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Improving the CO₂ performance of cement, part III: The relevance of industrial symbiosis and how to measure its impact

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Abstract

Cement production contributes to extensive CO₂ emissions. However, the climate impact can vary significantly between different production systems and different types of cement products. The market is dominated by ordinary Portland cement, which is based on primary raw materials and commonly associated with combustion of vast amounts of fossil fuels. Therefore, the production of Portland cement can be described as a rather linear process. But there are alternative options, for example, involving large amounts of industrial byproducts and renewable energy which are more cyclic and thus can be characterized as relatively “synergistic.”

The main purpose of this article is to study how relevant the leading ideas of industrial symbiosis are for the cement industry based on a quantitative comparison of the CO₂ emissions from different cement production systems and products, both existing and hypothetical. This has been done by studying a group of three cement plants in Germany, denoted as Cluster West, and the production of cement clinker and three selected cement products. Based on this analysis and literature, it is discussed to what extent industrial symbiosis options can lead to reduced CO₂ emissions, for Cluster West and the cement industry in general.

Utilizing a simplified LCA model (“cradle to gate”), it was shown that the CO₂ emissions from Cluster West declined by 45% over the period 1997 – 2009, per tonne of average cement. This was mainly due to a large share of blended cement, i.e., incorporation of byproducts from local industries as supplementary cementitious materials. For producers of Portland cement to radically reduce the climate impact it is necessary to engage with new actors and find fruitful cooperation regarding byproducts, renewable energy and waste heat. Such a development is very much in line with the key ideas of industrial ecology and industrial symbiosis, meaning that it appears highly relevant for the cement industry to move further in this direction. From a climate perspective, it is essential that actors influencing the cement market acknowledge the big difference between different types of cement, where an enlarged share of blended cement products (substituting clinker with byproducts such as slag and fly ash) offers a great scope for future reduction of CO₂ emissions.

Keywords: cement, CO₂ emissions, life cycle assessment (LCA), industrial symbiosis, granulated blast furnace slag (GBFS).

1. Introduction

Cement is an essential material in many ways that is used extensively worldwide, mainly as a component of concrete. Cement is very interesting from an environmental perspective, for example, due to the massive material and energy flows that are related to its production and use (Bernstein et al., 2007; Boesch et al., 2009; Reijnders, 2007; van Oss and Padovani, 2002).

In co-operation with the global cement producing company CEMEX a research project has been carried out to contribute to a better understanding of the climate impact¹ of different ways of producing cement, and different cement products. The focus has been on Cluster West, which is a cement production cluster consisting of three plants in Germany². This paper is the third in a series of three, all of which are included in this special issue. The first introduces cement production and the selected case, and includes information about the LCA-based methodology (Feiz et al., 2013a)³. It provides results from a comparison of different cement products and production systems. The second paper presents a systematic approach for assessing measures to reduce the CO₂ emissions related to the cement industry (Feiz et al., 2013b)⁴. This third article, based on the other two, provides further insight on the comparisons of different products and systems and considers to what extent industrial symbiosis options can lead to reduced CO₂ emissions.

1.1 Industrial symbiosis

Ordinary Portland cement dominates the cement market (WBCSD/CSI, 2009). As described in part I, this type of cement contains a large share of primary raw materials (lime) and the production commonly involves combustion of vast amounts of fossil fuels (WBCSD/CSI, 2012). Therefore, with some exceptions, production of Portland cement can be regarded as a rather linear process associated with a large share of material flows that are not closed. This is in line with the traditional view within the field of supply chain management, where a supply chain often is described or seen as linear flows of physical goods, information and funds between suppliers, producers and customers (Bansal and McKnight, 2009; referring to Mentzer et al., 2001). Bansal and McKnight (2009) describe this as mainly looking forward and pushing backward, meaning that companies focus on the market and the customers (forward) and on strategic suppliers (backwards). In addition to the many linear flows within the cement industry, it is important to note that a large share of the resources is non-renewable. This means that “ordinary cement production” faces many critical challenges from a long-term sustainability perspective (Imbabi et al., 2013; Meyer, 2009; Schneider et al., 2011).

The field of industrial ecology suggests an alternative approach, since one of the leading ideas is to mimic nature and strive for more closed loops (Frosch and Gallopoulos, 1989; Isenmann, 2002; Baas, 2005; Hardy and Graedel, 2002; cf. Erkman, 1997). Vigon (2002), writing about industrial ecology in the cement industry, says that “the heart of IE (i.e., Industrial Ecology, authors’ comment) concept is the idea that businesses can exchange materials or energy to mutual advantage.” Likewise, it is commonly stated that an important purpose of industrial symbiosis⁵ is to become more resource efficient (or competitive, Côté and

¹ Focusing on CO₂ emissions

² The project was financed by CEMEX Research Group AG Switzerland and focused on Cluster West (presented in part I) owned by CEMEX WestZement GmbH, Germany.

