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Improving the CO₂ performance of cement, part II: Framework for assessing CO₂ improvement measures in the cement industry

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Abstract

Cement production is among the largest anthropogenic sources of carbon dioxide (CO₂) and there is considerable pressure on the cement industry to reduce these emissions. In the effort to reduce CO₂ emissions, there is a need for methods to systematically identify, classify and assess different improvement measures, to increase the knowledge about different options and prioritize between them. For this purpose a framework for assessment has been developed, inspired by common approaches within the fields of environmental systems analysis and industrial symbiosis. The aim is to apply a broad systems perspective and through the use of multiple criteria related to technologies and organization strategies facilitate informed decision-making regarding different CO₂ performance measures in the cement industry.

The integrated assessment framework consists of two parts: a generic and a case-specific part. It is applied to a cement production cluster in Germany called Cluster West, consisting of three cement plants owned by CEMEX. The framework can be used in different ways. It can be used as a tool to perform literature reviews and categorize the state-of-the-art knowledge about options to improve the CO₂ performance. It can also be used to assess options for the cement industry in general as well as for individual plants.

This paper describes the assessment framework, the ideas behind it, its components and the process of carrying out the assessment. The first part provides a structured overview of the options for improvement for the cement industry in general, while the second part is a case-specific application for Cluster West, providing information about the feasibility for different categories of measures that can reduce the CO₂ emissions. The overall impression from the project is that the framework was successfully established and, when applied, facilitated strategic discussions and decision-making. Such frameworks can be utilized to systematically assess hundreds of different measures and identify the ones most feasible and applicable for implementation, within the cement industry but also possibly in other sectors. The results demonstrated that even in a relatively synergistic and efficient production system, like Cluster West, there are opportunities for improvement, especially if options beyond “production efficiency” are considered.

Keywords: industrial ecology, cement, CO₂ emissions, industrial symbiosis, environmental assessment framework, integrated assessment

1 Introduction

Cement is a key construction material with demand in very large quantities (van Oss, 2012) and its production requires use of considerable energy and materials and results in many different types of emissions causing environmental impacts. The cement industry is one of the largest sources of anthropogenic carbon dioxide (CO₂) (Bernstein et al., 2007; EIPPCB, 2013; IEA/WBCSD, 2009; Metz et al., 2007; van Oss and Padovani, 2003, 2002).

In co-operation with the global cement producing company CEMEX S.A.B. de C.V. (CEMEX) a research project has been carried out to contribute to a better understanding of the CO₂ performance 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 Germany. This paper is the second in a series of three, all of which are included in this special issue. The first introduces cement production, the selected case and includes information about the LCA-based methodology (Feiz et al., 2013)¹. It provides results from a comparison of different cement products and production systems (i.e., different versions of Cluster West). This paper presents a systematic approach for assessing measures to reduce the CO₂ emissions associated with the cement industry. The third paper (Ammenberg et al., 2013)² is focused on the relevance of industrial symbiosis when striving towards improved CO₂ performance of cement.

The cement industry is under increasing pressure to reduce its CO₂ emissions. During the last decade several reports and studies have dealt with a range of different measures (Benhelal et al., 2013; CSI, 2005; EIPPCB, 2013; Moya et al., 2011; Price et al., 2010; Schneider et al., 2011; US EPA, 2010; van Oss and Padovani, 2003; Vigon, 2002; WBCSD, 2000; Worrell et al., 2008, 2001, 2000). They are valuable sources of knowledge about existing and emerging technologies, for example, to improve energy efficiency and CO₂ performance. However, in general the reports can be described as presenting and describing available and emerging options for improvement rather than providing a structured overview that gives a broad picture of the strengths and weaknesses of different options. Moreover, a large share of the reports appears to have a technical and production-oriented focus (directed at clinker production) and does not include measures that can be highly relevant from a wider systems perspective. A framework with broader perspective allows the cement manufacturers to identify and sort a wider array of technological and strategic opportunities (see Ness et al., 2007).

1.1 Aim

The aim is to fill some of these gaps by establishing and presenting an integrated assessment framework developed for a broader and more systematic structuring and assessment of possible measures that could reduce the CO₂ emissions from the cement industry. Through the use of multiple criteria related to technologies and organization strategies, this framework contributes to increased knowledge and facilitates informed decision-making.

