 2010; Harder, 2011) |
| KLIN6 | ORC for low-temperature waste energy recovery | 31.04 | 0 | 0.00 | 10.00 | 0.00 | 35 | 0.2 | KLIN4 or KLIN5 & low moisture content of raw materials[h] | (NEW1) | 12 of 39 | 10,870 | (CSI/ECRA, 2009; Harder, 2013; LfU, 2001) |
| KLIN7 | Extending the cyclone preheater to 5 stages | 0.00 | 90 | 7.00 | 4.00 | 0.00 | 20 | 0.5 | Cyclone stages < 5 | KLIN3 (NEW1) | 19 of 39 | 18,358 | (CSI/ECRA, 2009) |
| KLIN9 | Optimisation of the process control system[b] | 8.46 | 116 | 4.39 | 1.59 | 0.00 | 10 | 0.2 | Last modernisation or construction year < 2000 | | 5 of 39 | 5300 | (Hasanbeigi et al., 2013b; Worrell and Galitsky, 2008) |
| KLIN11 | Consolidation of kiln lines/doubling of capacity to 6000 t/d | 10.80 | 175 | 6.62 | 240.00 | 0.00 | 30 | 0 | 1 < kiln lines & total capacity increase of Germany < 5% | (NEW1) KILN | 9 of 39 | 7772 | (CSI/ECRA, 2009) |
| Cement production | | | | | | | | | | | | | |
| CEM1 | | 0.00 | $3650x + 420$[f] $\{0.3 < x < 0.7\}$ | $825x + 100$[f] $\{0.3 < x < 0.7\}$ | 5.00 | 0.00 | 20 | 0 | Production of Portland or Portland | CEM5 | 12 of 50 | 8320 | (CSI/ECRA, 2009; Ehrenberg, 2006) |

(continued on next page)

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**Table 3** (*continued* )

| ID | Name | Electricity conservations [MJ/t product] | Fuel conservations [MJ/t product] | $CO_2$ abatements [kg $CO_2$/t product][c] | Capital expenditure [$EUR_{2013}$/ t capacity] | Operational expenditure [$EUR_{2013}$/ t product][d] | Technical lifetime [y] | Coupling factor (see Table 4) | Requirements for application[e] | Competing measures | Number of plants in 2013 to which the measure is applicable [# plants of# total plants] | …l clinker/ …ent capacity …13 to which …sure is …icable [kt/y] | Sources[i] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Additional use of granulated blast furnace slag | | | | | | | | slag cement (CEM II/ S) & current slag share < 70% & total slag usage Germany < 420 kt/y (see Ghenda, 2011) | | | | |
| CEM2 | Replacing ball mills with vertical roller mills | 93.35 | 0 | 0.00 | 15.09 | 0.00 | 20 | 0.2 | Ball mill for cement grinding | CEM4 | 29 of 50 | 23,250 | (CSI/ECRA, 2009; Harder, 2010b) |
| CEM3 | Retrofitting high efficiency separators[b] | 14.40 | 0 | 0.00 | 2.71 | | 20 | 0.2 | Last modernisation or construction year < 2000 | | 31 of 50 | 25,640 | (Clauser, 2010; CSI/ ECRA, 2009) |
| CEM4 | Improved grinding media for ball malls[b] | 21.96 | 0 | 0.00 | 2.37 | 0.00 | 10 | 0.2 | Ball mill for cement grinding and last | | | | |
| | modernisation < 2000 | CEM2 | 39 of 50 | 31,500 | (Hasanbeigi et al., 2013b; Madlool et al., 2013) | | | | | | | | |
| CEM5 | Additional use of fly ash | $432x + 54$[f] $\{0.25 < x < 0.35\}$ | $3800x + 220$[f] $\{0.25 < x < 0.35\}$ | $110x + 8$[f] $\{0.25 < x < 0.35\}$ | 6.00 | 3.00 | 20 | 0 | Production of Portland fly ash cement (CEM II/V) & current fly ash share < 35% & total fly ash usage Germany < 250 kt/y (see Backes et al., 2011) | CEM1 | 9 of 50 | 11,900 | (CSI/ECRA, 2009) |
| Fuel preparation | | | | | | | | | | | | | |
| (FUEL1) | Using 80% of secondary fuels | −3.00 | $-300x$[f] $\{0 < x < 0.8\}$ | $32.44x$[f] $\{0 < x < 0.8\}$ | 5.00 | −1.65[g] | 20 | 0 | Precalciner or KLIN2 & current rate < 80% | | 11 of 39 | 9147 | (CSI/ECRA, 2009; EIPPCB, 2010) |
| FUEL2 | Using vertical mills for coal grinding | 5.29 | 0 | 0.00 | 1.73 | 0.00 | 20 | 0 | Ball mill for coal grinding | | 2 of 39 | 2100 | (Harder, 2010b; Hasanbeigi et al., 2013b) |
| Radical process innovations[a] | | | | | | | | | | | | | |
| (NEW1) | Celitement[a] | 0.00 | 1210 | 278 | 203.5 | 0.00 | 30 | 0 | Production of Portland cement (CEM I) & total capacity Germany < 8300 kt/y | KLIN[j] (NEW2) FUEL[j] | 8 of 39 | 8300 | (Stemmermann et al., 2010) |
| (NEW2) | Fluidised bed advanced cement kiln systems[a] | −32.40 | 300 | 11.35 | 47.56 | 0.49 | 30 | 0 | Kiln with preheaters | (NEW1) | 34 of 39 | 30,175 | (CSI/ECRA, 2009; NEDO, 2008) |

[a] Measure has not reached market maturity and is not included in the assessment of the total energy conservation potential.
[b] Plant-related data for checking the applicability of the measure at the respective plant is partly based on assumptions.
[c] Only direct, i.e. fuel and process-related, $CO_2$ emissions are accounted for.
[d] Change in the annual operation expenditures that are not energy-related (e.g. increased maintenance costs).
[e] Additional requirement for adoption that go beyond the standard requirements (see Section 2.3).
[f] Specific energy conservations and $CO_2$ abatements depend on the current plant-specific utilisation rate $x$ (see Section 2.3).
[g] Operational expenditures are calculated as the difference of the average coal and secondary fuel prices of the period 2013–2035 (see Section 2.3.2).
[h] If no data could be obtained, we assumed that the moisture content correlates with geological age of raw materials. On this basis, we assumed that ORC can be used in plants utilising raw materials older than 205 million years and calculated the applicability on the basis of Basten et al. (2002).
[i] We list up to three main sources for each measure. The obtained parameter was discussed with plant manufactures (e.g. Gebr. Pfeiffer SE, ThyssenKrupp Resource Technologies GmbH, Aumund Fördertechnik GmbH) and operators and adapted accordingly.
[j] Competition applies to all measures of the respective subsection (see Section 2.1).

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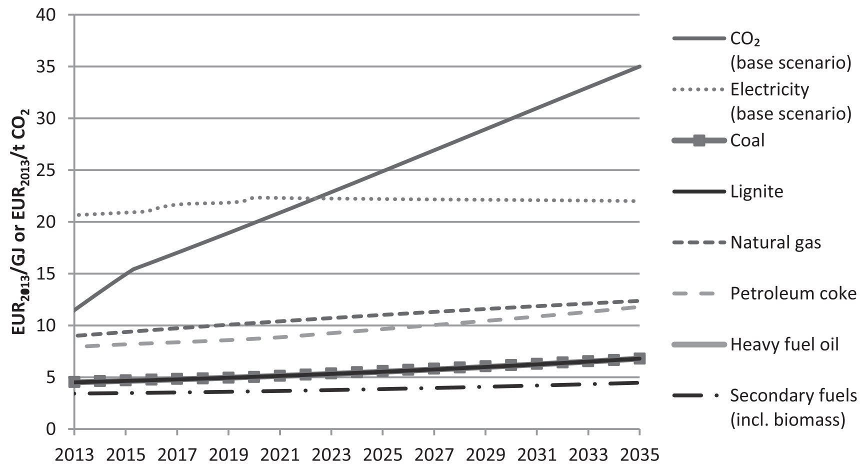


**Fig. 2.** Price developments of energy carriers and $CO_2$ certificates for the German cement industry in the period 2013–2035. The electricity and $CO_2$ price development give the base scenario (see Section 3.4.1).

in the fuel mix of German cement works was over 60% (see Fig. 3). Increasing the share up to 80% will additionally reduce the utilisation of primary energy carriers and abate $CO_2$ emissions, if $CO_2$-neutral biomass is included in the secondary fuel mix (see Gäbel and Tillman, 2005). However, from a final energy perspective, the use of secondary fuels will also increase the specific energy consumption due to a lower calorific value, higher heterogeneity and higher chlorine content (CSI/ECRA, 2009). The higher energy consumption $EC_{FUEL1,i}$ depends on the current utilisation rate of secondary fuels $X_{FUEL1,i}$ and the linear relationship for the measure FUEL1 given in Table 3

$$EC_{FUEL1,i} = \left((0.8 - X_{FUEL1,i}) \times (-300\ \text{MJ/t}) \times \text{Cap}_i[\text{t}]\right), \quad \text{if } 0 < X_{FUEL1,i} < 0.8. \tag{3}$$

The other two measures to which (2) applies are based on the same principle. Using additives like fly ash or granulated blast furnace slag (GBFS) in cement production changes the characteristics so that new types of cements are created (e.g. CEM II and CEM III, see EIPPCB, 2010) which reduce the need of the energy-intensive clinker production (see Ammenberg et al., 2014). In 2011, one unit cement produced in Germany contained in average 0.73 units of clinker (VDZ, 2013). Additional use of additives could further reduce the clinker input. In comparison to secondary fuels, the supply of fly ash and GBFS is more restricted. For GBFS, the prospective supply is linked to the utilisation of German blast furnaces. Although the production of oxygen steel in Germany is likely to decrease, we assess an average remaining potential of 420 kt/y GBFS in the period 2013–2035 due to a substitution of the capacity shares from the road construction sector to the steel sector, increasing granulation capacities and increasing nationwide GBFS transportation (see Fig. 5). Based on CEM1 in Table 3 and on (2), $EC_{CEM1,i}$ is calculated as follows:

$$EC_{CEM1,i} = \left((0.7 - X_{CEM1,i}) \times (-3650\ \text{MJ/t}) \times \text{Cap}_i[\text{t}]\right), \quad \textit{if } 0.3 < X_{CEM1,i} < 0.7 \text{ and } \sum_{i \in I}\left((0.7 - X_{CEM1,i} \times \text{Cap}_i)\right) < 420\ \text{kt}. \tag{4}$$

$X_{CEM1,i}$ represents the current utilisation of GBFS at plant $i$. In order to ensure that the annual input GBFS at all plants $I$ with $i \in I$ do not exceed the identified potential of 420 kt/y, a side condition is accordingly introduced.