³ From now on referred to as “part I”

⁴ From now on referred to as “part II”

⁵ The authors regard industrial symbiosis as a subfield of industrial ecology. In this article we mostly refer to industrial symbiosis for the sake of simplicity.

Hall, 1995; Lombardi and Laybourn, 2012), where improved material and energy flows can lead to economic benefits (Jensen et al., 2012; Mirata and Emtairah, 2005; cf. Ayres, 1989 as referred to in Chertow, 2000). Furthermore, one of the main points of Bansal and McKnight (2009) is that it might be advantageous to complement the “looking forward and pushing backward” (the traditional supply chain view) with “peering sideways.” This means to adopt one of the key ideas of industrial symbiosis – to look outside the traditional supply chain for options to improve resource efficiency. Figure 1 conceptually illustrates a linear case in comparison with a more “synergistic” example, excluding geographical aspects such as distances and transportation (which however have been included and accounted for in the project). Figures having the same logic are later used to illustrate assessed scenarios.

Figure 1. Illustration of a linear production system in contrast to a more synergistic example. The figure is only intended to roughly illustrate important differences, focusing on the main Plant/Company in the center for each case. For other plants/companies (C) only the flows related to the main Plant/Company are shown.

A few examples might clarify the logics of Figure 1 - to become more resource efficient a company could:

- Improve internal efficiency, for example, to increase production based on the same types and amounts of resources (leading to thicker product arrows) or to improve the quality of the products, i.e., to increase their value, still using the same types and amounts of resources (leading to lighter colors for the product arrows).

- Improve issues in relation to supplied raw materials and energy, for example, switch to materials associated with less environmental impact but still manage to produce equal amounts and quality (indicated by lighter colors for the raw material arrows).
- Manage to produce several products, for example, turning a waste flow associated with costs into revenue (additional product arrows) and/or produce more valuable products. Key terms are diversification and valorization.

There are many scientific articles focusing on industrial ecology or industrial symbiosis, where the cement industry (commonly one or a few cement plants) is part of the case (e.g. Hashimoto et al., 2010; Chertow and Miyata, 2011). Such articles provide information about existing or possible synergies and show that the cement industry can serve as an anchor tenant in industrial symbiosis networks (cf. Brent et al., 2012). A large part of the general industrial symbiosis literature has emphasized exchange of resources such as byproducts/wastes and energy across industries in geographical proximity (Chertow, 2000). There are already plenty of such examples within the cement industry as described in part I and II, for example, involving the use of alternative raw materials and fuels, and renewable energy (van Oss and Padovani, 2002, 2003; Van den Heede and De Belie, 2012; Hashimoto et al., 2010; Gäbel and Tillman, 2005). There are also several scientific papers focusing on the cement industry, dealing with or at least referring to industrial ecology and symbiosis (see part I and II and the reference list in this article). Among many things, literature tells us that what could be referred to as “industrial symbiosis measures” have been ongoing within the cement industry for a long time. For example, this is true for the use of alternative fuels. In addition, blended cements have been used for a long time, for example, slag cement at least since the 17th century (Lewis, 1981) and the use of GBFS⁶ was widespread in many countries during the 1950s (Meyer, 2009; cf. Morrison, 1944). As mentioned, Portland cement is the dominant product, but statistics from the Cement Sustainability Initiative indicate that the world clinker to cement ratio decreased about 6% between 1990 and 2006 (WBCSD/CSI, 2009). This means that the share of blended cements has increased during this period - there is ongoing development within this area. There are several studies that have compared the environmental impact of different types of cement and production systems (e.g. Van den Heede and De Belie, 2012; Hashimoto et al., 2010; Gäbel and Tillman, 2005).

Vigon (2002), in a report commissioned by the World Business Council for Sustainable Development, gives an overview of industrial ecology from a cement industry perspective, based on literature, experts and input from ten major, international cement companies. This report contains interesting information, mainly of a qualitative nature, about knowledge, practices and examples, incentives and obstacles, different actors and roles, and potential material and energy flows related to cement plants. However, there seems to be a lack of recent scientific papers giving an overview of how, and to what extent, industrial ecology and symbiosis options can lead to reduced CO₂ emissions. The authors find it relevant to provide complementary approaches and results and to further elaborate on the role that industrial symbiosis can play within this sector. Comparing different production systems, it is sometimes obvious that changes in the direction encouraged within industrial ecology and industrial symbiosis will lead to higher resource efficiency and reduced environmental impact. However, in many cases it would be good to have a more systematic method for evaluating the impact of industrial symbiosis (Sokka et al., 2011; Wolf and Petersson, 2007).