Furthermore, the framework has been applied to assess various improvement measures for Cluster West. Selected results from the application are shown.

2 Theoretical approach and structure of the framework

A theoretical and methodological assumption for this paper and the developed framework is that overall information about flows of materials and energy can be used to identify and assess improvement measures and their adherent environmental impact – due to CO₂ emissions in this case. In accordance with common approaches within the field of environmental systems analysis, the assessment framework builds on collection and analyses of overall information about important material and energy flows (see

¹ From now on referred to as “part I”

² From now on referred to as “part III”

Finnveden and Moberg, 2005). This makes it possible to understand important issues, without going into detail about all flows and without specific information about environmental impacts.

An overview of the assessment framework is shown in Figure 1. The framework consists of two parts and six steps. The first part (steps 1 to 4) concerns the cement industry in general, not necessarily any specific cement production system or site. The main source of information for part 1 of the assessment is literature. The second part of the framework (steps 5 and 6) is site-specific and assesses the feasibility of measures for a certain cement production system. The term “site” in site-specific refers to a “cement production system” that can be a single plant or a group of inter-related plants (such as Cluster West). For carrying out part 2 information about the specific production system is needed, in this case provided by CEMEX during site visits, workshops, meetings and via e-mail.

Parts	Steps	Parameters / Results
Part 1: Generic study	Step 1: Collection	Gross list
	Step 2: Classification	Categorization scheme
	Step 3: Improvement assessment	CO ₂ emission reduction potential
	Step 4: Feasibility assessment	Degree of inter-connectedness
		Technological maturity
Part 2: Site-specific study	Step 5: Applicability assessment	Technical applicability
		Organizational applicability
		Implementation maturity
	Step 6: Results and analysis	Best candidates
		Future candidates
		Industrial landscape

Figure 1. Overview of the framework for selection and assessment of CO₂ emission reduction measures

It is important for the framework to take the perspectives of industrial ecology and industrial symbiosis into account (see Ayres, 1992; Ayres and Ayres, 1996; Fischer-Kowalski and Haberl, 1997; Anderberg, 1998, and others). Such perspectives suggest that all material and energy related to cement production are to be treated as potentially valuable streams (including waste material and emissions). Furthermore, they promote more resource efficiency and better environmental performance (Boons and Howard-Grenville, 2009) by closing the material loops via synergistic exchanges of resources between different actors, often by taking advantage of geographical proximity (Chertow, 2000; Frosch and Gallopoulos, 1989). Graedel and Allenby (2003) also emphasize that industrial systems should be viewed in integration with their surrounding systems, not as isolated entities, meaning that not only the cement production plants should be included but also relevant streams and conditions of surrounding industrial and societal systems.

3 Development of the framework

Having decided on the structure of the framework, as shown in Figure 1, the process of carrying out the different steps began which is presented in the following sections. Due to heterogeneities and uncertainties involved regarding the time, place, technology and the context in which measures can be utilized, it is not possible to perform a meaningful and simple quantitative assessment. Therefore, ordinal qualitative parameters are used in this framework and for each parameter a corresponding grading scale is defined.

3.1 Collection

In the “collection” step, a wide range of relevant measures to improve CO₂ performance was collected and compiled into a gross list of options. For this purpose, a literature survey was performed and relevant information and ideas from various sources was compiled. The focus of this step is not limited to the cement industry. In line with the arguments above, a broader search for improvement measures has been done, especially regarding different options for utilizing material or energy streams which are common between the cement industry and other industries (such as excess heat or CO₂ emissions). The aim is to cover as many ideas as possible without considering their feasibility or applicability, so they will form a reasonably rich data set for the next steps of the assessment (Figure 1). The principles of industrial ecology (or industrial symbiosis) served as guidelines, i.e., to consider all inbound and outbound material and energy streams of the cement production system as potentially valuable and of importance from an environmental perspective (Ayres and Ayres, 1996; Graedel and Allenby, 2003).

The following major energy and material streams are relevant for a typical cement production system (cf. Benhelal et al., 2013): feedstock (materials), fuels (energy and materials), electricity (energy), products (materials), CO₂ from combustion of fuels and the calcination process (emissions), excess heat (energy), and other streams such as other emissions or wastes that can be categorized as “byproducts.”

