Improving climate performance of cement production-
Developing an assessment framework and applying it to a CEMEX cement production cluster in Germany

Thesis Report

Roozbeh Feiz Aghaei

Linköping University
Fall 2011

2011-Dec-19

ISRN: LIU-IEI-TEK-A--11/01220--SE
Thesis Report

Roozbeh Feiz Aghaei

Examiner: Mats Eklund
Supervisor: Jonas Ammenberg
Opponent: Kaveh Karimi Asli

Linköping University
Fall 2011

2011-DEC-19
**UPPHOVSRÄTT**
Detta dokument hålls tillgängligt på Internet – eller dess framtida ersättare – från publiceringsdatum under förutsättning att inga extraordinära omständigheter uppstår.

Tillgång till dokumentet innebär tillstånd för var och en att läsa, ladda ner, skriva ut enstaka kopior för enskilt bruk och att använda det oförändrat för icke-kommersiell forskning och för undervisning. Överföring av upphovsrätten vid en senare tidpunkt kan inte upphäva detta tillstånd. All annan användning av dokumentet kräver upphovsmannens medgivande. För att garantera äktheten, säkerheten och tillgängligheten finns lösningar av teknisk och administrativ art.

Upphovsmannens ideella rätt innefattar rätt att bli nämnt som upphovsman i den omfattning som god sed kräver vid användning av dokumentet på ovan beskrivna sätt samt skydd mot att dokumentet ändras eller presenteras i sådan form eller i sådant sammanhang som är kränkande för upphovsmannens litterära eller konstnärliga anseende eller egenart.

För ytterligare information om Linköping University Electronic Press se förlagets hemsida http://www.ep.liu.se/

**COPYRIGHT**
The publishers will keep this document online on the Internet – or its possible replacement – from the date of publication barring exceptional circumstances.

The online availability of the document implies permanent permission for anyone to read, to download, or to print out single copies for his/hers own use and to use it unchanged for non-commercial research and educational purpose. Subsequent transfers of copyright cannot revoke this permission. All other uses of the document are conditional upon the consent of the copyright owner. The publisher has taken technical and administrative measures to assure authenticity, security and accessibility.

According to intellectual property law the author has the right to be mentioned when his/her work is accessed as described above and to be protected against infringement.

For additional information about the Linköping University Electronic Press and its procedures for publication and for assurance of document integrity, please refer to its www home page: http://www.ep.liu.se/.

© Roozbeh Feizaghaei
ABSTRACT

It is very likely that human being is contributing to the process of global warming. Industrial activities such as cement production are among the largest sources of human-induced greenhouse gas emissions. Therefore, there are ongoing efforts to reduce the CO₂ emissions attributed to the cement production. In order to be able to systematically identify, classify, and evaluate the most effective, applicable, and feasible CO₂ improvement measures, it is essential to have an assessment framework, which has an environmental management perspective. Such a framework should be able to cover the widest range of potential CO₂ improvement measures, therefore it has to have a wide system perspective and consider all material, and energy flows within the industry as useful resources.

The first part of this thesis uses the concepts of Industrial Ecology and Industrial Symbiosis as the supporting theoretical concepts for developing such assessment framework. The framework has semi-qualitative approach for assessing different measures and is developed in two parts: (1) generic and (2) site-specific assessment. The first part considers general aspects of the measures such as level of Industrial Symbiosis (i.e. complexity of business approach), the potential of each measure for reducing CO₂ 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.

In the second part of this thesis, the developed framework is applied on a selected cement production system which is a cluster composed of three cement plants in Germany (owned by CEMEX) referred to as the Cluster West. The result of the assessment provides insights about the state-of-the-art of CO₂ improvement measures in cement industry in general and also demonstrates which of these measures are most (or least) suited for development in the Cluster West. The production system of the Cluster West has effectively applied CO₂ improvement measures in areas such as producing blended cement products, using alternative fuels (and renewable fuels) for clinker production. In addition, its clinker production (the Kollenbach plant that is part of the Cluster West) has relatively good energy efficiency. According to the results of the assessment, CO₂ improvement measures such as co-generation (producing electricity from excess heat of the plant), using renewable fuels, using alternative materials for clinker production, and increasing the usage of alternative fuels are among the most applicable choices for further implementation.

KEYWORDS

Industrial Ecology, Industrial Symbiosis, climate change, greenhouse gas emissions, CO₂ emission reduction, innovation, business approach, cement production
# TABLE OF CONTENTS

1  Introduction.......................................................................................................................... 1
   1.1  Aim .................................................................................................................................. 2
   1.2  Scope ............................................................................................................................... 3
   1.3  Background ..................................................................................................................... 4
      1.3.1  Industry background ............................................................................................... 4
      1.3.2  Introduction to cement production ........................................................................... 5
      Cement production process ................................................................................................. 7
      Kiln system ........................................................................................................................ 9
      Types of cement ................................................................................................................ 11
      Raw materials and fuels .................................................................................................... 13
         •  Raw materials ............................................................................................................. 13
         •  Fuels ............................................................................................................................ 15
      1.3.3  Introduction to CEMEX .......................................................................................... 16

2  Theory ................................................................................................................................. 18
   2.1  Industrial Ecology at different scopes .......................................................................... 18

3  Research process and Methodology ................................................................................... 21

4  Developing the assessment Framework .............................................................................. 22
   4.1  The overall view of the assessment framework ........................................................ 22
   4.2  Developing “Step 1: Collection” .................................................................................. 23
   4.3  Developing “Step 2: Classification” .............................................................................. 25
   4.4  Developing “Step 3: CO₂ improvement evaluation” ................................................ 27
   4.5  Developing “Step 4: Feasibility evaluation (generic)” ................................................. 28
      4.5.1  Complexity of business approach ......................................................................... 28
      4.5.2  Technological maturity ......................................................................................... 30
   4.6  Developing “Step 5: Feasibility evaluation (site-specific)” ......................................... 31
      4.6.1  Technical and infrastructural applicability ......................................................... 31
      4.6.2  Organizational applicability .................................................................................. 32
      4.6.3  Existing level of implementation .......................................................................... 33
   4.7  Developing “Step 6: Results and analysis” .................................................................. 34

5  Applying the assessment framework - Part I: Generic study ............................................. 35
5.1 Step 1: Collection ................................................................. 35
5.2 Step 2: Classification .......................................................... 35
  5.2.1 Production efficiency ..................................................... 37
    Energy efficiency .................................................................. 37
    • Electrical efficiency ......................................................... 37
    • Thermal efficiency ......................................................... 38
  Resource recovery .................................................................. 39
    • Pre-heating/drying ............................................................ 39
    • Co-generation (heat & electricity) ....................................... 39
    • Recycle/reuse .................................................................. 40
  Pollution control and prevention .............................................. 40
  5.2.2 Input substitution ............................................................. 41
    Feedstock change ................................................................ 41
    • Low temperature clinker production .................................. 42
    • Alternative materials (for clinker production) ...................... 42
    Input energy change ............................................................. 43
    • Fuel diversification (alternative/secondary fuels) ............... 43
    • Renewable energy (fuel and electricity) ............................. 44
  5.2.3 Product development ...................................................... 45
    Improve existing products ................................................... 45
    • Clinker substitution (alternative materials) ......................... 45
    • Blended cements with improved properties ....................... 46
    Develop new products .......................................................... 47
    • Clinkerless/no-calcine cement .......................................... 47
  5.2.4 External synergies ........................................................... 48
    CO₂ and waste excess solutions ............................................. 49
    • Carbon sequestration/carbon capture and storage .......... 49
    • Biological multi production .............................................. 50
    • Synergistic heating or cooling .......................................... 51
    Process integration and industry initiatives ............................ 51
    • Combined power and cement production (CPCP) ............. 51
    • Integration/colocation with waste-to-energy solutions ........ 52
• Synergies among already co-located firms ................................................................. 52
5.2.5 Management ........................................................................................................... 53
Corporate environmental strategy and innovation approaches ........................................ 53
Marketing, education, and public relations ..................................................................... 55
Standards and specifications ............................................................................................ 55
5.3 Step 3: CO₂ improvement evaluation ......................................................................... 56
5.4 Step 4: Feasibility evaluation (generic) ....................................................................... 56
6 Applying the assessment framework - Part II: Cluster West ........................................ 57
6.1 Cluster West ................................................................................................................ 57
   6.1.1 Plant Kollenbach .................................................................................................. 60
   6.1.2 Plant Schwelgern ................................................................................................. 62
   6.1.3 Plant Dortmund .................................................................................................... 63
   6.1.4 Data collection from Cluster West ........................................................................ 63
   • Input and output records ........................................................................................... 63
   • Site visit ....................................................................................................................... 63
   • Workshop ...................................................................................................................... 64
   • Feedback from company experts .............................................................................. 64
6.2 Step 5: Feasibility evaluation (for Cluster West) ......................................................... 64
6.3 Step 6: Results and analysis (for Cluster West) .......................................................... 64
   6.3.1 Currently implemented measures in Cluster West .............................................. 66
   6.3.2 Material and energy flows of Cluster West and the implemented CO₂ improvement measures ........................................................................................................ 66
   6.3.3 High potential CO₂ improvement measures implemented in Cluster West ....... 68
   6.3.4 Applicable measures for Cluster West ............................................................... 69
7 Discussion ......................................................................................................................... 71
7.1 Discussion on CO₂ improvement options for Cluster West ........................................ 71
   7.1.1 Existing level of Industrial Symbiosis in the Cluster West .................................. 71
   7.1.2 What can CEMEX learn from Cluster West? ...................................................... 72
7.2 Future of CO₂ emission reduction measures in cement industry ............................... 73
8 Conclusions ....................................................................................................................... 75
8.1 Conclusions regarding the assessment framework ..................................................... 75
8.2 Conclusions of the generic assessment ...................................................................... 76
8.3 Conclusions of the Cluster West assessment ............................................................... 77
LIST OF TABLES

Table 1. World cement production in 2009 and 2010 (USGS, 2011) ................................................................. 5
Table 2. Typical chemical composition of cement clinker .................................................................................. 6
Table 3. Typical mineralogical composition of Portland cement ........................................................................ 7
Table 4. Specific thermal energy (heat) requirement for different processes .................................................. 8
Table 5. Number of cement plants (with or without kiln) in a few European countries in 2008 (EIPPCB, 2010) ......................................................................................................................... 11
Table 6. Cement types according to DIN EN 197-1 standard (European Standard EN 197-1, 2000) ............ 12
Table 7. Types of cements produced in European (EU-25) countries (EIPPCB, 2010) ........................................ 13
Table 8. Raw materials group and few examples (VDZ, 2008; EIPPCB, 2010) ..................................................... 14
Table 9. Fuel usage in European cement industry in 2006 (EIPPCB, 2010) ......................................................... 15
Table 10. Waste fuels categorization (EIPPCB, 2010) ...................................................................................... 16
Table 11. Summary of CEMEX global operations (CEMEX, 2010) ................................................................. 16
Table 12. Qualitative scale for CO₂ emission reduction potential ................................................................. 27
Table 13. Various types of Industrial Symbiosis ............................................................................................... 29
Table 14. Qualitative scale for evaluating the complexity of business approaches required by various CO₂ emission reduction measures .................................................................................. 30
Table 15. Qualitative scale for evaluating the technological maturity of CO₂ emission reduction measures .................................................................................................................................................. 30
Table 16. Qualitative scale for evaluating the technical applicability of CO₂ emission reduction measures according to the conditions of the site under study ........................................................................ 32
Table 17. Qualitative scale for evaluating the organizational applicability of CO₂ emission reduction measures according to the conditions of the site under study .......................................................... 33
Table 18. Qualitative scale for evaluating the existing level of implementation of CO₂ emission reduction measures in a given site ........................................................................................................... 34
Table 19. Categorization scheme for CO₂ improvement measures in cement production ............................... 36
Table 20. Levels of corporate approaches regarding environmental concerns based on work by Arundel et al. (2006) ........................................................................................................................................... 53
Table 21. Evaluation of CO₂ improvement potentials for various improvement measures ............................ 56
Table 22. CEMEX plants in Germany and their production capacities ............................................................ 59
Table 23. Summary of equipments used in Kollenbach plant (CEMEX-DE, 2010a) ........................................ 62
Table 24. Fuels used in Kollenbach plant in 2009 (CEMEX-DE, 2010b) ........................................................... 62
Table 25. Evaluation results for CO₂ improvement measures for the Cluster West ........................................ 65
Table 26. Levels of sustainability and environmental management concepts ................................................. 93
Table 27 - Summary of Cluster West site visit .............................................................................................. 95
Table 28 – List of CO₂ emission reduction measures proposed during Cluster West workshop .................. 97
Table 29. Key performance indicators for the Cluster West cement production system and few other countries/regions ........................................................................................................................................... 99
Table 30 – Gross list of ideas for improvement of cement production .......................................................... 99
LIST OF FIGURES

Figure 1. Calcination chemical reaction (Worrell et al., 2001) ...................................................... 6
Figure 2. Major steps for cement production .............................................................................. 7
Figure 3. Simplified diagram of cement production processes .................................................. 9
Figure 4. Rotary kiln technologies and functional zones .............................................................. 10
Figure 5. Chemical composition of clinker and other materials which can be used in cement (CSI, 2005) ........................................................................................................ 14
Figure 6. Environmental management concepts at different scopes (based on Baas (2005)) .... 19
Figure 7. Assessment framework for evaluation of CO$_2$ emission reduction measures (developed and applied in this thesis) .............................................................................. 22
Figure 8. Simplified model of main material and energy flows in a cement production system. 24
Figure 9. Categories of improvement measures in cement production ...................................... 26
Figure 10. Strategies for improving CO$_2$ performance of cement production and complexity of business approaches .................................................................................................................. 29
Figure 11. CaO, SiO$_2$ and Al$_2$O$_3$+Fe$_2$O$_3$ diagram for cement clinker and the ash constituents of different raw materials and fuels ........................................................................................................ 41
Figure 12. Benefits of system optimization, re-design, and innovation ....................................... 54
Figure 13. Location of CEMEX plants in Germany ........................................................................ 58
Figure 14. Overview of Cluster West in 2009 (CEMEX-DE, 2010a) ............................................. 60
Figure 15. Production process in Kollenbach plant (CEMEX-DE, 2010a) .................................... 61
Figure 16. “Existing level of implementation of CO$_2$ improvement measures in the Cluster West” and the simplified cement production model .................................................................................. 67
Figure 17. “Existing level of implementation in the Cluster West” and “CO$_2$ emission reduction potential” for various CO$_2$ improvement measures .............................................................................. 69
Figure 18. “Organizational applicability” and “Existing level of implementation in the Cluster West” for various CO$_2$ improvement measures ...................................................................................... 70
Figure 19. “Complexity of business approach” and “existing level of implementation of various CO$_2$ improvement measures in Cluster West” .................................................................................. 72
Figure 20. “Complexity of business approach” and “CO$_2$ emission reduction potential” of various improvement measures .................................................................................................................. 73
Figure 21. The application of the framework in large cement producing companies with several cement production systems .................................................................................................................. 76
Figure 22 – Industrial Ecologyseeks system improvement by considering “all” input and output streams and discarding the notion of “waste” .................................................................................. 91
Figure 23 – Relation of Industrial Symbiosis with Industrial Ecology ......................................... 92
Figure 24. Environmental management concepts and levels of sustainability .......................... 94
1 INTRODUCTION

This thesis deals with the issue of climate impacts associated with cement production. Cement production releases large amounts of carbon dioxide (CO$_2$) which is a greenhouse gas (GHG). It is believed that increased concentration of greenhouse gases in atmosphere contributes to increasing of earth’s surface temperature (global warming) and the process of climate change (IPCC, 2007a).

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). In addition to this large increasing demand, cement production 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$^1$ 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$_2$ (Nicolas and Jochen, 2008; EIPPCB, 2010; Price et al., 2010).

Due to the mentioned facts, 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$_2$ emissions. From legal perspectives, several existing and emerging policies can affect the future of cement industry. However, the reasons for reducing CO$_2$ emissions are not limited to legal demands. Other imperatives such as cost saving and economic interests can also motivate cement producers to search for ways to decrease environmental impacts associated with cement production. In addition sometimes there is a relation between regulatory demands and economic benefits (if regulations are not followed the costs may become increasingly higher) (Rehan and Nehdi, 2005). Therefore, it is becoming more obvious “why” cement-producing companies should seek ways to reduce their CO$_2$ emissions. However, the question of “how” remains to be addressed: “How” companies can reduce their CO$_2$ emissions?

The first step for cement producers is to become aware of the existing options for improvement and assess the potentials and feasibility of them. 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$_2$ emissions. The report by the European Commission on “best available techniques in cement manufacturing” describes various cement production techniques and identifies the emerging new technologies (EIPPCB, 2010). In addition, the US Environmental Protection Agency (US EPA, 2010) provides an overview of the cement production industry in the United States and evaluates available and emerging

---

$^1$ Various types of cement will be introduced in later chapters. Here, the term “typical cement” is referring to “Ordinary Portland Cement” or OPC that is the most widely used cement in production of concrete.
technologies for reducing greenhouse gas emissions from this industry. Several other reports provide overview of various existing or emerging measures for reducing CO₂ emissions. (WBCSD, 2000; Worrell et al., 2000, 2001, 2008; Van Oss and Padovani, 2003; CSI, 2005; Price et al., 2010; Moya et al., 2011; Schneider et al., 2011).