⁶ In this article the term GBFS is used, but it should be noted that GBFS needs to be milled into Ground Granulated Blast Furnace Slag (GGBFS) for use as clinker substitute in the finished cement products.

1.2 Aim, scope and methodology

As described, cement production can be arranged in different ways and cements, providing similar functions, can be based on different materials. The environmental importance of cement means that it is highly relevant to assess different production systems and products, where CEMEX Cluster West was selected as a case because it provided information about alternative ways of producing cement and alternative, blended cement products. It is also interesting to study a production cluster, to complement studies about single plants.

Clearly, there are opportunities to reduce the CO₂ emissions associated with the cement industry and it is interesting to analyze to what extent industrial symbiosis can contribute. The main purpose of this article is to study how relevant the key ideas of industrial symbiosis are for the cement industry by comparing the CO₂ emissions of traditional, rather linear cement production with alternatives that can be seen as more “cyclic” or “synergistic.” From this perspective, based on part I and part II, the aim is to:

- Clarify which parts of the Cluster West cement life cycle and what “components” are most important from a climate perspective and emphasize important differences when comparing:
 - The existing production system of Cluster West, with older versions and possible, improved future versions.
 - The “traditional” CEM I product with blended CEM III products where Ground Granulated Blast Furnace Slag (GGBFS) is used as a clinker substitute.
- Provide and discuss results concerning allocation of impact to alternative materials, as more knowledge about IS allocation principles can influence the outcome to a large extent. The main focus is on blast furnace slag, since it is most relevant for Cluster West.
- Assess seven hypothetical improved production systems, chosen to illustrate different measures to reduce the CO₂ emissions and to learn more about the relevance of the key ideas within industrial ecology/symbiosis. This assessment shall give further information about how useful the simplified LCA model (from part I) is and also complement part II by providing quantitative results for different types of measures.
- Discuss lessons learned on how to measure the impact of industrial symbiosis.

The methodology is presented in part I and II, where it is relevant to keep in mind that it is an LCA-based methodology focusing on climate impact from “cradle to gate.” For this paper, the information was further structured and considered important industrial symbiosis aspects such as material and energy flows, involved organizations and geography, what processes that cause impact, different types of resources, possible improvements to assess, etc.

2. Comparison of different cement products

One main objective of the research project was to compare the climate impact of the studied cement products, where some of the results have been presented in part I. However, those results did not include any allocated CO₂ to GBFS from the pig iron production, which is important to consider in line with our

argument in part I. A key question regarding allocation is if the GBFS (or BFS) is to be seen as waste or a byproduct. The views on this issue vary within the cement industry although this is a decisive factor in any cement-related LCA study. If GBFS is a valuable byproduct, not only impact associated with upgrading and transport of the waste should be included, but also a part of the impact from the production of iron (ISO 14044, 2006). The research team, considering EU directives (European Parliament, 2008), found it reasonable to define GBFS as a byproduct of iron production and therefore to allocate some of the impact caused by iron production to it. The results of economic allocation are shown in Figure 2, based on a price estimation by Chen et al. (2010a) suggesting that 2.3% percent of the impact of iron production should be allocated to the GBFS per tonne.

Figure 2. Results from the LCA (see part I) showing the CO₂-eq emissions for clinker and the three selected cement products. The results include effect of economic allocation, where a share of the emissions associated with pig iron production has been allocated to the GBFS. Allocation has no impact for clinker and CEM I, since they do not contain GBFS (GGBFS).

Not surprising, the results 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 allocation as presented. These results are similar to those of Van den Heede and De Belie (2012) concerning economic allocation, but in addition that study shows that a mass allocation would lead to different conclusions (allocation of 20% of emissions from steel production to cement) – suggesting that it is not advantageous to utilize GBFS from a climate perspective. Consequently, the choice of allocation principle is very important.

