

Utilizing LCA and key performance indicators to assess development within the cement industry

-a case study of a cement production cluster in Germany

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Abstract

Cement is a vital and commonly used construction material that requires large amounts of resources and causes significant environmental impact. However, there are many different types of cement products, roughly ranging from traditional products with a rather linear production to more synergistic alternatives where byproducts are utilized to a large extent. Life Cycle Assessment (LCA) studies indicate the synergistic products are favorable from an environmental perspective.

This article has two main aims, where the first is to carry out a LCA and compare three different cement products, involving both linear and synergistic ones to further explore this issue. This has been done from cradle to gate, focusing on climate impact, where the case is a cement production cluster consisting of three plants in Germany. The second aim is to develop and test a simplified LCA model for this production cluster, with the intention to be able to assess additional production alternatives based on the information of a few parameters.

The more comprehensive LCA showed that cement products with a high share of byproducts, in this case granulated blast furnace slag from the steel industry, had the best climate performance. The difference between the best (CEM III/B) and worst (CEM I) cement product, regarding global warming potential, was about 66%. A simplified LCA model was developed and the research team could apply it to compare the present production with the situation in 1997 and also with possible future production systems. This simplified LCA model was based on 6 key performance indicators, instead of more than 50 parameters, which was the case for the comprehensive LCA model. For example, the simplified model showed that the CO₂ emission related to a virtual average product of the production cluster was reduced about 49 % in the period from 1997 to 2009.

Keywords: cement, clinker, climate change, simplified life cycle assessment (LCA), cement production system

1 Introduction

1.1 Cement and cement production

Cement is a very important material for the global construction industry, mainly used as a component in concrete. Cement production is highly energy and material intensive; e.g., causing about 5% of the global CO₂ emissions and substantial emissions of SO₂, NO_x and other pollutants (Van Oss & Padovani 2002; Van Oss & Padovani 2003; EIPPCB 2010). This makes it interesting to study cement production and products from an environmental point of view.

The most common form of cement is Portland cement, consisting of a material called clinker to about 95% (Locher 2006). Clinker is formed when the raw material limestone is burned at a high temperature in a cement kiln (Van Oss & Padovani 2002). In this process calcium carbonate decomposes and CO and CO₂ is produced (Worrell et al. 2001). It is called calcination and it is highly

important from a climate perspective, since carbon bound in minerals is transformed to CO₂ (Chen et al. 2010). The calcination typically causes about 50% of the total CO₂ emissions from cement production, and a large share of the remaining emissions originates from combustion of the fuels in the kiln (Deborah N. Huntzinger & Eatmon 2009a). The clinker is then grinded to a fine powder and blended with some additives.

In addition to Portland cement, there are other types of cement products and several formal categorization systems to define them. The ASTM standard in the USA and the European cement standard EN 197-1 are widely used. The latter standard defines five main types of cement (CEM I to V), where each main type has a few sub-types, ending up with 27 different cement types in total. The main distinguishing factor between these types is their material content. CEM I has the highest amount of clinker, corresponding to Portland cement. Other types have lower clinker content and instead alternative materials are used, referred to as “clinker substitutes”. These materials have clinker-like properties and thus can partially replace clinker. They are grinded and blended (mixed) in the required proportions in order to produce different types of cement. Examples of materials used as clinker substitutes are byproducts such as granulated blast furnace slag¹ (GBFS) from the steel industry and ash from coal incineration. Many types of waste can be used as substitutes to clinker or different fuels when producing cement and the cement industry has become a useful receiver of industrial and municipal wastes (Reijnders 2007).

1.2 Life Cycle Assessment of cement

Life Cycle Assessments (LCA) are commonly used to study the environmental impact from cement industry (H. Lu 2010; Ortiz et al. 2009) and such studies are important to learn more about this industry and about strategies for reducing the impact. For example, such studies tell us that commonly, production of Portland cement results in CO₂ emissions exceeding 0.9 ton CO₂/ton cement and that each ton might require input of 1.5 tons of raw materials, 3300-4300 MJ of fuel energy and 100-120 kWh of electrical energy (EIPPCB 2010; Nicolas & Jochen 2008; Lynn Price et al. 2010). Further on, LCA studies can be utilized to assess and compare the environmental performance of the different types of cement mentioned (Van den Heede & De Belie 2012; Gäbel & Tillman 2005).

However, full scale and detailed LCA studies (in compliance with the ISO 1404x standards) require a lot of resources (Wenzel et al. 1997). It can be very time consuming, and thus costly, to gather all the data needed and find case specific information of good quality (ibid.). If the production involves several cement plants, in the form of an industrial cluster, the task grows. Such projects tend to require more sophisticated and well-structured LCA approaches, to handle several external links to material and fuel suppliers while simultaneously having intermediate links between different plants within the cluster. In many cases it is also desirable to be able to handle development within the industry, such as changes of technology, fuel and raw materials. But dynamics in the production systems lead to changes of the Life Cycle Inventory (LCI).

The problems mentioned are of course not specific for LCA studies of cement. The need for simplified LCA methods is evident in many industrial sectors and different ways of streamlining the LCA process is commonly mentioned in literature, see (Bretz 1998; Fleischer et al. 2001; Hochschorner & Finnveden 2003; Mueller et al. 2004; Soriano 2004; Ross & Evans 2002; Sun et al. 2004). There are several ways of simplifying the LCA process, for example, to:

- Exclude some data and/or mainly focus on some key indicators,
- Use generic data instead of case specific data,
- Exclude some environmental impact categories,
- Exclude some parts of the life cycle, and

¹ Granulated blast furnace slag is a residue from the production of iron and steel which can be used to substitute clinker (M.E. Boesch et al. 2009b).

- Apply qualitative LCA methods.

This paper presents a study that is based on a quantitative, detailed LCA of cement, which is then used to develop a simplified LCA model applied to assess other alternatives concerning the production system and the products.

1.3 A studied case

CEMEX is a global manufacturer of building materials operating in more than 50 countries and the company is one of the largest cement producers in the world. In cooperation, researchers from Linköping University, Sweden, and staff from CEMEX during a one year project have studied the cement production within a production system in Germany, consisting of three cement plants. Together these plants are referred to as the Cluster West.

The overall aim of the project was to contribute to a better understanding of the climate performance of different ways of producing cement, and different cement products. The knowledge could be used by CEMEX to more systematically and rationally assess different cement sites and production approaches, from a climate perspective, thereby, making it easier for the company to analyze different options for improvements (cf. Gäbel & Tillman 2005 having a similar intention).

