

# Framework for assessing CO<sub>2</sub> improvement measures in cement industry: a case study of a German cement production cluster

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## **Abstract**

### **Justification of the paper**

Industrial activities such as cement production are among the largest sources of human-induced greenhouse gas emissions and there are ongoing efforts to reduce the CO<sub>2</sub> emissions attributed to them. In order to effectively improve climate performance of cement production, it is essential to systematically identify, classify, and evaluate various improvement measures and implement the most effective and feasible measures.

This has been done in this article by developing an assessment framework based on concepts of Industrial Ecology and Industrial Symbiosis which creates a structure for seeking and evaluating the performance and feasibility of various CO<sub>2</sub> improvement measures. The developed framework has a wide system perspective, takes a wide range of CO<sub>2</sub> improvement measures, and treats all material, and energy flows within the industry as potentially useful resources. This framework is applied in practice for assessing the most feasible measures to apply within the Cluster West in Germany, consisting of three cement plants that are owned by the multinational company CEMEX.

### **Purpose**

Use the concepts of industrial ecology and industrial symbiosis and develop an assessment framework for aggregating, categorizing, and evaluating various CO<sub>2</sub> improvement measures for a given production system. In addition, apply this framework on an actual cement production system and summarize the results both in qualitative and quantitative terms.

### **Theoretical framework**

The assessment framework developed in this article is based on the concepts of Industrial Ecology and Industrial Symbiosis: (1) study of the flows of material and energy in production systems is important, (2) emphasizing on the importance of studying industrial systems in integration with their surrounding systems, not as isolated entities, and (3) in an industrial ecosystem no material and energy stream should be treated as waste and all material and energy streams are potentially useful inputs for other industrial processes.

### **Results**

The result is an assessment framework which can be used to systematically gather, classify and evaluate different CO<sub>2</sub> improvement measures for cement production. This framework consists of two parts: (1) generic assessment and (2) site-specific assessment of CO<sub>2</sub> improvement measures. The first part considers general aspects of the measures such as level of Industrial Symbiosis (i.e. degree of connectedness which is required for their implementation), the potential of each measure for reducing CO<sub>2</sub> emissions, and their technological maturity. The second part assesses the feasibility of the measures regarding the conditions of a specific cement producing system. Aspects such as organizational applicability, technical and infrastructural applicability, and the existing level of implementation of each measure are considered.

The framework is also applied on three cement plants in Germany (owned by CEMEX) referred to as the Cluster West and the results of the assessment are summarized.

### **Conclusions**

As demonstrated in the case of Cluster West, the assessment framework developed in this article can be used by a cement producing companies such as CEMEX in order to systematically assess hundreds of measures and identify the most feasible and applicable ones for implementing on each of their cement production plants.

Lessons learned during development of this assessment framework, may be used when approaching industrial systems other than cement production.

**Keywords:** cement, climate impact, industrial ecology, industrial symbiosis, environmental performance

# 1 Introduction

Cement is a key construction material and is demanded in very large amounts. In 2010, about 3.3 billion tonnes (Gt) of cement was produced across the world (USGS, 2011), which corresponds to about 0.5 tonne cement per capita worldwide. This high demand for cement is expected to grow in the following decades (Nicolas and Jochen, 2008). Cement production releases large amounts of carbon dioxide (CO<sub>2</sub>) which is a greenhouse gas (GHG) and requires lots of energy and materials that is usually accompanied with various forms of environmental impacts. For instance, depending on the case, production of 1 tonne of typical cement may require about 1.5 tonnes of raw materials, 3300 to 4300 MJ of fuel energy, and 100 to 120 kWh of electrical energy; and emits more than 0.9 tonne of CO<sub>2</sub> (Nicolas and Jochen, 2008; EIPPCB, 2010; Price et al., 2010). Therefore, cement production is among the greatest sources of human-induced greenhouse gas emissions (Metz et al., 2007) and the cement industry is under increasing pressures to reduce its CO<sub>2</sub> emissions. Legal, as well as cost saving and economic interests can motivate cement producers to search for ways to decrease environmental impacts associated with cement production (Rehan and Nehdi, 2005).

Therefore, it is becoming more obvious “why” cement-producing companies should seek ways to reduce their CO<sub>2</sub> emissions. However, the question of “how” remains to be addressed: “How” companies can reduce their CO<sub>2</sub> emissions?

During the last decade, several reports and studies have tried to help cement manufacturing companies by providing a range of measures and strategies that can be taken in order to reduce CO<sub>2</sub> emissions (Worrell et al., 2008; WBCSD, 2000; Worrell et al., 2000, 2001; Van Oss and Padovani, 2003; CSI, 2005; EIPPCB, 2010; Price et al., 2010; US EPA, 2010; Moya et al., 2011; Schneider et al., 2011). These reports are valuable sources of knowledge about existing and emerging technologies for improving CO<sub>2</sub> performance (and other aspects such as energy efficiency) of cement production. However, they are generally not formulated in a way to reflect differences in the scale or complexity of measures. Moreover, they are often prioritizing certain aspects of cement production (such as clinker production phases) and therefore “may” fail to include some of the measures that are not directly linked to cement production, but are relevant and useful when looked from a wider system perspective.

This paper is filling these gaps by developing a framework which allows systematic evaluation of options for CO<sub>2</sub> improvement in a cement production system.

This framework is applied to an actual industrial system consisting of a cement production plant and two milling stations belong to CEMEX Company in Germany which is referred to as Cluster West in this article.

## 1.1 Aim of study

The aim of this paper is (1) to develop a framework for assessing measures for reducing CO<sub>2</sub> emission in cement production facilities and (2) use this framework to assess various improvement measures for an actual cement production system (CEMEX Cluster West). Finally, (3) quantify the potential CO<sub>2</sub> reduction of Cluster West, if these candidate measures are applied in future.

# 2 Material and Method

In this paper, first a framework for assessing different measures for reducing CO<sub>2</sub> emissions in cement production systems (or plants) is developed. Then the framework is applied on the CEMEX Cluster West

in Germany in order to get (1) a general scheme of measures (i.e. a structured list of various categories of measures) for improving CO<sub>2</sub> performance of cement industry and (2) a list of relevant and suitable measures for improving CO<sub>2</sub> performance of the Cluster West. Literature review, site visits, workshops and interviews with CEMEX team are performed and used for this part.

The CEMEX Cluster West, site visits and workshop

CEMEX Cluster West (Cluster West) consists of four plants, of which the three actively used are Kollenbach (cement production plant), Dortmund and Schwelgern (milling stations). They form a kind of work alliance, together producing several intermediate products and final products. They have interactions between each other and act as a larger united entity:

- Inbound flows - mainly raw materials, fuels and electricity
- Internal flows - clinker, GBFS (Granulated Blast Furnace Slag), and various intermediate products
- Outbound flows - final cement products. Concerning Cluster West, the focus of this paper has been on the different cement products (CEMI-III).

In order to apply the developed framework in this paper on the CEMEX Cluster West several visits from these sites were performed. In these visits CEMEX presented the company, the Cluster West, and showed the plants during which researches collected information about the status of the Cluster West production system.

In addition to the site visits, the research team from Linköping University and CEMEX management and technical team met at a workshop. Representatives for CEMEX Research Group AG Switzerland also participated. One of the aims of this workshop was to get information about the ideas and view of managers and experts within CEMEX concerning different options to reduce the climate impact. These views were later consolidated when the assessment framework was applied on the Cluster West.