In addition, there are possible ways to use the excess materials or energy streams in other industrial processes, either by closing the loops (reuse, recycling) or by integrating cement production with other industrial processes.

It is also essential to consider processes and activities within cement production plants. Therefore, ideas on how to improve the material and energy efficiency of different processes should be included.

Most of the measures for improving the CO₂ performance of cement are related to one or more of the following aspects of cement production:

- Inputs: Measures related to material or energy going into the plant including traditional inputs and alternatives (such as renewable fuels).
- Outputs: Measures related to products, capture and utilization of CO₂ or excess heat streams, and reuse or recycling of any other byproducts or waste streams.
- Plants: Measures related to improving the efficiency of the processes inside the plant.
- Others: Measures related to innovative approaches for recycling or integration with other industrial processes.

Based on this, the simplified cement production plant in Figure 2 has been used to facilitate identification and structuring of the improvement measures.

Figure 2. Categories of improvement measures in cement production

3.2 Classification

After the collection, the second step (in Figure 1) is the classification where a categorization scheme is formulated and the collected improvement measures are classified in accordance with that into some categories and sub-categories. In line with the text above, it was logical to base the categorization scheme on Figure 2, since any measure for improving the CO₂ performance of cement production is either about improving the efficiency of the internal processes (production efficiency), changing inputs (input substitution), changing products (product development including developing entirely new types of cements), or effectively utilizing currently wasted streams or other types of streams through synergistic solutions (external synergies).

In order to maintain flexibility regarding new ideas, the subcategories for each main category shown in Figure 2 are not predefined in the framework and the detailed categorization scheme should be developed when the framework is actually applied or implemented (see chapter 4).

The categorization scheme is intended to provide a basis for further assessment and analysis of various improvement measures. Therefore, it is essential to present the information in an organized manner.

3.3 Improvement assessment

In step 3, the CO₂ emission reduction potential of each measure is assessed. For a qualitative evaluation it is essential to consider which CO₂ emitting source each measure is addressing. The following alternatives exist to effectively reduce CO₂ emissions associated with cement production:

(1) Reducing or avoiding CO₂ emissions due to the calcination process (during clinker production):

The calcination process releases about 500 kg CO₂ for 1 tonne of clinker produced (Worrell et al., 2001). Depending on the production system, this amount may be more than 50% of the total CO₂ emitted during production of clinker.

(2) Reducing or avoiding CO₂ emissions due to combustion of fuels (mainly during clinker production): Another major source of CO₂ emissions during clinker production is “fuel combustion” in the kiln system. Therefore, measures that can address these can have relatively high potential for CO₂ emission reduction.

(3) Reducing CO₂ emissions by decreasing the specific energy consumption of clinker/cement: As most of the heat and electricity used in cement production has fossil origin (CSI, 2005, p. 18), their production and consumption emit large amounts of CO₂. Therefore reducing the energy demand of clinker/cement production (reducing specific energy consumption) can reduce CO₂ emissions due to clinker/cement production.

The difference between measures categorized as (2) and (3) is that category (2) measures are related to less nonbiogenic CO₂ per unit of energy (for example, by increasing the share of renewable fuels), while category (3) measures mean that less energy is needed per tonne of product (energy efficiency measures).

(4) Reducing or avoiding CO₂ emissions elsewhere (causing another process to emit less CO₂): If a measure can cause less combustion of fossil fuels “somewhere else,” then the CO₂ emissions saved by that avoidance are allocated to the cement production system. An example of such indirect measure is the utilization of the excess heat of the cement plant in another industrial process which otherwise would have generated its required heat by combustion of coal.

Each measure is assessed in accordance with the ordinal qualitative scale presented in Table 1.

Table 1. Qualitative scale for assessing the CO₂ emission reduction potential.

Level	CO ₂ emission reduction potential
	The following main sources of CO ₂ emissions are considered: (1) Calcination (clinker) (2) Fuel combustion (clinker) (3) High specific energy consumption (clinker/cement) (4) Replace CO ₂ emissions elsewhere (avoiding the emissions)
Low	The measure cannot significantly reduce CO ₂ emissions related to any of the above listed alternatives, but has limited improvement potentials for at least one of them.
Medium	The measure can significantly reduce CO ₂ emissions related to at least one of the above listed alternatives.
High	The measure can significantly reduce CO ₂ emissions related to two or more of the above listed alternatives.