1.4 Aim

This paper more specifically aims to assess the global warming potential for clinker and three selected cement products that were produced within the Cluster West:

- CEM I 42,5 (also called Portland cement, around 92% clinker content),
- CEM III/A 42,5 (a blended cement type, around 50% clinker content),
- CEM III/B 42,5 (a blended cement type, around 27% clinker content).

This has been done in detail for the year of 2009, by conducting a quantitative, comprehensive life cycle assessment (LCA), applying a “cradle-to-gate perspective” and using the functional unit of 1 ton of cement product.

In addition, it was to be investigated if a simplified LCA model could be developed and applied to assess the climate impact for other relevant production alternatives concerning Cluster West and also for other cement products than the selected ones. This was to be done with a reasonable accuracy based on a few key performance indicators. For example, such a model could be used to significantly facilitate an assessment of the climate performance of earlier versions of Cluster West. More importantly, also possible future versions could be assessed and compared with the situation in 2009 (regarded as the present situation).

2 Methodology

Here the case and the LCA based methodology are presented more in detail. The comprehensive LCA was carried out as a typical comparative LCA in line with the ISO 14040 and 14044 standards (ISO 14040 2006; ISO 14044 2006).

2.1 CEMEX Cluster West

The studied production system consists of three active cement production plants located in Beckum-Kollenbach, Dortmund and Schwelgern (Duisburg), in Germany. The first is a cement plant with a kiln which produces clinker, while the other two can be described as grinding and mixing stations. Products and effluents from one plant are in many cases used as input to another plant, and they produce several intermediate products and final cement products. An overview of the central material and energy flows of the production system of CEMEX Cluster West (CCW) in 2009 is given in Figure 1. The inbound flows generally consist of primary and secondary materials, fossil and alternative fuels, electricity and clinker. The internal flows (vertical arrows in blue color) are clinker, granulated blast furnace slag (GBFS) and various intermediate products. Furthermore the outbound flows consist

of clinker and several final cement products ready to be shipped to the market. However, the focus has been on clinker, CEM I 42.5, CEM III/A 42.5 and CEM III/B 42.5. All intermediate products (such as KLMB, HPS-2, HP-B4, EPZ-H, HP-A4, etc.) which are required to produce the selected products are taken into account in the LCA study, but are not explained or specified in this paper. More information about Cluster West can be found in (Ammenberg et al. 2011).

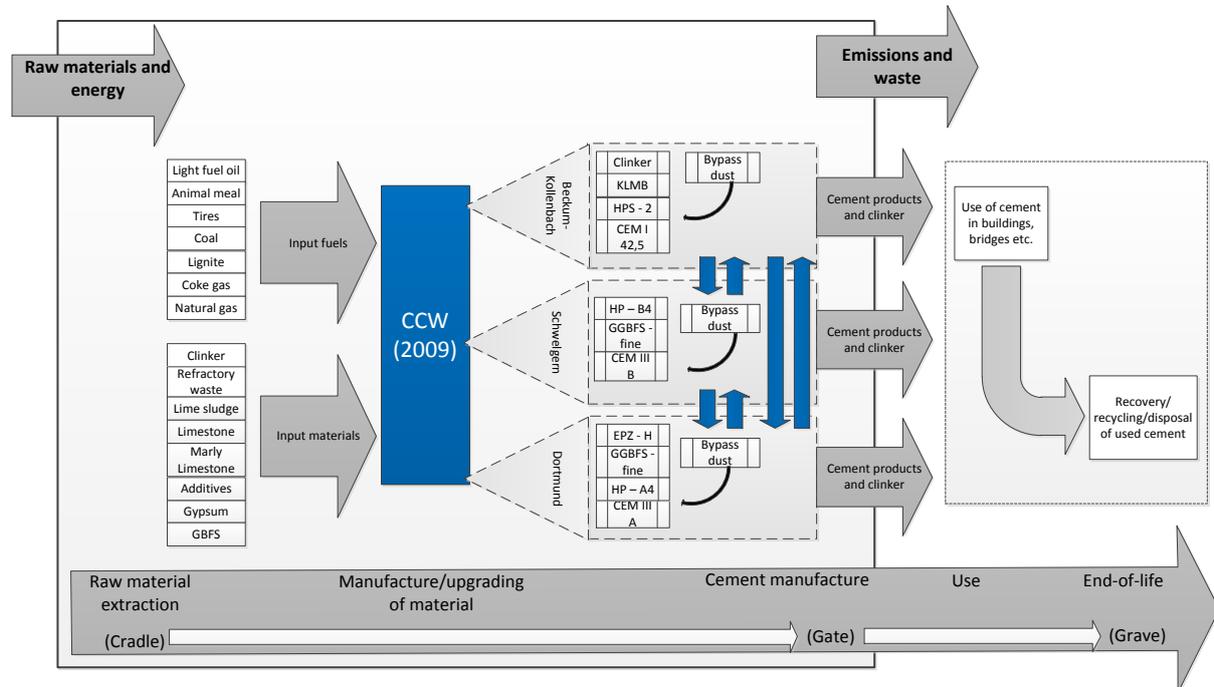


Figure 1. Overview of the CEMEX Cluster West in 2009. (Abbreviations such as KLMB, HPS-2, HP-B4, EPZ-H, HP-A4, etc are referring to names given to different intermediate products)

2.2 Scope and functional unit

In agreement with CEMEX it was decided to focus on the initial parts of the life cycle, from cradle to gate, including extraction of raw materials, production/upgrading of materials, manufacturing of cement and transportations within this scope. The use and end-of-life phase are thus excluded, because it was seen as prioritized and reasonable within the frames of the project to focus on cement and cement production. A broadened scope focusing on concrete would have been much more complex, since the cement products (as a part of concrete) are used for many different purposes and are reused or discarded in many ways. It appears to be a common choice to apply a cradle-to-gate perspectives in LCA studies of cement (see e.g. Chen et al. 2010; Huntzinger & Eatmon 2009; Michael Elias Boesch & Stefanie Hellweg 2010; Josa et al. 2004).

The functional unit was defined as *1 ton of cement*, which was seen reasonable since the scope does not include the use phase meaning that the key service delivered by cement is not included. This choice was also important to be able to realize the aim and assess several cement products with a broad range of qualities. The choice of functional unit is also in line with several other studies (see Josa et al. 2004; M.E. Boesch et al. 2009a). However, it is important to keep in mind that different cement products have a different quality.