### ***2.1 LCA modeling and conceptual model of Cluster West***

The research team also performed an LCA study of selected cement products of the Cluster West (clinker, CEM I 42,5, CEM III/A 42,5 and CEM III/B 42,5) (LIU, 2011). The results of this study were used in this paper for the quantification of CO<sub>2</sub> reduction potentials in Cluster West, if candidate measures were applied in the Cluster West in future. As it is explained in details in LIU (2011), the LCA model for certain products in the Cluster West is used to create a conceptual LCA model of the Cluster West in 2009. This conceptual model has several key performance indicators (KPI) as its input and produces a virtual cement product called “CEMEX Cluster West Cement Portfolio-2009” as its output. The sensitivity analysis on this LCA model is performed, so the effects of changes in each of the KPIs on the global warming potential (i.e. CO<sub>2</sub>-eq emissions) of Cement Portfolio-2009 are calculated (Table 1).

*Table 1. Improvement of CO<sub>2</sub> performance of the Cluster West if all KPIs are improved by 1%*

Key performance indicator (KPI)				Cluster West portfolio cement (future improved system)		
KPI name	Unit	Value	KPI Change %	Change kg CO <sub>2</sub> -eq/t	Amount kg CO <sub>2</sub> -eq/t	
		2009				
					385.0	
<b>KPI#1</b>	Baseline (2009) Clinker substitution rate	% weight	60%	1%	-5.2	379.9
<b>KPI#2</b>	CO <sub>2</sub> emissions due to calcination	Kg CO <sub>2</sub> /t	541	-1%	-2.2	382.9
<b>KPI#3</b>	Specific energy consumption (fuel)	MJ/t	3913	-1%	-1.0	384.0
<b>KPI#4</b>	Share of renewable (biogenic) fuels	% energy	41%	1%	-0.5	384.5
<b>KPI#5</b>	Specific energy consumption (electricity)	kWh/t	69	-1%	-0.6	384.4
<b>KPI#6</b>	Share of renewable electricity	% energy	0%	1%	-0.6	384.4
				Total:	-10.2	374.9
				<b>Comparison to baseline LCA (2009):</b>		-2.6%

In order to quantify the improvement potentials of the Cluster West after implementation of the “candidate improvement measures” (result of the assessment), the implemented measures are translated into “improving certain KPIs in the Cluster West” and by recalculating the global warming potentials of “Cement Portfolio-future” cement. This value represents the improvements in CO<sub>2</sub> emissions of the Cluster West production system in future.

### 3 Theory

#### 3.1 Systematic studies of flows of energy and materials

To a large extent, the assessment framework is based on mapping and analysis of relevant flows of material and energy, therefore, a theoretical and methodological cornerstone is that overall information about flows of materials and energy can be used to identify and assess relevant environmental impacts – climate change in this case. The following points in this regards are noted:

- The human life style has a great impact on the flows of material and energy (Ayres and Ayres, 1996; Fischer-Kowalski and Haberl, 1997).
- Industrial metabolism – a research area for improved understanding about the physical processes that convert raw materials and energy into finished products and wastes. (Ayres, 1992; Anderberg, 1998).
- The meaning and role of environmental systems analysis and different tools used within this field of research (Finnveden and Moberg, 2005), and especially concerning LCA (e.g. Russell et al., 2005).
- Industrial ecology and industrial symbiosis.

Shortly summarised, it is a common approach within the field of environmental systems analysis to gather information about important flows of materials and energy related to production/products, and therefore the assessment framework which seeks to find and evaluate different improvement measures can be built upon such a perspective. This approach makes it possible to understand important issues, without going into detail about all flows and without having to develop specific information about environmental

impacts. Concepts of industrial ecology and industrial symbiosis are regarded as key areas in this approach.

The “traditional” production of Portland cement can be regarded as a rather linear process, meaning that a majority of the adherent material flows 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 companies 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 notice that large portions of the resources are non-renewable, for example, involving a lot of fossil fuels. This means that “traditional cement production” faces many critical challenges from a long term sustainability perspective.

Having this in mind, the field of industrial ecology is very relevant. Since one of the leading ideas is to mimic nature, i.e. to strive for more closed loops (Isenmann, 2002; Baas, 2005). Optimal application of material and energy streams with the aim to reduce the consumption can provide lower manufacturing costs and better profits. The historical setting of companies can be seen in the context of a life cycle of an industrial system. In that setting the cement industry, as stated above, can be characterized as a traditional manufacturing industry. However, its routines of material use have been challenged in the recent decade. At the cement industry sector level, the use of alternative fuels and raw materials (AFR) are examples of exchange. The potential consequences for sustainable development of adopting the concept of industrial ecology are more broadly discussed within the cement industry, including a discussion of the drivers and barriers to implementation, and technologies and tools available to increase the potential of industrial ecology (WBCSD, 2002).

Although companies are respected as single entities with their own identity and dynamics, they can integrate external purchasing and co-operation with other companies into their organization. Baas (2005) found that there were a variety of views within organizations that need special attention. Rather than seeking to impose a dominant model, the healthier response was found to be: build on diversity. That means that companies’ management systems must be sensitive and in continuous interaction with their surroundings to make renewal in an open system development possible.

Therefore, the guiding principles in the development of the assessment framework, is to consider all material and energy into and from the cement production system as potentially useful streams (concept of industrial ecology) and also consider various degrees of connectedness with the surrounding industries (concept of industrial symbiosis). In addition, aspects such as feasibility or applicability for implementation in the given cement production system are considered. From the industrial ecology, one can learn:

1. Flows of material and energy: Studying the *flows of material and energy* related to industrial activities can provide a basis for developing approaches to *close cycles* in a way that *environmental performance* of these activities are improved (Boons and Howard-Grenville, 2009). So all major streams of material and energy related to cement production should be considered.
1. Integration: Industrial systems should be viewed in *integration* with their surrounding systems, not as isolated entities (Graedel and Allenby, 2003). So the relationship and integration between

the cement production plants and other relevant streams of surrounding industrial and societal systems should be considered.

2. **No waste in industrial ecosystem:** The energy and material efficiency of industrial systems can be improved by using the effluents of one industrial process as the raw material of another process (Frosch and Gallopoulos, 1989). To mimic the rather closed loops of nature is a key idea of industrial ecology. So all inbound or outbound materials and energy streams (including waste streams) should be viewed as potentially useful resources either for the internal use in the cement production system, or for other industrial processes.

## 4 Results

### 4.1 The developed framework

The overview of the developed framework for assessing improvement measures for CO<sub>2</sub> emission reduction in cement industry is presented in Figure 1.