The mentioned reports are valuable sources of knowledge about existing and emerging technologies for improving CO₂ 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 cement 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 thesis is trying to fill these gaps and scale up the existing frames for collecting and evaluating CO₂ improvement measures. The aim (refer to section 1.1) is to provide a framework, which covers a wide range of improvement measures and differentiate these measures by considering several generic or specific attributes such as their feasibility or applicability for implementation in a given cement production system. This assessment framework will allow cement producers to systematically collect, classify, and evaluate wide range of traditional or innovative improvement measures and use the results as supporting information in their planning and decision making processes.

Primarily, this report seeks to provide a framework for assessing various improvement measures for reducing climate impact of cement production. In addition, this framework is applied on an existing cement production system in Germany owned by CEMEX² which is a cluster composed of three plants. These plants have close operational links with each other and are called the “CEMEX Germany Cluster West”, or Cluster West in short, which will be introduced later (in chapter 6).

This thesis is carried out within the frames of a research project sponsored by CEMEX and performed by Linköping University (LIU, 2011).

## 1.1 Aim

The aims of this research is to (1) Develop a framework for assessing improvement measures for CO₂ emission reduction in cement industry; and (2) use this framework to assess various improvement measures for an actual cement production system.

These overall aims can be expressed in more details by the following research questions:

---

2 CEMEX is an international supplier of building materials and is one of the largest cement producing companies in the world (more information about CEMEX is available in section 1.3.3)
1. Which environmental management concepts are suitable to be used as the basis for development of a framework for assessing improvement measures for CO$_2$ emission reduction in cement industry? (Consider *Industrial Ecology and symbiosis and motivate their suitability for serving as theoretical basis for this framework*)

2. How can these improvement measures be aggregated, categorized, and evaluated under a unifying framework based on the selected environmental management concepts such as Industrial Ecology and symbiosis? (*develop the assessment framework*)

3. What is the result of applying the developed framework on an actual cement production system? (apply the framework on Cluster West)

### 1.2 Scope

**The selected cement production system:** The framework development part of this thesis is mainly theoretical; however, the framework is applied to an actual cement production system, which as defined before is referred to as Cluster West. Like other industrial systems, Cluster West is not isolated from its surrounding environment so it requires flows of energy and material (produced by other supporting systems) for its operation. Since this thesis is concerned with improving CO$_2$ performance of the overall system of study (Cluster West and all its required supporting systems), the geographical scope of Cluster West is not specifically set, however the information about the Cluster West production system is presented later in this report (refer to 6.1).

From temporal perspective, the source of information and the reference of study is the status of the Cluster West in the present time. However, some of the data used for applying the framework on Cluster West are from 2009 annual figures as well as the feedback received from CEMEX in 2001. In addition, whenever a comparison with past is required, the state of the Cluster West in year 1997 is considered. For future references, in most cases, no specific year is set and often a hypothetical “future” is assumed.

**Environmental performance:** From environmental perspective, the scope of this thesis is on climate change. According to IPCC (2007a), climate change (and global warming) has correlations with the release of greenhouse gases such as CO$_2$. Therefore, for simplicity and practical purposes, “improving environmental performance of a system” loosely refers to:

- *Improve climate performance:* decrease the release of CO$_2$ and other greenhouse gases of a given system.
- *Improve CO$_2$ performance:* decrease the release of CO$_2$ or other greenhouse gases of a given system.

It is also worthy to note that often there is a considerable correlation between CO$_2$ performance and the amount of energy used for manufacturing of a unit of production. Therefore, in many cases, reducing the energy demand (or energy intensity) of cement production leads to the reduction of CO$_2$ emissions as well. This of ‘course largely depends on the type of energy source used for cement production (Svensson et al., 2006). Therefore, this thesis assumes that
“improving energy efficiency of cement production” or “decreasing the energy demand of cement production” can improve (to some extent) the CO₂ performance of cement production.

**Biogenic CO₂:** If the source of carbon in the emitted CO₂ is from biological processes (biogenic source) then the emitted CO₂ is considered as biogenic CO₂ (in contrast to fossil CO₂). According to IPPC models for global warming and climate change model, the contribution of biogenic CO₂ emissions to these processes is considered zero. Therefore in this thesis, the term “CO₂” refers to “CO₂ from fossil or other non-biogenic sources”.

**Resources:** The term “resource” can have physical, social, economic, or other dimensions. In this thesis, the term “resource” refers to “material” and/or “energy” and other types of resource are not considered. Therefore, terms such as “improve resource efficiency” are assumed loosely equivalent with the following terms:

- Using less material and/or energy for producing the same product or delivering the same service
- Decreasing material intensity (dematerialization) of products or services
- Decreasing energy intensity of products or services

### 1.3 Background

In this section, general information about cement production is presented. This includes definitions of important terms, main parts of the system, standard types of cement and common fuels and materials used in cement production. In addition, CEMEX and its operation in Germany are introduced.

#### 1.3.1 Industry background

Globally, about 40% of energy and material flows, slightly less than 20% of fresh water withdrawal, and 25% of total wood harvest is related to construction industry (Horvath, 2004). One of the most used and important elements in this industry is cement which has been in use for a long time. Cement has been so essential in development of nations that often the amount of cement consumption can be used as an economic indicator (EIPPCB, 2010). In 2010, China was the largest cement producer in the world (55%) followed by EU-27 (7.7%), India (6.7%), US (1.9%) and Japan (1.7%) (Cembureau, 2010; USGS, 2011). Table 1 shows cement production figures for main cement producing countries (USGS, 2011).
Table 1. World cement production in 2009 and 2010 (USGS, 2011)

<table>
<thead>
<tr>
<th>Country</th>
<th>2009</th>
<th>Share (%)</th>
<th>Amount (Mt)</th>
<th>Share (%)</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1,629</td>
<td>53.2%</td>
<td>1,800</td>
<td>54.5%</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>205</td>
<td>6.7%</td>
<td>220</td>
<td>6.7%</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>65</td>
<td>2.1%</td>
<td>64</td>
<td>1.9%</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>55</td>
<td>1.8%</td>
<td>56</td>
<td>1.7%</td>
<td></td>
</tr>
<tr>
<td>Turkey</td>
<td>54</td>
<td>1.8%</td>
<td>60</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>52</td>
<td>1.7%</td>
<td>59</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>50</td>
<td>1.6%</td>
<td>46</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>Iran</td>
<td>50</td>
<td>1.6%</td>
<td>55</td>
<td>1.7%</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>50</td>
<td>1.6%</td>
<td>50</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td>47</td>
<td>1.5%</td>
<td>48</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>44</td>
<td>1.4%</td>
<td>49</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>40</td>
<td>1.3%</td>
<td>42</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>36</td>
<td>1.2%</td>
<td>35</td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>35</td>
<td>1.2%</td>
<td>34</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>31</td>
<td>1.0%</td>
<td>31</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>30</td>
<td>1.0%</td>
<td>31</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>World total (rounded)</td>
<td>3,060</td>
<td>100%</td>
<td>3,300</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

In the following section, a brief overview of important concepts related to cement production is presented.

1.3.2 Introduction to cement production

Cement is “a finely ground, non-metallic, inorganic powder, and when mixed with water, forms a paste that sets and hardens” (Locher, 2006; EIPPCB, 2010). The most common form of cement is called Ordinary Portland Cement (OPC) or simply Portland cement. At least 90 to 95% of OPC is made of a material called clinker (Locher, 2006).

Clinker is defined as “an intermediate cement product made by sintering limestone, clay, and iron oxide in a kiln at around 1450°C” (CEMEX, 2011). It is produced inside a special huge furnace that is known as cement kiln. Several minerals such as oxides of calcium, silicone, aluminum, iron, and magnesium are used in the formation of clinker. Inside the kiln, hydraulically active calcium silicate minerals are formed through high-temperature burning of limestone and other materials (Van Oss and Padovani, 2002; Locher, 2006).

One of the main phases of clinker production is the process of calcination. In this chemical reaction, which is presented in Figure 1, calcium carbonate decomposes at about 900 °C and calcium oxide and carbon dioxide are produced.
Calcium oxide (CaO) is the main compound of cement clinker. Inside cement kiln, the calcium oxide, which is the result of the calcination process, is sintered with other oxides such as silicone oxide (silica), aluminum oxide (alumina), iron oxide, magnesium oxide (magnesia) in temperature between 1400°C to 1500°C. A typical chemical composition of cement clinker is summarized in Table 2.

### Table 2. Typical chemical composition of cement clinker  
*Van Oss and Padovani, 2002; EIPPCB, 2010*

<table>
<thead>
<tr>
<th>Chemical formula</th>
<th>Share (%)</th>
<th>Short notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>65.0</td>
<td>C</td>
</tr>
<tr>
<td>SiO₂</td>
<td>22.0</td>
<td>S</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.0</td>
<td>A</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.0</td>
<td>F</td>
</tr>
<tr>
<td>MgO</td>
<td>1.0</td>
<td>M</td>
</tr>
<tr>
<td>K₂O + Na₂O</td>
<td>0.8</td>
<td>K+N</td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Other (including SO₃)</td>
<td>2.2</td>
<td>-</td>
</tr>
</tbody>
</table>

As mentioned above, cement clinker is a mixture of molecules in the general form of \((nCaO.mOxide)\) such as \(3CaO.SiO₂\), \(2CaO.SiO₂\), \(3CaO.Al₂O₃\), and so on. In order to simplify long chemical formulas, short notations and abbreviations are used in cement industry. The most common short notations for important ingredients of clinker are also presented in Table 2.

Clinker (and therefore cement) has hydraulic properties, which enables it to solidify after mixing with water. Hardening of clinker does not occur immediately and takes some time that is known as “setting time”. By adding a sulfate dehydrate additive like gypsum to clinker, the setting time of cement can be adjusted (Locher, 2006). Other properties of cement such as strength and durability depend on various constituents in the mixture that form the cement product. A summary of mineralogical compositions, their functions, and their share in ordinary Portland cement is presented in Table 3.
Table 3. Typical mineralogical composition of Portland cement (Van Oss and Padovani, 2002)

<table>
<thead>
<tr>
<th>Description</th>
<th>Chemical formula</th>
<th>Abbreviated formula</th>
<th>Share (%)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate ('alite')</td>
<td>3CaO·SiO₂</td>
<td>C₃S</td>
<td>50-55</td>
<td>Imparts early strength and set</td>
</tr>
<tr>
<td>Dicalcium silicate ('belite')</td>
<td>2CaO·SiO₂</td>
<td>C₂S</td>
<td>19-24</td>
<td>Imparts long-term strength</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>3CaO·Al₂O₃</td>
<td>C₃A</td>
<td>6-10</td>
<td>Contributes to early strength and set</td>
</tr>
<tr>
<td>Tetracalcium aluminoferite</td>
<td>2CaO·(Al₂O₃·Fe₂O₃)</td>
<td>C₄(A,F)</td>
<td>7-11</td>
<td>Acts as a flux, imparts gray color</td>
</tr>
<tr>
<td>Calcium sulfate dehydrate</td>
<td>CaSO₄·2H₂O</td>
<td>CSH₂</td>
<td>3-7</td>
<td>Controls early set</td>
</tr>
</tbody>
</table>

Cement production process

As shown in Figure 2, cement production has three major steps: (step 1) extract raw material from quarries and prepare them (e.g. crash them), (step 2) pyroprocessing\(^3\) (clinker production), and (step 3) grinding and blending clinker with other products to create cement. Generally, 99% of the energy content of the fuels plus about 20% of electricity input is used in pyroprocessing (step 2). Other two processes (step 1 and 3) mainly consume electricity (Khurana et al., 2002).

![Figure 2. Major steps for cement production](image)

Depending on the characteristics of raw materials to be used, there are different options concerning cement processes. There are four main types of processes, but the major distinction is between dry and wet processes. In the wet processes, the raw material is mixed with water and is fed into the kiln in the form of slurry with moisture content between 30 to 40 percent. In the dry processes, the raw material is fed into the kiln as a semi-grinded material with relatively low moisture content. In general, dry processes use less thermal energy than wet processes, since the latter require extra energy for drying. Consequently, dry processes are preferred and the wet alternative is only more suitable if the input materials have high moisture content (US EPA, 1994; EIPPCB, 2010). Other types of kiln systems exist that are called semi-dry or semi-wet kiln systems. In semi-dry, the input meal is pelletized with water and is fed into the kiln (with preheater or a long kiln). In semi-wet, the slurry is first dewatered in filter presses and a filter cake is formed which is extruded into pellets. These pellets are then fed into a grate preheater (or dryer) for producing raw meal. Wet processes are increasingly becoming outdated and plants are converting to dry or semi-dry processes instead. In general (at least in Europe), all wet or semi-dry plants are expected to be converted to dry process kiln systems (EIPPCB, 2010).

\(^3\) Refer to glossary.
For dry processes, three main types of kiln systems are used: long dry kilns (LD), preheater kilns (PH), and preheater/precalciner kilns (PH/PC). These systems are different concerning design/equipment, operation method and fuel consumption. For example, preheater kilns and preheater/precalciner kilns have better fuel efficiency and higher production capacities. Table 4 shows average energy (heat) figures for the different options mentioned, based on information for the United States.

Table 4. Specific thermal energy (heat) requirement for different processes (ECRA, 2009; Ali et al., 2011)

<table>
<thead>
<tr>
<th>Clinker production process</th>
<th>Specific thermal energy consumption (MJ/tonne Clinker)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet process</td>
<td>5,860 - 6,280</td>
</tr>
<tr>
<td>Long dry (LD)</td>
<td>4,600</td>
</tr>
<tr>
<td>1-stage cyclone pre-heater (PH)</td>
<td>4,180</td>
</tr>
<tr>
<td>2-stage cyclone pre-heater (PH)</td>
<td>3,770</td>
</tr>
<tr>
<td>3-stage cyclone pre-heater (PH)</td>
<td>3,400 - 3,800</td>
</tr>
<tr>
<td>4-stage cyclone pre-heater (PH)</td>
<td>3,200 - 3,600</td>
</tr>
<tr>
<td>4-stage cyclone pre-heater plus calciner (PH/PC)</td>
<td>3,140</td>
</tr>
<tr>
<td>5-stage cyclone pre-heater (PH)</td>
<td>3,100 - 3,500</td>
</tr>
<tr>
<td>5-stage pre-heater plus calciner plus high efficiency cooler (PH/PC)</td>
<td>3,010</td>
</tr>
<tr>
<td>6-stage cyclone pre-heater (PH)</td>
<td>3,000 - 3,400</td>
</tr>
<tr>
<td>6-stage pre-heater plus calciner plus high efficiency cooler (PH/PC)</td>
<td>2,930 or lower</td>
</tr>
</tbody>
</table>

Regardless of the type of the process, all of these processes share the following common sub-processes (EIPPCB, 2010):

- Preparation of raw materials (such as crushing, drying, and so on)
- Preparation of fuels (such as drying, pelleting, and so on)
- The kiln system (dehydration, calcination, sintering)
- Preparation and storage of products (grinding, blending or and mixing)
- Packaging and dispatch

Figure 3 shows a simplified model of these processes. All of them need energy and produce gaseous and particulate emissions.
**Figure 3. Simplified diagram of cement production processes**
*(Huntzinger and Eatmon, 2009)*

**Kiln system**

The kiln is the heart of every clinker producing plant. Pyroprocessing of raw materials is happening here and the result is the clinker. The kiln is a long tube (between 50 to 200 meters) with “length-to-diameter ratio” between 10:1 and 38:1, which rotates around its axis with the speed of about 0.5 to 5 revolutions per minute (EIPPCB, 2010).

Figure 4 shows four of the most commonly used kilns for wet and dry processes and their functional zones. Preheater/preciner rotary kilns (PH/PC) have the highest capacity, typically between 1300 to 5000 tonnes per day (up to more than 10000 tonnes per day), while the other three main kiln types rarely exceed capacities of more than 2000 tonnes per day. Less common kiln types such as vertical shaft kiln (VSK) are not shown in this figure because of their low capacity (between 20 to 200 tonnes per day) and since they are uncommon. China and India are exceptions - vertical shaft kilns are commonly used in these countries (Van Oss and Padovani, 2002).
Figure 4. Rotary kiln technologies and functional zones
(Van Oss and Padovani, 2002)

There are five different functional zones in the kiln system (US EPA, 1994; Van Oss and Padovani, 2002):

1. **Drying (evaporation):** water in raw materials evaporates so they become ready as an input for the kiln.
2. **Preheating (dehydration):** raw materials are preheated before the calcining process. The stream of hot gas used in this phase can be used for the drying process.
3. **Calcining:** In this phase, calcium oxide and carbon dioxide are produced. This phase is one the major contributors to the CO₂ emissions resulting from clinker production.
4. **Sintering or burning:** calcium oxide enters in a sintering phase with other chemicals such as silicone oxide (silica), aluminum oxide (alumina) and iron oxide and mineralogical compositions mentioned in Table 3 are produced in temperature range between 1200°C-1500°C.
5. **Cooling:** the temperature of the kiln outputs is reduced.