3.4 Feasibility assessment

In addition to the improvement potential, it is important to include the feasibility of different measures in the assessment. In the framework, feasibility is defined as a generic and a non-site-specific term consisting of two ordinal qualitative parameters: (1) degree of interconnectedness required for development of that measure and (2) its technological maturity level.

Inter-connectedness is of relevance since the collected measures might be very different regarding the number of involved actors. Some types of measures are internal by nature and therefore decision-makers of a single organization can decide about them and ensure their implementation. Others require well functioning co-operation with several external actors. Such more “symbiotic” measures, involving a large

number of organizations, are often much more challenging, since they, for example, comprise the objectives, strategies, budgets, resources, cultures, etc. of many actors.

In this framework, the degree of interconnectedness is defined as an aggregated indicator which incorporates concepts such as the number of involved actors in decision-making (required for effective implementation of the measure), the quality and intensity of waste or byproduct exchanges among nearby actors, as well as levels of cooperation among them. By considering different types of industrial symbiosis, similar to Chertow (2000), an ordinal qualitative scale for evaluating the degree of interconnectedness has been defined as described in Table 2.

Table 2. Qualitative scale for assessing the degree of interconnectedness.

Level	Degree of interconnectedness
Low	A single (small or large) organization.
Medium	Few organizations with relatively small geographical distances.
High	Many organizations and/or located in a wider geographical area or region.

The second part of the feasibility assessment concerns the maturity level of technologies required for effective implementation. To assess the level of technological maturity it has simply been considered how “available” or realistic the measures are from a technological standpoint, but this also indirectly reflects economic aspects because a mature technology is likely to be operationalized at lower costs compared to an emerging one. Traditional, widely used and tested technologies are considered to have high technological maturity, while new and unverified measures have low technological maturity. The scale of this ordinal qualitative parameter is defined as presented in Table 3.

Table 3. Qualitative scale for assessing the technological maturity.

Level	Level of technological maturity	Description
Low	Early development	The measure is in an early research and development stage.
Medium	Emerging practice	Either of the following is true about the measure: (1) Some successful demonstrations exist in the cement industry (pilot testing; application in small scales) (2) It is used in other industries, but not yet applied in the cement industry.
High	Established practice	Applied in the cement industry in several places under various conditions.

The technological maturity of different improvement measures can be assessed via information in existing literature and by determining the state-of-the-art of the technologies that are required for their implementation.

3.5 Applicability assessment

While step 1-4 of the framework (see Figure 1) concern the cement industry in general, the focus is shifted towards a specific cement production system (including management aspects) from step 5. The aim of this step is to assess the applicability of the collected and classified measures taking the case-

specific conditions and constraints into account. The applicability is assessed by considering: (1) technical applicability, (2) organizational applicability, and (3) the implementation maturity. The site-specific assessment should be performed by, or with the assistance of, technical experts and managers within the studied organization. The different parts are presented below.

Not every measure is suitable or applicable to every production system, even if it demonstrates high potentials for CO₂ emission reduction or is based on a mature technology. Every production system has certain “technical” constraints, which influence the applicability. Here “technical” refers to a broader concept including the availability of required infrastructure and geographic conditions. For example, if there is no district heating network in the vicinity of a studied production system, then measures requiring such infrastructure are not applicable without major investments. Other measures might require large available land areas of a certain type in the vicinity of the production system. These aspects can be assessed using a qualitative scale as shown in Table 4.

Table 4. Qualitative scale for assessing the technical applicability.

Level	Technical applicability
Low	<p>Either of the following is correct for a certain measure:</p> <ul style="list-style-type: none"> (1) Technically, it does not make sense for the specific production system. (2) The required infrastructure does not exist and/or geographical or other conditions are not fulfilled (implying unreasonably high costs).
Medium	<p>Both of the following are correct for a certain measure:</p> <ul style="list-style-type: none"> (1) Technically, it makes sense for this specific production system. (2) The required infrastructure partially exists, and geographical or other conditions are fulfilled to some extent and the situation can be improved without major challenges.
High	<p>Both of the following are correct for a certain measure:</p> <ul style="list-style-type: none"> (1) Technically, it makes sense for this specific site. (2) The required infrastructure exists, and geographical and other conditions are fulfilled.