Utilizing the simplified LCA model (see part I) it is possible to show how the CO₂ emissions vary dependent on the clinker content, keeping the other Key Performance Indicators (KPIs) constant – see Figure 3 (and information about the KPIs in Table 1). The figure has a continuous scale which makes it possible to assess the emissions for products (or product portfolios) other than those selected, only based on

knowledge about the clinker content. Figure 3 thus further clarifies the differences between traditional (rather linear) cement production and more synergistic alternatives (e.g., involving use of industrial byproducts, GBFS in this case).

Figure 3. Linear regression of the results of the comprehensive LCA and the estimation of CO₂-eq emissions for the average (portfolio) cement in 1997 and 2009. The figure shows that with good approximation, the CO₂ emissions per unit of cement produced has a linear (but reverse proportional) relation with the rate of clinker substitution, where in this case GBFS (GGBFS) is used as a clinker substitute.

3. Comparison of different cement production systems

There is an ongoing development within the cement industry to become more efficient. So far, many actors appear to have a rather site-oriented focus regarding improvements (see part II). However, it is important to remember that production of Portland cement (CEM I) involves burning of limestone, which means that a lot of CO₂ is released due to calcination as well as combustion of fuels. Improved energy efficiency, alternative fuels and other similar measures focusing on the production facilities are of importance from an environmental perspective, but they do not reduce the amount of calcined CO₂ from the cement kilns. Comparing the Cluster West production system of 1997 and 2009 (as presented in part I), this study showed the CO₂ emissions for product portfolio (average product) in 1997 was 703 kg CO₂-eq/tonne and the corresponding figure for 2009 was 385. Consequently, CEMEX has managed to reduce the emissions, per tonne of cement, by almost one-half, about 90% of which has been achieved by the increased clinker substitution rate. The combined contribution of other improvement measures, such as using more alternative fuels, was less than 10%.

Figure 4 roughly illustrates some of the main differences, where the production system of 2009 can be seen as more synergistic since it implies a greater supply from the steel industry, more alternative fuels and an increased share of renewable energy (and also additional raw materials which is not shown). In 2009, blended cements (CEM II & III) represented about 90% (in weight) of the cement product portfolio. The results of the LCA study (part I) showed that transportation causes a small part of the total CO₂ emissions and therefore transportation and geographical aspects such as distances are excluded in the figures of this type (cf. Chen et al., 2010b).

Figure 4. A comparison of the production system (CEMEX Cluster West) in 1997 and 2009, using the same logic as for Figure 1. The thicknesses of the arrows are proportional to show the relative size, within each type of flow (material, energy, product – see Figure 1). The total thickness of input arrows does not equal the total thickness of the output arrows and the figure is only intended to roughly illustrate important differences.

In addition to the assessment of the production systems of 2009 and 1997 (including different mixes of products) an important part of the project was to study future options for improvement. Therefore, the framework presented in part II was developed and applied to systematically collect, classify and assess

different options for improving the climate performance. That article, and the work behind it, clearly suggests that the leading ideas within industrial ecology and industrial symbiosis are highly relevant if the CO₂ emissions associated with the cement industry are to be reduced significantly. For example, Figure 6 in part II shows that almost all improvement options that are judged to have a high (or medium-high) potential to reduce the CO₂ emissions require cooperation with other organizations. Several of these organizations are rarely a part of the “traditional” supply chain of Portland cement. However, part II provides qualitative information and it is interesting to complement those results with quantitative data.

Assuming that managers of Cluster West want to reduce the CO₂ emissions associated with cement production, the results from part II structure the options and provide information about different types of measures. There are four main paths to CO₂ reduction (cf. Benhelal et al., 2013):

- Production efficiency – site-oriented, technological measures
- Input substitution – changes concerning feedstock, fuels or electricity
- External synergies – carbon sequestration, district heating, co-location with other industries, etc.
- Product development – blended cements and other options

To quantitatively indicate the potential for each main path, or category, and some of the most relevant measures within each category, seven cases were constructed. The simplified LCA model (part I) was used for the assessment by translating the changes each case implies to changes in the related key performance indicators (KPIs, see Table 1). Cases 1-5 are regarded as simpler and are defined to reflect specific improvements within a few areas (related to one or two KPIs), and to illustrate differences in unit emissions and total emissions, while cases 6 and 7 comprise several different types of changes and require more radical developments. The cases and their relations to the different paths for improvement and the KPIs are presented below and summarized in Table 1, with the system of 2009 as a basis:

Case 1 – Efficient cement plant, a case dealing with production efficiency, i.e., site-oriented measures. The total production of clinker and cement is unchanged and the same types of products are produced, but technical upgrades in the Kollenbach plant are implemented. This involves improvements such as adding a precalciner, upgrading the clinker cooling system and replacing a grinding system with vertical roller mills (new type of mills). This would improve both the thermal efficiency (EEE) and electrical efficiency (EEH). The case is modeled as a 15% reduction of the specific heat consumption (KPI₃) and a 10% reduction of the specific electricity consumption (KPI₅) (Table 1).