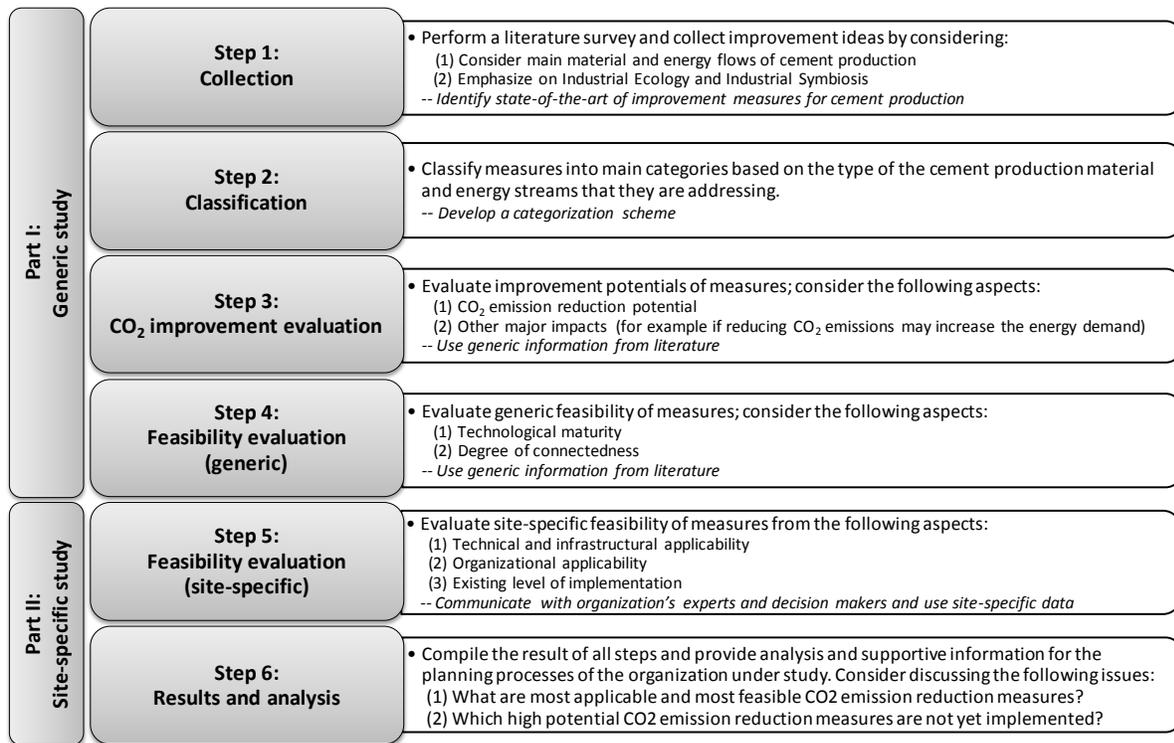


Figure 1. Assessment framework for evaluation of CO<sub>2</sub> emission reduction measures (developed and applied in this thesis)

The framework consists of two parts and six main steps. The first part of the framework (steps 1 to 4) has generic perspective and considers the whole cement industry as a potential target of study and does not necessarily refer to any specific cement production site. The main source of information for this part of

the assessment is the literature. The second part of the framework (steps 5 and 6) has site-specific<sup>1</sup> perspective and evaluates the feasibility of measures for a given cement production system. The source of information for this part of the assessment will be the organization under study.

#### 4.1.1 Collection

In this step, wide range of CO<sub>2</sub> improvement measures in cement industry must be collected and compiled into a gross list of ideas. For this purpose, a literature survey must be performed and relevant information and ideas from various academic, organizations, or industrial sources should be compiled. The aim is to cover as many ideas as possible without considerations regarding their feasibility or applicability. In order to increase the effectiveness of the survey, the principles of Industrial Ecology serve as the guidelines.

In order to visualize these essential concepts, it is helpful to consider a cement production system with all its essential energy and material streams identified.

The following major energy and material streams are recognizable in any typical cement production plant: feedstock (materials), fuels (energy and materials), electricity (energy), products (materials), CO<sub>2</sub> from incineration of fuels and the calcination process (materials or emissions), excess heat (energy), and other streams in terms of emissions, wastes, or byproducts, that can be categorized as “other by-products”. In addition, there are several actual or potential means to use the excess streams in other industrial processes, either by closing the flows (reuse, recycling) or by integrating cement production with other industrial processes. These major energy and material streams and their direct or indirect, practical or theoretical application in cement production, were used as the “guideline” for the literature survey. Ideas which were directly or indirectly (but meaningfully) related to any of these streams were collected and compiled.

As the focal concern of this research is on “CO<sub>2</sub> emission reduction measures”, it is essential to consider processes and activities happening inside the cement production plants. Therefore, ideas related to improving material or energy efficiency of the individual processes of cement production must be considered in the survey. However paying too much attention to details of technicalities of individual processes inside cement production plants should be avoided.

Most improvement ideas for cement production are somehow related to one or more the following aspects of cement production:

- Inputs: Measures related to various forms of material or energy going into the plant including traditional inputs or their secondary, alternative, or renewable replacements.
- Outputs: Measures related to products, utilization of CO<sub>2</sub> or excess heat streams, and reuse or recycling of any other byproducts or wastes streams.
- Plant: Measures related to improving the efficiency of individual or collection of processes inside the plant.
- Others: Measures related to innovative approaches for open-loop or close-loop recycling or integration with other industrial processes.

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<sup>1</sup> The term “site” (in site-specific) used in this framework refers to a “cement production system”. Such a system can be a single plant, or a group of inter-related plants belonging to a single company (such as Cluster West that has three plants).

The simplified cement production plant depicted in Figure 2 facilitates the identification of the relevant ideas regarding “improving CO<sub>2</sub> performance” of cement production. The result of the survey must be collected and structured systematically. Important information about each idea and the source in which it was introduced or developed must be recorded. After completion, the result of the survey serves as the foundation for the next steps of the assessment.

#### 4.1.2 Classification

This classification step is based on the list of improvement measures that are compiled in the first step of the assessment framework. The aim of the classification step is to make a categorization scheme, which organizes these ideas into groups of related improvement approaches. Various methods, techniques, practices, and solutions for CO<sub>2</sub> emission reduction from cement production process can be structured into several main categories and sub-categories. As this assessment framework aims to include main ideas for improvement, the process level measures (measures emphasizing on individual processes inside the plant) are aggregated into few main categories of solutions.

Figure 2 presents the selected overall categories to be used for structuring the collected improved measures. These selected categories are defined based on the simplified cement production model. Any strategy for improving CO<sub>2</sub> performance of cement production is either about improving the efficiency of the internal processes (production efficiency), changing inputs (input substitution), changing products (product development), or effectively utilizing traditionally unused (or wasted) streams such as CO<sub>2</sub> or excess heat through innovative synergistic solutions (external synergies).

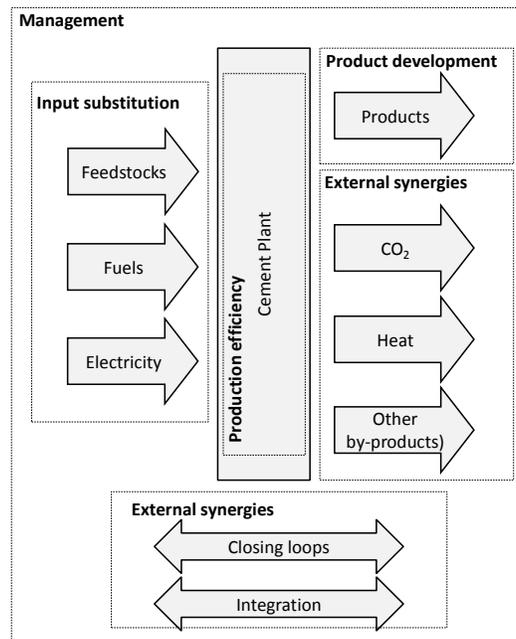


Figure 2. Categories of improvement measures in cement production

These main categories can cover most of the improvement solutions. In order to maintain flexibility regarding the new ideas, the subcategories are not defined in the framework and the detailed categorization scheme should be developed when the framework is actually applied or implemented.