The utilisation of fly ash is similar to the GBFS with the exception that the supply is linked to the usage of pulverised coal in combustions plants in Germany. In the light of the continuing expansion of renewable energies, the supply is likely to decrease in the future. According to Backes et al. (2011), coal-fired power plants will be needed during the transformation process and higher prices for fly ash will be paid so that the supply is redistributed in favour of the cement industry. On this basis, we assess an average additional potential of 250 kt/y from 2013 till 2035. Analogously to GBFS, the EC for fly ash $EC_{CEM5,i}$ is calculated as follows:

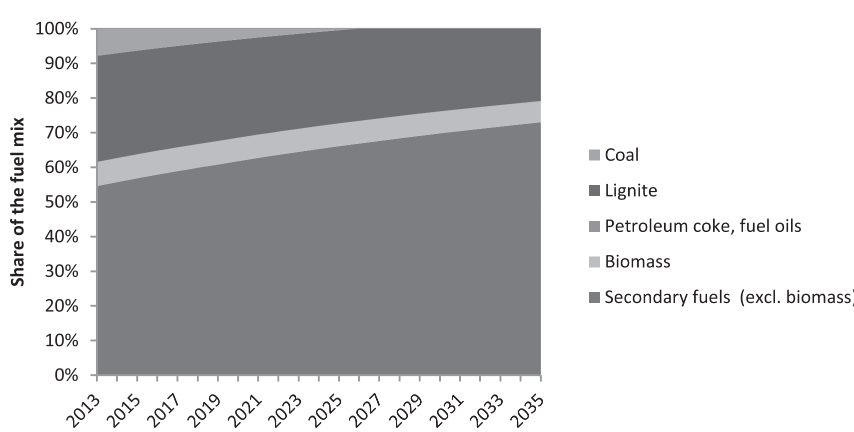


**Fig. 3.** Projected fuel mix of the cement industry in Germany in the period 2013–2035 with focus on the biomass and non-biomass share of secondary fuels. The distinction is made in order to account $CO_2$ abatements and cost reductions with regard to the EU ETS adequately.

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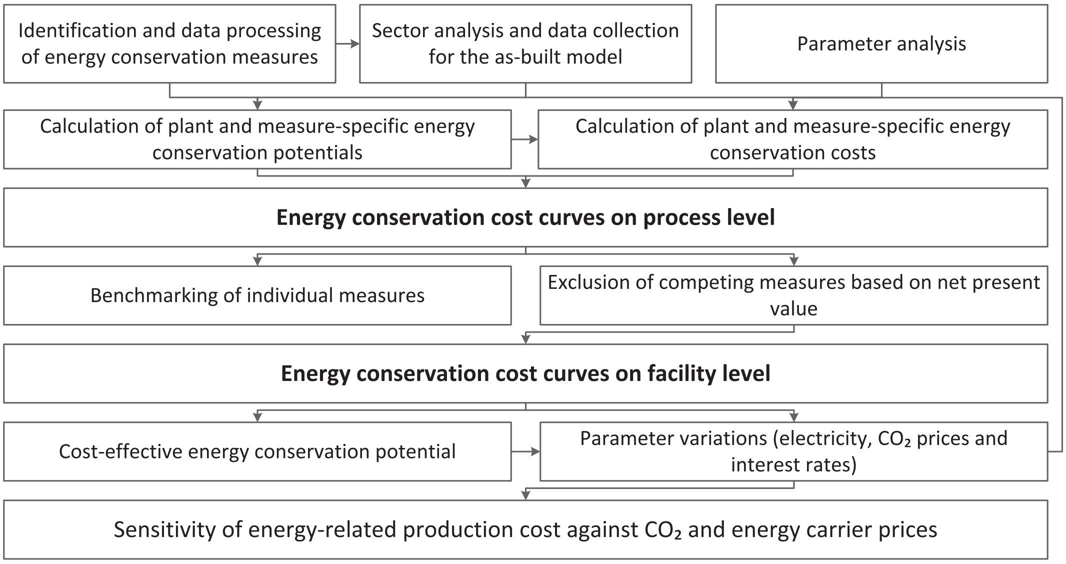


**Fig. 4.** Schematic overview of the bottom-up method to develop energy conservation cost curves for the German cement industry on process and facility level. For the subsequent sensitivity analysis, the scheme is repeated with varying electricity, $CO_2$ prices and interest rates which are defined in the parameter analysis (see Fig. 12).

$$\mathrm{EC}_{\mathrm{CEM5},i} = \left((0.35 - X_{\mathrm{CEM5},i}) \times (-4232\ \mathrm{MJ/t}) \times \mathrm{Cap}_i[\mathrm{t}]\right), \quad \textit{if}\ 0.25 < X_{\mathrm{CEM5},i} < 0.35 \text{ and } \sum_{i \in I}\left((0.35 - X_{\mathrm{CEM5},i}) \times \mathrm{Cap}_i\right) < 250\ \mathrm{kt}. \tag{5}$$

Besides energy conservations, the operational expenditures change in the extent of the adoption ($X_{\mathrm{BAT},k} - X_{k,i}$). This change is taken into account by calculating the differences between the prices for fossil fuels and secondary fuels, and the differences of the total production costs of clinker to the prices of GFBS, or fly ash, respectively (see Table 3).

At the end, the total EC potential $\mathrm{EC}_k$ of a measure $k$ results from the sum of the individual conservations $\mathrm{EC}_{k,i}$ from all plants $I$ with $i \in I$. The respective abatement of $CO_2$ emissions $\mathrm{CAbat}_k$ are calculated analogously to $\mathrm{EC}_k$.

$$\mathrm{EC}_k = \sum_{i \in I} \mathrm{EC}_{k,i} \tag{6}$$

#### 2.3.2. Calculation of the energy conservation costs

The calculation of the marginal EC costs $\mathrm{MECC}_k$ is divided into three steps:

In the first step, the annual cash flows $\mathrm{CF}_{k,i,t}$ for each plant $i$, measure $k$ and year $t$ are calculated. $\mathrm{CF}_{k,i,t}$ consists of the cost reduction due to the reduced fuel consumption ($\mathrm{FlC}_k \times \mathrm{FlCost}_t$), reduced electricity consumption ($\mathrm{ElC}_k \times \mathrm{ElCost}_t$) and reduced costs for $CO_2$ certificates ($\mathrm{CAbat}_k \times \mathrm{CCost}_t$), the non-energy and non-carbon-related change in operational expenditures $\mathrm{OPEX}_k$ (e.g. increased or decreased maintenance costs) as well as the condition-based capital expenditure $\mathrm{CAPEX}_{k,t}$

$$\mathrm{CF}_{k,i,t} = \left(\mathrm{FlC}_k \times \mathrm{FlCost}_t + \mathrm{ElC}_k \times \mathrm{ElCost}_t + \mathrm{CAbat}_k \times \mathrm{CCost}_t - \mathrm{OPEX}_k + \mathrm{CAPEX}_{k,t}\right) \times \mathrm{Cap}_i \tag{7}$$

$\mathrm{CAPEX}_{k,t}$ in (3) is separated into two cases: retrofit, or substitution by BAT. In the first case, it is assumed that measure $k$ expands the existing plant $i$ modularly. The level of coupling between the

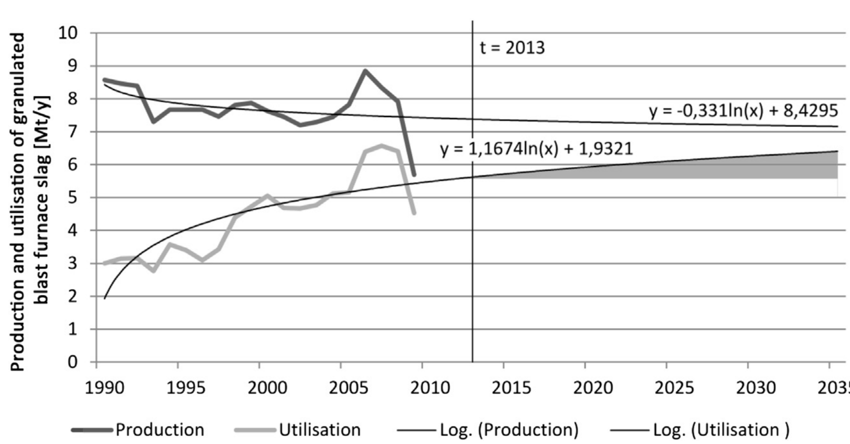


**Fig. 5.** Logarithmic extrapolated production and utilisation of granulated blast furnace slag in the German iron and steel industry based on Ghenda (2011). The grey area indicates the remaining potential of 420 kt/y in average for the period 2013–2035.

measure $k$ and the underlying plant $i$ is expressed as the factor $\alpha_k \in [0,1]$. The higher the factor, the more $k$ is integrated with $i$ and the higher is the complexity as well as the risk to adopt the measure for the end user. This factor was introduced in order to facilitate a company-oriented point of view. For instance, companies tend to postpone the adaption of EC measures until the renewal of the plant is necessary, and assess the retrofit of older plants with additional risks. The factor $\alpha_k$ comes into play every time the measure or the plant reaches its end of lifetime (see Table 4).

In the second case where measure $k$ replaces plant $i$ completely (e.g. KLIN1, KLIN11 in Table 3), the costs in the reference scenario, e.g. present plant needs to be renewed overtime, are included in $CAPEX_{k,t}$ (see Table 4). In contrast to the retrofit measures, the linear depreciations of both measure $k$ and the reference plant $i$ are credited to $CAPEX_{k,t}$ at the end of the investigated period $t_{End}$.