Case 2 – Limestone substitution, the path of input substitution. This case implies an increased use of alternative raw materials, such as fly ash and steel slag, to replace limestone. This means that clinker is still produced to the same extent, but from a partly different raw material base. A smaller share of the limestone (up to about 15%; Vigon (2002)) is replaced in the clinker manufacture, which is possible since, for example, steel slag contains the essential elements CaO and SiO₂ (van Oss and Padovani, 2003). Using alternative raw materials for clinker production (IFM) will reduce the emissions due to both the calcination process and the fuel consumption, modeled as a 10% reduction of CO₂ emissions due to calcination (KPI₂) and a 10% reduction of specific heat consumption (KPI₃).

Case 3 – More renewable fuels, also a type of input substitution. More renewable fuels are used for producing the same amount of clinker and cement, which corresponds to using more alternative fuels (IEF) and more renewable energy (IER) in the fuel mix. This change is modeled as a 50% increase in the share of renewable fuels (KPI₄) which was 40% in 2009.

Case 4 – Clinker substitution, defined as product development. In this case, existing technologies are used to produce the same amount of cement, however less clinker and more blended cements are produced (usage of more GGBFS and from that production of more blended cements such as CEM III/A and/or CEM III/B). So from the mass perspective, the level of the total production is about the same. This corresponds to increasing the clinker substitution rate (PPC) which is modeled as a 10% reduction in clinker production and a 7% increase of KPI₁ to keep the total mass produced in level with 2009.

Case 5 – Increased production, defined as product development. Production of the same amount of clinker utilizing existing technologies, however utilizing more clinker substitutes (PPC) such as GGBFS in turn requiring an increased cement capacity. This is modeled as increasing clinker substitution rate (KPI₁) by 25% and increasing the total production of cement (portfolio cement) by about 60%. This case is added to note that reducing the CO₂ emissions of 1 tonne of portfolio cement may lead to a net increase of CO₂ emissions, if the total cement production is increased. It is assumed that there is enough supplementary cementitious materials (in this case, GBFS) and grinding capacity to realize these changes.

The more comprehensive cases 6 and 7 are illustrated in Figure 5, both implying a further development of the cluster in an “industrial symbiosis direction.” Compared to the system of 2009, the cases can be described as:

Case 6 –More synergies; This case is somewhat similar to case 5, but incorporates further improvements within the same areas as in the period between 1997 and 2009. It assumes production of the same amount of portfolio cement, but with a lower clinker production and increased share of blended cements by using more clinker substitution (PPC). It also involves major investments to be able to produce electricity from the waste heat at Kollebach and use it internally (ERE), purchasing less electricity from the grid. Finally, more alternative fuels with higher renewable share are utilized (IEF and IER). These changes are modeled by 15% less clinker production, a 10% increase of clinker substitution rate (KPI₁), a 20% increase of the share of renewable fuels (KPI₄) and a 10% decrease of specific electricity consumption (KPI₅). It is assumed that there is enough supplementary cementitious materials (in this case, GBFS) and grinding capacity to realize these changes.

Case 7 – More and new synergies; This case is even more radical than the previous. The changes are mainly within the same areas, but the clinker substitution rate (PPC) is even higher and more and better alternative fuels are used (IEF and IER). In addition, more electricity is produced and utilized from the waste heat (ERE), some improvements within the plants lead to lower specific energy consumption (EEE and EEH) for producing clinker, and some of the externally supplied electricity is of renewable origin (IER). These changes are modeled as a 30% reduced clinker production, a 20% increase of the clinker substitution rate (KPI₁), a 50% increase in the share of renewable fuels (KPI₄), a 5% decrease in the specific heat consumption (KPI₃), a 30% decrease in the specific electricity consumption (KPI₅) and a 5% share of renewable electricity (KPI₆).

Table 1. Overview of the seven cases in relation to the main and sub categories of improvement measures (from part II) and changes of the Key Performance Indicators (KPIs) (see part I) in comparison with 2009.