The categorization scheme (result of this step of the assessment after it is applied) should provide a basis for further evaluation and analysis of various improvement measures. Therefore, it is essential to present the information in an organized manner.

#### 4.1.3 CO<sub>2</sub> improvement evaluation

In this step of the framework, each category of measures should be analyzed in order to evaluate its CO<sub>2</sub> emission reduction potential. Due to the uncertainties involved regarding the time, place, and context in which measures can be applied, a qualitative grading system is used in order to find measures with low, medium, or high potential for reducing CO<sub>2</sub> emissions from cement production. For this purpose, the qualitative scale presented in Table 2 can be used.

Table 2. Qualitative scale for CO<sub>2</sub> emission reduction potential

Level	CO <sub>2</sub> emission reduction potential	Estimated theoretical CO <sub>2</sub> emission reduction potential (%)
	The following main sources of CO <sub>2</sub> emissions are considered: (1) Calcination (clinker) (2) Fuel incineration (clinker) (3) High specific energy consumption (clinker/cement) (4) Replacing CO <sub>2</sub> emissions elsewhere (avoiding)	
Low	The measure cannot effectively improve CO <sub>2</sub> emissions from any of the above sources, but has practically significant improvement impacts on at least one of them.	less than 20%
Medium	The measure can effectively improve CO <sub>2</sub> emissions from at least one of the above sources.	between 20% to 50%
High	The measure can effectively improve CO <sub>2</sub> emissions from two or more of the above sources.	More than 50%

For qualitative evaluation of the CO<sub>2</sub> emission reduction potential for each measure, it is essential to consider which CO<sub>2</sub> emitting source it is addressing. If the measure effectively addresses several or all sources of CO<sub>2</sub> emissions, it would be considered as high potential. Effective measures can improve CO<sub>2</sub> emissions due to cement production by having one or more of the following aims:

**(1) Reducing or avoiding CO<sub>2</sub> emissions due to calcination process (during clinker production):** Calcination process releases about 500 kg CO<sub>2</sub> 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 CO<sub>2</sub> emitted during production of clinker.

**(2) Reducing or avoiding CO<sub>2</sub> emissions due to incineration of fuels (mainly during clinker production):** As also mentioned before, another major source of CO<sub>2</sub> emissions during clinker production is “fuel incineration” which occurs in the kiln system. Therefore, measures that can address CO<sub>2</sub> emissions due to fuel incineration can have relatively high potentials for CO<sub>2</sub> emission reduction.

**(3) Reducing CO<sub>2</sub> emissions by decreasing the specific energy consumption of clinker/cement:** As most of the heat and electricity used in cement production have fossil origin and are from non-biogenic sources, their production and consumption emits large amounts of CO<sub>2</sub>. Therefore reducing the energy

demand of clinker/cement production (reducing specific energy consumption) can reduce CO<sub>2</sub> emissions due to clinker/cement production.

The difference between (2) and (3) is that in (2) CO<sub>2</sub> emissions from fuel is addressed (after the CO<sub>2</sub> is released from incineration) but in (3) less fuel is required and therefore less CO<sub>2</sub> is emitted.

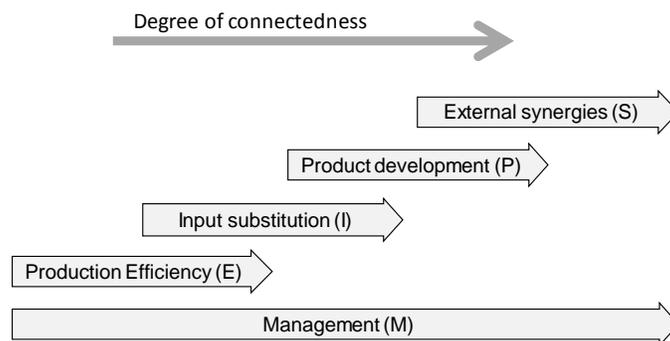
**(4) Reducing or avoiding CO<sub>2</sub> emissions elsewhere (causing another CO<sub>2</sub> emitting process to use less energy, or to use less CO<sub>2</sub> emitting energy):** If a measure can cause less incineration of fossil fuels “somewhere else”, then the CO<sub>2</sub> emissions saved by that avoidance is 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 incinerating coal.

#### 4.1.4 Feasibility evaluation (generic)

The aim of this step of the assessment framework is to analyze each category of measures in order to evaluate its generic feasibility of implementation. The term “generic” here refers to the non-specific nature of the evaluation at this step. In order to determine generic feasibility of each measure, two aspects are considered: (1) degree of connectedness required for development of that measure and (2) its technological maturity level.

##### *Degree of connectedness*

This aspect assesses the level of symbiotic connectedness that a business has to deal with in order to implement a given measure. Measures that fall into category of “production efficiency” are mainly focused on the internal state of the plant and therefore their implementation require less symbiotic connectedness (decision makers of a single company can manage implementation of these kind of measures, without requiring to involve external parties, therefore it require relatively less complex management processes); however, solutions under “external synergies” category, involve cooperating with non-traditional actors, therefore may require more connectedness (decision makers of a single company cannot manage implementation of these measures, and external parties should be involved, therefore it requires relatively more complex management processes). These differences are schematically shown in Figure 3.



*Figure 3. Strategies for improving CO<sub>2</sub> performance of cement production and degree of connectedness required for their implementation*

In this framework, the concept of “degree of connectedness” is defined in relation to the types of Industrial Symbiosis activities that it promotes. Industrial Symbiosis encourages various forms of energy

and material exchanges between organizations on various scales. The complexity of Industrial Symbiosis increases with the number of organizations that are involved or the spatial scopes that it covers.

If a measure is fully managed and controlled by a single actor then it requires business approaches with relatively low complexity (lower connectedness). On the contrary, if it can only be planned and managed by incorporating several actors that are spread across a relatively wide geographic area and require longer term forms of cooperations, then the complexity of business approach required for such arrangement is higher (higher connectedness). By considering different types of Industrial Symbiosis (Chertow, 2000), a qualitative scale for evaluating complexity of business approaches for each category of measures is defined as described in Table 3.

*Table 3. Qualitative scale for evaluating the degree of connectedness required by various CO<sub>2</sub> emission reduction measures*

<b>Level</b>	<b>Degree of connectedness</b>	<b>Spatial scope</b>	<b>Temporal scope</b>
Low	Industrial symbiosis type 0 (no IS), type 1 (no IS), and type 2 (inside a facility or corporation)	Micro level	Short term
Medium	Industrial symbiosis type 3 (industrial park, local)	Meso level	Medium term
High	Industrial symbiosis type 4 (area), and type 5 (region)	Meso to macro level	Medium to long term

#### *Technological maturity*

Another factor that can influence generic feasibility of a CO<sub>2</sub> emission reduction measure is the maturity level of the technologies that are required for its effective implementation. Table 4 defines a qualitative scale for describing technological maturity of different measures.

*Table 4. Qualitative scale for evaluating the technological maturity of CO<sub>2</sub> emission reduction measures*

<b>Level</b>	<b>Technological maturity level</b>	<b>Description</b>
Low	Early development	The measure is in early research and development stage.
Medium	Emerging practice	Either of the following is true about the measure: (1) Some successful demonstrations are done in 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 cement industry in several places under various conditions.