In the second step, the annual cash flows $CF_{k,i,t}$ are discounted with an interest rate $r$ and summed together over the observation period 2013–2035 to get the net present value $NPV_{k,i}$ of measure $k$ for the base year 2013

$$NPV_{k,i} = \sum_{t=2013}^{2035} CF_{k,i,t} \times (1+r)^{-t+2013}. \tag{8}$$

For the base scenario (see Section 3.4.1), we selected an interest rate $r = 15\%$ that can be compared with the return of on investment in the production of saleable goods and is commonly used in company-oriented bottom-up investigations (e.g. Hasanbeigi et al., 2013c; Fleiter et al., 2012). The third step combines (8) with the annuity factor $ANF_{r,m}$

$$ANF_{r,m} = \frac{(1+r)^m \times r}{(1+r)^m - 1} \tag{9}$$

and (6), in order to get the marginal energy conservation costs $MECC_{k,r,m}$

$$MECC_{k,r,m} = \frac{\sum_{i \in I} NPV_{k,i} \times ANF_{r,m}}{EC_k}. \tag{10}$$

## 3. Results

Following the method outlined in Section 2, the ECCCs are calculated by applying the identified EC measures to each of the German cement plants and by aggregating the individual potentials and costs afterwards. The fossil fuel and electricity conservations are displayed separately in order to respect the heterogeneity of the energy carriers in terms of exergy and price. It is further distinguished between the process and facility boundary as outlined in Section 2.1. All following cost curves up to the sensitivity analysis (see Section 3.4) are based on the price developments of Fig. 2 with an interest rate of 15%.

### 3.1. Fuel conservation cost curves

For a start, the fuel conservation cost curve (FCCC) on process level is considered (see Fig. 6). As outlined in Section 2.1, process boundaries are used for benchmarking individual measures. The major drawback, however, is that the $x$-axis shows the measure-specific fuel conservations and not the total fuel conservation potential of the whole sector. Basically, all measures left from the intercept with the $x$-axis are economical, but the size of their rectangle, marginal conservation costs ($y$-axis) multiplied by energy conservations ($x$-axis), show their NPV and thus their total cost-effectiveness.

Increasing the share of secondary fuels in the fuel mix to 80% (FUEL2) bends the traditional concept of the ECCC. Besides plastics, tyres and oily wastes, industrial and commercial materials have comparatively lower specific heating values (10–18 GJ/t) and a higher chlorine content (CSI/ECRA, 2009). Thus, the higher the secondary fuel share the more energy per tonne of clinker is needed (see (2)) (Table 3). Increasing the secondary fuel share to 80% will therefore lead to an increase of the final energy usage of 1.7 PJ/y, but will decrease the energy costs by 1.02 EUR/GJ, or 1.74 million $EUR_{2013}$ for all respective plants. It needs to be noted that other studies (e.g. Hasanbeigi et al., 2013a; Morrow et al., 2013) account for primary energy conservations and thus achieve a reduction of the energy intensity due to the lower primary energy factors of secondary fuels (see Section 4).

The development of new hydraulic binders such as "Celitement" (NEW1), providing they are commercially available, would be obviously the most effective measure. The fluidised bed advanced cement kiln system (NEW2) achieves only poor results, because of its high capital and maintenance expenditures (see Table 3). Both measures, NEW1 and NEW2, have not reached market maturity and are therefore not respected in the total conservation potential. Of the available measures, the substitution of Lepol kilns by BAT (KLIN1) and the further reduction of clinker content in cement by using GBFS (CEM1) are the most cost-effective measures. A similar cost-effectiveness of clinker substitutes was also identified by Ammenberg et al. (2014). With the given prices in the base scenario, changing from rotary or satellite cooler to modern grate coolers (KLIN4) as well as retrofitting of precalciner (KLIN2) are not cost-effective, although both could achieve considerable ECs of 5.93 and 3.06 PJ/y. The consolidation of kiln lines, or doubling of the kiln capacity to 6000 t/d (KLIN11), respectively, is only cost-effective when the according plant is near its end of lifetime. Recently modernised plants and lifetimes of 30 years resulted in high marginal conservation costs for this measure.

**Table 4**
The table shows the different states of the capital expenditure $CAPEX_{k,t}$ in dependence on the type of measure $k$, time $t$ and on the event. $CAPEX_k$ refers to the capital expenditure of a measure $k$ in Table 3. $CAPEX_i$ represents the capital expenditure for renewing the existing plant with the same efficiency. $\alpha_k \in [0,1]$ expresses the level of coupling between measure $k$ and plant $i$ which impacts negatively the cost for adoption.

| Type of measure | Time and event (Description) | | | |
|---|---|---|---|---|
| | $t = 2013$ (Begin of investigation) | $2013 < t < 2035$, $i_{age} = i_{lifetime}$ (Plant $i$ is at the end of its technical lifetime and needs to be renewed.) | $2013 < t < 2035$, $k_{age} = k_{lifetime}$ (Measure $k$ is at the end of its technical lifetime and needs to be renewed.) | $t = 2035$ (End of investigation: Measures and reference plants are linear depreciated.) |
| Retrofit: $CAPEX_{k,t}=$ | $CAPEX_k$ | $\alpha_k \cdot CAPEX_k$ | $CAPEX_k$ | $-\frac{k_{lifetime}}{k_{age}} CAPEX_k$ |
| Substitution: $CAPEX_{k,t}=$ | $CAPEX_k$ | $-CAPEX_i$ | $CAPEX_k$ | $-\frac{k_{lifetime}}{k_{age}} CAPEX_k + \frac{i_{lifetime}}{i_{age}} CAPEX_i$ |

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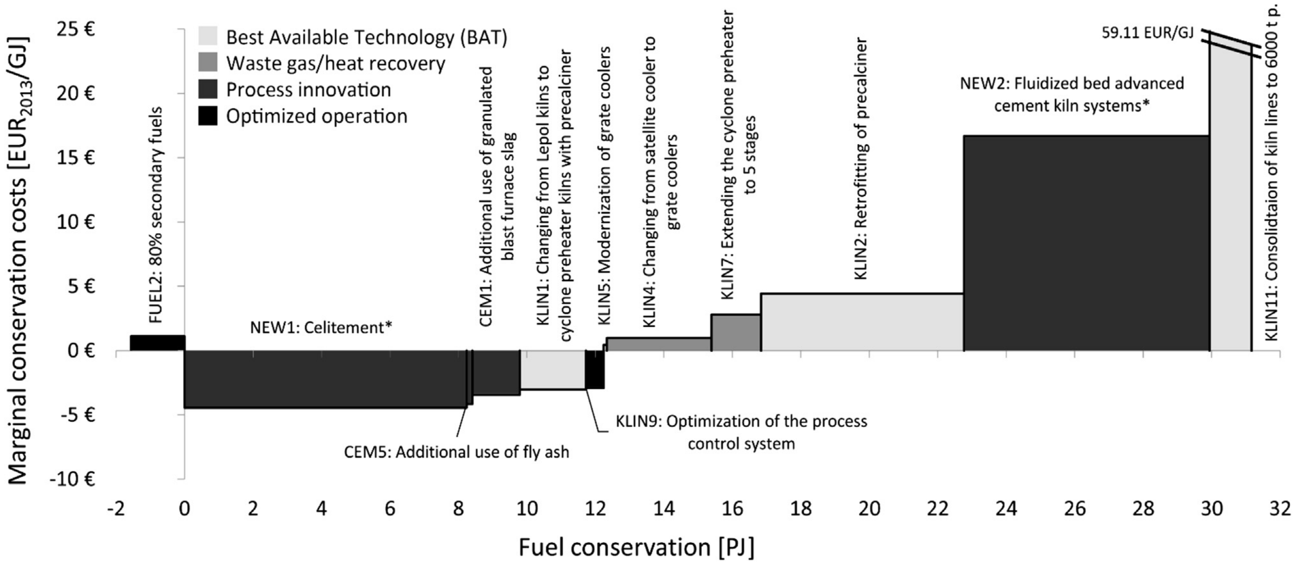


**Fig. 6.** Fuel conservation cost curve on process level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$ for the year 2013). On process level, the *x*-axis shows the fuel conservation potential of individual measures without respecting the influences of other measures.

On facility level, when two measures influence each other in their conservation potential and both can be applied to a plant, the measure with the higher NPV is adopted (see Section 2.1). In this way, the total EC potential of the facility is inevitably decreased, but, at the same time, the cost-effectiveness is increased. However, this effect is not significant enough to shift the measures KLIN5 and KLIN4 into the cost-effective area. The application of both measures would result in additional costs of 3 million $EUR_{2013}$/y for the German cement industry. On facility level, the total economical fuel conservation potential can be derived from the intersection (see Fig. 7) and accumulates to 4.00 PJ/y or 4% of the fuel demand in 2012 on the basis of DESTATIS (2014). This EC leads to a cost reduction of 12.8 million $EUR_{2013}$/y for industry as a whole.