In addition to the technical applicability and other mentioned conditions, there are challenges of an organizational character to plan and implement a certain CO₂ improvement measure. Organizations have goals, strategies, processes, and other organizational aspects that affect their approach toward changes. Some changes are considered necessary and high priority while others are seen as unnecessary or low priority. For example, barriers might prevent changes within an organization. Such barriers are lack of information or expertise, lack of awareness of issues related to the environment that surrounds the organization, and competing priorities such as pressure for short-term profits (Gunningham and Sinclair, 1997). In addition, there might be situations in which implementation of a measure subject the production system to more stringent environmental regulations. Sometimes regulations demand lower emissions limit for newer or more modern production systems. Examples would be conversions of a wet kiln to dry technology, adding a precalciner to a preheater kiln, or building an additional kiln line.

An improvement measure requires an organization to allocate some of its limited resources such as time, money, managerial efforts and competence to its adoption and implementation. Therefore, when a supposedly good improvement idea is proposed to an organization, its decision-makers need to evaluate

the alignment and compatibility of this change with the business approach and the other mentioned organizational aspects.

In this framework, the parameter “organizational applicability” is defined as “the degree to which a certain proposed improvement measure is in alignment with current goals and the long-term strategies of the organization.” The “organizational applicability” should also be assessed qualitatively by, or with the assistance of, experts and managers within the studied organization. The qualitative scale for assessment is defined in Table 5.

Table 5. Qualitative scale for assessing the organizational applicability.

Level	Organizational applicability
Low	Any of the following statements about this measure or the changes it induces is true: <ul style="list-style-type: none"> (1) The measure is not in line with the organization's goals and strategies. (2) The measure is considered unimportant by the organization. (3) The necessary organizational resources (time, budget, etc.) are not available, and/or should not be directed at this measure.
Medium	All of the following statements about this measure or the changes it induces are true: <ul style="list-style-type: none"> (1) The measure is partially in line with the organization's goals and strategies. (2) The measure is considered relatively important by the organization. (3) The necessary organizational resources (time, budget, etc.) are not available, but this could be changed.
High	All of the following statements about this measure or the changes it induces are true: <ul style="list-style-type: none"> (1) The measure is in line with the organization's goals and strategies. (2) The measure is considered important by the organization. (3) The necessary organizational resources (time, budget, etc.) are available and can be allocated to this measure without major challenges.

In this scale, measures that are in line with the organization’s goals and strategies and are considered high priority have high organizational applicability. In addition, the “organizational resource” aspects such as availability of the required time and funds play a key part.

Another parameter of high relevance for the applicability is the degree of its existing implementation in the organization. If a certain measure is already implemented to a high degree in the production system which is being assessed, then further improvement of a similar character might be easier for the organization. However, it is also possible that less room is left for further development and implementation of that measure, which will make the measure less “technically applicable” (see above). Maturity of implementation of a measure is not limited to technical and physical aspects. Another important indicator is the existing level of knowledge about that measure or the changes that it requires and induces in the organization. Maturity of implementation of a measure requires a learning process which is integral to its success. If the knowledge is relatively good within the organization, the implementation has already begun to some extent.

In order to evaluate the implementation maturity the following qualitative scale can be used (Table 6):

Table 6. Qualitative scale for evaluating the implementation maturity.

Level	Implementation maturity
Low	Any of the following statements about this measure are true: (1) The required knowledge is not available in the organization. (2) The measure is not implemented.
Medium	All of the following statements about this measure are true: (1) The required knowledge is partially present in the organization and learning is in progress. (2) Some previous attempts have been made, but there is room for further implementation of the measure.
High	All of the following statements about this measure are true: (1) The required knowledge is present in the organization. (2) The measure is effectively implemented as part of the existing operations, however, further improvement may still be possible.

3.6 Results and analysis when the framework has been applied

Having gone through all the steps 1-6 (Figure 1), the results of the assessment are summarized and analyzed in order to facilitate decision-making regarding future improvements in the organization. It is important to highlight the following groups of measures:

- **Best candidates** are the most attractive measures to implement – “low-hanging fruit” that can relatively easy be harvested and give a high yield.
- **Future candidates** are measures that have high potential to reduce the CO₂ emissions associated with cement production, also being applicable but currently less feasible. Such measure could be included in the long-term planning and prioritized in research and development programs.