Technological maturity of measures can be qualitatively determined by exploring the existing literature and determining the state-of-the-art of the technologies that are required for their implementation.

#### *4.1.5 Feasibility evaluation (site-specific)*

The aim of the second part of the framework is to evaluate the feasibility and applicability of improvement measures considering the conditions and constraints of a specific cement production system (and its organization), which is called “site-specific” in this paper. The site-specific feasibility of various

improvement measures is evaluated by considering three different aspects: (1) the technical and infrastructural applicability, (2) organizational applicability, and (3) the existing level of implementation of each category of measures.

The site-specific assessment should be performed with the assistance of the experts (technical experts and managers) of the organization under study.

*Technical and infrastructural applicability*

Not every measure is suitable or applicable to every site, even if it demonstrates high potentials for CO<sub>2</sub> emission reduction or is based on a mature technology. Every site has certain technical, infrastructural, or geographical constraints, which influence the applicability of various improvement measures. The qualitative scale for evaluation of technical and infrastructural applicability of various measures for a given cement production system is defined in Table 5.

*Table 5. Qualitative scale for evaluating the technical applicability of CO<sub>2</sub> emission reduction measures according to the conditions of the site under study*

<b>Level</b>	<b>Technical and infrastructural applicability</b>
Low	Either of the following is correct about the measure: (1) It does not make any sense for this specific site. (2) It requires technical infrastructure or geographical conditions which are not currently available.
Medium	Either of the following is correct about the measure: (1) It makes sense for this specific site. (2) The required technical infrastructure and geographical conditions are partially available and they can become fully available without major technical or infrastructural challenges.
High	All of the following conditions are met about the measure: (1) It makes sense for this specific site. (2) The required technical infrastructure or geographical conditions are fully available.

*Organizational applicability*

Corporations have goals, strategies, processes, and other organizational aspects that determine their approach toward changes: “what kind of changes are considered necessary and high priority and which kind of changes are non-necessary or low priority?”. How should an organization allocate its limited organizational resources such as time, money, managerial efforts, and employees’ expertise to a change (due to implementing an improvement measure)? In other words, when a supposedly good improvement idea is proposed to an organization, its decision makers may ask “how compatible is this change with our organizational goals?” or “how much it is aligned with our strategic business approach?” .

In this framework, the term “organizational applicability” is defined as “the degree that a certain proposed improvement measure is in alignment with the short-term, medium-term or long-term vision of the organization”. Like the previous indicator “Technical and infrastructural applicability”, the “organizational applicability” should be evaluated qualitatively by a group of experts and decision makers

from the organization. The qualitative scale for evaluation of organizational applicability of various measures for a given cement production system is defined in Table 6.:

*Table 6. Qualitative scale for evaluating the organizational applicability of CO<sub>2</sub> emission reduction measures according to the conditions of the site under study*

<b>Level</b>	<b>Organizational applicability</b>
Low	Any of the following statements about this measure or the changes it induces is true: (1) The measure is not in line with organization's goals and strategies. (2) The measure is seen as unimportant and having low priority. (3) The necessary organizational resources (time, budget, expertise, etc.) are not available, and/or their provision cannot be considered.
Medium	All of the following statements about this measure or the changes it induces are true: (1) The measure is relatively in line with organization's goals and strategies. (2) The measure is seen as relatively important and having medium or high priority. (3) The necessary organizational resources (time, budget, expertise, etc.) are not yet available, but their provision can be considered.
High	All of the following statements about this measure or the changes it induces are true: (1) The measure is in line with organization's goals and strategies. (2) The measure is seen as important and having high priority. (3) The necessary organizational resources (time, budget, expertise, etc.) can be allocated without major challenges.

In this scale, measures that are in-line with organizations goals and strategies and are considered to be important and high priority, have high organizational applicability. In addition, the “organizational resource” aspects such as availability of the required time, funds, and expertise play a key part in determining the organizational applicability of a certain measure. If the organization has enough resources and determines that spending those resources on the implementation of a certain measure is the most effective way of utilizing those resources, the applicability of that measure will increase.

The above mentioned are few examples of internal barriers that an organization may face when approaching a certain change. To sum up, some of the main organizational barriers toward change are (Gunningham and Sinclair, 1997):

- Lack of information or expertise
- Lack of awareness of environmental issues
- Competing priorities in business approaches (such as pressure of short-term profits)

*Existing level of implementation*

Another aspect that can influence the feasibility of implementation of certain measure is the degree of its existing implementation in the organization. If a certain measure is already implemented to a very high degree in the target production system, then there is not much room left for further development and implementation of that measure. In order to evaluate the existing level of implementation of each category of measures the following qualitative scale can be used (Table 7):

Table 7. Qualitative scale for evaluating the existing level of implementation of CO<sub>2</sub> emission reduction measures in a given site

Level	Existing level of implementation
Low	All 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 relatively present in the organization and learning is in progress. (2) Some successful approaches have occurred, but there is room for further implementation.
High	All of the following statements about this measure are true: (1) The required knowledge is present in the organization. (2) Effectively implemented as part of routine operations (further improvement may be possible)

One of the prerequisites for applying certain measure in an organization is the existing level of knowledge about that measure or the changes that it will induce in the organization. If knowledge about a certain measure is relatively present in an organizational context, its implementation has already progressed to some extent.

#### 4.1.6 Results and analysis

The aim of this step is to put together the results of the previous steps of the assessment, and analyze the result in order to help the planning processes for future improvements in the organization. It is possible to discuss issues such as:

- **Suitable candidates for implementation:** Which technologically mature, high potential CO<sub>2</sub> improvement measures have high technical and organizational applicability and low level of implementation?
- **Research candidates:** Which high potential CO<sub>2</sub> improvement measures have high technical and organizational applicability, but are not implemented in the organization and have low level of technological maturity?
- **Not suitable measures:** Which CO<sub>2</sub> improvement measures are the least feasible and applicable.

The results of the analysis can help the planning process for the future implementations, or research and development paths of the organization.

## 4.2 Applying the framework on CEMEX Cluster West

### 4.2.1 Classification of measures for improving CO<sub>2</sub> performance of the cement industry in general

As introduced before, the assessment framework has two parts. The first part is the generic part which classifies different measures for improving CO<sub>2</sub> emissions in the cement industry.

The objective of classification was to organize and classify the collected measures into few distinct categories which in the framework are compiled in the “categorization scheme”. As shown in Figure 2, five overall strategies for improvements were identified, showing that different measures can deal with the efficiency of the internal processes (production efficiency), changing inputs (input substitution),

changing products (product development), or more effective utilization of traditionally unused (or wasted) streams such as CO<sub>2</sub> or excess heat through innovative synergistic solutions (external synergies).

*Table 8. Categorization scheme for different measures to reduce the CO<sub>2</sub> emissions related to cement production.*

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

M	Management
MB	Environmental strategy and innovation approaches
MM	Marketing, education, and public relations
MS	Standards and specifications

These categories and sub-categories are based on the gross list of ideas that were collected in the first step. The description of each of these strategies and categories are available in (Ammenberg et al., 2011).

#### 4.2.2 Measures for improving CO<sub>2</sub> performance of the Cluster West

In the second part, the framework is applied for CEMEX Cluster West and the feasibility for each category of measures was qualitatively analyzed concerning implementation for Cluster West. The feasibility evaluation was performed in two steps. First, a preliminary evaluation was performed based on the knowledge that was acquired from Cluster West during the project. Then, the result of this preliminary evaluation was sent to CEMEX in order to be re-evaluated and confirmed. The results of the evaluation by CEMEX managers and experts have been updated in the assessment and the results were compiled. These results demonstrated an overview of the most feasible and applicable improvement measures which can be candidate for implementation in the Cluster West.