		→ Key performance indicators (Part I)	KPI1	KPI2	KPI3	KPI4	KPI5	KPI6			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Improvement measures (Part II)			Clinker substitution rate	CO ₂ emissions due to calcination	Specific heat consumption	Share of renewable fuels	Specific electricity consumption	Share of renewable electricity	Total clinker production	Total cement production	Efficient plant	Alternative raw materials	Renewable fuels	Clinker substitution	Increased production	More synergies	More and new synergies
Production Efficiency	EEE	Electrical efficiency					X				EEE						
	EEH	Thermal efficiency			X						EEH						EEH
	ERH	Pre-heating / drying			X												
	ERE	Co-generation					X									ERE	ERE
	ERR	Recycle / reuse		X	X												
	ERP	Pollution prevention and control															
Input Substitution	IFC	Low temperature clinker production			X												
	IFM	Alternative raw materials for clinker		X	X							IFM					
	IEF	Alternative fuels				X							IEF			IEF	IEF
	IER	Renewable energy				X	X						IER			IER	IER
Product Development	PPC	Clinker substitution	X											PPC	PPC	PPC	PPC
	PPB	Improve blended cements	X											PPB	PPB	PPB	PPB
	PNC	Clinkerless / no-calcine cement	X	X	X		X										
External Synergies	SEC	Carbon capture and storage		X		X		X									
	SEB	Biological production				X											
	SEH	Synergistic heating			X		X										
	SIP	Integration with power plant		X	X		X										
	SIW	Integration with waste treatment				X											
	SIC	Synergies among co-located firms		X	X	X	X	X						SIC	SIC	SIC	SIC
Case 1	Efficient plant				-15%		-10%										
Case 2	Alternative raw materials			-10%	-10%												
Case 3	Renewable fuels					50%											
Case 4	Clinker substitution		7%						-10%								
Case 5	Increased production		25%							60%							
Case 6	More synergies		10%			20%	-10%										
Case 7	More and new synergies		20%		-5%	50%	-30%	5%

Figure 5. An illustration of case 6 and 7, involving more comprehensive and radical developments for CEMEX Cluster West, using the same logic as for Figure 1. The figure is only intended to roughly illustrate important flows and highlight differences between the two cases, and to be compared with the system of 2009 (i.e., Figure 4).

For each case, the CO₂ emissions per one tonne of cement and the total (non-biogenic) CO₂ emissions have been calculated - see Figure 6. These results do not include any allocation of the impact from the iron/steel industry, via the slag (GBFS), to the cement products. As expected, every case results in lowered unit emissions for the portfolio cement, compared with 2009. For case 1-5 the reduction is in the range of 5-13

%, case 6 reaches a bit further and the more radical “industrial symbiosis case” 7 could lead to about 40% less emitted CO₂. Regarding the total emissions from Cluster West, all cases lead to improvements, except case 5. Case 1-3 result in reductions from about 5 to 10%, while case 4 is close to 20%. The total emissions for case 5 are increasing, in spite of lower unit emissions, due to the increased production. The figure also clearly demonstrates that for a certain case, the unit emissions can be very different for clinker compared to the average portfolio cement. This is of course expected, but it seems to be a common practice within the cement industry to benchmark clinker rather than unit emissions for different types of cement.

Figure 6. CO₂-eq emissions for clinker and the (average) portfolio cement for the seven cases, i.e., improved hypothetical versions of Cluster West. The results are presented as relative figures in comparison with the production system of 2009, both regarding unit emissions and total emissions. They do not include any allocation of the impact from the iron/steel industry, via the slag (GBFS), to the cement products.

Regarding case 7, “More and new synergies,” there is a scattered arrow in Figure 5 indicating that some part of the CO₂ emissions could be utilized by customers, for example, a company growing plants in greenhouses. From an LCA perspective, the effect of such measures is very dependent on the choice of allocation principle. For example, applying economic allocation (as for the GBFS) and assuming that the CO₂ has a low value, would mean a small change of the LCA results for Cluster West. On the contrary, a system expansion with the assumption that the sold CO₂ replaces other similar CO₂ products, could motivate allocating all the CO₂ supplied to a customer to the products of that company.

4. Concluding discussion

The key question for this article is how relevant the key ideas of industrial symbiosis are for the cement industry in striving for reduced CO₂ emissions. In our attempt to answer it, we touch upon case-specific and more general conclusions, combining quantitative results from this article and information in literature.

Starting with a general cement industry perspective, it is essential to remember that world cement production is dominated by Portland cement, with a high clinker fraction. The share of blended cements is increasing, but still a large portion has fairly high clinker content (WBCSD/CSI, 2009). It can thus be concluded that an absolute majority of the cement is based on limestone that is combusted in cement kilns. Consequently, it is highly relevant to consider such typical, or average, cement production and assess

different options to reduce the emissions of CO₂. To judge the relevance of industrial symbiosis, it is of interest to compare the organizational and geographical scale for different types of improvement measures.