For wet and long dry kilns, the first two phases of pyroprocessing (drying and preheating) are occurring in the kiln. However, in dry kilns with preheater, these phases happen in separate tower that is called preheater tower. The output of the preheater goes to the kiln for further thermal treatment. Raw materials enter from top end of the kiln and as they go through the kiln, they become warmer. By increasing of the temperature during their path, process of sintering is happening. The fuels are injected into a burner at the lower part of the kiln. Output of the kiln system is clinker (Van Oss and Padovani, 2002).
Some cement plants do not produce clinker and therefore do not have cement kiln. These plants are built only for milling and blending purposes and can produce various cement products. Table 5 shows number of cement plants (with or without kiln) in a few European countries.

**Table 5. Number of cement plants (with or without kiln) in a few European countries in 2008 (EIPPCB, 2010)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of cement plants with kilns</th>
<th>Number of cement plants without kilns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>Italy</td>
<td>59</td>
<td>35</td>
</tr>
<tr>
<td>Spain</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>France</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Poland</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Greece</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Austria</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Romania</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

**Types of cement**

Hydraulic properties of cement allow it to be used as the binding element in concretes and mortars used in construction. Cements can be divided into two types: inherently hydraulic cements and pozzolanic cements. The first type needs water to become active and the second type shows hydraulic cementitious properties when react with hydrated lime\(^4\) (USGS, 2005).

There are several formal categorization systems for defining standard cement types. Among them, the ASTM standard in the USA along with the European cement standard DIN EN 197-1 are widely used. Table 6 presents the summary of the cement categorization system according to DIN EN 197-1 European standard.

\(^4\) Ca(OH)\(_2\)
As it can be seen in Table 6, in the DIN EN 197-1 standard, five major types of cements are defined (CEM I to CEM V) and each of these types have a few sub-types, therefore there are 27 different cement types in total. The main distinguishing factor between these cement types is the materials used in their constituents. CEM I has the highest amount of clinker and is the typical Portland cement or OPC. Other types have lower clinker content and instead use materials that are generally called “clinker substitutes”. These materials have clinker-like properties and therefore can partially replace clinker in the final cement products. They are grinded and blended (mixed) in the required proportions in order to produce different types of cements. Examples of such materials are granulated blastfurnace slag (GBFS) from steel industry and fly ash from coal incineration.

All of the major cement types are produced in Europe, however CEM I and II are much more common. Table 7 shows the share of each cement types in European (EU-25) countries.
In the next section, raw materials used for cement production are explained in detail.

**Raw materials and fuels**

Cement production requires large amounts of energy (fuel and electricity) and raw materials. Here each of these main inputs are briefly introduced.

- **Raw materials**

  CEM I (the closest product to Portland cement) has the highest clinker content compared to the other cement types that use alternative materials to partially replace clinker in their composition. These materials are referred to as “clinker substitutes” and have clinker-like properties. They are grinded and blended (mixed) in the required proportions in order to produce different types of cements. Examples of such materials used as clinker substitutes are granulated blast furnace slag (GBFS) from the steel industry and ash from coal incineration. In the United States, the use of coal fly ash is increasing. It is normally mixed with Portland cement, replacing about 50% of the cement in concrete.

  In section 1.3.2 (see Error! Reference source not found.) it was mentioned that clinker consists of different types of oxides. Similarly, many of the materials used in cement production have different combinations of CaO, SiO$_2$, and Al$_2$O$_3$ as depicted in in Figure 5.
Figure 5. Chemical composition of clinker and other materials which can be used in cement (CSI, 2005)

Table 8 provides few examples of materials that can be used as raw material for clinker production or as clinker substitutes in the final blending.

Table 8. Raw materials group and few examples (VDZ, 2008; EIPPCB, 2010)

<table>
<thead>
<tr>
<th>Raw material group</th>
<th>Examples of materials</th>
<th>Raw material group</th>
<th>Examples of materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>Lime stone/marl/chalk</td>
<td>Si-Al-Si</td>
<td>Fe</td>
</tr>
<tr>
<td></td>
<td>Lime sludges from drinking water and sewage treatment</td>
<td>Si-Al-Ca</td>
<td>Aluminium hydroxide</td>
</tr>
<tr>
<td></td>
<td>Hydrated lime</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foam concrete granulates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calcium fluoride</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbid sludge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Used foundry sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si-Al</td>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bentonite/kaolinite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residues from coal pre-treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>Iron ore</td>
<td>S</td>
<td>Al</td>
</tr>
<tr>
<td></td>
<td>Roasted pyrate</td>
<td></td>
<td>Residues from the chemical or ceramic industries</td>
</tr>
<tr>
<td></td>
<td>Contaminated ore</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iron oxide/fly ash blend</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dusts from steel plants</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mill scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blast furnace and converted slag</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Synthetic hematite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Red mud</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• *Fuels*

The main energy intensive phases of cement production process occur inside the kiln and during the production of cement clinker. In order to create enough heat for the cement kiln and other parts of the process large amount of thermal energy is required which is typically generated by incineration of fuels. Fossil fuels such as coal and petroleum coke are typically used in Europe, but other fuels such as natural gas, oil, and different types of waste such as used tyres, spent solvents, waste oils, and plastics are widely used. These fuels are generally considered as “secondary fuels”\(^5\). Main sources of fuels and their shares in the European cement industry in 2006 are summarized in Table 9.

*Table 9. Fuel usage in European cement industry in 2006 (EIPPCB, 2010)*

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Usage share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petcoke (fossil)</td>
<td>39</td>
</tr>
<tr>
<td>Coal (fossil)</td>
<td>19</td>
</tr>
<tr>
<td>Petcoke and coal (fossil)</td>
<td>16</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>3</td>
</tr>
<tr>
<td>Lignite and other solid fuels (fossil)</td>
<td>5</td>
</tr>
<tr>
<td>Natural gas (fossil)</td>
<td>1</td>
</tr>
<tr>
<td>Waste fuels</td>
<td>18</td>
</tr>
</tbody>
</table>

As mentioned, different kinds of waste-derived fuels can be used as fuel in the cement manufacturing processes. These fuels are categorized in different groups as shown in Table 10. Groups 1 to 10 are considered as non-hazardous wastes and groups 11 to 13 are categorized as hazardous wastes (EIPPCB, 2010).

---

\(^5\) Refer to glossary.
In this section, basic concepts related to cement production were introduced. In the following section, a brief overview of CEMEX Company and its operations in Germany is presented.

### 1.3.3 Introduction to CEMEX

CEMEX was founded in 1906 in Mexico and since then has grown into a global manufacturer of construction materials operating in more than 50 countries in the world. It has about 46,000 employees worldwide. The summary of CEMEX global operations in year 2010 is presented in Table 11 (CEMEX, 2010).

**Table 10. Waste fuels categorization (EIPPCB, 2010)**

<table>
<thead>
<tr>
<th>Group</th>
<th>Type</th>
<th>Waste fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>Non-hazardous Wood, paper, cardboard</td>
</tr>
<tr>
<td>2</td>
<td>Textiles</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Plastics</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Processed fractions</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rubber/tires</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Industrial sludge</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Municipal sewage sludge</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Animal meals, fats</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Coal/carbon waste</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Agricultural waste</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Hazardous Solid waste (impregnated sawdust)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Solvents and related waste</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Oil and oily waste</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Others</td>
<td></td>
</tr>
</tbody>
</table>

**Table 11. Summary of CEMEX global operations (CEMEX, 2010)**

<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Cement production capacity (million tonnes/year)</th>
<th>Cement plants</th>
<th>Aggregates quarries</th>
<th>Sales (million USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>29.3</td>
<td>15</td>
<td>16</td>
<td>3,435</td>
</tr>
<tr>
<td>USA</td>
<td>17.2</td>
<td>13</td>
<td>83</td>
<td>2,491</td>
</tr>
<tr>
<td>Europé</td>
<td>25.7</td>
<td>19</td>
<td>247</td>
<td>4,793</td>
</tr>
<tr>
<td>South/Central America and Caribbean</td>
<td>12.8</td>
<td>11</td>
<td>17</td>
<td>1,444</td>
</tr>
<tr>
<td>Africa &amp; Middle East</td>
<td>5.4</td>
<td>1</td>
<td>9</td>
<td>1,035</td>
</tr>
<tr>
<td>Asia</td>
<td>5.7</td>
<td>3</td>
<td>4</td>
<td>515</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td>357</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96.1</strong></td>
<td><strong>62</strong></td>
<td><strong>376</strong></td>
<td><strong>14,069</strong></td>
</tr>
</tbody>
</table>
CEMEX produces different types of cement, ready-mix concrete\textsuperscript{6}, aggregates\textsuperscript{7}, and other construction materials. About 48\% of CEMEX global sales and 87\% of its earnings (before deduction of interests and taxes) are from cement products (CEMEX, 2010).

CEMEX is active in Germany and have few plants in this country. The operation of CEMEX in Germany is briefly introduced in section \textbf{Error! Reference source not found.}.

\begin{flushright}
\begin{tabular}{l}
\textsuperscript{6} Refer to glossary. \\
\textsuperscript{7} Refer to glossary.
\end{tabular}
\end{flushright}
2 THEORY

In the previous sections, an overview of cement industry and a brief introduction to cement production techniques were presented. In this part of the report, main theoretical concepts used in this thesis are introduced.

This research is performed in relation to a larger research project within the field of Industrial Ecology (as mentioned before). However, this relation has not been the only reason behind the selection of Industrial Ecology as the theoretical basis of this thesis. Industrial Ecology emphasizes on the following concepts:

1. Flows of material and energy: Studying the flows of material and energy from 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).
2. Integration: Industrial systems should be viewed in integration with their surrounding systems, not as isolated entities (Graedel and Allenby, 2003).
3. 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).

This thesis is concerned with improving CO₂ performance of cement production. The emission of CO₂ during cement production is related to the large flows of material and energy in the industrial process in which cement is produced. In order to create a framework that allows systematic selection and evaluation of improvement measures (one of the aims of this thesis), it is essential that the main inbound and outbound flows of material and energy to/from a cement production system are studied. The discipline of Industrial Ecology, emphasizes on the study of material and energy flows in industrial systems, promotes integrating industrial processes, and rejects the concept of “waste”. These principles create a foundation for developing the assessment framework in this study.

2.1 Industrial Ecology at different scopes

In this thesis, the term environmental management refers to the principles, views, or approaches regarding industrial activities that allow them to become more efficient, less harmful to the environment, or in general more sustainable. Various prevailing environmental management concepts exist and while they have different sets of priorities and areas of concern, many of them have overlapping domains with each other as well. Marinova (2006) and Van Berkel (2007a) provide an overview of these concepts and their standing point in relation to each other. Baas (2005) provides an alternative way of looking at various environmental management concepts. According to this author, “temporal scope” and “scope of environmental concerns” are main

---

8 Brief introduction to “Industrial Ecology” is available at Appendix.
differentiating factors among various environmental management concepts. Traditional preventive environmental approaches such as pollution prevention are principally focused on the “products’ manufacturing” and “use phase”, therefore have shorter spatial or temporal span of concern. On the other hand, approaches such as “life cycle design”, tend to consider wider scopes that includes all life cycle stages of a product from “extraction of raw material” to its “production”, “use phase”, and “disposal”. Industrial Ecology can be used to consider even wider scopes and may include environmental impacts from several products or manufacturers during all stages of their life cycle over several decades or longer temporal intervals. Figure 6 demonstrates the relation between few environmental management concepts from these perspectives.

**Figure 6. Environmental management concepts at different scopes (based on Baas (2005))**

However, why scopes are important? One reason is that in different scales (different scopes) there are certain aspects of the industrial system that can be studied and improved. By looking at plant level (smaller spatial scope), it is possible to concentrate on production efficiency and improve energy or electricity demand. If wider scopes of industrial activities (such as activities in the surrounding area) are considered, other solutions for improving environmental performance of the studied plant can be found. For instance, the possibility to use the wastes or byproducts of other nearby plants as feedstock or using the wastes or byproducts of the studied
plant as feedstock for other industrial systems. The same argument is true for having different temporal scopes. A short-term scope allows the identification and improvement in certain areas, while considering longer-term scopes creates further opportunity to explore other solutions as well as minimizing the risk of shifting an immediate problem into another problem in future.

The concept of Industrial Ecology is related to (and sometimes overlapping with) other environmental management approaches such as Cleaner Production and Eco-Efficiency (EE)⁹ (Ayres and Ayres, 1996). One of the important aspects of Industrial Ecology is its flexibility in studying systems with different layers or scopes. Industrial Ecology can be used in various scales. It can be applied in systems with small temporal or spatial scales (micro level), such as a single firm or facility. Here Industrial Ecology is closer to concepts such as “pollution prevention”. Industrial Ecology can also be applied in medium scales (meso level), such as study of the flow of material and energy in an industrial park where several firms are exchanging resources with each other. This approach of Industrial Ecology is called Industrial Symbiosis (IS)¹⁰. Industrial Symbiosis is a sub discipline within Industrial Ecology and promotes the study of exchanges between industrial (or other actors) which are located in a common geographical area. Industrial Ecology can also be used in wider scales (macro level) such as studying the flow of material and energy through a region (or nation). This approach of Industrial Ecology is called industrial metabolism (Chertow, 2000; Baas, 2005).

In this section, the multi-layered property of Industrial Ecology that allows it to be applied on different scales was introduced. Industrial Ecology (IE) provides a suitable foundation for the aim of this project that is to develop a framework for assessing various CO₂ improvement measures in the cement industry.

A brief introduction to Industrial Ecology and Industrial Symbiosis and their relation to other environmental management concepts are presented in the Appendix.

---

⁹ Brief introduction to “Cleaner Production” and “Eco-efficiency” is available at Appendix.
¹⁰ Brief introduction to “Industrial Symbiosis” is available at Appendix.
3 RESEARCH PROCESS AND METHODOLOGY

Although the actual research process of this thesis has been iterative, for improved readability and simplicity, the process is described linearly and sequentially. In general, this research uses a qualitative approach based on literature review (used for developing an assessment framework) and a case study (the developed framework is applied on this case).

The research has two main parts, which address its two aims. The first part of this research (chapter 4) deals with the development of an assessment framework for evaluating various CO₂ improvement measures from different aspects. This framework is built upon several theoretical concepts in the field of industrial environmental management with the primary focus on Industrial Ecology and Industrial Symbiosis. In order to develop this framework, a general study of the related literature on theories such as Industrial Ecology, Industrial Symbiosis, and cement production was performed (section 1.3.2 and section 2). The process of development of the framework is described later (chapter 4).

The second part of this thesis (chapter 5 and 6) deals with applying the developed framework on a given cement production system which in this case is the Cluster West. This part of the research is divided into the following two parts:

**Applying part I of the framework**: This is the generic part of the assessment (section 5), which is the study of CO₂ improvement measures in cement industry. Data for this part of the research is primarily collected from literature review.

**Applying part II of the framework**: This is the site-specific part of the assessment (section 6), which is applied on the Cluster West (Cluster West) cement production system. Data for this part of the research is gathered from various company sources such as the company’s annual reports, information received from the company, site visit, idea workshop with company’s experts and managers, and communication with company’s experts. In addition to the data received from company, the result of the Cluster West modeling during CEMEX project ((LIU, 2011)) was used in order to gain knowledge about the existing conditions of production system in Cluster West. The result of the assessment, allows the identification of the find the most feasible CO₂ improvement measures for Cluster West. These measures can be used as a basis for planning for improving measures in the future Cluster West cement production system.
4 DEVELOPING THE ASSESSMENT FRAMEWORK

In this chapter, the process of developing the framework is explained in the following order:

- The overall view of the framework is introduced in order to make it easier for the reader to go through the steps.
- Individual elements (steps) of the framework are explained.

4.1 The overall view of the assessment framework

For more clarity, the process of developing the assessment framework is explained as if the framework is already developed (i.e. overview of the developed framework is presented and the process of developing each step is explained).

The overview of the developed framework for assessing improvement measures for CO₂ emission reduction in cement industry are presented in Figure 7.

![Diagram of the assessment framework](image)

**Figure 7. Assessment framework for evaluation of CO₂ 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\textsuperscript{11} 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.

In the first steps, theoretical information is gathered which are generic in nature. In the next steps, site-specific attributes are added to the y.

In the following sections, the process of development of each of these steps of the framework is explained.