2.3 Data collection

Site-specific data was collected for each plant, divided into five categories; input of energy and fuels; input of materials; input of consumables; output of products; and waste. CEMEX also provided information about the composition of different cement products and the composition of fuels that were used, implying that the company has accurately allocated the relevant flows to the cement products. In

addition, CEMEX provided data about heat values of fuels, transportation and CO₂ emission factors for incineration of the fuels at Beckum-Kollenbach. The company was able to provide all the data that the researchers from Linköping University requested. A majority of the data regarded the year of 2009, considered as the 'present situation', since it was the most current data available when the project started. In addition, some information about the sites concerning the year of 1997 has been used to estimate emissions from previous production.

A rather extensive input/output tool was created to facilitate the management of the data. It provided structure and was needed to convert and link the inputs/outputs, originally expressed in annual figures for each plant, to the functional unit.

CEMEX has mainly provided data about the flows within the cluster as well as inbound and outbound flows. However, the scope of the LCA study was cradle to gate, meaning that it covered all phases from the extraction of raw materials to finished cement products at "the gate" of Cluster West. Therefore, the Ecoinvent LCA database (Ecoinvent 2012) has been used to be able to include the upstream parts of the life cycle for which CEMEX could not provide the needed information. For example, data from Ecoinvent was used for animal meal, refuse-derived fuel fluff (RDF-fluff) and tires.

In this study the environmental impacts associated with infrastructures such as construction of the cement plant or other supporting infrastructures such as roads, rail roads, electricity networks and similar processes were not considered. However, a test was performed to estimate the impact of this exclusion, by using generic information of the Ecoinvent database. It showed that the impact of including infrastructural processes in the LCA model concerning clinker production increased the overall CO₂ emissions by less than one percent, indicating that the exclusion was reasonable.

To facilitate the choice of generic data and secure good data quality an evaluation method by Weidema & Wesnæs (1996) was applied. The influence of the generic data sets were tested and for data of importance the research team made a data quality check in line with the mentioned methodology, then to decide whether site-specific data should be requested instead.

Several previous LCA studies of cement are based on generic data from LCA databases, as the primary data source. To calculate the elementary flows regarding the upstream processes almost all identified LCA studies have utilized LCA databases, especially regarding the emissions related to upstream processes (Nisbet & Van Geem 1997a; Pade & Guimaraes 2007; M.E. Boesch et al. 2009b; D.N. Huntzinger et al. 2009; Chen et al. 2010; Michael Elias Boesch & Stefanie Hellweg 2010). Consequently, the impression is that this project is based on more case specific data than many other similar studies.

2.4 Allocation

Inbound materials and fuels originating from upstream product systems where they are considered as waste, have not been accounted any environmental impact in this study. This assumption is based on the fact that they would have been produced anyway, regardless of being inputs to the Cluster West. In such cases, it can be seen as reasonable to allocate all the impact to the upstream products system. Nevertheless, transportation of these materials and fuels has been included and also impact caused by treatment and upgrading processes in cases they were carried out to make the materials or fuels suitable for CEMEX. Such examples are:

- Animal meal and bone meal (MBM) - a special fraction of slaughterhouse waste.
- All RDF-fluff materials - waste fractions from the municipal waste treatment that has been grinded and mixed together.
- Shredded tires - wasted tires are being shredded.
- Granulated Blast Furnace Slag (GBFS) - the blast furnace slag has been granulated to be suitable.

For several reasons the GBFS requires special attention. GBFS can be considered a byproduct, since it in contradiction to the others has not been handled as a waste by definition and it can be bought on a market. In addition, the amounts of GBFS is much higher than those for other “waste materials” and it is related to the steel industry contributing to significant environmental impact. Consequently, it is reasonable to argue that more impact should be allocated to this material than only the minor impact caused when granulating the slag (i.e. mainly cooling it with water).

In the comprehensive LCA that formed the foundation of the study, only the impact caused by upgrading was considered. But to complement the picture, economic allocation was carried out for the GBFS. This means that a portion of the potential climate impact from the upstream product system, which is the production of pig iron, has been allocated to the GBFS. Generally, the choice of allocation principles is controversial and can have large influence on the final results (Reap et al. 2008; Van den Heede & De Belie 2012). In the reviewed LCA studies of cement, allocation is handled in different ways. Some studies have choices similar to those of this paper (Michael Elias Boesch & Stefanie Hellweg 2010; Chen et al. 2010), while others use system expansion (Lee & Park 2005) or do not explain this issue (Nisbet & Van Geem 1997b; Navia et al. 2006; Flower & Sanjayan 2007; Deborah N. Huntzinger & Eatmon 2009b).

2.5 Simplified LCA model

In addition to the more comprehensive LCA model, focusing on 2009 and the selected products, the intention was to create and test a simplified model that could be used to analyze other cement products and dynamics in the production system. The simplified LCA model was developed in a five step process shown in figure 2. All LCA models were created and calculated using the LCA software *SimaPro, ver.7.3*.

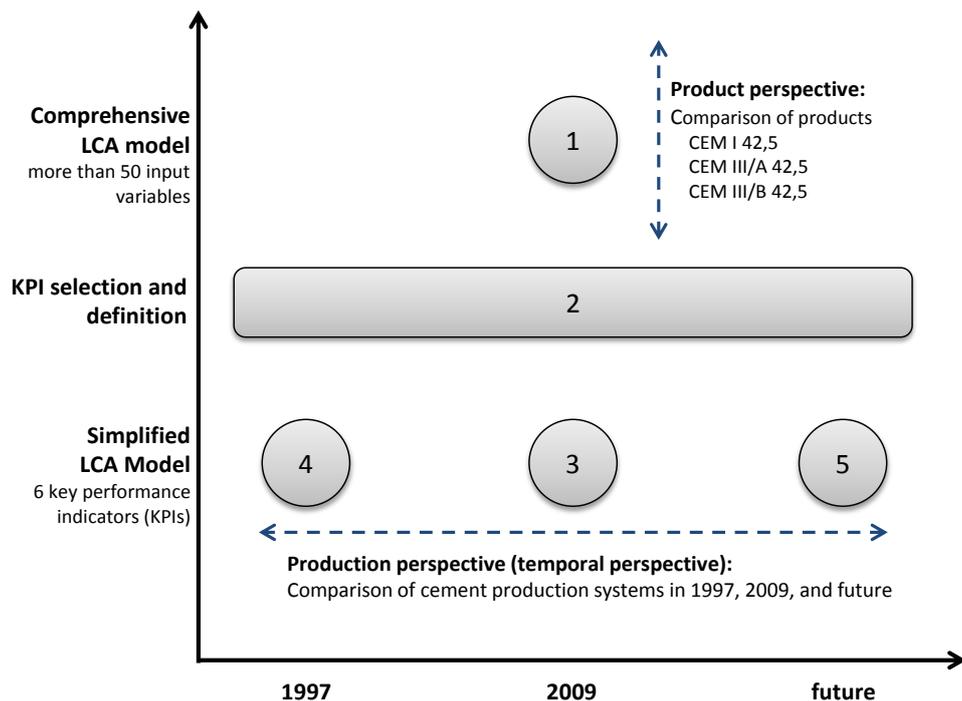


Figure 2. Illustration of the main steps of the methodology, going from comprehensive to a simplified LCA model for analyzing different products as well as production systems.