According to the result of the assessment, the Cluster West has been successful in implementing several CO<sub>2</sub> improvement measures. Examples of already implemented measures in Cluster West are :

1. **Clinker substitution (PPC):** Cluster West is substituting clinker to a large extent and produces various blended cement products. The main clinker substitute material in Cluster West is granulated blastfurnace slag (GBFS) which is used in slag cement products (i.e. CEM III). The clinker substitution rate constantly increased during the last decade and has increased to about 60% in 2009.
2. **Fuel diversification (IEF):** A major part of the fuel used within Cluster West is incinerated at the Kollenbach plant. A wide array of alternative fuels are used there, and this share is increasing. The share of secondary fuels compared to total fuels for Kollenbach is higher than European average. In 2009 it was about 67% for the Kollenbach plant.
3. **Renewable energy (IER):** The share of renewable fuels, or fuels with a biogenic origin, was about 40% for Cluster West in 2009.
4. **Pre-heating/drying (ERH):** The Kollenbach plant has a 4-stage cyclone preheater kiln system. However, the thermal efficiency of the clinker cooler can be improved considerably by replacing the drum cooler of the plant (which is a thermal efficiency measure (EEE)) so that the specific thermal energy consumption for the clinker produced in Kollenbach become similar to typical 4-stage cyclone pre-heater kiln systems.
5. **Electrical efficiency (EE):** The electrical equipments, motors and transportation systems used in the plants of Cluster West are relatively efficient. The electrical efficiency has been improved continuously the last decades. The energy management system for Cluster West will lead to further improvements.

Figure 4 shows the relation between the “existing level of implementation” of the measures and their “CO<sub>2</sub> emission reduction potential”, including information about the technological maturity. Most of the

highly implemented measures in the Cluster West have low or medium CO<sub>2</sub> improvement potential. However, “clinker substitution” (PPC) and “Improve blended cements’ properties” (PPB) are high potential measures that are widely used in the Cluster West and their further implementation should have high priority.

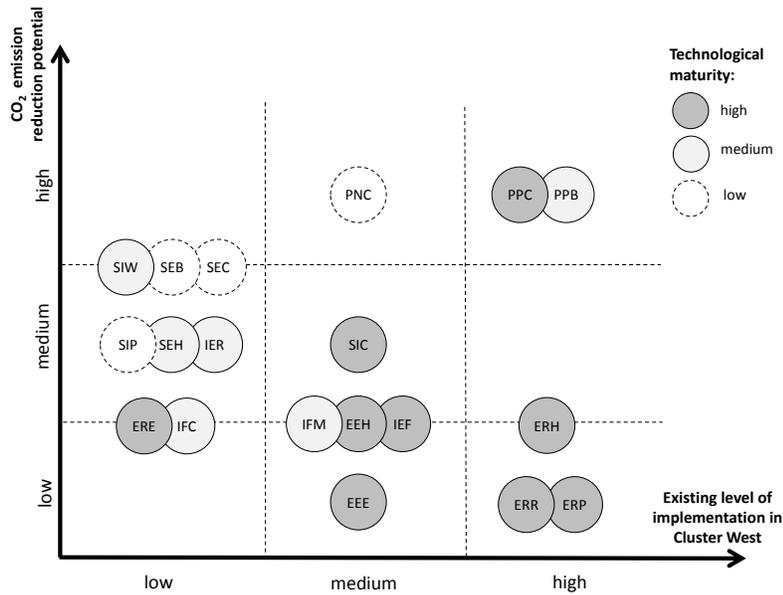


Figure 4. Result of assessment for Cluster West in 2009; (x) the existing level of implementation; (y) the CO<sub>2</sub> emission reduction potential; and (different colors) the technological maturity.

Among the least implemented, but most promising measures are Clinkerless / no-calcine cement (PNC), Integration/co-location with waste treatment (SIW), Biological production (SEB), and Carbon sequestration/carbon capture and storage (SEC). However, applicability of these measures for the Cluster West must also be considered.

The relation between “degree of connectedness” and the “existing level of implementation in Cluster West” for various categories of measures is shown in Figure 5, including information about the technological maturity.

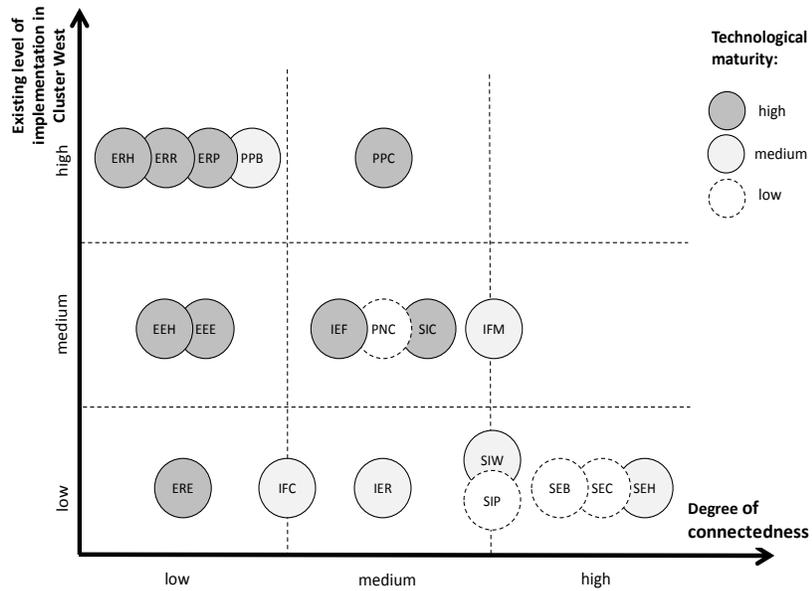


Figure 5. Result of assessment for Cluster West in 2009; (x) the degree of connectedness; (y) the existing level of implementation of various CO<sub>2</sub> improvement measures; and (different colors) the technological maturity

Most of the measures that have relatively low degree of connectedness (i.e. require no or low levels of IS) are implemented in the Cluster West (top left of the above diagram). On the other hand, most of the measures that require a higher degree of connectedness are not yet implemented (such as SIW, SIP, SEB, SEC, SEH and SEC) and their possibilities should be further investigated.

However, it is important to mention that some of the relatively implemented (medium or high) measures in the Cluster West are at the medium level of industrial symbiosis (or degree of connectedness). These measures are clinker substitution (PPC), using alternative materials for clinker production (IFM), fuel diversification (IEF), production of clinkerless or no-calcine cements (PNC) and synergies among already co-located firms (SIC). This demonstrates the fact the CEMEX in Cluster West has already implemented several forms of industrial symbiosis and that this production system is relatively synergistic.