4.2 Developing “Step 1: Collection”

In this step, wide range of CO\textsubscript{2} 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 (chapter 2) can serve as the guidelines. Therefore, by considering a cement production system and the mentioned principles, the following issues are important:

1. Study of all major streams of material and energy related to a cement production plant.
2. The relationship and integration between the cement production plant and its related streams with the surrounding systems.
3. All material or energy waste streams viewed as potentially useful raw materials for other industrial processes.

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 (Figure 8).

\footnotesize{\textsuperscript{11} 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 following major streams are recognizable in any typical cement production plant: feedstocks (material), fuels (energy and material), electricity (energy), products (material), CO₂ that is produced due to incineration of fuels and the calcination process (material), the excess of the heat generated during fuel incineration (energy), and other streams in terms of emissions, wastes, or byproducts, which can be categorized under “other by-products”. In addition, there are actual or potential means to use the excess streams in other industrial processes, either by closing the loops (reuse, recycling) or by integrating cement production with another industrial processes (Figure 8).

The streams identified in this simplified model of cement production can be used as guidelines for the literature survey. Ideas which are directly or indirectly (but meaningfully) related to any of these elements must be collected and compiled in this survey. For instance, publications that address topics such as “cement production” and “CO₂ emission reduction” (or their equivalent alternative terms) must be considered.

As the focal concern of this research is on “CO₂ 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$_2$ 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.

Therefore, the simplified cement production plant depicted in Figure 8 is a good basis that facilitates the identification of the relevant ideas regarding “improving CO$_2$ performance” of cement production.

The result of survey must be collected 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.

### 4.3 Developing “Step 2: Classification”

This classification step is based on the list of improvement measures that was compiled in the first step of the assessment framework (described in section 4.2). 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$_2$ emission reduction from cement production process can be categorized into several main classes and sub-classes. 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 classes of solutions.

Figure 9 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 that was described before (Figure 8). Any strategy for improving CO$_2$ 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$_2$ or excess heat through innovative synergistic solutions (external synergies).
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. Each category of measures should at least include:

- **Name**: name of each category or sub-category of improvement measures.
- **Short code**: A short form of the name for easier references in diagrams where there is not enough space for long labels.
- **Summary**: A descriptive text, which explains detailed information about the ideas and measures that are included in that category or sub-category. The summery should be relatively concise and mention the related references.

Once the categorization scheme is completed, the next steps of the assessment framework (steps 3, 4, and 5) will evaluate different aspects of each category of measures.
4.4 Developing “Step 3: CO₂ improvement evaluation”

In this step of the framework, each category of measures should be analyzed in order to evaluate its CO₂ 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 CO₂ emissions from cement production. For this purpose, the qualitative scale presented in Table 12 can be used.

Table 12. Qualitative scale for CO₂ emission reduction potential

<table>
<thead>
<tr>
<th>Level</th>
<th>CO₂ emission reduction potential</th>
<th>Estimated theoretical CO₂ emission reduction potential (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>The measure can not effectively improve CO₂ emissions from any of the above sources, but has practically significant improvement impacts on at least one of them.</td>
<td>less than 20%</td>
</tr>
<tr>
<td>Medium</td>
<td>The measure can effectively improve CO₂ emissions from at least one of the above sources.</td>
<td>between 20% to 50%</td>
</tr>
<tr>
<td>High</td>
<td>The measure can effectively improve CO₂ emissions from two or more of the above sources.</td>
<td>More than 50%</td>
</tr>
</tbody>
</table>

For qualitative evaluation of the CO₂ emission reduction potential for each measure, it is essential to consider which CO₂ emitting source it is addressing. If the measure effectively addresses several or all sources of CO₂ emissions, it would be considered as high potential. Effective measures can improve CO₂ emissions due to cement production by having one or more of the following aims:

(1) **Reducing or avoiding CO₂ emissions due to calcination process (during clinker production):** 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. As long as clinker is produced, the production of calcination CO₂ is inevitable. Therefore, CO₂ emission reduction measures that do not address this issue are limited to theoretical maximum of at most about 50%.

(2) **Reducing or avoiding CO₂ emissions due to incineration of fuels (mainly during clinker production):** As also mentioned before, another major source of CO₂ emissions during clinker production is “fuel incineration” which occurs in the kiln system. Therefore, measures that can address CO₂ emissions due to fuel incineration can have relatively high potentials 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 have fossil origin...
and are from non-biogenic sources, their production and consumption emits 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 (2) and (3) is that in (2) CO2 emissions from fuel is addressed (after the CO2 is released from incineration) but in (3) less fuel is required and therefore less CO2 is emitted.

(4) Reducing or avoiding CO2 emissions elsewhere (causing another CO2 emitting process to use less energy, or to use less CO2 emitting energy): If a measure can cause less incineration of fossil fuels “somewhere else”, then the CO2 emissions saved by that avoidance is allocated to the cement production system. Depending on the extent that a certain measure can cause “avoidance of CO2 emissions”, the CO2 emission reduction potential of that measure can be low, medium, or even high. 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.

The next step of the framework establishes a method for evaluating the generic feasibility of CO2 improvement measures.

4.5 Developing “Step 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) complexity of a business approach required for development of that measure and (2) its technological maturity level.

4.5.1 Complexity of business approach

This aspect assesses the level of complexity that a business has to deal with in order to implement a given measure. By referring to the main improvement strategies that were defined based on the simplified cement production model (Figure 9), some of the differences in the required level of complexity can be described. For instance, measures that fall into category of “production efficiency” are mainly focused on the internal state of the plant and therefore their implementation require less complexity in business approach (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 complex business approaches (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 10.
In this framework, the concept of “complexity of business approach” 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. Chertow (2000) identifies several types of Industrial Symbiosis exchanges, which are summarized in Table 13.

Table 13. Various types of Industrial Symbiosis
Based on the work by Chertow (2000)

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Description</th>
<th>IS scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No waste exchange</td>
<td>Use virgin materials via traditional supply chain.</td>
<td>Facility (no IS)</td>
</tr>
<tr>
<td>1</td>
<td>Through waste exchange</td>
<td>One-way relations happening at the end-of-life stages; trade-by-trade basis and not performed consciously.</td>
<td>Facility (no IS)</td>
</tr>
<tr>
<td>2</td>
<td>Inside a facility or firm</td>
<td>Exchanges happening inside large organizations.</td>
<td>Corporation</td>
</tr>
<tr>
<td>3</td>
<td>Between co-located firms in an eco-industrial park</td>
<td>Exchanges between several firms or organizations that are located inside the borders of a defined industrial park or with “over the fence” partners.</td>
<td>Industrial park</td>
</tr>
<tr>
<td>4</td>
<td>Between not colocated local firms</td>
<td>Between firms located within an area, not particularly inside a well-defined industrial park, but with relative geographical nearness.</td>
<td>Area</td>
</tr>
<tr>
<td>5</td>
<td>Between firms, virtually organized across a wider region</td>
<td>Synergistic collaborations beyond colocated or local firms and expanded to include regional economic actors. Wider options for by-product exchange and possible formation of virtual networks of diverse types of industries.</td>
<td>Region</td>
</tr>
</tbody>
</table>
If a measure is fully managed and controlled by a single actor then it requires business approaches with relatively low complexity. On the contrary, if it can only be planned and managed by incorporating several actors that are spread across a relatively wide geographic area, then the complexity of business approach required for such arrangement is higher. By considering different types of Industrial Symbiosis (Table 13), a qualitative scale for evaluating complexity of business approaches for each category of measures is defined as described in Table 14.

**Table 14. Qualitative scale for evaluating the complexity of business approaches required by various CO₂ emission reduction measures**

<table>
<thead>
<tr>
<th>Level</th>
<th>Complexity of business approach</th>
<th>Spatial scope</th>
<th>Temporal scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Industrial symbiosis type 0 (no IS), type 1 (no IS), and type 2 (inside a facility or corporation)</td>
<td>Micro level</td>
<td>Short term</td>
</tr>
<tr>
<td>Medium</td>
<td>Industrial symbiosis type 3 (industrial park, local)</td>
<td>Meso level</td>
<td>Medium term</td>
</tr>
<tr>
<td>High</td>
<td>Industrial symbiosis type 4 (area), and type 5 (region)</td>
<td>Meso to macro level</td>
<td>Medium to long term</td>
</tr>
</tbody>
</table>

Measures involving no or low Industrial Symbiosis activities do not require complex business approaches regarding their material or energy exchanges with other local or regional actors. The complexity of business approach increases when higher degrees of Industrial Symbiosis activities are involved.

### 4.5.2 Technological maturity

Another factor that can influence generic feasibility of a CO₂ emission reduction measure is the maturity level of the technologies that are required for its effective implementation. Traditional, widely used, and tested technologies are considered to have high technological maturity, while new and unverified measures have low technological maturity. Table 15 defines a qualitative scale for describing technological maturity of different measures.

**Table 15. Qualitative scale for evaluating the technological maturity of CO₂ emission reduction measures**

<table>
<thead>
<tr>
<th>Level</th>
<th>Technological maturity level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Early development</td>
<td>The measure is in early research and development stage.</td>
</tr>
<tr>
<td>Medium</td>
<td>Emerging practice</td>
<td>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.</td>
</tr>
<tr>
<td>High</td>
<td>Established practice</td>
<td>Applied in cement industry in several places under various conditions.</td>
</tr>
</tbody>
</table>
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.

Once the generic feasibility of measures is evaluated, the first part of the assessment is completed. The second part of the assessment deals with a specific cement production system and evaluates the specific feasibility of improvement measures for that site (Figure 7). This site-specific feasibility evaluation is the aim of the next step of the assessment framework.

4.6 Developing “Step 5: Feasibility evaluation (site-specific)”

In the previous sections the development of the first part of the framework (steps 1 to 4) was explained. Now the development of the second part of the framework is explained (Figure 7).

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). For simplicity, the cement production system to be studied is referred to as “The Site” in this framework. The site-specific feasibility of various improvement measures for “The Site” 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.

4.6.1 Technical and infrastructural applicability

Not every measure is suitable or applicable to every site, even if it demonstrates high potentials for CO₂ emission reduction (section 4.4) or is based on a mature technology (section 4.5.2). Every site has certain technical, infrastructural, or geographical constraints, which influence the applicability of various improvement measures.

An example of technological conditions that can affect the applicability of certain measures is a cement production plant that is located far from other residential or industrial areas and there is no district heating network available in the region. For such a cement production system, a measure such as “providing excess heat of the plant to nearby residential or industrial areas” may not be applicable, because the required infrastructure for its implementation is not available.

An example of geographical constraints that can affect the applicability of certain measures is a CO₂ emission reduction measure that requires large area of free land near a cement producing plant; however, the area around the plant is not free or available. In this situation, that measure is not applicable due to geographical conditions.

The qualitative scale for evaluation of technical and infrastructural applicability of various measures for a given site (“The Site”) is defined in Table 16.
Table 16. Qualitative scale for evaluating the technical applicability of CO$_2$ emission reduction measures according to the conditions of the site under study

<table>
<thead>
<tr>
<th>Level</th>
<th>Technical and infrastructural applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>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.</td>
</tr>
<tr>
<td>Medium</td>
<td>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.</td>
</tr>
<tr>
<td>High</td>
<td>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.</td>
</tr>
</tbody>
</table>

Measures that are compatible with the existing technical, infrastructural, or geographic conditions of “The Site” have high level of applicability.

### 4.6.2 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 site (“The Site”) is defined in Table 17:
Table 17. Qualitative scale for evaluating the organizational applicability of $\text{CO}_2$ emission reduction measures according to the conditions of the site under study

<table>
<thead>
<tr>
<th>Level</th>
<th>Organizational applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>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.</td>
</tr>
<tr>
<td>Medium</td>
<td>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.</td>
</tr>
<tr>
<td>High</td>
<td>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.</td>
</tr>
</tbody>
</table>

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)

4.6.3 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 (The Site), 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 18):

Table 18. Qualitative scale for evaluating the existing level of implementation of CO₂ emission reduction measures in a given site

<table>
<thead>
<tr>
<th>Level</th>
<th>Existing level of implementation</th>
</tr>
</thead>
</table>
| 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.

4.7 Developing “Step 6: Results and analysis”

This section describes the final step of the assessment framework. 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.

For easier analysis of the information gathered in the assessment, a simple software tool has been developed which allows simple visualization of different aspects of improvement measures in the context of specific cement production. Various aspects of the data gathered in the framework, it is possible to discuss issues such as:

- **Suitable candidates for implementation**: Which technologically mature, high potential CO₂ improvement measures have high technical and organizational applicability and low level of implementation?
- **Research candidates**: Which high potential CO₂ 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 CO₂ 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.
5 APPLYING THE ASSESSMENT FRAMEWORK - PART I: GENERIC STUDY

In the first part of this research (section 4) an assessment framework for evaluating various CO\textsubscript{2} improvement measures for cement production was developed. In this stage of the research, this first part of this assessment framework is applied (the generic part of the assessment) in order to identify and categorize the existing and emerging CO\textsubscript{2} improvement measures in cement industry.

5.1 Step 1: Collection

This step follows the aims developed in section 4.2 which is to “to collect, wide range of CO\textsubscript{2} improvement measures in cement industry, and compile them into a gross list of ideas based on literature survey of various academic, organizations, or industrial sources”. The literature review is performed, considering all types of CO\textsubscript{2} improvement measures, however the emphasis is on the “system level” improvement measures. Therefore, although all of the “process-level” improvement ideas are studied, they are not included in the result of the survey as individual measures. These types of “micro-improvement” measures were often merged into a group of measures and only the most important ones were added to the gross list of ideas. Details of these micro-improvement ideas are presented in many studies such as US EPA (2010), EIPPCB (2010), Price et al. (2010), E. Worrel et al. (Worrell et al., 2000, 2008), and Martin et al. (1999).

The summary of the literature review performed in this step is presented as a gross list of improvement ideas in the Appendix.

5.2 Step 2: Classification

As defined in section 4.3, the aim of this step of the assessment framework is to develop a categorization scheme for classifying different improvement measures in the cement industry. In section 4.3, the main improvement strategies in cement production were identified (Figure 9). It is time to explore each of these strategies and define them in terms of relevant categories and sub-categories. The result is a categorization scheme for classifying various improvement measures and allowing further systematic evaluation of measures in the next steps of the assessment. Table 19 shows the result of applying this step of framework that is the categorization scheme of various improvement approaches in the cement production.
Table 19. Categorization scheme for CO₂ improvement measures in cement production

<table>
<thead>
<tr>
<th>Short Code</th>
<th>CO₂ emission reduction strategy or measure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E</strong></td>
<td><strong>Production efficiency</strong></td>
</tr>
<tr>
<td>EE</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>EEH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>ERE</td>
<td>Co-generation (heat &amp; electricity)</td>
</tr>
<tr>
<td>ERR</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td><strong>I</strong></td>
<td><strong>Input substitution</strong></td>
</tr>
<tr>
<td>IF</td>
<td>Feedstock change</td>
</tr>
<tr>
<td>IFC</td>
<td>Low temperature clinker production</td>
</tr>
<tr>
<td>IFM</td>
<td>Alternative materials (for clinker production)</td>
</tr>
<tr>
<td>IE</td>
<td>Input energy change</td>
</tr>
<tr>
<td>IEF</td>
<td>Fuel diversification (alternative/secondary fuels)</td>
</tr>
<tr>
<td>IER</td>
<td>Renewable energy (fuel and electricity)</td>
</tr>
<tr>
<td><strong>P</strong></td>
<td><strong>Product development</strong></td>
</tr>
<tr>
<td>PP</td>
<td>Improve existing products</td>
</tr>
<tr>
<td>PPC</td>
<td>Clinker substitution (alternative materials)</td>
</tr>
<tr>
<td>PPB</td>
<td>Improve blended cements’ properties</td>
</tr>
<tr>
<td>PN</td>
<td>Develop new products</td>
</tr>
<tr>
<td>PNC</td>
<td>Clinkerless/no-calcine cement</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td><strong>External synergies</strong></td>
</tr>
<tr>
<td>SE</td>
<td>CO₂ and heat solutions</td>
</tr>
<tr>
<td>SEC</td>
<td>Carbon sequestration/carbon capture and storage</td>
</tr>
<tr>
<td>SEB</td>
<td>Biological production</td>
</tr>
<tr>
<td>SEH</td>
<td>Synergistic heating</td>
</tr>
<tr>
<td>SI</td>
<td>Process integration and industry initiatives</td>
</tr>
<tr>
<td>SIP</td>
<td>Integration with power plant</td>
</tr>
<tr>
<td>SIW</td>
<td>Integration/co-location with waste treatment</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
</tr>
<tr>
<td><strong>M</strong></td>
<td><strong>Management</strong></td>
</tr>
<tr>
<td>MB</td>
<td>Environmental strategy and innovation approaches</td>
</tr>
<tr>
<td>MM</td>
<td>Marketing, education, and public relations</td>
</tr>
<tr>
<td>MS</td>
<td>Standards and specifications</td>
</tr>
</tbody>
</table>

These categories and sub-categories are based on the gross list of ideas that were collected in the first step of the assessment (section 5.1). Overall, various CO₂ emission reduction measures can
be classified by this categorization scheme. Here each of these approaches is introduced and few examples of their implementation (if any) are presented.