### 3.2. Electricity conservation cost curves

Electricity is investigated separately from other energy carriers in order to account for its higher price and exergy. Similar to the fuel conservation results, we use the process perspective to assess the effectiveness of measures among each other. New process control systems that continuously monitor the chemical composition of the raw material and the product (KLIN9) achieve the highest cost-effectiveness followed by an increased substitution of clinker by fly ash (CEM5). In contrast to GBFS, fly ash needs no additional grinding and, thus, conserves electricity as well (see (3)). However, the application potential is restricted due to the dependency on coal-fired furnaces (see Section 2.3.1). Improved grinding media for ball mills (CEM4) is with 0.49 $EUR_{2013}$/GJ not

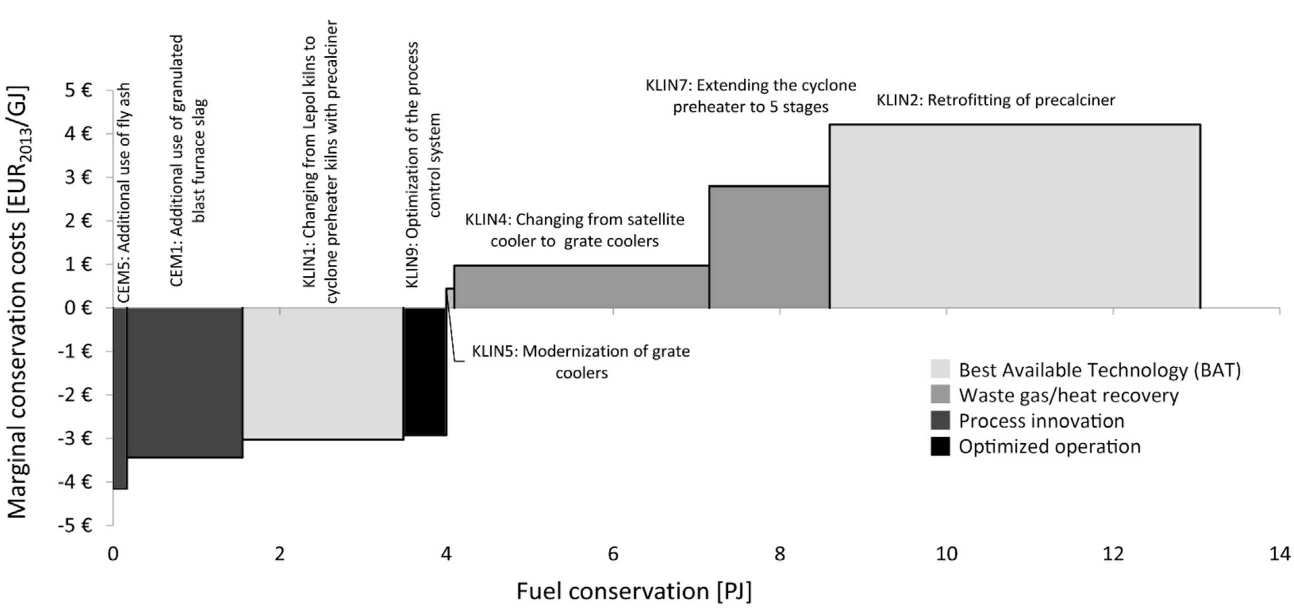


**Fig. 7.** Fuel conservation cost curve on facility level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, average prices for the period 2013–2035 of 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$). On facility level the influence of other measures is respected so that the *x*-axis shows the fuel conservation potential of the whole sector.

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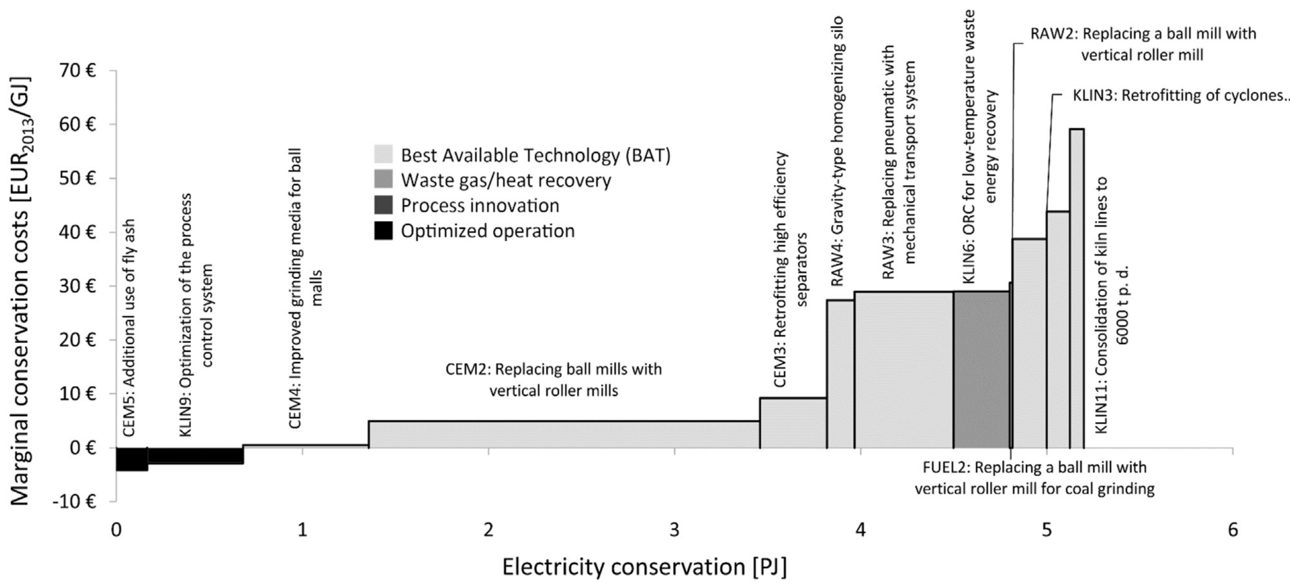


**Fig. 8.** Electricity conservation cost curve on process level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, average prices for the period 2013–2035 of 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$). On process level, the *x*-axis shows the electricity conservation potential of individual measures without respecting the influences of other measures.

cost-effective, but holds with 0.68 PJ the second largest measure-related electricity conservation potential. The largest EC potential of a single measure is with 2.1 PJ/y the replacement of balls mills with vertical roller mills (CEM2). However, replacing working balls mills becomes only cost-effective when the underlined electricity prices are increased by 4.95 EUR/GJ, or 0.02 EUR/kWh, respectively. With mechanical transportation systems (RAW3), the inefficiencies in the supply of compressed air can be avoided. Mechanical transportation is associated with comparatively high capital expenditure (see Table 3) so that this measure does not achieve a positive NPV in any of the German cement facilities (Fig. 8).

On facility level, competing measures are adopted according to the highest NPV (see Section 2.1). In the case of vertical roller mills (CEM2) and improved grinding media for ball mills (CEM4), the latter generally achieves a higher NPV and displaces CEM2 in some of the plants. Thus, the electricity conservation potential of CEM2 drops from 2.00 PJ on process level to 1.30 PJ on facility level. In the same manner, the EC potential of cyclones with lower pressure drop (KLIN3) is reduced by 0.10 PJ/y due to the expansion of the cyclone preheater stages (KLIN7) which are equipped with the same lower pressure drop technology. The consolidation of kiln lines (KLIN11) is completely displaced by all other kiln-related measures (KLIN1–KLIN10). Finally, the intersection indicates the cost-effective electricity conservation potential to be 0.68 PJ/y which is 5% of the sector's electricity use in 2012 according to DESTATIS (2014). The annual electricity cost conservations of the whole sector add up to 2.19 million $EUR_{2013}$ (Fig. 9).

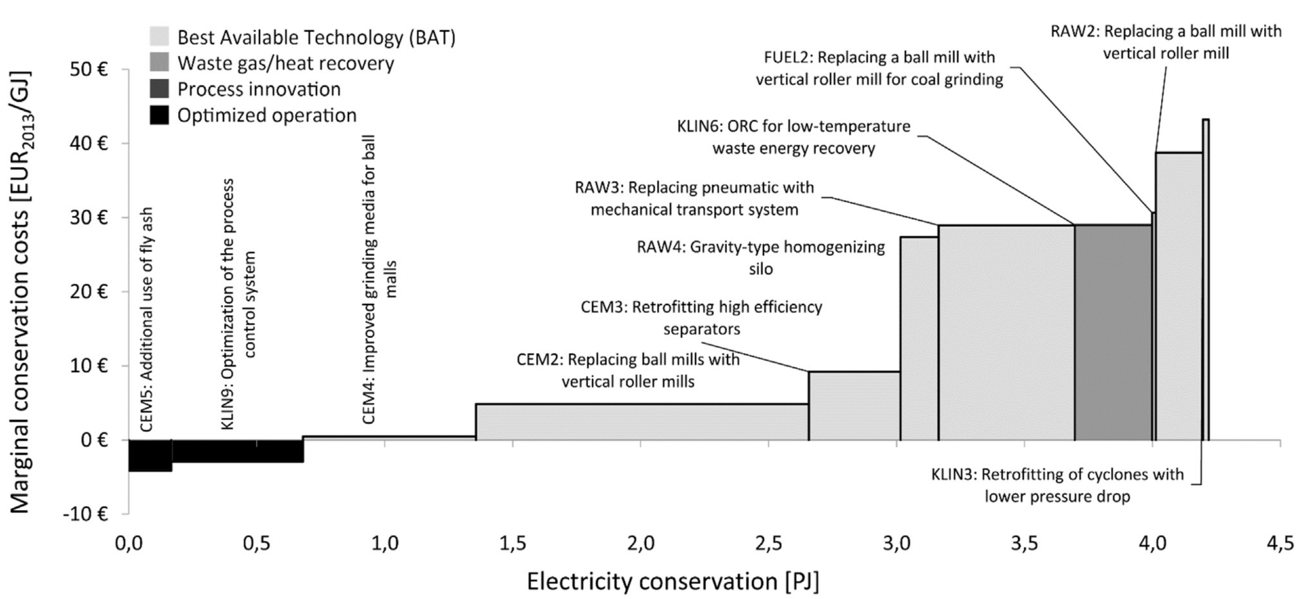


**Fig. 9.** Electricity conservation cost curve on facility level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, average prices for the period 2013–2035 of 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$). On facility level the influence of other measures is respected so that the *x*-axis shows the electricity conservation potential of the whole sector.

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### 3.3. $CO_2$ abatement cost curve

A welcomed side effect of the adoption of fuel conservation measures is the reduction of $CO_2$ emissions. In order to consider this effect in the cost evaluation of the measures, we calculated the measure-related $CO_2$ abatements (see Section 2.3.2). Hereby, we do not investigate measures that solely focus on the abatement of $CO_2$ emissions like carbon capture and storage (CCS) due to their questionable economy and energy efficiency. Thus, with the exception of measures NEW1 and FUEL1, all $CO_2$ abatements are achieved by reducing the specific fuel input. The development of new types of cement such as Celitement (NEW1) (see Stemmermann et al., 2010) could not only lower the thermal requirements, but also reduce the process-related $CO_2$ emissions of the clinker burning process. The latter could lead to a reduction of 231 kg $CO_2$ per tonne of clinker (see Table 3). Compared to the other measures, CEM1 alone could abate more $CO_2$ emissions than the other measures combined (see Fig. 10). Hereby, the adoption potential is limited to the annual demand of the comparable cement type CEM I which was 8286 kt in 2011 (VDZ, 2013).