Of course, the analysis will reveal the least appealing options for implementation. An important purpose is to contribute to increased knowledge regarding options for improvement and their potential, feasibility and applicability and thus to facilitate decision-making.

4 Applying the framework for CEMEX Cluster West

Having developed the assessment framework as described in chapter 3, it contained the main categories of improvement measures (see Figure 2). When applying the framework for the selected case, i.e., the cement industry and the CEMEX Cluster West, the general, first part (step 1-4) was also further specified. These more general results are presented in 4.1 while the results from the case-specific steps (5-6) are described in 4.2.

4.1 Classification and assessment of measures for the cement industry in general

After a more thorough literature survey the categories in Figure 2 were further broken out into several categories and sub-categories. The result of the generic assessment (part 1 of the framework) including assessment of improvement potential and applicability is shown in Table 7, then further discussed in section 4.2.

Table 7. Categorization scheme for different measures to reduce the CO₂ emissions associated with cement production.

Category of CO ₂ emission reduction measures	Feasibility	Improvement potential
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Code	Category	Degree of interconnectedness	Technological Maturity	CO ₂ emission reduction potential
E	Production efficiency			
<i>EE</i>	<i>Energy efficiency</i>			
EEE	- Electrical efficiency	low	high	low
EEH	- Thermal efficiency	low	high	low-medium
<i>ER</i>	<i>Resource recovery</i>			
ERH	- Pre-heating/drying	low	high	low-medium
ERE	- Co-generation (heat & electricity)	low	high	low-medium
ERR	- Recycle/reuse	low	high	low
ERP	- Pollution prevention and control	low	high	low
I	Input substitution			
<i>IF</i>	<i>Feedstock change</i>			
IFC	- Low temperature clinker production	low-medium	medium	low-medium
IFM	- Alternative materials (for clinker production)	medium-high	medium-high	low-medium
<i>IE</i>	<i>Input energy change</i>			
IEF	- Fuel diversification (alternative/secondary fuels)	medium	high	low-medium
IER	- Renewable energy (fuel and electricity)	medium	medium	medium
P	Product development			
<i>PP</i>	<i>Improve existing products</i>			
PPC	- Clinker substitution (alternative materials)	medium	high	high
PPB	- Improve blended cements' properties	low	medium-high	high
<i>PN</i>	<i>Develop new products</i>			
PNC	- Clinkerless/no-calcine cement	medium	low	high
S	External synergies			
<i>SE</i>	<i>CO₂ and heat solutions</i>			
	- Carbon sequestration/carbon capture and storage	high	low	medium-high
SEB	- Biological production	high	low	medium-high
SEH	- Synergistic heating	high	medium	medium
<i>SI</i>	<i>Process integration and industry initiatives</i>			
SIP	- Integration with power plant	medium-high	low	low-medium
SIW	- Integration/co-location with waste treatment	medium-high	medium-high	medium-high
SIC	- Synergies among already co-located firms	medium	medium-high	medium-high

These categories and sub-categories are based on the gross list of ideas that were collected in the first step. It is important to note that these measures will not be implemented if the factors which are needed to enable them do not exist. In these framework, these indirect factors are referred to as “Management,” but are not included in the above table. Management include sub-categories such as “environmental strategy and innovation approaches,” “marketing, education, and public relations,” and “standards and specifications.”

A description of each of these strategies and categories are available in Ammenberg et al. (2011).

4.2 Assessment of measures for CEMEX Cluster West

After having conducted the first, generic part, the framework was applied to CEMEX Cluster West and the applicability of each category of measures was qualitatively analyzed. The applicability assessment was performed in two stages. First, a preliminary assessment was performed based on the knowledge that was acquired about Cluster West, where several site visits played an important part. In addition, a workshop was arranged where the researchers and managers and staff from CEMEX research organization discussed the conditions and improvement measures. After having conducted the preliminary assessment, the researchers sent it to CEMEX to be re-evaluated and confirmed. The input from CEMEX

was considered and the results updated, for example, leading to an overview of the most feasible and applicable improvement measures for Cluster West.