5.2.1 Production efficiency

“Production efficiency” are the collection of measures, which are applied within the scope of the plant (applied internally) in order to improve the efficiency of individual processes or the overall plant. All of these measures are happening at process-level (or sub-plant) or plant-level. Solutions beyond the scope of the plant and having external focus (either in input or output side) are not considered in this category.

In this categorization scheme, production efficiency measures are divided into three categories: (1) energy efficiency, (2) resource recovery, and (3) pollution prevention and control.

Energy efficiency

“Energy efficiency” are process-level measures that aim to reduce the energy consumption of individual processes. These measures seek improvement by focusing on individual set of equipments or processes. They are divided into two main groups: measures to improve electrical efficiency and measures to improve thermal efficiency.

- **Electrical efficiency**

Considerable amount of electricity is used in a cement plant. Various equipments in different stages of cement production are electrically operated. For instance, motors for kiln rotary system, various cooling fans, equipments for crushing, grinding and preparation of raw meal, final milling and blending, compressors as well as internal transport systems are all operated by electricity. Reducing electricity consumption of these devices leads to total reduction of energy intensity (i.e. the fuel or electricity consumption per unit of output product) of cement production.

Several studies have highlighted various potentials for improving electrical efficiency of cement production inside the plant. Here only few examples of the main improvement measures that can lead to higher electrical efficiency in sub-plant level are presented:

- **Use adjustable speed drives (ASD):** In cement plant, motor drives are among the major consumers of electricity. Most electrical motors are fixed-speed alternative current (AC), however motors are rarely required to operate at full speed. Therefore having a system for flexible adjustment of the motor speed depending on the load demand can save electricity. ASD’s can be used for kiln fans, preheater and cooler, mills and separator and other motor drives.

- **Use high efficiency motors:** There are about 500 to 700 electric motors in a typical cement plant (Worrell et al., 2008) and depending on the status of these motor, this measure can lead to 3 - 8% improvement in electricity consumption (Van der Vleuten, 1994).
- **More efficient mills**: In the final grinding stage, replace ball mills older than 10 years with vertical roller mill. If the ball mill is less than 10 years old, add a high-pressure roller press as pre-grinding to ball mill.

The type and quality of the instruments used is only one of the aspects of having less electricity consumption. Process control and the sequence of performing milling and grinding can also influence the efficiency of sub-systems. For instance, it is more efficient to grind GBFS and clinker separately and then mix them together using a roller mill (Liu and Li, 2009).

More detailed information about electricity improvement measures inside the plant, is available in the works by Price et al. (2010), Worrel et al. (2008) and US EPA (2010).

- **Thermal efficiency**

Almost all of the fuel consumed by a cement manufacturing plant is used in the kiln system and during the production of clinker. Therefore improving the thermal efficiency of the kiln system can have great impact on the overall energy intensity and consequently CO₂ emissions attributed to cement production. Here only process-level (sub-plant) measures are considered and solutions such as electricity or heat recovery are discussed in another category.

The main thermal efficiency point of concern is the kiln system and therefore improving the kiln insulation and decreasing heat loss from kiln shell is considered as a potential thermal efficiency improvement measure. This can be achieved by improving the refractories or adding an external thermal insulation layer to the kiln. Improving kiln insulation by adding a secondary kiln shell can lead to about 10 to 12% of total input energy saving.

It is also possible to save energy by improving the kiln system itself. For instance, by adding more pre-heating stages or adding a pre-calciner the clinker production becomes more efficient and can lead to about 5% improvement in fuel requirement (Locher, 2006). Improving the burning efficiency of fuels inside the kiln also improves the thermal efficiency of the kiln. An example is oxygen enrichment that improves the combustion efficiency by injecting certain amount of oxygen into the kiln (Frank, 2009).

There are newer technologies regarding cement kiln systems that are emerging. These technologies can be considered when planning to build new cement plants. One promising example is the “fluidised bed cement manufacturing technique” which uses a suspension preheater (a conventional four-stage cyclone preheater) for preheating and calcining the raw meal. This system has two kilns: first, the calcined meal is converted into granules in granulating kiln (at temperature of 1300°C) and second is sintered thoroughly in the sintering kiln (at temperature of 1400°C). The hot cement clinker is quickly cooled in fluidised bed quenching cooler from 1400 to 1000 degC and finally cooled down to 100°C in a packed bed cooler. Some studies have shown that in a 3000 tonne/day plant this system can reduce thermal energy demand of the plant by 10-12% and the clinker quality and the construction cost is also lower than a typical plant (EIPPCB, 2010).
**Resource recovery**

“Resource recovery” are plant-wide measures that tend to improve the resource (energy and material) efficiency of the overall plant and therefore create positive impact on the overall CO₂ emissions attributed to plant activities.

- **Pre-heating/drying**

Considerable amount of heat is going out from clinker cooler and later from the final exhaust with temperatures as high as 200-400°C. Approximately 40% of total kiln energy input is going out from the “kiln exhaust”, “cooler exhaust” and “the combined convective and radiative heat transfer from kiln surfaces” (Kabir, 2010). One way to utilize part of the exhaust gas thermal energy is to use it for drying or pre-heating the raw material or fuels, which are fed into the plant (Engin and Ari, 2005; Al-Hinti et al., 2008).

If input materials (feedstock or fuels) have high moisture content, it is often more economical to use the waste heat to pre-heat and dry the input materials/fuels compared to converting it to electricity.

- **Co-generation (heat & electricity)**

Depending on the type of the kiln system, various exhaust streams may exist in a typical cement plant: kiln exhaust, clinker cooler, kiln preheater, & precalciner exhaust, and kiln surface. Another approach for improving the overall energy efficiency of the plant is to use part of the excess (waste) heat of these streams in order to produce electricity.

Electricity production from low temperature heat sources can be achieved by steam cycle or by organic rankine cycle (ORC) or its variations. In either method, the working fluid which is under pressure is heated and vaporized by the heat source (i.e. hot exhaust gases) inside the heat recovery boiler or heater and is expanded and depressurized through a turbine driving a generator. The total electricity produced can vary between 7-20 KWh/tonne cement (ECRA, 2009). By utilizing this form of co-generation it is possible to meet 25-30% of the plant total electrical demand (Khurana et al., 2002; PCA, 2008).

Various technologies exist for producing electricity from low temperature heat sources by using Waste Heat Recovery Steam Generator in a combined cycle (WHRSG), Organic Rankine Cycle (ORC) (Legmann, 2002), Kalina cycle (Kalina and Leibowitz, 1989; Mirolli, 2005; Wang et al., 2009; Kalina, 2010), cryogenic power generation cycle (Qiang et al., 2004; Wei-ping, 2007), and theremo-electric (TE) solid state heat engines (Hendricks and Choate, 2006; Bell, 2008). The performance and the degree of technological maturity of these techniques are not equal and some (such as TE solid-state heat engines) are still far from becoming commercially available for large-scale industrial applications.

- **Waste heat recovery steam generator (WHRSG):** According to Khurana et al. (2002), a cogeneration system utilizing a Waste Heat Recovery Steam Generator (WHRSG), can produce about 30% of the plant electricity requirement and improve the primary energy
efficiency of the plant by 10% with a payback time of 2 years. In addition, a study by Engin & Ari (2005) on another cement plant demonstrated that utilization of such a conventional WHRSG could save about 4% of total input energy with a payback time of 1.5 years.

- **Organic rankine cycle (ORC):** In a study by Legmann (2002), the low-heat electricity generation by utilizing an organic rankine cycle was investigated. By converting 18% of the plant cooler exhaust gas waste heat into electricity, 29% CO₂ reduction (due to saving electricity) was achieved.

According to a study by Moya et al. (2011) the cost of adding WHR to an existing typical cement production plant in EU will not exceed 10 million euros and it saves between 0.45 to 1.38 million euros per year.

- **Recycle/reuse**

Aside from gaseous emissions, there is not much wastes produced in a cement manufacturing plant. However, utilizing the collected wastes in form of reuse or recycling can improve the resource efficiency of the plant.

Most of the solid wastes produced in cement plant are in form of cement bypass dust (CBPD) or cement kiln dust (CKD), refractory wastes (spent refractories), and other materials absorbed by exhaust air pollution control devices and other filters. CKD is produced during the production of clinker and is mainly in form of partially calcined raw feed, clinker dust, ash, alkali sulfates, and other volatile compounds. It is collected in control devices such as electrostatic precipitators or cyclones. Application of CKD can vary depending on its composition, which is in turn related to the plant conditions and feed types. Normally, large part of CKD can be recycled back into the production process as kiln raw feed or directly be reused. It is also possible to reuse the previously landfilled CKD as raw material for clinker production, which decreases the demand for limestone (Adaska and Taubert, 2008).

For insulation and protection of cement rotary kilns, mainly magnesia-spinel (MgO-MgAl2O4) refractories are used (Shikano, 1998). In certain cases spend refractories can be used as secondary raw material for clinker raw meal production (Fang et al., 1999; CEMEX-DE, 2010a).

**Pollution control and prevention**

This is the collection of plant level measures in order to control and secure emission of banned or unwanted material into air, land, or water. List of various pollution control mechanisms for cement production is available at INECE (2011).

This category is only for plant level (internal) measures, therefore more complex or synergistic solutions such as carbon capture and storage (CCS) are filed under another category.
5.2.2 Input substitution

There are two forms of inputs into a cement production plant. Energy, which is in the form of fuel used for providing heat for the pyroprocessing process in the kiln and electricity for crushing, grinding, milling, blending and other applications. Raw materials (feedstock) such as limestone and clay (BGS, 2005) are required for the production of clinker. Since cement production requires large amounts of fuel, electricity and raw materials and production and usage of these resources are accompanied with greenhouse emissions, substituting these inputs with the other suitable alternatives can be an effective measure to reduce the amount of emitted greenhouse gases from cement production.

In this categorization scheme, the group called “input substitution” mainly referred to substitution of inputs for clinker production and other strategies such as substituting clinker with alternative materials are classified under another category (discussed in section “Clinker substitution”).

Feedstock change

As explained in the background section of this report, clinker can be created from various types of materials, if those materials have the essential ingredients necessary for clinker formation. Figure 11 provides a general overview of the composition of materials and fuel ashes that are used in clinker production (EIPPCB, 2010).

Figure 11. CaO, SiO₂ and Al₂O₃+Fe₂O₃ diagram for cement clinker and the ash constituents of different raw materials and fuels
In order to produce clinker with proper composition, careful selection of materials and fuel ashes containing different amounts of CaO, SiO$_2$, or Al$_2$O$_3$+Fe$_2$O$_3$ are required (ibid.).

- **Low temperature clinker production**

  Clinker production is the most energy intensive part of cement manufacturing. As mentioned before, the feedstock are calcined in temperature about 900°C, and sintered at temperatures between 1350 to 1500°C. If clinker can form (sinter) at lower temperatures, less fuel energy would be required. For a modern kiln with cyclone preheater and precalcination, it is estimated that reducing the sintering temperature by 200°C would save 5% of fuel energy (Locher, 2006).

  By producing new types of clinker and/or modifying the composition of input raw materials to increase their combustion properties, it might be possible to decrease the temperature requirement for clinkerization and save fuel energy. For instance, it has been demonstrated that by applying combustion synthesis techniques, the temperature requirement for clinker production can be decreased to about 1200°C (Zapata and Bosch, 2009).

  One example of using special feedstock to decrease the clinker formation temperature is to use spent-pot-lining (SPL) from aluminum industry as coal fuel admixture. Electrolytic production of aluminum is performed in large smelter vessels with carbon-lined pots. The carbon lining acts as cathode and can be used for about 2 to 6 years. After this period, large amount of SPL, which is considered a toxic waste, is produced with about 50% carbon content (Pong et al., 2000). By properly crushing SPL and mixing it with coal/coke, it is possible to form clinker at approximately 80°C lower temperature (Mikša et al., 2003; Venancio et al., 2010). This technique is already in use in some plants (MES, 2007). Other benefits of such addition will be discussed in the following sub-sections.

- **Alternative materials (for clinker production)**

  Another measure for improving the CO$_2$ emissions of cement production is to use less CO$_2$ emitting alternative materials (secondary materials) for the production of clinker. These measures may be primarily in the form of feedstock diversification, which means using wider array of materials as feedstock along with traditional materials such as limestone, clay, and shale. Feedstock diversification allows materialization of the potential benefits of using various materials while maintaining the economic benefits of continuing usage of cheap, available traditional sources from nearby quarries (CEMEX-DE, 2010a).

  It is important to notice that clinker substitute materials are not considered in this category. Usage of materials such as granulated blastfurnace slag (GBFS) is classified under another category called “Improve existing products; clinker substitution”. Here only the secondary materials that can replace raw material for clinker production are considered (and it is assumed that clinker production is relatively unchanged in this group of measures).

  - **Recycle/reuse concrete crusher sand**: Although the crushed concrete can be reused as aggregate for the production of new concrete, the concrete crusher sand cannot be used for such purpose. The chemical compositions of concrete crusher sands are close to
natural sand and therefore they can replace the required sand for cement clinker manufacture. On average, they can be used to replace about 3% of a typical raw material mix (Schneider et al., 2011).

- **Incineration ash residues**: Incineration residues (bottom and fly ash) from municipal solid waste (MSW) from municipal solid waste incinerators (MSWI) or sewage sludge incineration can be used as secondary material for clinker production (Lam et al., 2010). By adding small amounts of iron oxide and silica, about 44% of such ashes can be used to produce cement clinkers. This process requires less CaCO3 (approximately 50%) compared to conventional process (more than 70%) (Saikia et al., 2007).

**Input energy change**

Cement production is an energy intensive process, therefore aside from reducing the energy intensity of products, changing and improving the portfolio of energy sources (fuel or electricity) can be an effective measure for reducing emissions of CO2 and other greenhouse gases. It is important to remember that these strategies cannot affect about 50% of CO2 emissions attributed to clinker production, which is emitted during chemical process of calcination. However, these strategies can affect the CO2 emissions due to fuel incineration, which depending on fuel source can be as high as 40-50% of CO2 emissions attributed to cement industry (Oates, 1998).

- **Fuel diversification (alternative/secondary fuels)**

Replacing fossil fuels with various alternative fuels may not only prove to be economical, but also may be effective in reducing the CO2 emissions accounted to cement production. Many of the alternative fuels are originated from wastes and therefore the CO2 emissions related to their production are allocated to their producer upstream the cement production value chain. Having wider and richer array of available fuels for burning in cement kiln decreases the dependency of the production to single or few fuel types and unexpected fluctuations in their availability or price (GTZ-Holcim, 2006; Murray and Price, 2008).

Net carbon reduction or energy savings due to usage of waste fuels or waste-derived fuels depend on the carbon content of such fuels as well as the alternative usage of the wastes (conversion efficiency of those alternatives, for instance incineration with or without heat recovery).

The typical alternative fuels in cement industry have been tyres (including tired-derived fuels), animal residues, solid and liquid spent solvents, filter cake, carpet and plastic wastes, paint residue, dried (dewatered) sewage sludge or even hazardous wastes (Worrell et al., 2008; Schneider et al., 2011). High temperature of kiln system along with effective dust filters allows effective method for disposal of organic hazardous wastes (Reijnders, 2007; Worrell et al., 2008).

Using alternative fuels is a relatively established practice in the cement industry, and the range of their usage and applications is increasing. Here an example of newer ideas related to the use of alternative fuels is presented.
Fly ash from the gasification of biomass (FABG): One of the main limiting factors in large-scale biomass gasification plants is the quality of the fly ash. Fly ash from the gasification of biomass (FABG) is not similar to conventional fly ash, because its mass contains between 10-60% unburned carbons. Additionally FABG contains polyaromatic hydrocarbons (PAHs) compounds and if the source of biomass is waste, heavy metals and chlorine can be present. If the carbon content of FABG could be converted to energy (or used in other applications), the overall efficiency of the gasification plant would improve. Gómez-Barea et al. (2009) have highlighted the possibility of using untreated FABG as cement kiln fuel (injected at main burner), especially in plants which are equipped with “chlorine by-pass” system, which allows higher chlorine content in their fuel mix feed.

Renewable energy (fuel and electricity)

While fuel diversification measures can be useful from economic or corporate sustainability perspectives, these strategies will not necessarily lead to less CO₂ emissions from cement production. This is because many of these “alternative fuels” have non-renewable origins and may not be considered as carbon-neutral. Using alternative fuels with higher renewable or carbon neutral fractions (such as fuels produced from biogenic origins) is therefore an effective way of reducing CO₂ emissions from clinker (and therefore cement) manufacturing.

The CO₂ emitted from alternative fuels is generally from two sources: (1) CO₂ emitted due to the production of fuels, and (2) CO₂ emitted due to their incineration.