The first step is the comprehensive LCA model previously described, that was based on a thorough life cycle inventory. In accordance with the aim, the focus is on 2009 and on a comparison of the selected products (therefore *product perspective* in the figure). Step 1 included more than 50 different input variables.

In the second step it was tested if any parameters were of special importance, referred to as Key Performance Indicators (KPI). If a few such parameters can be found that provide most of the information needed, the complexity of the problem is reduced significantly without losing too much accuracy. Such influential parameters concerning the CO₂ emissions existed and were identified, see Figure 3. According to the results of the comprehensive LCA, the main sources of CO₂ emissions (or avoided emissions) were identified as CO₂ from combustion of fuels, calcination, production of electricity, and CO₂ emissions which can be avoided by substituting clinker. More information about the definitions of the selected KPIs is available in Ammenberg et al. (2011).

In step 3 a simplified model of the production system was developed based on KPIs, as shown in the Figure 3. To test this simplified model, the results of the comprehensive and simplified LCAs for clinker and the selected products were compared.

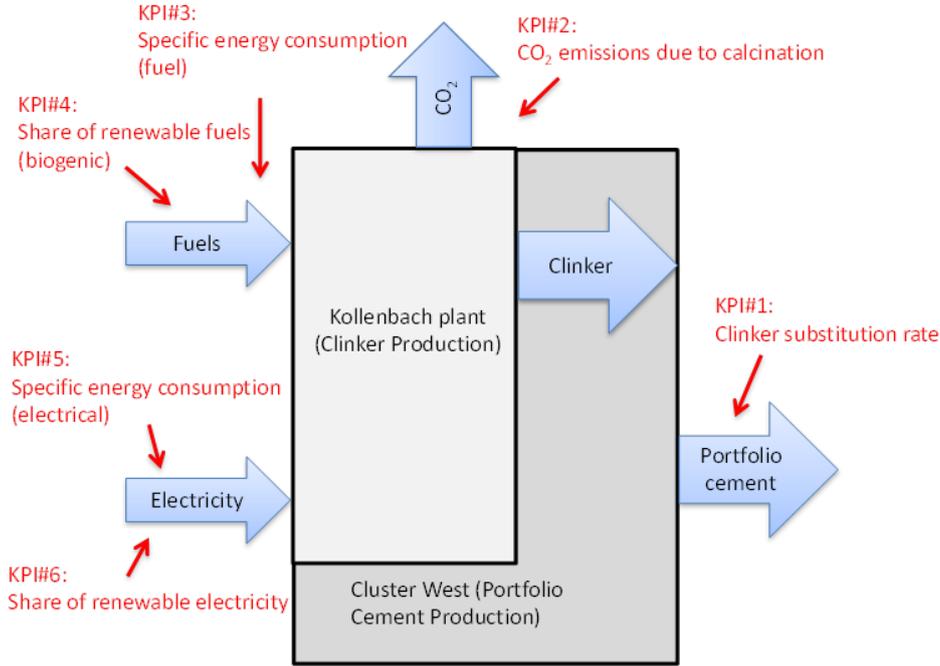


Figure 3. A simplified production system and illustration of the simplified LCA model where Cluster West is modeled based on the key performance indicators and only producing clinker and the virtual Cluster West portfolio cement.

With this simplified model, only data to calculate the KPIs was needed, which was the case for Cluster West in 2009 (step 3) and partly for 1997 (step 4), However, to be able to analyze future versions of the production system (step 5), a more simplified and abstract way to model was required to better demonstrate the changes in the inventory and in the system. The energy input was modeled as shown in Figure 4, without specifying each fuel in detail (coal, oil, etc.).

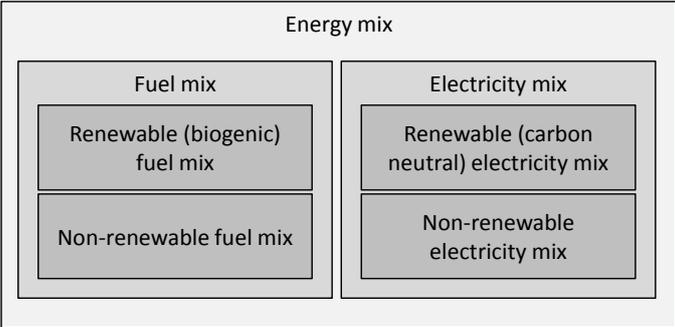


Figure 4. Simplified energy parameters used for the calculation of the KPIs.

Instead, it was seen as an ‘energy mix’, consisting of a share of a ‘fuel mix’ and an ‘electricity mix’. Further on, these two parts consisted of a ‘renewable fuel mix’ and a ‘non-renewable fuel mix’, and a ‘renewable electricity mix’ and a ‘non-renewable electricity mix’, respectively. It was also assumed that the composition of the fuels, and the corresponding emissions from Cluster West in 2009, was representative for all other assessed time periods as well. However, the share of the renewable fuel mix of the total fuel mix, and the share of the electricity mix of the total energy mix, could vary. The same assumption was used for the electricity mix.

In addition, the cement products changes over time and if the performance of the production system (and its development) is to be evaluated, a simple and representative product is required. To be able to handle earlier versions and changes of the production system, a representative product was defined. It can be described as a virtual product called *Cluster West portfolio cement*, defined as the weighted average of all the products in Cluster West. For example, the clinker substitution rate of the portfolio cement was calculated as the weighted average of all products. Based on the previous steps, it seemed reasonable to model the Cluster West portfolio cement as a product consisting of only clinker, clinker substitutes (mainly GBFS in this case) and ‘others’ (any other additives being a part of the product). Important reasons behind this choice were the fact that the clinker production contributed to the majority of the CO₂ emissions and that GBFS was used extensively. Together clinker and clinker substitutes (mainly GBFS) represented about 90-95% of the total mass of the final product. Step three transformed the production system into a system that only produced clinker and the virtual Cluster West portfolio cement - see Figure 3.

Step 4 and 5 were used to get results concerning the Cluster West as it was in 1997 and also to analyze future developments. To be able to use the simplified LCA model for these production systems, information about the key performance indicators 1-6 was required that for 1997 was derived from data about the energy input (fuel and electricity) to calculate the KPI#3-KPI#6.