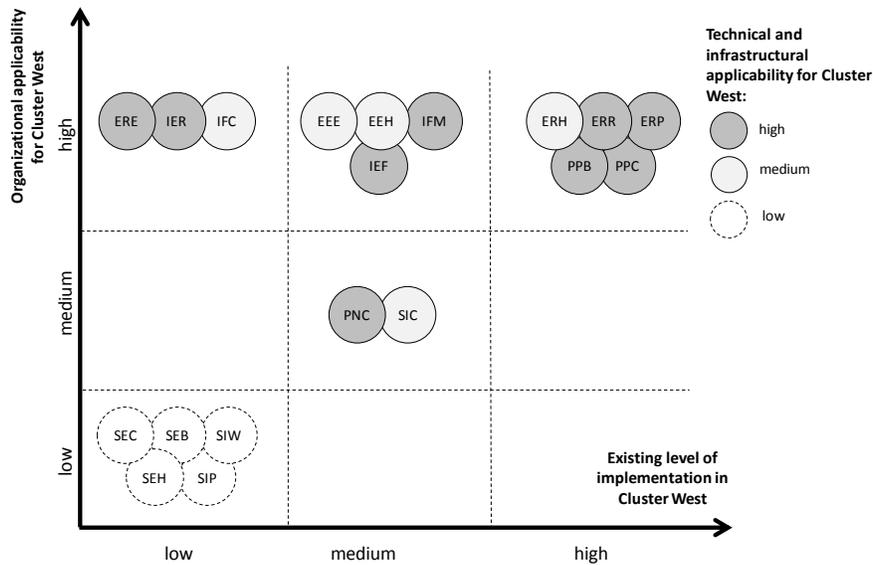


Figure 6. Result of assessment for Cluster West in 2009; (x) the existing level of implementation; (y) the organizational applicability; and (different colors) the technical and infrastructural applicability.

Figure 6, demonstrates the most applicable measures for implementation in the Cluster West.

#### 4.3 Quantifying CO<sub>2</sub> improvement potentials for the CEMEX Cluster West

By using the result of the assessment (qualitative result) and also the method developed in LIU (2011) it is possible to quantify the CO<sub>2</sub> improvement potentials in the Cluster West if the most suitable and applicable improvement potentials are implemented.

Two scenarios for future production system in Cluster West is considered. In the first scenario (which according to result of assessment is a conservative forecast for future), clinker substitution rate (KPI#1) is increased by 10%; share of renewable fuels in the Cluster West fuel mix (KPI#4) is increased by 20% and specific electricity consumption (KPI#5) is decreased by 10%. If the implemented measures lead to these improvement in the KPIs, the CO<sub>2</sub> performance of clinker and portfolio cement can be reduced by 4% and 18% respectively (Figure 6).

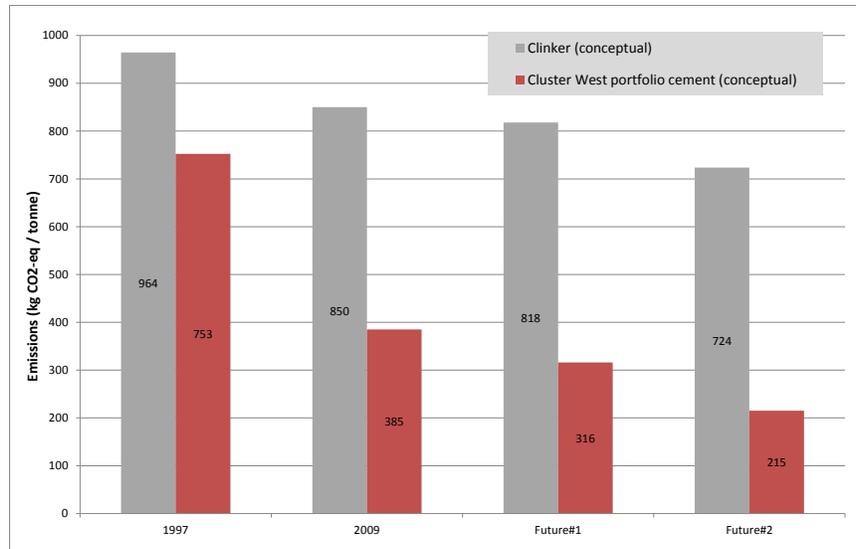


Figure 7. Results of the traditional LCA and future improvements for Cluster West (based on the work done by LIU (2011)).

In the second scenario (a more optimistic and longer term view), clinker substitution rate (KPI#1) is increased by 20%; share of renewable fuels in the Cluster West fuel mix (KPI#4) is increased by 50%, specific electricity consumption (KPI#5) is decreased by 30%, CO<sub>2</sub> emissions due to calcination (KPI#2) is decreased by 10%, specific fuel consumption (KPI#4) is decreased by 5%, and share of renewable electricity (KPI#6) is increased to 5%. If the implemented measures lead to these improvement in the KPIs, the CO<sub>2</sub> performance of clinker and portfolio cement can be reduced by 17.9% and 46.8% respectively (Figure 6).

## 4.4 Discussion

### 4.4.1 Future of CO<sub>2</sub> emission reduction measures in cement industry

On a general level (the result of applying part1 of the framework), it is possible to speculate about the most viable measures for reducing CO<sub>2</sub> emissions within the cement industry. For this purpose, the relation between “CO<sub>2</sub> emission reduction potential” and “degree of connectedness” for the different categories of measures are considered in Figure 7, also including information about the technological maturity.

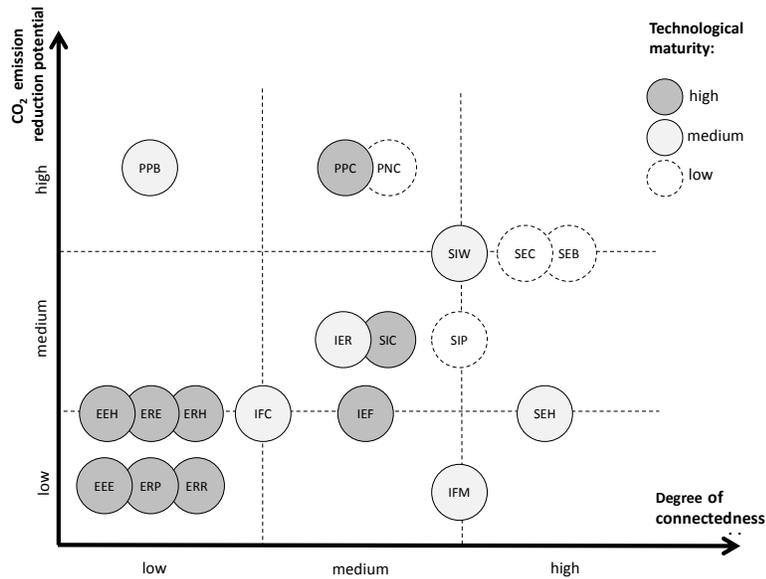


Figure 8. The figure for the categories of improvement measures shows: (x) the degree of connectedness; (y) the CO<sub>2</sub> emission reduction potential of various improvement measures; and (different colors) the technological maturity

Most of the measures that require both mature technologies and less symbiotic connectedness have low potential to reduce the emissions of CO<sub>2</sub>. These measures mostly regard the production plant, i.e. internal measures. This is mainly because cement production systems have evolved during at least a 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 low space for maneuverability and improvements. There are a few exceptions (high potential and mature technologies) worth mentioning:

- Clinker substitution (PPC) is a mature technology and has high CO<sub>2</sub> improvement potential.
- Improved blended cements’ properties (PPB)
- Synergies among already co-located firms (SIC)

More complicated solutions requiring more connectedness and dealing with higher degrees of uncertainty are less implemented. Most of them are not commercially available and therefore with existing technologies are not technologically feasible. However, these approaches demonstrate high potentials for improvement in future. Some of the most viable approaches, which are gradually emerging, but are still not mature enough are:

- Clinkerless / no-calcine cement (PNC)
- Integration/co-location with waste treatment (SIW)
- Carbon sequestration / carbon capture and storage (SEC)
- Biological production (SEB)

#### 4.4.2 *Application of the assessment framework for large companies*

The framework developed is based on the concepts of industrial ecology and industrial symbiosis. It has been developed for systematic collection, classification and evaluation of a wide range of CO<sub>2</sub> improvement measures of relevance for the cement industry. This framework can be used in different ways. It can be used as a tool for performing literature reviews and categorize the state-of-the-art knowledge about options to improve the climate performance. It can also be used to assess options for the cement industry in general as well as for individual plants.