According to the results of the assessment, CEMEX Cluster West has been successful in implementing several CO₂ improvement measures:

- Clinker substitution (PPC); Cluster West is already substituting for clinker in its cement product to a large extent and produces various blended cement products. The main clinker substitute is ground granulated blast furnace slag (GGBFS) which is used in slag cement products (e.g. CEM III). The clinker substitution rate constantly increased during the last decade and was about 60% in 2009. However, there is still a considerable potential for improvement regarding clinker substitution. Regarding GGBFS this potential depends on market conditions and whether there is additional GBFS capacity. In the U.S. blending is carried out to a large extent by concrete producers, rather than at the cement production plants. It is possible that the European market will develop in that direction (van Oss, 2005, p. 10).
- Fuel diversification (IEF); A major part of the fuel used within Cluster West is combusted at the Kollenbach plant, where a wide array of alternative fuels are used and this share is increasing. The share of secondary fuels compared to total fuels for Kollenbach is higher than the European average (34% (CEMBUREAU, 2013)). In 2009 it was about 67% of the total heat.
- Pre-heating/drying (ERH); The Kollenbach plant has a four-stage cyclone preheater kiln system. However, the thermal efficiency of the kiln system can be improved considerably by upgrading the rotary (drum) cooler of the plant (which is a thermal efficiency measure (EEH)). This will allow better utilization of waste heat which is fed into the kiln system.
- Electrical efficiency (EEE); The electrical equipment, motors and transportation systems used in the plants of Cluster West are relatively efficient. The electrical efficiency has been improved continuously in recent decades. The energy management system for Cluster West is expected to lead to further improvements.

Best and future candidates

Measures having both a high “technical” and “organizational” applicability should be selected as possible “best candidates” to prioritize (Figure 3). The list of best candidates can be narrowed by prioritizing measures having a high technological maturity (assessed as feasible from a technological and economic perspective) and a considerable improvement potential (a potential to reduce CO₂ emissions assessed to better than “low,” see Figure 4). Considering Cluster West, such an analysis indicates that the best candidates for improvement are measures such as to increase the clinker substitution rate (PPC), improve the properties of blended cement (PPB), use more alternative fuels (IEF) and materials for clinker production (IFM), and apply co-generation of electricity (ERE).

Figure 3. Results of the assessment for Cluster West in 2009; (x) the implementation maturity; (y) the organizational applicability; and (different colors) the technical applicability.

There are less technologically mature (medium) measures which have high applicability for Cluster West and therefore can be included in the list of “future candidates.” Examples are measures such as using more renewable energy (IER) and using low-temperature clinker production (IFC).

Figure 4. Results of the assessment for Cluster West in 2009; (x) the implementation maturity; (y) the CO₂ emission reduction potential; and (different colors) technological maturity.

Increased synergies among co-located firms (SIC) and low-temperature clinker production (IFC) can also be added to the list of future candidates because, considering all parameters, they have medium to high applicability, feasibility and emission reduction potential.

How synergistic is Cluster West?

The relation between “degree of interconnectedness” and the “implementation maturity” in Cluster West gives some insight about the synergistic activities of Cluster West (Figure 5).

Figure 5. Results of the assessment for Cluster West in 2009; (x) the degree of inter-connectedness; (y) the implementation maturity of various CO₂ improvement measures; and (different colors) the technological maturity.

Most of the measures that have relatively low degree of inter-connectedness are implemented in the Cluster West (top left of the above diagram). One of the most promising measures that demands low degree of inter-connectedness, and therefore can be decided internally, is the co-generation of electricity from excess heat (ERE) which is already mentioned as one of the best candidates. However, regarding the symbiotic activities in the Cluster West, the most interesting measures that require medium degree of inter-connectedness and are implemented are clinker substitution (PPC), use of alternative fuels (IFM) and synergies with other co-located firms (SIC) involving extensive usage of blast furnace slag from a nearby steel plant. This demonstrates the fact that CEMEX in Cluster West is already a relatively synergistic production system.

Industrial landscape

On a general level, it is possible to speculate about the most viable measures for reducing CO₂ emissions within the cement industry. For this purpose, the relation between “CO₂ emission reduction potential” and “degree of interconnectedness” for the different categories of measures are considered in Figure 6, also including information about the technological maturity.