The results concerning 1997 were thus calculated by changing several of the KPIs according to the production conditions of 1997. For instance, KPI#1 changed due to a lower rate of clinker substitution and KPI#4 was changed to reflect that the share of renewable (biogenic) fuels was lower in 1997.

A possible future production system was modeled both qualitatively and quantitatively. The qualitative modeling is presented in Feiz et al. (2012) and it resulted in a list of relevant options for improvement. This list formed the basis for deciding about an improved production system that was modeled quantitatively using the previously described KPIs and the simplified LCA model (meaning that the KPIs were updated to reflect the possible, future, improved production system).

Since there was no actual data regarding the future scenario, the impact of each individual KPI on the CO₂-performance of the Cluster West was evaluated. This was achieved by performing a sensitivity analysis on the simplified LCA model of 2009 assuming the inputs of the model were the KPIs and the output was the CO₂-eq emissions. The sensitivity analysis was performed by applying 1%, 5%, 10% and 20% changes (decrease or increase) on each KPI and calculating the resulting change in the CO₂-eq emissions from the considered product (clinker or portfolio cement). Knowing the sensitivity of the output (CO₂ emissions) related to different KPIs, it was also possible to calculate LCA results for different versions of the production system.

3 Results and discussion

3.1 Life cycle inventory for 2009

Table 1 shows the required amounts of inputs such as materials, fuels, transportation and electricity for the production of 1 ton clinker and the selected cement products in 2009.

Table 1. Required amounts of inputs of materials, fuels, transportation and electricity for the production of 1 ton of different products. These are based on the life cycle inventory (LCI) for Cluster West in 2009 (step 1). Some of the LCI figures, such as the ones concerning transportation of intermediate products internally within the cluster, are calculated in the LCA model but are not included in this table.

		Inbound materials/fuels/electricity	Unit	Clinker	CEM I 42,5	CEM III/A 42,5	CEM III/B 42,5
Clinker production (Beckum-Kollenbach)	Animal meal		MJ	1098	-	-	-
	Crushed marly limestone		Kg	1002	35	-	-
	Electricity		kWh	69	-	-	-
	RDF-Fluff		MJ	1440	-	-	-
	High grade limestone		Kg	502	-	-	-
	Kiln-coal		MJ	968	-	-	-
	Light fuel oil		MJ	17	-	-	-
	Lignite		MJ	316	-	-	-
	Lime sludge		Kg	7	-	-	-
	Rail transport		Tkm	26	-	-	-
	Refractory waste		Kg	0,5	-	-	-
	Road transport		Tkm	32	3.2	-	-
	Tires		MJ	72	-	-	-
Cement production (Beckum-Kollenbach, Dortmund and)	Additives		Kg	-	2	9	-
	Bypass dust		Kg	-	24	0.1	-
	Clinker		kg	-	896	3	-
	Clinker meal		Kg	-	-	4	-
	Clinker-RA		Kg	-	-	-	-
	Coke gas		MJ	-	-	-	-
	Electricity		kWh	-	49	6	1
	GBFS		Kg	-	-	3	-
	GGBFS-fine		Kg	-	-	377	603
	Gypsum (normal, 90/10, REA)		Kg	-	45	0.4	-
	Natural gas		MJ	-	-	0.0006	-
	Other intermediate products		Kg	-	-	612	397
	Road transport		Tkm	-	-	1.1	-

The majority of direct inputs of raw materials to the Cluster West 2009 were related to the production of clinker at the Beckum-Kollenbach plant. The direct input of raw materials is significantly smaller for the rest of the cement products since their main inputs come from intermediate products manufactured within the cluster. Most of the fuel is burned at the kiln of Beckum-Kollenbach. Only small amounts of fossil fuels, i.e. natural gas and coke gas, are used for the production of CEM III/A 42.5 and CEM III/B 42.5. Electricity is used for the production of all products, but for different purposes. Concerning the production of clinker at Beckum-Kollenbach, electricity is mainly used for the preparation of raw materials. In Schwelgern and Dortmund the use of electricity is primarily due to the process of milling and blending clinker with GBFS, gypsum and other additives.

Many different intermediate products are produced within the Cluster West. These intermediate products are used in the production of the studied cement products and therefore have been taken into consideration. This means that all intermediate products have been modeled in detail, with complete life cycle data inventories, in the comprehensive LCA (step 1). Table 2 shows compiled information about the products and intermediate products. It contains information about the composition in terms of clinker, clinker substitutes (assumed to be GBFS in Cluster West) and other materials (such as gypsum and other additives).

Table 2. The composition of the studied cement products and intermediate products. Abbreviations such as EPZ-H, HP-A4 and so on are names given to different intermediate products.

Product/inter-mediate product	Production plant	Clinker % weight	Clinker substitutes (GBFS) %weight	Others %weight
Bypass dust	Different sites	0	0	100
CEM I 42,5	Beckum-Kollenbach	90	0	10
CEM III/A 42,5	Dortmund	47	45	8

CEM III/B 42,5	Schwelgern	25	70	5
Clinker	Beckum-Kollenbach	100	0	0
Clinker meal	Beckum-Kollenbach	66	0	34
EPZ-H	Dortmund	66	27	7
GBFS	Schwelgern	0	100	0
GGBFS-fine	Dortmund, Schwelgern	0	100	0
GGBFS-standard	Dortmund, Schwelgern	0	100	0
HP-A4	Dortmund	67	23	10
HP-A5	Dortmund	0	27	73
HP-B4	Schwelgern	62	24	14
HPS-1	Beckum-Kollenbach	79	0	21
HPS-2	Beckum-Kollenbach	91	0	9

3.2 Life cycle impact assessment for 2009

The comprehensive LCA from cradle to gate (step 1 in Figure 2) gave the results shown in Table 3. Within the cement industry benchmarking is often based on figures concerning clinker, where the global warming potential for Cluster West was found to be 850 kg CO₂-eq. This could be compared to the world average, that according to Moya et al.(2010) is in the range 900-1000 kg CO₂-eq per ton.

Table 3. The global warming potential for the selected cement products from Cluster West in 2009 and also the virtual, average product – Cluster West Portfolio Cement (CCWCP 2009).