Beginning at an intra-organizational level, it should be noted that much of the development within the cement industry has been site-oriented, focusing on the cement plants and their internal processes (part II). Without any doubt, site-oriented measures can contribute to important reduction of CO₂ (Benhelal et al., 2013; IEA/WBCSD, 2009; cf. Morrow III et al., 2013; Valderrama et al., 2012), for example, investments in precalciners, efficient coolers and grinders, etc. For CEMEX Cluster West, this could reduce the unit emissions roughly about 5% (case 1). Producing electricity from the waste heat would lead to further reduction (around 10-30%⁷ of electricity demand of the plant (Engin and Ari, 2005; H.REII/EC, 2012; Khurana et al., 2002)). Several of these options require significant investments. However, it is crucial to remember that “inside-the-fence measures” have a limited potential, because the commonly high clinker content is bound to the calcination process, typically causing more than 50% of the total CO₂ emissions⁸. It is the single most important source of CO₂ and that process is not affected by measures addressing the production efficiency.

Moving outside the fence in a shift towards using more renewable fuels and renewable electricity can lead to avoidance of many tonnes of CO₂ (cf. Imbabi et al., 2013). For example, IEA (2009) states that fuel-related CO₂ emissions typically represent about 40% of the total emissions from cement manufacture. For Cluster West 40% of the required thermal energy was provided from renewable fuels which corresponded to slightly less than 30% of total CO₂ emissions of the portfolio cement in 2009. A 50% increase of the share of renewable fuels would reduce unit emissions about 10% (case 3). Nevertheless, fuels and electricity associated with less CO₂ do not have an impact on the emissions due to calcination either. Even including all the options regarding thermal and electrical efficiency, and alternative fuels, it seems very hard to be able to produce clinker with unit emissions below 700 kg per tonne, because of the calcination.

To more radically reduce the CO₂ emissions from “traditional” cement production one option is carbon capture (Benhelal et al., 2013), but the technology for that must be seen as relatively unproven and expensive (Li et al., 2013), even if it probably will play an important role in the future (e.g. Schneider et al., 2011; IEA/WBCSD, 2009). It might be seen as a site-oriented measure, but storage or usage of the CO₂ often involves additional actors and land. Excluding carbon capture, measures need to result in less calcination to make a big difference. One option is then to use alternative raw materials, such as fly ash and steel slag, to replace limestone. It means that clinker is still produced to about the same extent, but up to 15% (Vigon, 2002) less limestone is combusted leading to a corresponding decrease of CO₂ due to calcination, and reductions due to a reduced combustion of fuels. Blended cements, where clinker is substituted with GGBFS or fly ash, provide opportunities to more radically decrease the unit emissions of CO₂. Habert et al. (2010) conclude that clinker substitution is a promising, low-cost solution with great potential. Benhelal et al. (2013), reviewing different strategies for CO₂ mitigation, refer to it as “one of the prominent approaches,” and Morrow et al. (2013) see it as the most cost-efficient measure for the Indian cement industry. Mainly due to a large share of blended cement, CEMEX Cluster West has managed to

⁷ In case 7, the 30% reduction of electricity demand is considered, assuming a favorable future possibility.

⁸ It could also be mentioned that there is a theoretical minimum primary energy need in the form of heat for the chemical and mineralogical reactions - approximately 1.6-1.85 GJ/t according to Locher (2006). However, it could be generated from renewable sources.

decrease the unit CO₂ emissions by about 45% for their product portfolio. It should be emphasized though that the choice of allocation principle for the clinker substitutes plays an important role (Van den Heede and De Belie, 2012). Economic allocation was used in this study, where a part of the impact caused by pig iron production was allocated to the GBFS. Applying mass allocation instead would lead to very different results (ibid.) and main conclusions. Economic allocation is arguably a more reasonable method, without doubt iron/steel is the main product for the producers, but a negative effect of it is that the LCA results vary with the prices of steel/iron and GBFS (their relation).

Summing up, there are many different options to reduce the CO₂ emissions associated with cement. Excluding CO₂ capture, dramatic reductions of CO₂ require dramatic changes in the product portfolio. As the product mix is of great importance, there are strong reasons from a climate perspective to shift the focus within the cement industry from benchmark based on clinker towards the cement products. This is very well illustrated by the study of Cluster West, where it was concluded that clinker is produced rather efficiently, which to a large extent mirrors the unit CO₂ emissions for the Kollenbach kiln line (part I). Instead shifting focus towards the products makes Cluster West much more outstanding.