Figure 6. . Results of the generic assessment for the cement industry: (x) the degree of inter-connectedness; (y) the CO₂ emission reduction potential of various improvement measures; and (different colors) the technological maturity

Most of the measures that require both mature technologies and less interconnectedness have relatively low potential to reduce the emissions of CO₂. These measures mostly regard the production plant, i.e., internal measures. This is mainly because cement production systems have evolved during the past century and the “process” has become a highly mature one, leaving low potential for further development in the traditional domains. Most of the solutions on process, plant or corporate level are implemented to some extent, in some cases to a very mature level. This leaves relatively little room for maneuverability and improvements. There are a few exceptions (high potential and mature technologies) worth mentioning:

- Clinker substitution (PPC) is a mature technology with high CO₂ improvement potential.
- Synergies among already co-located firms (SIC)
- Improved properties of blended cements (PPB)
- Integration or co-location with waste treatment (SIW)
- Use of more renewable energy (electricity or fuels) (IER)

More complicated solutions (in terms of inter-organizational cooperation and arrangements) requiring more interconnectedness and dealing with higher degrees of uncertainty are currently less mature and less implemented across the cement industry. Most of them are not commercially available and therefore with

existing technologies are not feasible. However, these approaches demonstrate high potential for improvement in the future. Some of the most viable approaches that are gradually emerging are:

- Clinkerless / no-calcine cement (PNC)
- Carbon sequestration / carbon capture and storage (SEC)
- Biological production (SEB)
- Integration with power plant (SIP)

Measures requiring process integration are mostly beneficial due to the fact that they often lead to sharing of resources, savings and fewer emissions. One example of such integration is integrating cement and power production plants. In this system, the heat required for the calcination stage is compensated by the heat released during the carbonation stage (i.e., the capturing of CO₂) and can be integrated efficiently in the steam cycle of a power plant (Bosoaga et al., 2009; Rodríguez et al., 2008; Romeo et al., 2011).

5 Concluding discussion

There are many valuable reports, articles and books spreading knowledge about different options to improve the CO₂ emissions from the cement industry. However, the authors see a need for initiatives to assess different improvement measures in a more structured way. It is also essential to complement the common site-oriented and technical focus in other studies with a broader picture, including a wider systems perspective. Therefore the aim was to develop a framework for systematic collection, classification and assessment of possible measures through the use of multiple criteria, comprising a wide range of possible measures, even those that may not seem applicable to cement production at first glance.

The methodology is inspired by common approaches within the field of environmental systems analysis, for example, studies of materials and energy flows and common ideas, concepts, etc., regarding industrial ecology and industrial symbiosis. Only when all inbound and outbound streams of cement production are considered as potentially useful resources and cement production is seen as an integral part of a larger industrial eco-system, can we argue that the approach for seeking and evaluating measures for improvement is thorough.

The integrated assessment framework can be used in different ways. It can be used as a tool for performing literature reviews and categorizing the state-of-the-art knowledge about options to improve CO₂ performance. It can also be used to assess options for the cement industry in general as well as for individual plants. An important purpose was to develop a tool to facilitate informed decision-making in the cement industry. For example, a large company such as CEMEX with many cement production plants in different parts of the world can use the results of the general study (Part 1 of the assessment) for the whole company. It can also be applied to the cement industry in general. Then, part 2 of the assessment can be applied to assess several individual plants or production clusters. If certain measures are found to be “suitable” for many of the plants, then the larger organization may decide to strategically move in that direction. The framework was successfully developed and then applied to a specific cement production system - CEMEX Cluster West in Germany. Clearly, this highlighted different aspects of the assessed improvement measures in a structured way and facilitated a constructive discussion about different options during the workshop where researchers and staff from CEMEX met. A framework as developed can be utilized to systematically assess hundreds of different measures and identify the most feasible and applicable ones for implementation for specific cement production plants. Similar approaches can be used for evaluations within other industrial sectors as well, i.e., not only for cement production. The results

demonstrated that even in a relatively synergistic production system, like Cluster West, there is room for improvement, especially if options beyond “production efficiency” are considered.

Combining the qualitative results of the assessment framework with the quantitative LCA modeling (as demonstrated in Part I and Part III) can generate more tangible results regarding improvement figures for CO₂ emissions and future improved cement production systems.

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