Cement products	Production plant	Clinker-to-cement ratio (%)	GBFS-to-cement ratio (%)	Other contents (%)	Clinker substitution rate (%)	Global warming potential (kg CO ₂ -eq/ton)
Clinker	Kollenbach	100	0	0	0	850
CEM I 42,5	Kollenbach	90	0	10	10	779
CEM III/A 42,5	Dortmund	47	45	8	53	452
CEM III/B 42,5	Schwelgern	25	70	5	75	265
CCWCP 2009	CCW	40	53	7	60	385

About 88% of the CO₂-eq emissions for clinker are linked to the production process of the Beckum-Kollenbach plant (Table 4), to a large extent explained by the calcination corresponding to about 64%. The second and third most contributing processes can also be found within the Kollenbach plant - the incineration of kiln coal and RDF-fluff (silo) that emitted about 10% and 8% respectively. This was not surprising since relatively large amounts of these fuels are incinerated to produce 1 ton of clinker. The part of the life cycle where raw materials are extracted, upgraded and transported to the Kollenbach plant contributed to 12% of CO₂-eq emissions for clinker. This was mainly due to the electricity used for production of clinker and the animal meal that is used as alternative fuel. Each contributed to about 5% of the total emissions from clinker. Together, the transportation contributed to less than 0.5% of the total impact for clinker.

Table 4. CO₂-eq emissions from the different processes in the life cycle of clinker.

Life cycle phase	Processes	Emissions kg CO ₂ -eq / 1 ton clinker	Share %
	Electricity (German mix)	46	5%
	Upgrading of animal meal	39	5%
	Kiln coal	12	1%
	Transport (road)	3	0,3%
	Calcareous marl	2	0,3%
Raw material extraction	Transport (rail)	1,0	0,1%
	Upgrading of RDF-fluff (silo)	1,2	0,1%
Cradle-to-gate (entrance)	Limestone	0,9	0,1%
	Refractory waste	0,6	0,1%
	Light fuel oil	0,3	0,03%
	Lignite	0,2	0,03%
	Upgrading of RDF-fluff (kiln)	0,1	0,01%
	Upgrading of tire	0,1	0,01%
	Upgrading of RDF-fluff (agglomerate)	0,0	0,003%

Total raw material extraction phase		106	12%
Production Gate-to-gate	Calcination of raw materials	541	64%
	Incineration of kiln coal	89	11%
	Incineration of RDF-fluff.silo	71	8%
	Incineration of lignite	31	4%
	Incineration of tires	4,7	0,6%
	Incineration of RDF-fluff.agg	3,2	0,4%
	Incineration of RDF-fluff.kiln	2,0	0,2%
	Incineration of light fuel oil	1,3	0,2%
	Total production phase	744	88%
	Total clinker cradle to gate life cycle	850	100%

It is important to remember that these results do not include any allocation of the impact from the iron/steel industry, via the slag (GBFS), to the cement products. But it is reasonable to see the GBFS as a byproduct of iron production (not as waste) and therefore allocate some of the impact caused by iron production to it. An economic allocation was carried out based on a price estimation performed by Chen et al. (2010a). It suggested that 2.3% percent of the impact of iron production should be allocated to the GBFS per ton. Some of the results from Table 3 are illustrated in Figure 5, which also shows the impact of economic allocation based on data about pig iron production from the Ecoinvent database. Naturally, it only makes a difference for the two products with GBFS content.

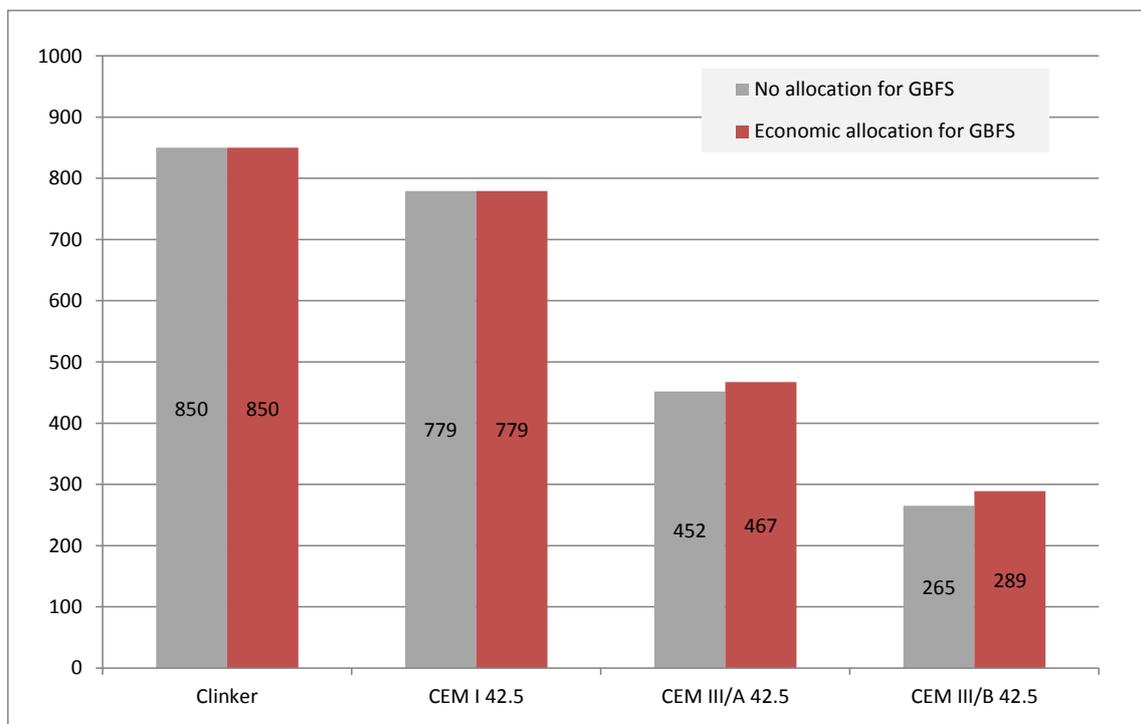


Figure 5. CO₂-eq emissions from the comprehensive LCA model, but also showing the impact if economic allocation is performed allocating 2,3% of the impact from pig iron production to the selected products.

Not surprising, the results in Table 3 and Figure 5 verify that the climate performance clearly differs between the selected cement products, where less clinker means reduced CO₂-eq emissions. For example, the emissions associated with CEM III B 42,5 only corresponds to 34% of those for CEM I 42,5 without allocation and about 37% including an allocation as presented. These results are similar to those of Van den Heede & De Belie (2012) concerning economic allocation, but that study in addition shows that a mass allocation would lead to very different results – suggesting that it is not an advantage to utilize GBFS from a climate perspective.

3.3 Key performance indicators

The key performance indicators (KPIs) were shown in Figure 3. Figure 5 provides information about their values for the Cluster West portfolio cement of 2009.

Table 5. The key performance indicators, their units and values for the Cluster West portfolio cement of 2009.