For example, a large company such as CEMEX which operates several cement production plants in different parts of the world, can use the results of the general study (Part I of the assessment) for the whole CEMEX company (cement industry in general). Then, part II of the assessment can be applied to assess individual plants or clusters. If certain measures are shown as “suitable” for many of the plants, then the larger organization may decide strategically to go for that direction.

## 5 Conclusion

Most of the efforts for identifying CO<sub>2</sub> improvement measures for cement industry has been focused on improving the production plant itself and have lacked a structured and systematic approach to cover all aspects, from plant to local industrial contextual levels. In this paper, this issue is addressed by developing an assessment framework inspired by systematic material and energy flow analysis, industrial ecology and industrial symbiosis concepts. The framework provides a structured way to approach wide range of measures, even the ones which may not seem to be applicable for cement production. 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, then we can assume that the approach for seeking and evaluating measures for improvement is thorough.

The developed framework in this paper is intentionally divided into two parts (and 6 steps). The first part has a general view, the global cement industry. The results of this part are a structured list of major strategies for improving CO<sub>2</sub> performance of any cement production system. The second part of the assessment, focuses on a specific cement production system and qualitatively evaluates each of the strategies (identified and structured in the first part) in order to find their feasibility and applicability for that specific cement production system.

The application of this framework on an actual cement production system (CEMEX Cluster West), demonstrated that even in a relatively synergistic production system, there are rooms for improvement, especially if options beyond “production efficiency” are considered. The quantitative evaluation of the candidate improvement measures, demonstrated that future production system of Cluster West can decrease its CO<sub>2</sub> emissions per tonne of average cement product by about between 18% to 47%, compared to 2009 LCA results.

In addition, as demonstrated in the case of Cluster West, the assessment framework developed in this article can be used by large cement producing companies such as CEMEX in order to systematically assess hundreds of measures and identify the most feasible and applicable ones for implementing on each of their cement production plants.

As demonstrated, combining the qualitative results of the assessment framework, with the quantities results of the simplified LCA modeling technique (developed in LIU (2011)) can generate tangible and quantified improvement figures for CO<sub>2</sub> emissions in the future improved cement production systems.

Lessons learned during development of this assessment framework, may be used when approaching industrial systems other than cement production.

## 6 References

- Ammenberg, J., Feizaghahi, R., Helgstrand, A., Eklund, M., Baas, L., 2011. Industrial symbiosis for improving the CO<sub>2</sub>-performance of cement production : Final report of the CEMEX-Linköping University industrial ecology project, 2011. Linköping University Electronic Press.
- Anderberg, S., 1998. Industrial metabolism and the linkages between economics, ethics and the environment<sup>1</sup>. *Ecological Economics* 24, 311–320.
- Ayres, R.U., 1992. *Industrial metabolism: theory and policy*.
- Ayres, R.U., Ayres, L., 1996. *Industrial ecology: towards closing the materials cycle*. E. Elgar.
- Baas, L.W., 2005. *Cleaner production and industrial ecology: Dynamic aspects of the introduction and dissemination of new concepts in industrial practice*. Eburon Uitgeverij BV.
- Bansal, P., Mcknight, B., 2009. Looking forward, pushing back and peering sideways: analyzing the sustainability of industrial symbiosis. *Journal of Supply Chain Management* 45, 26–37.
- Boons, F., Howard-Grenville, J.A., 2009. *The social embeddedness of industrial ecology*. Edward Elgar Publishing.
- Chertow, M.R., 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment* 25, 313–337.
- CSI, 2005. *Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process*. CSI.
- EIPPCB, 2010. *Integrated Pollution Prevention and Control (IPPC): Reference document on Best Available Techniques in the Cement, Lime and Magnesium Oxide manufacturing Industries*.
- Finnveden, G., Moberg, A., 2005. Environmental systems analysis tools-an overview. *Journal of Cleaner Production* 13, 1165–1173.
- Fischer-Kowalski, M., Haberl, H., 1997. Tons, joules, and money: Modes of production and their sustainability problems. *Society & Natural Resources* 10, 61–85.
- Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for manufacturing. *Scientific American* 261, 144–152.
- Graedel, T.E., Allenby, B.R., 2003. *Industrial ecology*. Prentice Hall.
- Gunningham, N., Sinclair, D., 1997. Barriers and motivators to the adoption of cleaner production practices.
- Isemann, R., 2002. Further efforts to clarify industrial ecology's hidden philosophy of nature. *Journal of Industrial Ecology* 6, 27–48.
- LIU, 2011. CEMEX industrial ecology project.
- Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D., Zacharia, Z.G., 2001. Defining supply chain management. *Journal of Business logistics* 22, 1–25.
- Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., 2007. *Climate change 2007-Mitigation of climate change*. Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working Group III.
- Moya, J.A., Pardo, N., Mercier, A., 2011. The potential for improvements in energy efficiency and CO<sub>2</sub> emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria. *Journal of Cleaner Production* 19, 1207–1215.
- Nicolas, M., Jochen, H., 2008. *A blueprint for a climate friendly cement industry*. wwF.
- Price, L., Hasanbeigi, A., Lu, H., 2010. Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: A case study of 16 cement plants. *Energy* 35, 3461–3473.
- Rehan, R., Nehdi, M., 2005. Carbon dioxide emissions and climate change: policy implications for the cement industry. *Environmental Science & Policy* 8, 105–114.
- Russell, A., Ekvall, T., Baumann, H., 2005. Life cycle assessment - Introduction and overview. *Journal of Cleaner Production* 13, 1207–1210.
- Schneider, M., Romer, M., Tschudin, M., Bolio, H., 2011. Sustainable cement production--present and future. *Cement and Concrete Research* 41, 642–650.

- US EPA, 2010. Available and emerging technologies for reducing greenhouse gas emissions from the portland cement industry.
- USGS, 2011. Mineral Commodity Summaries. U.S. Geological Survey.
- Van Oss, H.G., Padovani, A.C., 2003. Cement manufacture and the environment, Part II: Environmental challenges and opportunities. *Journal of Industrial Ecology* 7, 93–126.
- WBCSD, 2000. Eco-efficiency: creating more value with less impact. World Business Council for Sustainable Development.
- WBCSD, 2002. Toward a sustainable cement industry.
- Worrell, E., Galitsky, C., Price, L., 2008. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making. An ENERGY STAR Guide for Energy and Plant Managers.
- Worrell, E., Martin, N., Price, L., 2000. Potentials for energy efficiency improvement in the US cement industry. *Energy* 25, 1189–1214.
- Worrell, E., Price, L., Martin, N., Hendriks, C., Meida, L.O., 2001. Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment* 26, 303–329.