We do not take radical process innovations, i.e. NEW1 and NEW2, into account in the economical CA assessment, due to their lacking technological maturity. Further, the ranking of measures is alternated and their CA potential is reduced on facility level due to the preference of cost-effective CA measures. The cost-effective $CO_2$ abatement potential is therefore 0.67 Mt $CO_2$ or 3.4% of the total $CO_2$ emissions in the year 2012. With the underlying prices, the adoption of cost-effective EC measures could save the whole sector 14.54 million $EUR_{2013}$ (Fig. 11).

### 3.4. Sensitivity analysis

#### 3.4.1. Sensitivity of the economical energy conservation potentials

In the previous sections, the economical EC potential of the German cement sector has been derived from ECCCs. Hereby, the cost-effectiveness of EC measures strongly depends on the underlying energy carrier and carbon prices. Thus, the effect of price variations on the cost-effective EC potential is investigated (see Fig. 12).

Besides the external (e.g. market and policy-driven) influences, the interest rate that companies demand to invest in EC measures has a strong impact on the cost-effectiveness of these measures. The fact that the majority of companies demand a payback time of less than three years can be seen as a barrier to the adoption of energy-efficient technology (Fleiter, 2012). In order to include the companies favour for short payback times, we respect an interest rate of 30% (R30) according to Sathaye et al. (2010) additional to the interest rate of 15% (R15) of base scenario. Further, the German Federal Environment Office recommends an interest rate of 3% (R3) for the economical assessment of environmental damages with a period up to 20 years which is also included (UBA, 2007). The three interest rates (i.e. R3, R15 and R30), the high electricity prices (R15 El), the high $CO_2$ prices (R15$CO_2$) and the combination of both, i.e. high $CO_2$ and electricity prices (R15$CO_2$El), give six scenarios that are summarised in Table 5. The seventh scenario (R15INNO) includes the effects of radical process innovations such as new types of cements (NEW1) on the cost-effective EC potential, which are discussed in the analysis to a limited degree due to the lacking technological maturity.

When considering the cost-effective conservation potentials throughout the scenarios, a correlation between the potentials and parameters can be found. We find the highest correlation (−0.98) between the interest rate and the economical CA potential. Accordingly, the second highest correlation (−0.90) is found between the interest rate and the economical fuel conservation potential. This result verifies the strong impact of the interest rate on the economical EC potential as previous research identified (see Section 3.4.1). The next highest correlation (0.67) is between electricity prices and economical electricity conservation potentials which indicates a higher flexibility of the German cement sector against rising electricity prices. At the same time, the fuel conservation potential is reduced (−0.17) due to the fact that EC measures that primarily conserve electricity are favoured in case they are competing with fuel conserving measures. The lowest correlation (0.19) between two subjects with the same parameter is found between the $CO_2$ price and the economical $CO_2$ abatement potential. On this basis, the idea behind the EU ETS, to provide additional cost incentives to adopt cost-effective CA measures, has little effect on the cement industry. At the same time, the economical fuel conservation potential is slightly reduced (−0.16) due to the effect of competing measures. It needs to be noted that the correlation coefficient is sensitive against outliers and that correlations do not

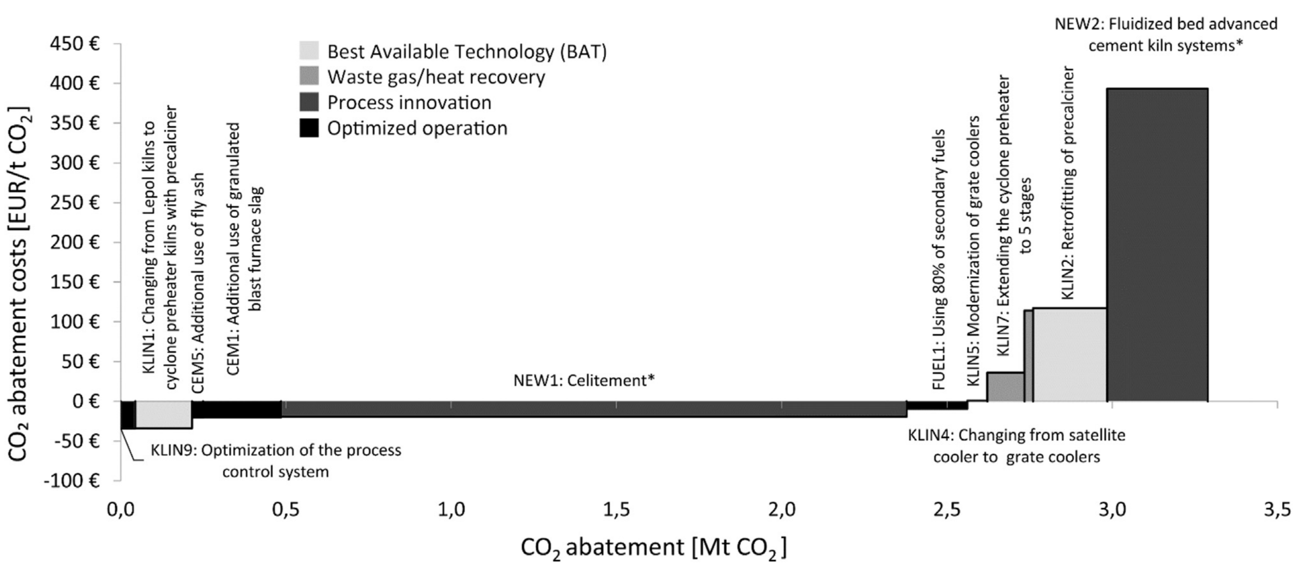


**Fig. 10.** $CO_2$ abatement cost curve on process level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, average prices for the period 2013–2035 of 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$). On process level, the $x$-axis shows the $CO_2$ abatement potential of individual measures without respecting the influences of other measures.

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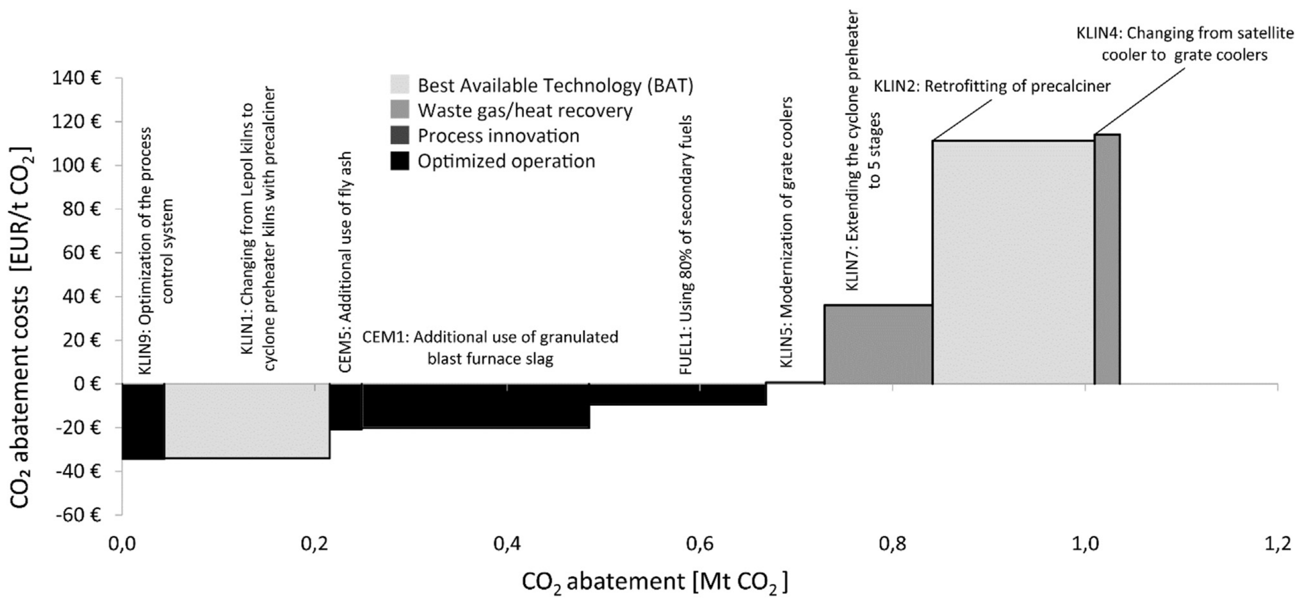


**Fig. 11.** $CO_2$ abatement cost curve on facility level of the German cement industry for the year 2013 in the base scenario (interest rate of 15%, average prices for the period 2013–2035 of 0.078 EUR/kWh electricity and 24.50 EUR/t $CO_2$). On facility level the influence of other measures is respected so that the *x*-axis shows the $CO_2$ abatement potential of the whole sector.

imply causal relationships. Therefore, we only used the coefficients to identify the effects on the cost-effective ECs and we did not work with their absolute figures.

### 3.4.2. *Effects on the specific energy and $CO_2$ emission costs*

There is hardly any other industrial sector that has such a high share of energy costs on the total production costs as the cement industry. The fuel costs make up to 30–40% of the clinker production costs (EIPPCB, 2010). Also the European Commission acknowledges with Article 10a of the EU ETS directive the special position of the cement industry by including them in the carbon leakage list, because $CO_2$ certificates could increase the production cost by at least 30% of the gross value-added. In this section, we therefore quantify the production cost increase within the presented scenarios. For reasons that are outlined hereafter, we focus on the energy-related part of the production costs which include the cost for energy carriers and as well for $CO_2$ certificates. First, we need to develop reference costs for the base scenario (R15) and the base year (2013) to which we can compare the results to. For this, we multiply the specific EC with the cost assumptions for the year 2013 to create Table 6.

Here, it needs to be noted that, even if the exact cost structure of individual cement facilities would be available, due to the nature of average values, a single cement facility might not identify itself with Table 6. Instead, we put the following results in relation to Table 6 in order to provide relative changes in the energy-related production costs (see Fig. 13) which enhances the transferability of the results.