Key Performance Indicator (KPI)	Unit	2009 value
KPI#1 Clinker substitution rate	% weight	60%
KPI#2 CO ₂ emissions due to calcination	Kg CO ₂ /ton	541
KPI#3 Specific energy consumption (fuel)	MJ / ton	3913
KPI#4 Share of renewable (biogenic) fuels	% thermal energy	41%
KPI#5 Specific energy consumption (electricity)	kWh / ton	69
KPI#6 Share of renewable electricity	% electricity	0%

3.4 Validation of the simplified LCA model

As described earlier, a test was performed comparing the results of the simplified model and the comprehensive LCA model. For this purpose, different products in 2009 were compared, and it showed that the difference was less than 4% (Figure 6).

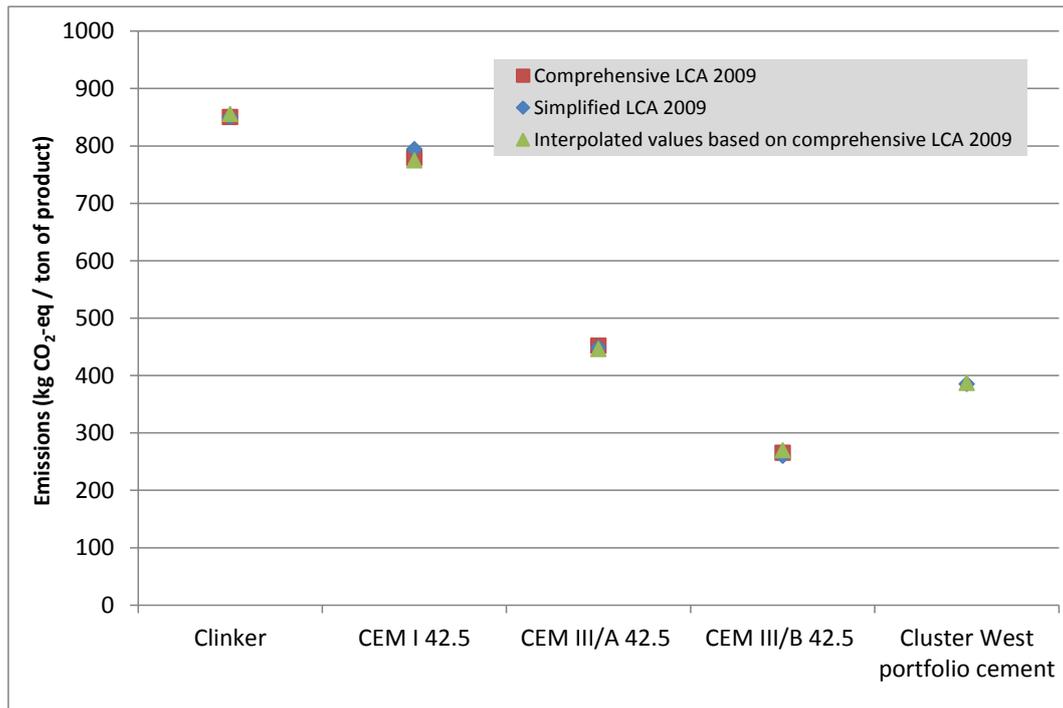


Figure 6. Comparison of the results of the traditional and simplified LCA approach for the selected cement products and the simulated CCWCP.

The sensitivity analysis was performed as described to quantify the relation between changes of each KPI and the results of the LCA (global warming potential as CO₂-eq). See Figure 7, where KPIs with bigger impact have more negative slopes.

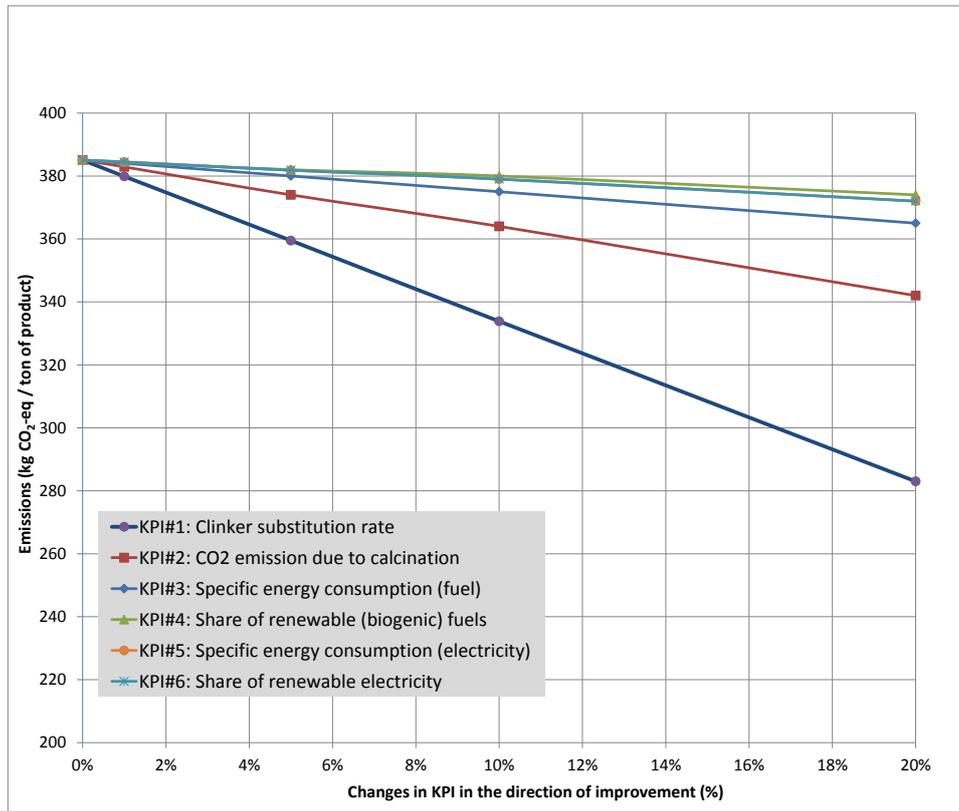


Figure 7. The linear relation between changes of KPIs and the output of the LCA model.

The purpose of developing the simplified LCA was to make it possible to consider different conditions for the production system (i.e. Cluster West in 1997, 2009 and future) without losing too much accuracy. Having conducted the comprehensive LCA, important results could be generated based on knowledge about six key performance indicators (KPIs) regarding overall information about materials, the fuel and electricity mix. The simplified LCA approach was then used for other products and versions of Cluster West, without collecting large amounts of additional specific Life Cycle Inventory (LCI) data for those products or production systems.