Regarding CO₂ emissions due to the production of fuels, the allocation of CO₂ between cement manufacturer and the producer of waste is typically straightforward: the burden of waste is going to the producer of the waste and the cement producer accepts only the CO₂ burden due to processes that are required for upgrading the waste (producing waste-derived fuels). Therefore, depending on how CO₂ due to production of waste-derived fuels is allocated, the attributed CO₂ to cement production can vary considerably.

Regarding the CO₂ from incineration of fuels, in almost all cases, the burden of CO₂ is assigned to the cement manufacturer. However, if the fuels are from renewable sources (such as many biogenic fuels), part of the emitted CO₂ will be neutralized by the CO₂ absorbed during the production of those fuels and therefore can be deducted from total emitted CO₂ during incineration phase.

The same concept for using renewable or carbon-neutral fuels applies to the electricity or heat well. By using renewable sources of heat or electricity, the net CO₂ emissions from cement manufacturing can be reduced. An example of using renewable source of heat for cement production is using solar energy for the calcination process:

Calcination in solar reactor: Calcination reaction (CaCO₃ → CaO + CO₂) requires temperatures about 900°C and is traditionally performed inside the kiln system heated by fuel incineration. However, it may be possible to perform the calcination separately by solar rotary kiln reactor heated by concentrated solar energy (Meier et al., 2004, 2006).
5.2.3 Product development

Typically, the core business of cement production is to produce various cement-based products. Therefore, a range of CO2 improve measures are related to improving the products of cement production systems. These strategies can be divided into two main categories: (1) improving the existing products and (2) developing new products.

Improve existing products

Most of the cement types use clinker as one of their main ingredients (Table 6). Improving the CO2 performance of these existing cements types is the aim of measures in this category.

- **Clinker substitution (alternative materials)**

Clinker production attributes to high CO2 emissions, because of high-energy requirement (clinker has high embodied energy) in the pyroprocessing phase (kiln) as well as the calcination. Therefore replacing clinker with supplementary cementitious materials (SCM) and using less clinker in final products known as “blended cements” is a viable strategy to decrease CO2 emissions associated with cement production. In other words, in blended cements, SCM replace portion of the clinker required to make Portland cement. The SCM materials are divided into two main categories (US EPA, 2010):

  - **Cementitious materials**: These materials have similar characteristics of ordinary cement. A common example of such materials is special form of steel slag called Granulated Blast Furnace Slag (GBFS).

  - **Pozzolan materials**: These materials do not have cementitious properties under normal conditions, however when mixed with calcium hydroxide (Ca(OH)$_2$), behave as cementitious materials. Most widely used examples of such materials in cement industry are silica fume and fly ash from coal combustion. Other examples of pozzolan SCMs are diatomite, metakaolin, calcined clay (heated clay), calcined shale, and volcanic ash.

Normal blended cement product includes clinker and one SCM. However, it is possible to mix more than one SCM with clinker and produce ternary blended cements: For instance using fly ash and silica fume along with clinker, which can make high strength concretes (Nochaiya et al., 2010).

  - **Granulated blastfurnace slag (GBFS)**: Use of GBFS, which is a common cementitious material, can offset CO2 emissions attributed to clinker production on almost one-to-one basis; for example, blended cement with 40% GBFS and 60% clinker has 40% less CO2 emissions attributed to cement production (US EPA, 2010). It is important to note that the issue of CO2 allocation between cement and GBFS production can influence this one-to-one CO2 offset gains.

  - **Fly ash from coal combustion**: Use of fly ash which is a widely used pozzolanic for blending can significantly offset the CO2 emissions attributed to cement production. If the quality of fly ash is high and consistent, it can be used for concrete blending, however
in many cases it is better to grind and blend it with clinker inside the cement plant. A blended cement with 30% fly ash (mass) can lead to about 10% in CO₂ emission reduction for produced cement (US EPA, 2010).

**Natural pozzolans:** Natural pozzolans occur in limited areas and require the plant to be in the proximity of the source. The benefits of using these pozzolans depend on their moisture content and the amount of heat required drying them (US EPA, 2010).

Aside from the common and widely used SCMs, other materials (often wastes or byproducts of other industrial processes) can be used as clinker substitutes or SCMs. Here few examples of such less common materials are presented:

- **Spent fluid catalytic-cracking catalyst (FCC):** Antiohos et al. (2006) have investigated the possibility of using spent catalyst (containing silica and aluminum) from oil-cracking refineries as SCM. In their evaluation, blended cements containing up to 30% spent FCC were found to have comparable compressive strength, but slower strength development properties.

- **Paper sludge waste:** With certain treatment (including heating for two hours at 700°C for calcination), paper de-inking sludge waste can be converted to a pozzolanic material and serve as clinker substitute in blended cements. The study by García et al. (2008) shows that blended cements including up to 10% this material compares well with ordinary Portland cement (OPC) both from compressive strength development and initial setting time perspectives.

- **Gas quenched steel furnace slag (SFS):** Steel furnace slag is rich in silicates and aluminosilicates of calcium and is very close to blastfurnace slag (BFS) (produced in iron blastfurnace). About 35% of SFS produced in Europe is landfilled which is about 4 million tons per year. SFS like BFS is produced by chemical conversion of limestone in high temperatures, but is produced at much lower temperatures and contains more iron and magnesium, which makes its usage as clinker substitute more challenging. SFS can be regarded as a weak cement clinker, but not a ready substitute for it. So if used for cement production, it has to go in to the kiln and sinter with other materials and be treated as “alternative feedstock” for clinker production (Tsakiridis et al., 2008). However according to Long et al. (2011) it is possible to utilize gas quenched (by nitrogen) steel slag in order to produce blended cement with about 20%-40% SFS content in the mix.

Another method of reducing the clinker content of the blended cements is to add filler material such as limestone to the mix. Under certain conditions, limestone filler (LF) content as high as 0-24% added to create Portland limestone cement (PLC) (Irassar et al., 2011).

**Blended cements with improved properties**

Blended cements due to substitution of clinker with SCM’s tend to have lower CO₂ emissions, however in order to create market acceptance and the properties of these cements have to be comparable with Portland cement. Improving the characteristics of various types of blended cements will make them more favorable for more consumers and suitable for applications. This can be achieved through research and by developing special admixtures that allow more clinker
substitution rates (lower clinker factor) while maintaining or improving the characteristics of the blended cements.

- **Slag cement and early age strength development**: Many of conventional blended cements (such as slag cement) have slower strength development, which makes them unsuitable where fast track construction is required. One method of improving the early age strength development of slag cement is to use a ternary blend by adding limestone filler to the blend. Limestone improves early strength of cement, while the GBFS increases its late strength. Menéndez et al. (2003) suggest ternary blending of LF-GBFS with 20%-35% ratios with clinker. Another way of improving early strength development of blended cements is by adding special accelerator chemicals (Riding et al., 2010). O’Rourke et al. (2009) have demonstrated that early strength development of various GBFS-based binders can improve by adding small amounts of Anhydrite II and gypsum without affecting their later strength. In addition, mechanically activated GBFS allows higher clinker substitution rates without compromising early strength development (Kumar et al., 2008).

**Develop new products**

Clinker production due to calcination process and high sintering temperature requirement produces large amount of CO\(_2\). Therefore, one strategy to decrease CO\(_2\) emissions attributed to cement is to develop new forms of products, which do not need calcination or have no clinker content.

- **Clinkerless/no-calcine cement**

Most commonly used cement types use calcium-based cementitious material. However, it would be interesting to seek other forms of cements, which require less energy, release less CO\(_2\) and have more natural resources availability.

- **Silica-alumina based cement (Sialite)**: Sialite cement is invented based on mimicking (and accelerating) existing rock forming processes in nature. It has two main parts: grounded silica rich industrial wastes and synthetic rock forming agent. Compared to Portland cement, Sialite has very large resources of raw material, requires less energy for manufacturing, and is economically more cost effective. The structural framework of Sialite is aluminosilicate, which comprises more than 70% of earth crust. Sialite creates great synergistic potentials, because many industrial wastes such as red mud (solid waste product in manufacturing of aluminum), fly ash, gangue (unwanted mining waste), blast-furnace slag and steelmaking slag, etc. contain aluminosilicate and can be used as raw feed for its production. Unlike ordinary cements, which have limitations for waste utilization (as in blended cements) regarding degradation of setting time and strength development, Sialite can have up to 95% of solid waste materials. Sialite production does not require calcination and requires only one time grinding (Sun et al., 2007, 2009). According to Yi et al. (2009) and Sun et al. (2007) the performance of Sialite is...
comparable (and generally better) than ordinary Portland cement in aspects such as acid/base/salt resistance, durability, strength, and curing time.

- **MgO based cement**: These forms of cements require lower processing temperature and releases less CO$_2$ emissions. They harden by absorbing atmospheric CO$_2$, which improves their net greenhouse gas emissions. The performance of these cements is still not fully studied yet (Li et al., 2008; Robinson, 2008; ECRA, 2009).

- **Ground limestone powder (GLP) based cement**: Even using conventional raw materials, there are ways to produce clinker-less cement. For instance, it is possible to make composite non-calcined cement by mixing ground limestone powder (40 wt%-60 wt%), blastfurnace slag (40 wt%-60 wt%), steel slag (10 wt%), and gypsum (8 wt%). This cement does not require clinker and is suitable for architectural engineering masonry applications (Lin and Zhao, 2009).

- **Cement from flue gas desulphurization residues and fly ash**: Sulfur control technologies are essential part of coal burning power plants and as the result, large amount of sulfur containing wastes are produced. In a technique proposed by Rust et al. (2009), clinker-less cement can be produced by mixing these wastes products of sulfur dioxide removal system and fly ash in order to produce low energy cement.

There are other clinker-less cement types such as calcium-sulfoaluminate-based cements (CSA) (Quillin, 2001; Pera and Ambroise, 2004; Gartner and Quillin, 2007) or Alkali activated cements (Palomo et al., 1999).

In addition, there are a few emerging technologies such as nano-engineered concrete and Calera cement as well:

- **Nano-engineered concrete**: The idea behind nano-engineering concrete is the hypothesis that the nano-scale structure and organization of material has more impact on the strength of concrete than the material used to make it. Therefore, with correct nano-scale material structuring it would be possible to use alternative material to create strong cements (Brehm, 2008).

- **Calera cement**: This process mimics the process of marine cement formation produced by coral. In order to make their shells and reefs, they take calcium and magnesium from seawater and form carbonates under normal marine pressures and temperatures. The process (at least in small scale) has proved to be able to use CO$_2$ and polluted water for producing cementitious materials. Due to secrecy large amount of data about Calera process is still not available to public (Biello, 2008). The Calera process can also be considered a carbon sequestration (section 5.2.4) technology (US EPA, 2010).

### 5.2.4 External synergies

Extensive amounts and types of resources (material and energy) are fed into a modern cement plant. According to the general principles of Industrial Ecology (IE) described in previous sections (section 2 and section 4.2), all of the inbound or outbound material or energy streams of cement production must be regarded as potentially useful byproducts. Large quantities of these streams (either in the input or output sides of a cement plant), create a potentially versatile
situation for creating various synergistic links between the cement traditional value chain and the other industrial networks in the neighborhood or the wider region.

**CO₂ and waste excess solutions**

Commercial cement plants, even equipped with best available technologies (BAT) have considerable amount of waste heat and CO₂. Theoretically, these resources can be integrated with another processes and create useful byproducts.

- **Carbon sequestration/carbon capture and storage**

It is believed by many that due to large demand for cement worldwide, which is also increasing, even with the help of new technologies, the cement production will still be faced with the problem of CO₂ emissions and its impact on climate. Therefore, it is essential to mitigate the CO₂ emissions from existing cement production methods and utilization of carbon sequestration or carbon capture and storage technologies at cement plant (and power plants) is inevitable.

Most of carbon capture technologies are divided into three main categories: oxyfuel combustion, pre-combustion, and post-combustion systems (Jordal et al., 2004; Metz et al., 2005):

- **Post-combustion**: The idea is to simply have the same existing plants, but add a CO₂ capturing system in the final exhaust and collect the emitting CO₂. The fuel (fossil or biomass, in many cases coal) is combusted with air (as in traditional boilers) and flue gas is created. Firstly particles are removed, secondly sulfur dioxide is removed by a process called flue gas desulphurization (FGD), thirdly the flue gas is cooled and its CO₂ is absorbed by liquid sorbent (CO₂ absorber). Consequently, the CO₂ is regenerated (by heating the sorbent) and compressed into liquid.

- **Pre-combustion**: The idea is to burn the carbon from the fuel (fossil or biomass, in many cases coal) first and then burn the carbon-free fuel such as hydrogen. In the most developed method, which is called Integrated Gasification Combined Cycle (IGCC), the carbon containing fuel (e.g. coal) is first gasified and syngas (mixture of CO, H₂, and H₂O) is created. After particle removal, the syngas is converted into hydrogen (H₂) and carbon dioxide (CO₂). After removing the sulfur from the stream, the CO₂ is separated and compressed and the hydrogen is used as fuel for plant. This process requires extensive modification of the existing processes.

- **Oxyfuel combustion CCS**: The idea is to burn fuel (fossil or biomass, in many cases coal) in oxygen (not air) and gets relatively pure CO₂ in the exhaust. The exhaust is cleaned by removing fly ash and sulfur from it to reach at least 95% CO₂ that can be compressed for storage or other applications. There are several technical issues related to using oxy fuel combustion techniques in the cement industry, which are described by Barker et al. (2009).

Carbon capture and storage (CSS) technologies are considered technically feasible, however since they require more energy and have higher costs, more development is required in order to make them widely accepted (Gibbins and Chalmers, 2008). Some studies have evaluated the
carbon capture and storage solutions for cement industry (IEA GHG, 2008; Barker et al., 2009; Bosoaga et al., 2009; ECRA, 2009).

Regarding the application of oxyfuel combustion CCS in cement industry it is observed that adding oxygen to combustion and flue gas recycling requires modification of process conditions, therefore additional research is required to provide a viable design (Barker et al., 2009; Zeman, 2009). The commercial-scale deployment of CCS systems in cement industry will not happen in near future. This is due to existing uncertainties of these technologies and the fact that retrofitting the technologies to suit the requirements and conditions of cement industry is still a major limiting factor (Naranjo et al., 2011). A relatively new solution for CCS, which has high potential and suitability for deployment in cement industry is the calcium looping cycle which is described in the section 5.5.4.2.

- **Carbonation and recycling of waste concrete:** Portland cement concrete absorbs CO₂ (carbonates) slowly during time. The amount and speed of carbonation depends on different factors, but the main is the surface area exposed to CO₂. It is possible to utilize considerable amount of waste CO₂ of the cement plant by flowing the CO₂ exhaust through crushed construction and demolition waste concrete (C&D wastes). This not only sequester some of the emitted CO₂ from cement production, but also upgrades the quality of the crushed waste concrete and improve its suitability to be used as concrete aggregate. Normal waste concretes have considerable amount of cement, which leads to more water absorption, expansion, and lower performance characteristics (compared to new aggregates). Many of these undesirable characteristics can be eliminated by carbonation of crushed & grounded waste concrete (Stolaroff et al., 2005).

- **Biological multi production**

  Many biological processes require CO₂ and heat, therefore a group of synergistic possibilities around cement plant involve utilization of biological process to produce various byproducts.

  - **Algae-to-energy/bio-products:** The idea is to co-locate cement plant with algae or microalgae production system in order to feed it with waste heat and CO₂ from cement plant and use the biomass to manufacture various bio-products including but not limited to biofuels. Some systems do not use the algal biomass in order to produce biomass; instead use the algal biological process in order to create biofuel. Generally, algae-to-energy technologies are still under development and large scale algae-to-energy solution has not yet developed for commercial purposes (Malcata, 2011). The study by Rosenberg et al. (2011) which investigates production of biodiesel using microalgal cultivation highlights that the efficiency of biodiesel production is limited to the amount of available heat source (as well as land). This is obviously a case where large amount of waste heat from cement plant gains higher potential. Singh & Gu (2010) suggest that a hybrid production of biofuels and along with other bio-products is probably the most economical configuration for an algae bio-refinery fed by industrial wastes such as CO₂ and heat.

  - **Dried sludge as alternative fuel:** Use waste heat from cement plant to dry sludge from wastewater treatment plant (WWTP) and use the dried sludge as alternative fuel in
cement kiln. In addition to fuel savings, 1 tonne of dried sludge can replace up to 1/3 of raw material required for clinker production. From energy, economic and environmental perspectives, co-firing in the cement kiln is an appropriate and suitable solution for treating waste sludge, both for cement plant and WWTPs (Stasta et al., 2006).

- **Synergistic heating or cooling**

  - **Underground thermal energy storage (UTES):** The idea of UTES, which is a form of thermal storage (TES), is to store excess heat in an underground reservoir and use it in a later time when required. The UTES technology has been primarily developed and practiced in built environment in many countries in Europe (Midttømme et al., 2008; Bonte et al., 2011); however, it can have industrial potentials as a synergistic technique to utilize the excess heat from industry such as cement manufacturing. Two main methods are open and closed systems. The open system known as aquifer thermal energy storage (ATES) or open loop ground source heat pumps (open loop GSHP) uses groundwater for storing heat. The closed system known as borehole thermal energy systems (BTES) uses a well-defined subsurface reservoir made of plastic conductor pipes or trenches (Semadeni, 2003; Goricanc et al., 2010; Lee, 2010).