It should also be emphasized that the combined articles provided and tested a methodology to collect, categorize and assess different types of improvement measures. The simplified LCA model made it possible to rather simply give quantitative estimations of different cases – it could estimate the impact of industrial symbiosis. It makes it possible to handle dynamics in a complicated production system relatively efficiently. Instead of resource-demanding updates of more than 50 parameters, information about the six key performance indicators was enough.

The most fruitful option seems to be a significantly increased share of blended cement, meaning that the average clinker fraction is much lower (cf. Imbabi et al., 2013). For producers of Portland cement, this means engaging with new actors such as the steel and power industry and closing material and energy loops by making use of their byproducts. Similarly, it appears important and rather straightforward to increase the share of renewable energy and alternative raw materials substituting limestone, measures that in many cases imply co-operation with actors that are not part of the “traditional” supply chain. Likewise, to efficiently utilize the waste heat, electricity production in combination with district heating, involving the local community, would be favorable. Such a development is very much in line with the key ideas of industrial ecology and industrial symbiosis, meaning that it appears highly relevant for the cement industry to move further in this direction, as illustrated in Figure 7, being an important actor or even an anchor tenant in industrial symbiosis networks. Brent et al. (2012) provide interesting input on a more radical development, where the need for large-scale “carbon solutions” could induce new or developed symbiosis options for the cement industry, where the most energy-intensive and carbon-intensive industries could be co-located.

Figure 7. Illustration of a key message from the project - radical reduction of CO₂ emissions require improvement measures going beyond the production site level. This involves several actors that are commonly not part of the “traditional” supply chain. This can be seen as moving from a narrow cleaner production focus to a broader industrial symbiosis perspective (inspired by Baas, 2005).

When discussing clinker substitution it is essential to acknowledge that it affects the characteristics of the cement. Blended cement products have a slower strength development over time (Schneider et al., 2011) and might require a few weeks to harden. But after that, they appear to be stronger than concrete based on CEM I and also demonstrate a better resistance to chemicals. Moreover, it should be mentioned that the availability of suitable cementitious materials such as GBFS and fly ash is constraining the potential of blended cements (ibid.). In 2009 the Cement Sustainability Initiative and the European Cement Research Academy estimated the existing amount of clinker substitutes (including GBFS, fly ashes and pozzolans) to about 0,8 Gtonnes/year, to be compared with the cement consumption that then was exceeding 2,4 Gtonnes/year (CSI/ECRA, 2009). They estimated that if all the potential clinker substitutes were used, the clinker-to-cement ratio could decrease to about 60% as a minimum, also stating that this value is rather theoretical and does not reflect that a share of the accounted clinker substitutes does not have the required quality. Further on, development within the energy sector may impact the available amounts of fly ash and its quality (IEA, 2009), for example, an increased share of natural gas may reduce the amounts of ash from coal-fired power plants and tougher regulations regarding mercury emissions may result in more mercury in the ash (making it less attractive).

Nevertheless, there is room for a significant increase of blended cement production (Habert et al., 2010); earlier also indicated by Vigon, 2002). The major impact on the unit emissions of CO₂ means that clinker substitutes can be transported rather long distances, maintaining a favorable performance. A faster development regarding blended cements might need different types of initiatives, to strengthen drivers and remove barriers. IEA (2009), regarding policy support for increased clinker substitution, recommends new standards and codes allowing a more widespread use and acceptance of blended cements (also supported by WBCSD/CSI, 2009), focusing more on performance than composition, and further research on the environmental impact. Furthermore, barriers mentioned are, for example, lack of knowledge by customers

and the public, availability of cementitious materials, and legislation (cf. Watkins et al., 2013; Benhelal et al., 2013). There is a need to support good markets for blended cements, since it is one of the most powerful options available. If, for example, property owners and the construction industry want to improve the total climate footprint of buildings and constructions built of concrete and mortar, products such as CEM III are very favorable. However, for a cement producer such as CEMEX, there might be strong motives to produce and plan for a significant share of CEM I. One important reason is that their quarries and permits might ensure access to essential raw materials for many years ahead (could be about 30 years) which makes more long-term planning possible compared to contracts regarding clinker substitutes (such as GBFS) that are often rather short term. The access to clinker substitutes is more uncertain. It should of course also be noted that it is not necessarily the cement industry that has to do the blending. In the U.S., commonly the concrete industry does the blending and therefore demands most of the supplementary cementitious materials.

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