Our results show that in the period 2013–2035 the average energy-related production costs of the German cement industry will increase by 33–77% despite the adoption of cost-effective EC measures. When looking at individual scenarios and energy carriers, it is striking that higher electricity prices can be compensated to some degree by EC measures that become cost-effective.

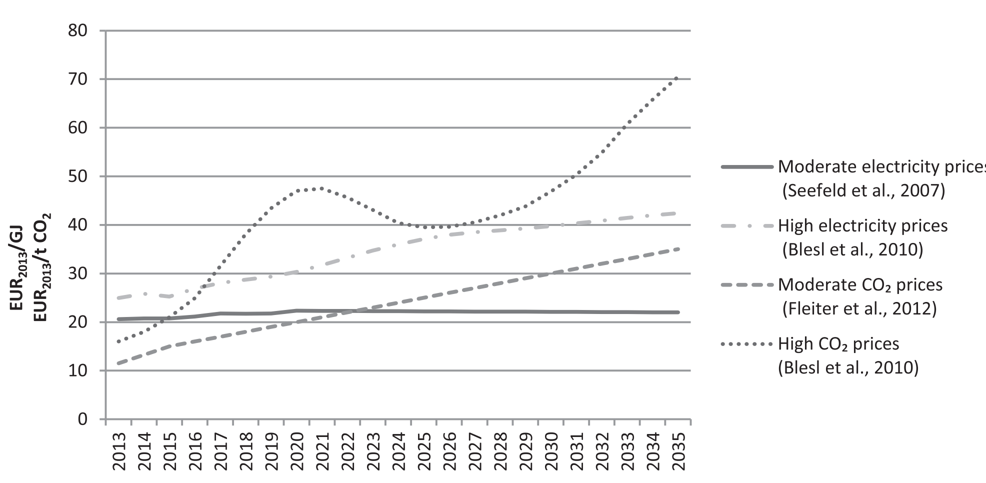


**Fig. 12.** Parameter variations for the sensitivity analysis. The combination of different price developments gives four scenarios: moderate prices are used for the base scenario, high $CO_2$ price ($CO_2$), high electricity price (El) and high electricity and $CO_2$ prices combined ($CO_2$El). Price for the reaming energy carriers remain the same (see Fig. 2).

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**Table 5**
The interest rates, $CO_2$ and electricity prices and the achieved economical fuel, electricity conservation and $CO_2$ abatement potential of the German cement industry in the year 2013 in the seven investigated scenario. Four scenarios are based on different price developments: moderate prices (R15), high $CO_2$ price (R15$CO_2$), high electricity price (R15 El) and high electricity and $CO_2$ prices combined (R15$CO_2$El) (see Fig. 12). The remaining three scenarios represent lower (R3) and higher (R30) interest rates as well as the effect of radical process innovations (R15INNO).

| Scenario | Interest rate (%) | Electricity price | $CO_2$ price | Cost-effective fuel conservation potential [PJ/y] | Cost-effective electricity conservation potential [PJ/y] | Cost-effective $CO_2$ abatement potential [Mt $CO_2$/y] |
|---|---|---|---|---|---|---|
| R30 | 30 | Moderate | Moderate | 0.68 | 0.68 | 0.08 |
| R15[a] | 15 | Moderate | Moderate | 4.00 | 0.68 | 0.67 |
| R3 | 3 | Moderate | Moderate | 13.05 | 3.48 | 1.04 |
| R15$CO_2$ | 15 | Moderate | High | 4.10 | 0.68 | 0.73 |
| R15 El | 15 | High | Moderate | 4.00 | 3.07 | 0.67 |
| R15$CO_2$El | 15 | High | High | 4.10 | 3.46 | 0.73 |
| R15INNO[b] | 15 | Moderate | Moderate | 12.20 | 0.46 | 2.54 |

[a] An interest rate of 15% with moderate $CO_2$ and electricity price developments represents the base scenario.
[b] This scenario includes radical process innovations (i.e. NEW1, NEW2) which are in the sensitivity analysis and in the energy-related production costs discussed in the analysis to limited degree due to the lacking technological maturity.

In the base scenario (R15), a moderate electricity price increase by 6% results in lowered electricity costs in the clinker production and slightly increased electricity costs (+4%) in the cement production. When the electricity price is in average 50% higher, the electricity costs of the clinker production raises by 37%, but the electricity cost of the cement production is only slightly increased (+7%). This can be explained by the substitution of ball mills with vertical rollers mills in cement grinding (CEM2) which becomes cost-effective with higher electricity prices, even if the ball mill has not reached its end of lifetime. The prices of the 13 fossil fuels are not varied in the sensitivity analysis and increase slightly overtime (see Fig. 2). The average fossil-fuel price increase of 16% is reduced to 13% through the adoption of cost-effective EC measures. However, through the variation of the carbon price, the usage of fossil fuels is charged with additional costs. Hereby, the cost of $CO_2$ certificates increased with 107% (R15) and 267% (R15$CO_2$ and R15$CO_2$El) throughout the scenarios significantly. The CACC on facility level (see Fig. 11) shows that the options for the German cement industry to abate $CO_2$ emissions are limited. As a matter of fact, the adoption of cost-effective EC can suppress the cost increase only to 256% (R15$CO_2$ and R15$CO_2$El) or to 102% (R15), respectively. Obviously, the highest sensitivity of the cement industry's energy-related production costs is the $CO_2$ price. With a 46% share of $CO_2$ costs on the total energy-related production costs in the base scenario (R15) and 57% in the high $CO_2$ price scenario (R15$CO_2$), a 100% increase of the $CO_2$ price will lead in average to 36% increase of the energy-related production costs. This means that, even with the adoption of cost-effective EC measures, the production cost increase due to raising $CO_2$ prices (+16.40 EUR/t clinker in R15 compared to 2013) will still be more than 40% of the gross value-added, when assuming according to Baeza (2013) a value-added of 29 EUR/t cement and a clinker factor of 73%. Following the European Commission's definition, the cement industry is in the period 2013–2035 still associated with a carbon leakage risk.

## 4. Concluding discussion

Whether it is through the EU ETS which allocates free allowances based on a BAT-oriented benchmark, through the energy concept of the German government which demands a certified energy management systems from companies to receive electricity tax exemption, or ultimately, rising energy prices and increasing competitive pressure: The issue of energy efficiency is becoming of even more importance for the German cement industry. In this research, we identified 21 EC measures applicable to the German cement industry. In a two-step bottom-up approach, we first assessed the effectiveness of the individual measures in terms of ECs and costs on process level. In the second step, we assessed the cost-effective EC and CA potential of the whole sector by combining the individual measures and taking into account technological restrictions and interactions. At the end of each step, we ranked the measures in cost curves. The results of the fuel and electricity conservation as well as $CO_2$ abatement cost curves are discussed hereafter.

**Table 6**
Specific energy consumption and energy-related production costs of the German cement industry in the year 2013 and base scenario (interest rate of 15%, average prices for the period 2013 of 0.074 EUR/kWh electricity and 11.50 EUR/t $CO_2$). The production costs built the reference costs to which the costs of the different scenarios are put in relation to (see Table 5).

| Type | $EUR_{2013}$/GJ or -/t $CO_2$ | GJ/t clinker or t $CO_2$/t clinker[a] | $EUR_{2013}$/t clinker | GJ/t cement or t $CO_2$/t cement | $EUR_{2013}$/t cement |
|---|---|---|---|---|---|
| Coal | 4.54 | 0.40 | 1.83 | 0.00 | 0.00 |
| Lignite | 4.54 | 0.96 | 4.34 | 0.00 | 0.00 |
| Petrol coke | 7.86 | 0.08 | 0.67 | 0.00 | 0.00 |
| Crude oil | 10.69 | 0.02 | 0.17 | 0.00 | 0.00 |
| Fuel oil | 17.40 | 0.01 | 0.14 | 0.00 | 0.00 |
| Natural gas and other gases | 9.03 | 0.01 | 0.07 | 0.00 | 0.00 |
| Other fossil fuels | 4.54 | 0.00 | 0.02 | 0.00 | 0.00 |
| Secondary fuels (total) | 3.40 | 2.33 | 7.92 | 0.00 | 0.00 |
| Fuels (total) | – | 3.81 | 15.16 | 0.00 | 0.00 |
| Electricity | 20.6 | 0.15 | 3.07 | 0.24 | 5.01 |
| $CO_2$ | 11.5 | 0.82[b] | 9.38 | 0.00 | 0.00 |
| **Total** | **-** | **7.10** | **27.62** | **0.24** | **5.01** |

[a] Values are based on VDZ (2013) for the year 2011.
[b] The $CO_2$ value includes the fuel and process-related $CO_2$ emissions and is based on the ratio of verified $CO_2$ emissions (see Ecofys et al., 2009) and the amount of clinker produced in the period 2005–2008 (VDZ, 2013).

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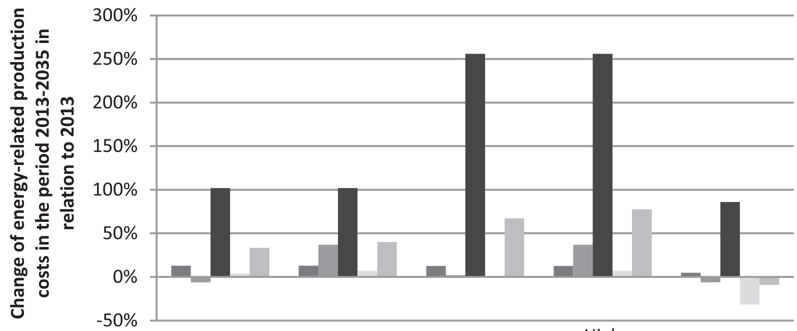


| | Base scenario (R15) | High electricity prices (R15El) | High $CO_2$ prices (R15CO2) | High electricty and $CO_2$ prices (R15CO2El) | Radical innovation s* (R15) |
|---|---|---|---|---|---|
| Clinker: fuel costs | 13% | 13% | 13% | 13% | 5% |
| Clinker: electricity costs | -6% | 37% | 2% | 37% | -6% |
| Clinker: $CO_2$ costs | 102% | 102% | 256% | 256% | 86% |
| Cement: clectricity costs | 4% | 7% | 0% | 7% | -32% |
| Total energy-related production costs | 33% | 40% | 67% | 77% | -9% |

**Fig. 13.** Average energy-related production costs of the German cement industry in the period 2013–2035 in relation to the reference costs in the year 2013 (see Table 5). The cost reduction effects through the adoption of cost-effective energy conservation measures are included. The energy-related production costs for cement only includes the electricity that is needed to grind the clinker and additives. The total energy-related production costs are weighted with an assumed clinker factor of 73% during the investigation period (VDZ, 2013).