Clearly, the simplified LCA approach conformed well to the result of the comprehensive LCA approach. The small difference between the traditional and simplified LCA approach (ranged between -2% to 2%) is acceptable, since the simplified approach is not intended to be used for exact calculations of the global warming potential. Its purpose was to simplify LCA modeling of dynamic developments of a rather complicated production system and to be able to draw overall conclusions based on a few important parameters (the KPIs), instead of having to carry out a detailed analysis, like the comprehensive LCA (step 1), for all the changes in the cement production systems.

3.5 Simplified LCA for 1997 and possible future

To assess the historical production system of 1997 (step 4 in Figure 2), the key performance indicators were altered to reflect that system. For example, the clinker substitution rate, use of alternative fuels and electrical efficiency were lower. Using the calculated KPIs for 1997, the simplified LCA gave results as shown in Figure 8.

During the project several future options for development of Cluster West were identified and assessed (Ammenberg et al. 2011) and for all of them the simplified LCA model could be applied via translating changes in terms of the KPIs. One possible scenario is that Cluster West continues to develop similarly to the studied period between 1997 and 2009. Regarding the KPIs, that would mean (conservatively) about 10% increase of clinker substitution rate (KPI#1), 20% increase of the share of renewable fuels (KPI#4) and 10% reduction of specific electricity consumption (KPI#5). The results

for this scenario for clinker and the virtual cement portfolio product that have been assessed are shown in Figure 8.

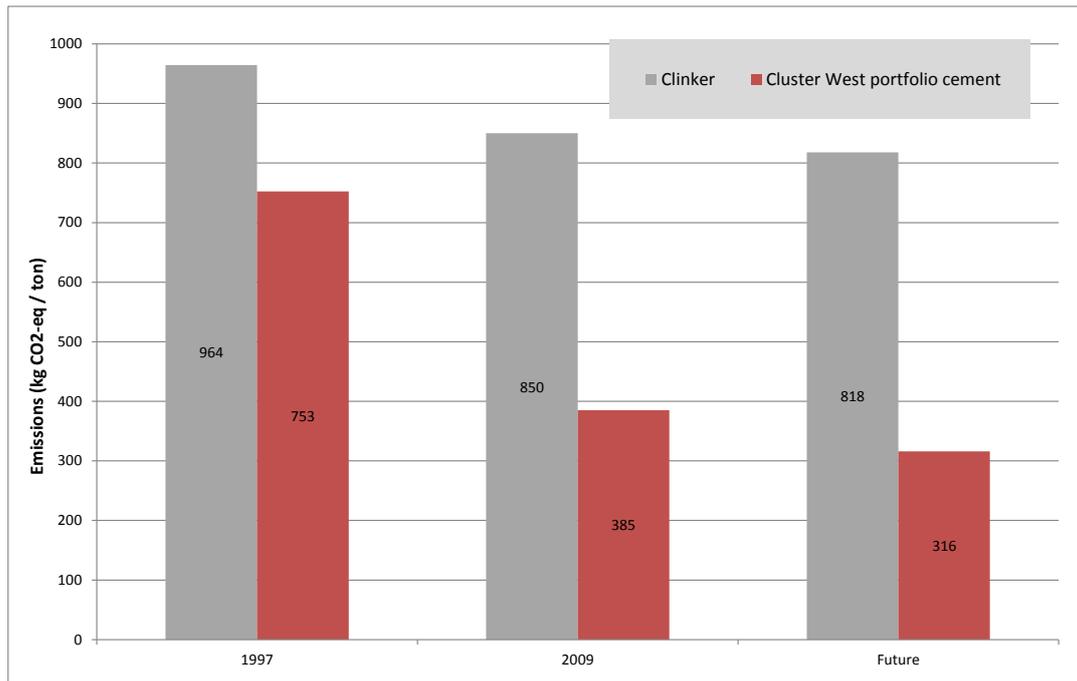


Figure 8. Global warming potential for clinker and portfolio cement produced at the Cluster West, for 1997, 2009 and a possible future version as described above.

A comparison of the clinker production systems in 1997 and 2009 shows that improvement measures have been effectively implemented within the cluster. During the 12 years between 1997 and to 2009 the global warming potential of the virtual portfolio product (the average product) has decreased by about 368 kg CO₂-eq/ton. Most of the measures of relevance for the clinker production can be characterized as local production efficiency measures at the plant level, for example, increasing the thermal efficiency of the kiln and decreasing the electrical energy consumption in the production processes. There are however more important initiatives having a wider scope, comprising flows and actors outside the production plants. The main reason behind the improvements since 1997 was the increased production of blended cements within the cluster, where GBFS to a large extent has substituted clinker. Another important reason is that fossil fuels have been replaced with alternative fuels, including renewable fuels, since alternative fuels are causing less CO₂ emissions.

4 Conclusions

Based on a comprehensive LCA from cradle to gate for 2009, this study showed that CEMEX Cluster West is producing clinker rather efficiently, in comparison with average cement production in Europe and many other regions in the World (Japan being one exception). There are several reasons for this, for example measures within the facilities leading to improved energy efficiency. Another important explanation is the increased share of alternative fuels, of which a part is renewable.

Shifting focus from the production and clinker to the cement products showed that the Cluster West cement product portfolio (a virtual average product) is very favorable from a climate perspective. This is mainly a consequence of using a high share of clinker substitutes, where granulated blast furnace slag (GBFS) from a steel company is replacing clinker. To illustrate the importance of the production facilities in relation to the type of cement, an interesting conclusion is that the emissions for clinker were reduced about 12% in the period from 1997 to 2009 (very much reflecting changes of technology, fuels, etc.). In the same period the corresponding figure for the portfolio cement was close to 49%. As expected, less clinker means a lower global warming potential. This impression clearly

remained even after an economic allocation concerning the GBFS, where some of the impact from pig iron production was included.

Based on the comprehensive LCA a much simpler LCA model was developed and applied. This was possible since six key performance indicators to a large extent decided the results. The simplified model made it viable to assess older and future versions of Cluster West. Utilizing information from 1997 the key performance indicators were altered to reflect that production system and therefore the changes from 1997 until 2009 could be analyzed. Similarly, potential improved future versions of Cluster West could also be assessed.

In addition to the LCA results, the study illustrated how the results from a comprehensive LCA study can be utilized to create a much simpler model with reasonable accuracy. The model made it possible to handle dynamics in a complicated production system efficiently. In this case, instead of gathering information about more than 50 parameters, it was enough to monitor 6 key indicators.

The same approach can be used for other cement production systems and it would be interesting to explore the possibilities of using similar approaches in other industrial sectors.

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