  - **Using low-grade heat for heating/cooling:** The idea is to collect waste heat from cement plant and utilize it for heating and cooling purposes in residential or industrial district heating networks (Ammar et al., 2011).

**Process integration and industry initiatives**

Many industrial activities are evolved independently and during the course of time have been optimized based on the specific goals and demands of each individual process. However, innovative ideas for combining different processes and benefit from joint optimization cannot be neglected. These are relatively new concepts; however, a few examples of such innovations, which can be utilized in cement industry, are presented here.

- **Combined power and cement production (CPCP)**

  This solution considers process integration between power and cement production plants. Compared to other carbon capture technologies, this method leads to relatively low efficiency loss (less than 6%). In this system, the heat required for calcination stage is compensated by the heat released during carbonation stage (i.e. the capturing of CO\(_2\)) and can be integrated efficiently in the steam cycle of a power plant. The process can be fed by normal cheap limestone for cement production and the resulting lime (calcined limestone) purged out of the cycle can be used as raw material for clinker production. In this technique, cement and power plants do not need to be co-located (Rodríguez et al., 2008; Bosoaga et al., 2009; Romeo et al., 2011).

  - **CCS with lime-enhanced gasification (LEGS):** This is a calcination-carbonation looping process, which use CaO and CO\(_2\) and utilizes two reactors. One is a gasifier in which carbonation of CaO creates hydrogen rich gas and the other reactor is a regenerator in which the sorbent is calcined and high purity CO\(_2\) is released suitable for storage. The
system requires fresh limestone and the purged CaO can be used in clinker manufacturing. If integrated with cement production, the electricity production efficiency of about 40% is achievable using a modern combined cycle (Weimer et al., 2008).

- **Integration/colocation with waste-to-energy solutions**

Co-locating or integrating waste-to-energy and cement plants can create economical and environmentally sound solutions, which can benefit both industries. This will allow the cement plant to include wider types of wastes as energy source, because using waste-derived fuels as direct kiln fuel is limited to quality and type and availability of those fuels. However, integration with large-scale waste-to-energy systems can rectify this issue (Papageorgiou et al., 2009).

Among various waste-to-energy strategies, a few which are more suitable for closer cooperation with cement industry (Golush, 2008) are presented here:

- **Pyrolysis and gasification of mixed wastes (syngas production):** Large-scale municipal waste gasification plant, which converts biodegradable wastes to syngas as kiln fuel (Giugliano et al., 2008). It has been demonstrated that even a hybrid approach of co-gasification of solid wastes with fossil fuels (such as lignite) can have environmental and economic potentials (Koukouzas et al., 2008).

- **Anaerobic digestion of organic substrates and mixed wastes (biogas production):** With this technique, the organic materials are converted the biogas (methane) (Weiland, 2009) and under certain conditions, the final sludge may be used as fertilizer. The valuable nutrition’s (such as phosphorus) are not dissipated in this method.

- **Pretreatment of waste for later co-firing in kiln (waste-derived fuels production):** Wastes, which cannot be directly burned in kiln, are pre-processed in order to make fuels. This method is widely used for waste-derived fuels such as refused derived fuel, tire derived fuel etc. that are already used as alternative fuels in many cement plants. A hybrid solution of mixing waste-derived fuels with fossil fuels (upgrading the waste-derived fuel) is also suggested (Zabaniotou and Theofilou, 2008; Nadal et al., 2009).

- **Synergies among already co-located firms**

Existing colocation of industrial plants may provide potentials for synergistic relations. One example of such relations is the colocation (or proximity) of a cement plant with iron & steel production plant. By mutual agreement and cooperation, the slag produced in the steel plant can be converted to granulated blastfurnace slag (GBFS) and used by cement plant in various blended products.

- **Improve quality of raw materials:** In cases such as cooperation between steel and cement plants, it is possible to increase the level of cooperation in such a way that the supplier of GBFS, provides certain treatment on this byproduct before sending it to cement plant. This can be in form of dryer materials (GBFS with less moisture content) which demand less drying process in the cement plant.

- **Use waste heat of neighboring industries:** Some of the cement sites are not producing clinker and are only large-scale milling and blending sites. However they still require
heat for drying raw materials. In this case, if the neighbor industry such as iron and steel production plant has lot of waste heat, it may be economical to use this waste heat for drying and other applications.

5.2.5 Management

Management practices can have great influence on the overall CO₂ performance of cement production. The term “management” here is not referring to a traditional “management” in a single company, but is referring to a wider notion of management that encompasses all forms of organizational or business activities in order to effectively and efficiently utilizing the available human, financial, technological or natural resources through planning, organizing, leading, and controlling (Koontz and Weihrich, 2006).

An important consideration is that these “management” measures do not have direct influence on the CO₂ emission levels of the production system. However, they are viable and influential enabling factors that can influence all other CO₂ improvement measures.

This thesis will not go into details of management practices and how they can influence business strategies, approaches regarding CO₂ emission reduction measures. However, few important aspects are presented briefly here.

Corporate environmental strategy and innovation approaches

Adopting improvement innovations and measures induces “change” in any organization. In order to effectively deal with these changes, organizations require “transition management”. Transition management incorporates conscious attempts to develop social, economic, and ecological performance of organization progressively, adaptively, and sustainably. When deciding about “adopting” various measures, organization often faces short-term concerns versus long-term demands. Transition management seeks to deal with these (Marinova et al., 2006).

Environmental strategies of firms can significantly influence the type of technical or organizational approaches that they adopt for improving their environmental performance. Table 20 summarizes various levels of corporate approaches regarding environmental concerns.

Table 20. Levels of corporate approaches regarding environmental concerns

<table>
<thead>
<tr>
<th>Level</th>
<th>Vision on the environment</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Not important</td>
<td>No response</td>
</tr>
<tr>
<td>Reactive</td>
<td>Is a threat</td>
<td>Minor changes in production system and products</td>
</tr>
<tr>
<td>Proactive</td>
<td>Is an opportunity</td>
<td>R&amp;D is focusing on development of new products or production system</td>
</tr>
<tr>
<td>Innovative</td>
<td>Is strategic</td>
<td>R&amp;D programmes aimed for developing radical alternative approaches</td>
</tr>
</tbody>
</table>

These responses for improving environmental performance of organizations can happen at various levels: (1) system optimization, (2) system re-design, and (3) system innovation as depicted in Figure 12.
In more detail, these levels are defined as (Butter, 2002; Marinova et al., 2006):

- **System optimization**: Innovations aiming for optimizing existing products, processes, or infrastructures that improve system efficiency through incremental steps. The benefits from these types of innovations yield in short term and relatively low gains in environmental performance (for example by a maximum improvement factor of 2).

- **System re-design**: Innovations through re-designing system elements like products, processes, and infrastructures without changing overall system concept. These types of innovations yield in medium-term and higher gains in environmental performance (for example by a maximum improvement factor of 5).

- **System innovation**: These innovations involve development of new systems that perform the same functions in a better way. These types of innovations yield in long term and aim at high gains in environmental performance of system (for example by a maximum improvement factor of 10 or more).

All these forms of innovations are important and must be taken into account by organizations. Incremental improvements can be very effective in reducing costs and improving existing products, but sole emphasis on these incremental improvements, may result in small gains on
environmental performance and losing competence in long term. Radical development innovations (ex. developing a new product) have higher potentials for environmental benefits, however may not have direct short-term benefits (Arundel et al., 2006; Marinova et al., 2006).

Marketing, education, and public relations

Various cement products have different environmental performances. Some types of blended cements with relatively low “clinker content” have lower CO₂ emissions during their life cycle. For instance, cement products such as CEM III (Table 26) have lower clinker content and life cycle CO₂ emissions compared to high clinker content products such as CEM I (LIU, 2011). However, often production of these “greener” cement products is limited due to market demand. If stakeholders and various actors downstream the supply chain (construction companies, ordinary residents of buildings, and others) have used certain types of cement for long time, they may be hesitant in adapting new and greener cement types. If customer preferences are not changed, marketing of environmentally sound cement products will remain challenging (Seaden, 1996).

Aside from technological development, strategies that can disseminate stakeholder’s knowledge of benefits of newer products can be an effective way of reducing various forms of social resistance.

Standards and specifications

Legal development for materials (cement products) in construction projects demand standardization of newer “greener” cement products with industry wide agreed specifications. Collaborations and joint efforts by various stakeholders in construction industry (especially actors in cement industry) can lead to incorporation of newer types of cement products into formal standardization systems.

The existing standardization system for cement types is purely technical and identifies various types of cement based on their composition and material used. One example of new forms of standards and specifications for cement is to include some environmental indicators into the classification system in order to reflect, “How green the specific type of cement is produced?”. In this way, a certain cement type, which is manufactured under a specific production system with significantly lower life cycle CO₂ emissions, will have a formal competitive advantage when viewed from customers and other stakeholders in the market.

Existing standard systems sometimes are not only “not promoting” environmentally sound cement types, but also in some case, they are demotivating their usage. For instance, there are evidences that existing standard cube curing regimes in production of concrete heavily penalizes usage of supplementary cementitious materials (Soutsos et al., 2009).
5.3 Step 3: CO₂ improvement evaluation

Now that the categorization scheme is developed (in section 5.2) it is possible to evaluate the CO₂ emission reduction potential of each category of measures. This evaluation is performed according to the guidelines and qualitative scales developed in the section 4.4. The aim of this evaluation is to identify low, medium, and high potential measures by considering the type of CO₂ emissions that they are addressing (as described in section 5.2). The result of this evaluation is summarized in Table 21.

Table 21. Evaluation of CO₂ improvement potentials for various improvement measures

<table>
<thead>
<tr>
<th>Short Code</th>
<th>CO₂ emission reduction strategy or measure</th>
<th>CO₂ Emissions which are effectively reduced</th>
<th>Potential for reducing CO₂ emissions</th>
<th>Literature estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEE</td>
<td>- Electrical efficiency</td>
<td>Partially</td>
<td>Low</td>
<td>Less than 10% (max 20% theoretical limit) reduction in total energy demand.</td>
</tr>
<tr>
<td>EEH</td>
<td>- Thermal efficiency</td>
<td>Yes</td>
<td>Low-Medium</td>
<td>Energy saving: with pre-calcination &amp; preheater (5%) (Löcher 2006), kiln insulation (12%) (Engin &amp; Ari 2005)</td>
</tr>
<tr>
<td>ERH</td>
<td>- Pre-heating/drying</td>
<td>Yes</td>
<td>Low-Medium</td>
<td>Energy saving: about 4% reduction of total energy demand.</td>
</tr>
<tr>
<td>ERE</td>
<td>- Co-generation (heat &amp; electricity)</td>
<td>Yes</td>
<td>Low-Medium</td>
<td></td>
</tr>
<tr>
<td>ERR</td>
<td>- Recycle/reuse</td>
<td>Yes</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>IFM</td>
<td>- Alternative materials (for clinker production)</td>
<td>Partially</td>
<td>Low-Medium</td>
<td></td>
</tr>
<tr>
<td>IEF</td>
<td>- Fuel diversification (alternative/secondary fuels)</td>
<td>Partially</td>
<td>Low-Medium</td>
<td></td>
</tr>
<tr>
<td>IER</td>
<td>- Renewable energy (fuel and electricity)</td>
<td>Yes</td>
<td>Medium</td>
<td>Depends on how the CO₂ from waste-derived-fuels are allocated.</td>
</tr>
<tr>
<td>PPC</td>
<td>- Clinker substitution (alternative materials)</td>
<td>Yes, Yes, Maybe</td>
<td>High</td>
<td>By requiring less clinker, less calcination, preheating, and heat (for producing clinker is required).</td>
</tr>
<tr>
<td>PPB</td>
<td>- Improve blended cements’ properties</td>
<td>Yes, Yes, Maybe</td>
<td>High</td>
<td>More sales of blended sales, less clinker is used in cements.</td>
</tr>
<tr>
<td>PNC</td>
<td>- Clinkerless/no-calcine cement</td>
<td>Yes, Maybe, Maybe</td>
<td>High</td>
<td>Requires additional energy.</td>
</tr>
<tr>
<td>SEC</td>
<td>- Carbon sequestration/carbon capture and storage</td>
<td>Yes, Maybe, Maybe</td>
<td>Medium-High</td>
<td>Requires additional energy.</td>
</tr>
<tr>
<td>SEB</td>
<td>- Biological production</td>
<td>Yes, Maybe, Maybe</td>
<td>Medium-High</td>
<td></td>
</tr>
<tr>
<td>SEH</td>
<td>- Synergistic heating</td>
<td>Yes</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>SIP</td>
<td>- Integration with power plant</td>
<td>Maybe</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>SIW</td>
<td>- Integration/co-location with waste treatment</td>
<td>Yes, Yes, Maybe</td>
<td>Medium-High</td>
<td></td>
</tr>
<tr>
<td>SIC</td>
<td>- Synergies among already co-located firms</td>
<td>Maybe, Maybe</td>
<td>Medium-High</td>
<td></td>
</tr>
</tbody>
</table>

5.4 Step 4: Feasibility evaluation (generic)

In this step of the assessment each of the improvement measures (in the categorization scheme developed in 5.2) is evaluated from the perspective of “complexity of business approach” and the “level of technological maturity”. To avoid unnecessary repetition, the result of these evaluation are presented later in the “Step 6: Results and analysis” in section 6.3 (Table 25).
6 APPLYING THE ASSESSMENT FRAMEWORK - PART II: CLUSTER WEST

Part I of applying the assessment framework was the generic assessment of CO\textsubscript{2} improvement measures in cement industry (section 5). Now, the second part (Part II) of the assessment framework will be applied on an actual cement production system. The aim of this part of the assessment is to assess the feasibility of various CO\textsubscript{2} improvement measures recognized in Part I, for the Cluster West (Cluster West) production system.

Before proceeding with the assessment, the Cluster West production system will be introduced.

6.1 Cluster West

The CEMEX Germany AG (CEMEX Deutschland AG) is headquartered in Düsseldorf and is one of the largest producers of cement, ready-mixed concrete and other similar types of building materials in the country. Since 2005, cement plants of WestZement GmbH (at Beckum in North-Rhine Westphalia) and OstZement GmbH (at Rüdersdorf in the state of Brandenburg) have been part of CEMEX. These plants are equipped with rotary kiln and produce clinker and several other intermediate and final products. In addition, there are several high capacity milling and blending plants that do not produce clinker (do not have kiln). The location of CEMEX cement plants in Germany are depicted in Figure 13.
Figure 13. Location of CEMEX plants in Germany

(1: Rüdersdorf, 2: Kollenbach, 3: Mersmann, 4: Dortmund, 5: Schwelgern, 6: Eisenhüttenstadt) (CEMEX-DE, 2010a)

Table 22 summarizes the production capacities of these plants (CEMEX-DE, 2010a). Beckum-Mersmann plant is currently transferred to a cold reserve (not producing), but if required, can return to service at any time. The plant Mersmann is not included in this study.
Kollenbach is part of a work alliance with the sites in Dortmund, and Schwelgern. Together, these three plants are considered as Cluster West (Cluster West in this report). These plants produce several intermediate products as well as final products. Figure 14 provides an overview of the Cluster West in terms of the main inbound flows (which are mainly material and energy), the interflows (clinker, GBFS, and various intermediate products), and the outbound flow of the final cement products.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Plant</th>
<th>Production Capacity (million tonnes/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Clinker</td>
</tr>
<tr>
<td>Cluster West</td>
<td>Kollenbach ¹</td>
<td>0.9</td>
</tr>
<tr>
<td>Cluster West</td>
<td>Mersmann ²</td>
<td>0.4</td>
</tr>
<tr>
<td>Cluster West</td>
<td>Dortmund</td>
<td>0.0</td>
</tr>
<tr>
<td>Cluster West</td>
<td>Schwelgern</td>
<td>0.0</td>
</tr>
<tr>
<td>Cluster East</td>
<td>Rüdersdorf</td>
<td>2.4</td>
</tr>
<tr>
<td>Cluster East</td>
<td>Eisenhüttenstadt (Ehs)</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total Cluster West</strong> ³</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total Germany</strong> ³</td>
<td></td>
<td>3.3</td>
</tr>
</tbody>
</table>

¹ Clinker production capacity is based on the assumption of 300 days production in each year. The legal installed capacity for Kollenbach plant is 3000 tonnes/day or about 1.1 million tonnes/year.

² Mersmann kiln has been closed in 2005 and dismantled in 2009.

³ Total sum does not include production capacity of Mersmann plant.