For fuel conservations, we identified an economic potential of 4.00 PJ or 4% of the final energy use of the German cement industry in the year 2012. Moreover, the adoption of cost-effective EC measures would save 12.8 million $EUR_{2013}$ fuel and $CO_2$ costs annually. However, the identified potential does not meet any of the energy reduction goals set by different energy polices. The Directive 2012/27/EU on energy efficiency determines annual ECs of 1.5% over the years 2014–2020. The German cement industry would have to conserve 7.15 PJ until 2020, an equal contribution for all sectors provided. In order to conserve additional 3.15 PJ, the German cement industry would have to adopt currently non-cost-effective measures such as modern grate coolers before the end of lifetime of the current coolers (see Fig. 7) which would evolve in additional costs of 3 million $EUR_{2013}$ for the whole sector. Besides, the energy concept of the German government has set ambitious targets such as a reduction of primary energy consumption by 20% over 2008–2020. When the final energy use of DESTATIS (2014) is weighted with the primary energy factors for Germany according to Pehnt et al. (2012), the cement sector would have to conserve 14.95 PJ until 2020. Without economical restrictions, the technical EC potential of the investigated measures is only 14 PJ. The adoption of all measures would result in additional annual costs of 25.8 million $EUR_{2013}$ for the whole sector. It needs to be noted that due to the policies focus on primary energy, remarkable final ECs could be achieved when the share of secondary fuels is increased, because these energy carriers are accounted with very low primary energy factors, e.g. 0.11–0.13 according to Pehnt et al. (2012). However, we do not consider secondary fuels in the EC potential assessment, because an increased use can lead to a higher specific final energy consumption (see Section 2.3.1).

With regard to electricity, the German government has set the goal of an electricity reduction of 10% until 2020. Compared to the identified economical conservation potential of 0.68 PJ, or 5% of the electricity requirement of the sector in 2012 according to DESTATIS (2014), the German cement industry would need to conserve additional 0.56 PJ electricity to meet the 2020 target. Adopting non-cost-effective cement grinding-related measures would fulfil the target with comparatively low additional costs of 0.33 million $EUR_{2013}$ for the whole sector. Even the 2050 target of an electricity reduction of 25% could be achieved when vertical roller mills, mechanical transport systems and gravity-type homogenising silos are adopted. From a today's perspective, this, however, would result in additional costs of 14 million $EUR_{2013}$. Still, the results show a significant potential for electricity conservation measures which become cost-effective with higher electricity prices and, moreover, can compensate for the rising electricity prices. In particular, replacing operating ball mills with vertical roller mills in cement grinding becomes cost-effective with a higher electricity price of 20 EUR/MWh which is in the region of the German electricity tax (20.5 EUR/MWh). The results reflect the ambivalence effects of the Germany electricity tax exemption for energy-intensive industries: On the one hand, it facilitates international competiveness, on the other hand, it inhibits the adoption of electricity conservation measures.

We further analysed the effect of the reduced fuel requirement on $CO_2$ emissions. We identified a cost-effective CA potential of 0.67 Mt $CO_2$ which is 3.4% of the average German cement industry's $CO_2$ emissions between 2005 and 2008 according to Ecofys et al. (2009) and nowhere near the EU ETS 2020 goal of a 21% reduction compared to 2005. Above that, the results of the sensitivity analysis showed that high $CO_2$ prices have a low effect on the cost-effective EC and CA potential, but a significant effect on the energy-related production costs. In fact, $CO_2$ prices until 2035 accounted in average for more than 40% of the gross value-added which validates the carbon leakage risk for the cement sector in the period 2013–2035. Accordingly, the European Commission adopted a benchmark for the third EU ETS phase after 2013 of 766 kg $CO_2$/t of grey cement clinker for free allocation to the cement industry which was recommended by the European Cement Association CEMBUREAU (2011) and Ecofys et al. (2009). Compared to the identified average specific $CO_2$ emissions of the German cement industry (810 kg $CO_2$/t grey cement clinker), the benchmark takes the low CA potential into account but, at the same time, leads to the situation that $CO_2$ certificates provide hardly any cost incentives to invest in CA and CE measures. Besides, the sensitivity analysis showed that the interest rate had the highest leverage effect on the cost-effective CE and CA potential. In order to accept longer payback times, or lower internal rates of return, respectively, cement companies consequently require a stable environment with long-term cycles between policy changes. Further, Vogt-Schilb and Hallegatte (2013) discovered a risk of technological lock-in from using cheapest abatement measures in short-term optimisation which additionally speaks in favour of firm long-term policy targets.

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## References

Achternbosch, M., Bräutigam, K.-R., 2000. Manufacture of Cement Clinker. Process Description and Analyzes of the Use of Alternative Fuels (in German). www.ubka.uni-karlsruhe.de/volltexte/fzk/6508/6508.pdf (accessed 06.05.14.).

Ammenberg, J., Leenard, B., Eklund, M., Roozbeh, F., Helgstrand, A., Marshall, R., 2014. Improving the $CO_2$ performance of cement, Part III: The relevance of industrial symbiosis and how to measure its impact. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2014.01.086.

Backes, H.-P., Brandenburger, D., Meißner, M., 2011. Fly Ash – Availability, Logistics, Potential (in German). www.baumineral.de/news/p/Flugasche_-_Verfuegbarkeit_Logistik_Potential_-_Stand_14_11_2011.pdf (accessed 11.04.13.).

Baeza, R., 2013. The Cement Sector: A Strategic Contributor for Europe's Future. www.cembureau.eu/sites/default/files/documents/The%20Cement%20Sector%20-%20A%20Strategic%20Contributor%20to%20Europe's%20Future.pdf (accessed 06.05.14.).

Basten, M., Bröker, H., Eber, B., Hilger, J., Lütkehaus, M., Reimer, T., Rosemann, H., Schauer, M., Sprung, S., Wertel, C., 2002. Cement Raw Materials in Germany. Geology, Mass Balance, Case Studies (in German). www.vdz-online.de/fileadmin/gruppen/bdz/Themen/Rohstoffe/Zementrohstoffe.pdf (accessed 22.01.13.).

Benhelal, E., Zahedi, G., Shamsaei, E., Bahadori, A., 2013. Global strategies and potentials to curb $CO_2$ emissions in cement industry. J. Clean. Prod. 51, 142–161. http://dx.doi.org/10.1016/j.jclepro.2012.10.049.

Bezirksregierung Arnsberg, 2011. 251. Request of the Company Portland Cement Works Seibel and Söhne GmbH & Co. KG, Str 100, 59597 Erwitte for Approval of Amending the Cement Plant in Accordance with § 16 BImSchG (in German). www.bezreg-arnsberg.nrw.de/themen/a/amtsblatt/2011/abl_11_19.pdf (accessed 06.05.14.).

Blesl, M., Kober, T., Bruchof, D., Kuder, R., 2010. Effects of climate and energy policy related measures and targets on the future structure of the European energy system in 2020 and beyond. Energy Policy 38, 6278–6292. http://dx.doi.org/10.1016/j.enpol.2010.06.018.

Bracht, A., 2011. Rüdersdorf: a cradle of the German lime and cement industry (Rüdersdorf: Eine Wiege der deutschen Kalk- und Zementindustrie). ZKG Int. 65, 28–32.

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

Castañón, A.M., García-Granda, S., Guerrero, A., Lorenzo, M.P., Angulo, S., 2014. Energy and environmental savings via optimisation of the production process at a Spanish cement factory. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2014.03.028.

CEMBUREAU, 2011. CEMBUREAU Welcomes Draft Decision on Benchmarks and Calls for Interpretative Guidance on Allocation Rules. www.cembureau.eu/newsroom/article/cembureau-welcomes-draft-decision-benchmarks-and-calls-interpretative-guidance-allo (accessed 23.06.13.).

Cemnet, 2007. The Global Database. www.cemnet.com/GCR/country/Germany (accessed 25.04.14.).

Clauser, S., 2010. 1.2 million Euros for New Separators. Pfeiffer-separator is Installed at Phoenix Cement Plant (in German). www.phoenix-zement.de/cms/upload/presse/31-07-2010_presse.pdf (accessed 06.04.14.).

CSI/ECRA, 2009. Development of State of the Art-techniques in Cement Manufacturing: Trying to Look Ahead. www.wbcsdcement.org/pdf/technology/Technology%20papers.pdf (accessed 22.02.13.).

DESTATIS, 2014. Survey on the Use of Energy. Table 2: Energy Consumption by Energy Source. Reporting period: 2012 (in German), Wiesbaden, Germany.

EC, 2012. Guidance Document. Biomass Issues in the EU ETS. MRR Guidance document No. 3, Final Version of 17 October 2012. http://ec.europa.eu/clima/policies/ets/monitoring/docs/gd3_biomass_issues_en.pdf (accessed 10.06.13.).

Ecofys, ISI, Öko-Institut, 2009. Methodology for the Free Allocation of Emission Allowances in the EU ETS Post 2012. Sector report for the cement industry. http://ec.europa.eu/clima/policies/ets/cap/allocation/docs/bm_study-cement_en.pdf (accessed 30.06.13.).

Ehrenberg, A., 2006. Granulated blast furnace slag – a powerful material with tradition and future (in German). Beton Inform. 4, 35–63.

EIPPCB, 2009. Reference Document on Best Available Techniques for Energy Efficiency. http://eippcb.jrc.ec.europa.eu//reference/BREF/ENE_Adopted_02-2009.pdf (accessed 23.06.13.).

EIPPCB, 2010. Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries. http://eippcb.jrc.ec.europa.eu/reference/BREF/cer_bref_0807.pdf (accessed 06.05.14.).

Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A., Marshall, R., 2014. Improving the $CO_2$ performance of cement, Part II: Framework for assessing $CO_2$ improvement measures in the cement industry. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2014.01.103.

Fleiter, T., 2012. The Adoption of Energy-efficient Technologies by Firms. An Integrated Analysis of the Technology, Behavior and Policy Dimensions. PhD Thesis. Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany.

Fleiter, T., Fehrenbach, D., Worrell, E., Eichhammer, W., 2012. Energy efficiency in the German pulp and paper industry – a model-based assessment of saving potentials. Energy 40, 84–99. http://dx.doi.org/10.1016/j.energy.2012.02.025.

Gäbel, K., Tillman, A.-M., 2005. Simulating operational alternatives for future cement production. J. Clean. Prod. 13, 1246–1257. http://dx.doi.org/10.1016/j.jclepro.2005.05.023.

Ghenda, J.-T., 2011. 10. $CO_2$ Monitoring Progress Report of the Steel Industry in Germany (in German). www.stahl-online.de/wp-content/uploads/2014/03/10_CO2-Monitoring-Fortschrittsbericht_Stahlindustrie_2010.pdf (accessed 06.05.14.).

Hammerich, J., 2009. A New Clinker Cooler for Wössingen – Installed in Existing Plant (Ein neuer Klinkerkühler für Wössingen – Bauen im Bestand). www.ikn.eu/files/zkg_0903_ikn_woessingen_0309.pdf (accessed 12.03.13.).

Harder, J., 2010a. Current modernization and maintenance concepts in the cement industry (Aktuelle Modernisierungs- und Instandhaltungskonzepte in der Zementindustrie). ZKG Int. 64, 24–38.

Harder, J., 2010b. Grinding trends in the cement industry. ZKG Int. 64, 46–58.

Harder, J., 2011. Latest Trends in Clinker Coolers (in German). www.zkg.de/de/artikel/zkg_2011-03_Neueste_Trends_bei_Klinkerkuehlern_1090260.html (accessed 29.04.14.).

Harder, J., 2013. Latest Trends in the Use of Waste Heat in Cement Plants (in German). www.zkg.de/de/artikel/zkg_Neueste_Trends_bei_der_Abwaermenutzung_in_Zementanlagen_1741634.html (accessed 29.04.14.).

Hasanbeigi, A., Menke, C., Price, L., 2010a. The $CO_2$ abatement cost curve for the Thailand cement industry. J. Clean. Prod. 18, 1509–1518. http://dx.doi.org/10.1016/j.jclepro.2010.06.005.

Hasanbeigi, A., Menke, C., Therdyothin, A., 2010b. The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry. Energy Policy 38, 392–405. http://dx.doi.org/10.1016/j.enpol.2009.09.030.

Hasanbeigi, A., Lobscheid, A., Lu, H., Price, L., Dai, Y., 2013a. Quantifying the co-benefits of energy-efficiency policies: a case study of the cement industry in Shandong Province, China. Sci. Total Environ. 458–460, 624–636. http://dx.doi.org/10.1016/j.scitotenv.2013.04.031.

Hasanbeigi, A., Morrow, W., Masanet, E., Sathaye, J., Xu, T., 2013b. Energy efficiency improvement and $CO_2$ emission reduction opportunities in the cement industry in China. Energy Policy 57, 287–297. http://dx.doi.org/10.1016/j.enpol.2013.01.053.

Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T., 2013c. A bottom-up model to estimate the energy efficiency improvement and $CO_2$ emission reduction potentials in the Chinese iron and steel industry. Energy 50, 315–325. http://dx.doi.org/10.1016/j.energy.2012.10.062.

Holcim, 2013. Environmental Report, 2012. Environmental Measures of the Cement Plant Dotternhausen (in German). www.holcim-sued.de/fileadmin/templates/DEUB/doc/Umwelt/Allgemein/Hol_Umweltbericht_2012_internet.pdf (accessed 06.05.14.).

Krogmeier, W., 2012. Cemex Invests 20 Million Euros (in German). www.die-glocke.de/lokalnachrichten/kreiswarendorf/beckum/Cemex-investiert-20-Millionen-Euro-769545ed-29e1-4589-be10-d2378ac2f9fc-ds (accessed 06.05.14.).

LfU, 2001. Low-temperature Power Generation with an ORC Plant at Lengfurt Heidelberger Zement AG (in German). www.lfu.bayern.de/energie/co2_minderung/doc/orc_endbericht.pdf (accessed 22.01.13.).

Li, J., Tharakan, P., Macdonald, D., Liang, X., 2013. Technological, economic and financial prospects of carbon dioxide capture in the cement industry. Energy Policy, 1377–1387. http://dx.doi.org/10.1016/j.enpol.2013.05.082.

Liu, G., Müller, D.B., 2012. Addressing sustainability in the aluminium industry: a critical review of life cycle assessments. J. Clean. Prod. 35, 108–117. http://dx.doi.org/10.1016/j.jclepro.2012.05.030.

Madlool, N., Saidur, R., Rahim, N., Kamalisarvestani, M., 2013. An overview of energy savings measures for cement industries. Renew. Sustain. Energy Rev. 19, 18–29. http://dx.doi.org/10.1016/j.rser.2012.10.046.

McKinsey, 2009. Pathways to a Low-carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve. https://solutions.mckinsey.com/climatedesk/default.aspx (accessed 02.05.14.).

Morrow, W.R., Hasanbeigi, A., Sathaye, J., Xu, T., 2013. Assessment of energy efficiency improvement and $CO_2$ emission reduction potentials in India's cement and iron & steel industries. J. Clean. Prod. 65, 131–141. http://dx.doi.org/10.1016/j.jclepro.2013.07.022.

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NEDO, 2008. Global Warming Countermeasures. Japanese Technologies for Energy Savings/GHG Emissions Reduction. www.iipnetwork.org/Japanese_Technologies_for_Energy_Savings.pdf (accessed 06.05.14.).

Pehnt, M., Herbert, F., Gärtner, S., Vogt, R., Fehrenbach, H., 2012. Primary Energy Factors of Biogenic Energy Sources, Waste Heat Sources and Waste Incineration Plants (in German). www.bbsr.bund.de/BBSR/DE/Veroeffentlichungen/BMVBS/Online/2012/ON122012.html (accessed 24.06.13.).

Sathaye, J., Xu, T., Galitsky, C., 2010. Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector. http://eaei.lbl.gov/publications/bottom-representation-industrial-ener (accessed 06.05.14.).

Schlomann, B., Fleiter, T., Hirzel, S., Arens, M., Rohde, C., Eichhammer, W., Cebulla, F., Elsland, R., Singer, N., Gerspacher, A., Idrissova, F., Jochem, E., Mai, M., Reitze, F., Toro, F.-A., Hassan, A., 2011. Options, Potentials, Barriers and Policies to Reduce Energy Consumption and the $CO_2$ Emissions from the Industrial Sector Technologies through Process Optimization and Implementation of New Process Technologies (in German). www.isi.fraunhofer.de/isi-media/docs/x/de/publikationen/Branchentechnologien-FraunhoferISI-IREES-Hassan-Schlussbericht-Maerz2011-ueberarbeitet_v3.pdf (accessed 06.05.14.).

Seefeld, F., Claaßen, T., 2011. Investigation of a Succession Plan for Energy and Electricity Tax Relief (in German). www.bmwi.de/DE/Mediathek/publikationen,did=463362.html (accessed 06.05.14.).

Siitonen, S., Tuomaala, M., Ahtila, P., 2010. Variables affecting energy efficiency and $CO_2$ emissions in the steel industry. Energy Policy 38, 2477–2485. http://dx.doi.org/10.1016/j.enpol.2009.12.042.

Stemmermann, P., Schweike, U., Garbev, K., Beuchle, G., Möller, H., 2010. Celitement – a sustainable prospect for the cement industry (Celitement – eine nachhaltige Perspektive für die Zementindustrie). Cem. Int. 8, 52–66.

UBA, 2007. Economic Evaluation of Environmental Damage. Methodological Convention for the Estimation of External Environmental Costs (in German). www.umweltdaten.de/publikationen/fpdf-l/3193.pdf (accessed 17.12.12.).

VDEh, 2011. PLANTFACTS Database. www.stahl-online.de/english/linke_Navigation/Technology_Research/_documents/PLANTSFACTSE.pdf (accessed 25.04.14.).

VDZ, 2013. Umweltdaten der deutschen Zementindustrie (Environmental Data of the German Cement Industry). www.vdz-online.de/fileadmin/gruppen/vdz/3LiteraturRecherche/Umweltdaten/Umweltdaten_2012_DE_GB.pdf (accessed 08.06.14.).

Vogt-Schilb, A., Hallegatte, S., 2013. Marginal abatement cost curves and the optimal timing of mitigation measures. Energy Policy 66, 645–653. http://dx.doi.org/10.1016/j.enpol.2013.11.045.

Wächter, P., 2013. The usefulness of marginal $CO_2$-e abatement cost curves in Austria. Energy Policy. http://dx.doi.org/10.1016/j.enpol.2013.06.125.

Weber, T., 2010. Closed process. Pneumatic conveying systems in the cement and cement-manufacturing industry (in German). Verfahrenstechnik 44, 2–3.

Weiß, T., Reiff, H., Bracht, A., 2012. Handbook for the Construction of Cement Plants 2012/2013 (in German). Bauerverlag BV GmbH, Gütersloh, Germany.

Winkelhage, J., 2007. Deafening Loud and Hot as Hell (in German). Frankfurter Allgemeine Zeitung. www.avt.rwth-aachen.de/AVT/uploads/media/FAZ_Dyckerhoff_Lengerich.pdf (accessed 06.05.14.).

Worrell, E., Galitsky, C., 2008. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making. An ENERGY STAR® Guide for Energy and Plant Managers. www.energystar.gov/ia/business/industry/LBNL-54036.pdf?5d92-a6b3= (accessed 22.02.13.).

Xi, Y., Fei, T., Gehua, W., 2013. Quantifying co-benefit potentials in the Chinese cement sector during 12th Five Year Plan: an analysis based on marginal abatement cost with monetized environmental effect. J. Clean. Prod. 58, 102–111. http://dx.doi.org/10.1016/j.jclepro.2013.07.020.