Intermediate products are semi-finished or half products which are used in the production of final products. Intermediate products are not sold to external customers and are used only internally in the Cluster West.
The Schwelgern plant is co-located with a steel manufacturing plant, which according to a special agreement supplies it with granulated blast furnace slag (GBFS). This material, which was briefly introduced before, has cementitious properties and therefore can partially substitute clinker in several cement products. For example, products such as CEM III (depending on their sub-types) can have between 36 to 95 percent GBFS in their composition (Table 6).

In the following sections, each of the Cluster West plants is briefly introduced.

**6.1.1 Plant Kollenbach**

Kollenbach or in short “Kollenbach” is a cement production plant founded at 1911. It is located near Beckum, located in the west of Germany (in North-Rhine Westphalia) and is the only plant in Cluster West that produces clinker. In 1953, Kollenbach plant was the first plant in the world that installed a cyclone preheater (CEMEX-DE, 2010a).
In 2009, Kollenbach clinker production was about 0.8 Mt\textsuperscript{13} and more than half of it was shipped to Dortmund and Schwelgern plants for production of various blended cements. Figure 15 summarizes the production process of Kollenbach plant (CEMEX-DE, 2010a).

\textbf{Figure 15. Production process in Kollenbach plant (CEMEX-DE, 2010a)}

The Kollenbach plant uses dry process with a rotary kiln, four-stage cyclone preheater and drum cooler. In order to reduce the amount of chlorine in the produced clinker, a chlorine bypass system is placed downstream the preheater. This bypass will lead to the collection of “bypass dust” which later will be recycled for the production of blended cements.

The summary of main equipments used in Kollenbach plant is presented in Table 23 (CEMEX-DE, 2010a).

\textsuperscript{13} Mt: Megatonne (million tonnes)
Due to modifications done in years 2000, 2001 and 2004, the Kollenbach plant is now equipped with feeding system for secondary fuels such as animal meals, various fluffy materials, and shredded tyres. Table 24 shows the types of fuels used in Kollenbach plant in year 2009 (CEMEX-DE, 2010b).

Table 24. Fuels used in Kollenbach plant in 2009 (CEMEX-DE, 2010b)

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Share from total input fuel energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluffy Materials</td>
<td>36.8%</td>
</tr>
<tr>
<td>Animal Meal</td>
<td>28.0%</td>
</tr>
<tr>
<td>Coal</td>
<td>24.7%</td>
</tr>
<tr>
<td>Lignite</td>
<td>8.1%</td>
</tr>
<tr>
<td>Tires</td>
<td>1.9%</td>
</tr>
<tr>
<td>Light Fuel Oil</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Kollenbach produces several cement types but its main production is CEM I as well as several intermediate products (mainly composed of clinker) which are shipped to Schwelgern and Dortmund. These intermediate products are used for production to other types of cements.

### 6.1.2 Plant Schwelgern

The Schwelgern plant is a grinding and mixing station and does not produce clinker (does not have kiln). It is the newest member of Cluster West and has been part of it since 1998. Schwelgern plant is co-located with Thyssen Krupp Steel plant and based on special agreements.
between two companies, the blastfurnace slag (BFS) produced in the steel factory is quenched by water in order to convert it to granulated blastfurnace slag (GBFS). The produced GBFS is sent to the Schwelgern plant by an electrical conveyer system. In order to reduce the moisture content of the received GBFS, the Schwelgern plant uses coke gas and lignite fuel to dry the received GBFS. Schwelgern is the supplier of GBFS for the other plants in the Cluster West, mainly the Dortmund plant (CEMEX-DE, 2010b, 2010c).

The annual cement production capacity of the Schwelgern plant is about 1 Mt. It produces various blastfurnace cements (CEM III) such as CEM III/A or CEM III/B that have different GBFS content and properties.

### 6.1.3 Plant Dortmund

Like Schwelgern, the Dortmund plant is a grinding and mixing station and does not have any kiln. Here the intermediate products from Kollenbach along with GBFS from Schwelgern are milled and mixed in special silos in order to produce various cement products, mainly CEM III/A. The GBFS from Schwelgern is shipped to the plant by rail and the rest of the transports are performed by road transportation.

### 6.1.4 Data collection from Cluster West

The site-specific data required for this case study was collected from several sources including CEMEX Germany annual reports, annual production figures, input/output material and energy figures for each of the plants, visiting Cluster West (all three plants), workshop, and dialogue with experts from the company. Here a summary of the steps for data collection are presented.

- **Input and output records**
  
  Data was collected from Cluster West for each of the plants individually (annual figures for 2009). All operational data regarding input and output streams of fuel, electricity, materials, and products for each plant were collected. In addition, all the inter-plant exchanges, such as the amount of clinker, GBFS, and other intermediate products were compiled. These data were compiled and aggregated into a unified inventory for overall Cluster West production system. This inventory was used for measuring the key performance indicators (KPI) of the Cluster West production system. These figures describe the current conditions of the production system.

- **Site visit**
  
  In addition to numerical data received from CEMEX Germany, a site visit to three plants was performed which helped to get more better understanding of the production system in the Cluster West and get detailed information about its conditions and constraints. The summary of main points, which were noticed during site visit, is provided in the Appendix (Table 27).
• **Workshop**

In order to better understand the view of company’s experts and managers, regarding future options for CO₂ improvement measures, a workshop was held during the CEMEX project in which several academic members from Linköping University (along with the author of this thesis) were gathered with managers and experts from CEMEX company (LIU, 2011). In this workshop, an overview of the future vision of a cement production system inspired by concepts of Industrial Ecology and Industrial Symbiosis was presented to the audience. Next, the CEMEX team members were asked to share their ideas about the most feasible (effective and applicable) CO₂ reduction measures in Cluster West. The result of this idea sharing (a list of suggested ideas), is available in the Appendix (Table 28).

• **Feedback from company experts**

In several occasions, contact with experts from the company was established and information about different aspects of the Cluster West’s production system was received. In the later stage of the thesis, when the assessment framework was developed, evaluation sheets (based on Microsoft Excel) was sent to CEMEX that was filled by a team including managers and technical experts.

More information about the performance of the production system of the Cluster West is available in the Appendix.

### 6.2 Step 5: Feasibility evaluation (for Cluster West)

In this stage, each category of measures is qualitatively analyzed in order to evaluate its feasibility of implementation in the Cluster West. These evaluations are done according to the aim and guidelines described in section 4.6. The feasibility evaluation (consisting of the three dimensions described in section Developing “Step 5: Feasibility evaluation (site-specific)” was performed in two steps. First, a preliminary evaluation was performed based on the knowledge that was acquired from Cluster West during the project. Later, the result of this preliminary evaluation was sent to CEMEX in order to be re-evaluated and confirmed.

### 6.3 Step 6: Results and analysis (for Cluster West)

In this step, the results of the assessment including the generic evaluation of CO₂ emission reduction measures (Part I) and their site-specific evaluation for the Cluster West (Part II) are compiled and presented in Table 25.
Table 25. Evaluation results for CO₂ improvement measures for the Cluster West

<table>
<thead>
<tr>
<th>Category of CO₂ emission reduction measures</th>
<th>Feasability (Generic)</th>
<th>Feasability (Site-Specific)</th>
<th>Improvement potential (Generic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>Category</td>
<td>Complexity of business approach</td>
<td>Technological Maturity</td>
</tr>
<tr>
<td>EEE</td>
<td>Electrical efficiency</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>EHH</td>
<td>Thermal efficiency</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>ER</td>
<td>Resource recovery</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>ERH</td>
<td>Pre-heating/drying</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>ERE</td>
<td>Recycle/reuse</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>ERP</td>
<td>Pollution prevention and control</td>
<td>●</td>
<td>❄❄❄❄❄</td>
</tr>
<tr>
<td>I</td>
<td>Input substitution</td>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>IF</td>
<td>Feedstock change</td>
<td>EHH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>IFM</td>
<td>Alternative materials (for clinker production)</td>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>IE</td>
<td>Input energy change</td>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>IEF</td>
<td>Fuel diversification (alternative/secondary fuels)</td>
<td>ERE</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>IER</td>
<td>Renewable energy (fuel and electricity)</td>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td>P</td>
<td>Product development</td>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>PP</td>
<td>Improve existing products</td>
<td>EHH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>PPC</td>
<td>Clinker substitution (alternative materials)</td>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>PPB</td>
<td>Improve blended cements’ properties</td>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>PN</td>
<td>Develop new products</td>
<td>ERE</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>PNC</td>
<td>Clinkerless/no-calcine cement</td>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td>S</td>
<td>External synergies</td>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>SE</td>
<td>CO2 and heat solutions</td>
<td>EHH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>SEC</td>
<td>Carbon sequestration/carbon capture and storage</td>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>SEB</td>
<td>Biological production</td>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>SEH</td>
<td>Synergistic heating</td>
<td>ERE</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>SI</td>
<td>Process integration and industry initiatives</td>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>SIW</td>
<td>Integration/co-location with waste treatment</td>
<td>EHH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
<td>ERE</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>SIC</td>
<td>Synergies among already co-located firms</td>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td>M</td>
<td>Management</td>
<td>EEE</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>MB</td>
<td>Environmental strategy and innovation approaches</td>
<td>EHH</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>MM</td>
<td>Marketing, education, and public relations</td>
<td>ER</td>
<td>Resource recovery</td>
</tr>
<tr>
<td>MS</td>
<td>Standards and specifications</td>
<td>ERH</td>
<td>Pre-heating/drying</td>
</tr>
<tr>
<td>MS</td>
<td>Standards and specifications</td>
<td>ERE</td>
<td>Recycle/reuse</td>
</tr>
<tr>
<td>MS</td>
<td>Standards and specifications</td>
<td>ERP</td>
<td>Pollution prevention and control</td>
</tr>
</tbody>
</table>

*Code Category:
* Complexity of business approach:
* Technological Maturity:
* Technical and infrastructural applicability:
* Organizational applicability:
* Existing level of implementation:
* CO2 emission reduction potential:
* Other impacts:

- ** low
- *** low-medium
- **** medium
- ***** medium-high
- ****** high
Now that the results of the assessment are compiled and put together, it is possible to analyze them and look at them from different angles.

6.3.1 Currently implemented measures in Cluster West

Cluster West has been successful in implementing several CO₂ improvement measures in its cement production system. Examples of already implemented measures (high or medium) in Cluster West are (Figure 19):

1. **Pre-heating/drying (ERH) and thermal efficiency (EEH):** Kollenbach uses a 4-stage cyclone preheater kiln system (Table 23). 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 (EEH)) so that the specific thermal energy consumption for the clinker produced in Kollenbach become similar to typical 4-stage cyclone pre-heater kiln systems (Table 4 and Table 29).

2. **Clinker substitution (PPC) and improved blended cements properties (PPB):** Cluster West is extensively applying clinker substitution strategy and produces various blended cement products. The main clinker substitute material in the Cluster West is granulated blastfurnace slag (GBFS) which is used in the slag cement products (CEM III). The clinker substitution rate has been constantly increasing in the last decade. The clinker-to-cement ratio for Cluster West portfolio cement has decreased about 44% since 1997 and in 2009 was about 42%. Although the clinker substitution is a highly implemented measure in the Cluster West, there is lot of room for further development of this measure. These improvements can be achieved by either producing more blended cements (ex. by influencing the market), or by using other materials as clinker substitutes.

3. **Fuel diversification (IEF):** Major part of the fuel demand of Cluster West is for the Kollenbach plant, which has a cement kiln. Wide array of alternative fuels are used in this plant and the trend is increasing. The share of secondary fuels from total fuels energy in Cluster West is higher than European average and in 2009 was about 65% (Table 29 in Appendix). Again, although Cluster West already has high alternative fuel usage, there are still many opportunities for further development in this area.

4. **Renewable energy (IER):** About 40% of the thermal energy of Cluster West is provided by fuels with biogenic sources (alternative fuels with biogenic fractions in their composition). Improving the share of biogenic fuels (and other renewable energy sources) will bring further opportunities for improving CO₂ emissions.

Although these measures are highly implemented in Cluster West, there are still place for improvement. The clinker substitution rate of the average Cluster West cement (portfolio cement) can become higher, more alternative fuels can be used, more biogenic fuels and renewable energy can be utilized, and energy recovery measures such as co-generation (ERE) can be implemented.

6.3.2 Material and energy flows of Cluster West and the implemented CO₂ improvement measures
Another way of looking at various CO₂ improvement measures in Cluster West is to organize them according to the material and energy streams that they are addressing. In other words, it is interesting to know, which input and output streams of Cluster West cement production system are affected by the implemented CO₂ improvement measures?

In order to see how the already implemented CO₂ emission reduction measures are related to cement production material and energy streams, the simplified cement production model (defined previously in section Figure 8) is considered. Inspired by the principles of Industrial Ecology this model does not recognize any “waste” and assumes all input and output streams are consisted of useful resources such as feedstock, fuel, products, or byproducts for cement production or other industrial processes. CO₂ improvement measures and their existing level of implementation in the Cluster West are overlaid (or mapped) onto this model (Figure 16)

*Figure 16. “Existing level of implementation of CO₂ improvement measures in the Cluster West” and the simplified cement production model*

By this mapping (Figure 16), it is possible to observe that most of the measures which demand “external synergies” are not implemented in the Cluster West. These measures have relatively
low technological maturity and require complex business approaches, which in most cases are identified as forms of Industrial Symbiosis at higher levels.

The only measure in the category of “external synergies” which is implemented in Cluster West is “synergies among already co-located firms” (SIC). This is due to the cooperation between Schwelgern plant (part of Cluster West) and the co-located steel producing plant. Based on this agreement, the slag is upgraded on-site into granulated blastfurnace slag (GBFS) prior to shipment to Schwelgern. In addition to this main cooperation, the steel plant provides gas fuel for Schwelgern plant.

6.3.3 High potential CO₂ improvement measures implemented in Cluster West

Figure 17 shows the relation between the “existing level of implementation” of the measures and their “CO₂ emission reduction potential”. Measures such as “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 may be considered as high priority.
Among the least implemented, but most promising measures, the followings can be highlighted:

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

### 6.3.4 Applicable measures for Cluster West

Based on the result of the assessment, the most applicable measures for implementation in the Cluster West can be identified. Aspects that can be considered are “organizational applicability”, “technical and infrastructural applicability” and the “existing level of implementation” (Figure 18).
Figure 18. “Organizational applicability” and “Existing level of implementation in the Cluster West” for various CO₂ improvement measures

Measures that have high level of applicability from organizational perspective but are not yet implemented in the Cluster West are co-generation (ERE), using renewable energy (fuel and electricity) (IER) and reducing the temperature required for clinker production (IFC).

And if technical and infrastructural situation improves, measures such as using alternative materials for clinker production (IFM), using most alternative fuels (IEF), improving electrical and thermal efficiency (EEE and EEH) are also applicable for implementation in the Cluster West.
7 DISCUSSION

Large cement producing companies such as CEMEX have different operating plants in various locations of the world operating in different contexts. It is essential for these companies to systematically search for various CO\textsubscript{2} improvement measures, identify the most “effective”, “applicable”, and “feasible” ones, and define goals and strategies for materializing the envisioned potentials. The assessment framework provided in this thesis, can be used for such applications.

Here the results of the assessment (Part I and II) are discussed from two perspectives. The discussion about Cluster West and a general discussion about future of CO\textsubscript{2} improvement measures from cement industry.

7.1 Discussion on CO\textsubscript{2} improvement options for Cluster West

Several decades of improvements has made Cluster West a cement production system, which is outstanding from many aspects. The Cluster West aims to use less fossil fuel; use less virgin materials, emit less CO\textsubscript{2}, and continue to produce qualified and competent cement products. The following points are worth to be discussed briefly:

- Consider the simplified cement production model (Figure 8). The study of materials and energy flows depicted in this model show that in the production system of Cluster West no significant solid waste streams is produced. Two major and potentially useful streams in this system are the excess heat and the CO\textsubscript{2} in the exhaust.
- The Cluster West (compared to European average) has high clinker substitution rates, and high degree of alternative fuels usage.
- Cluster West should increase efforts on the areas that are its strong points, such as improving the performance of blended cements (CEM III containing GBFS) to compete for larger market shares. This strategy can lead to production of more blended cements, therefore higher clinker substitution rates for the cement portfolio of Cluster West.
- Cluster West can consider not only increasing the rate of alternative fuels, but also prioritizing using carbon-neutral (such as many fuels waste-derived fuels with biogenic origins).

7.1.1 Existing level of Industrial Symbiosis in the Cluster West

In section 4.5.1, the concept of “complexity of business approach” was defined according to the scope of Industrial Symbiosis and the exchanges that are present in the production system under study. The relation between “complexity of business approach” and the “existing level of implementation in the Cluster West” for different measures is shown in Figure 19.
Most of the measures that have been implemented in the Cluster West have low complexity in their required business approach (i.e. lower types of Industrial Symbiosis). It is important to mention that some of the highly implemented measures in the Cluster West have high or medium level of complexity. Examples of such measures are clinker substitution (PPC), fuel diversification (IEF), and synergies among already co-located firms (SIC). This demonstrates the fact the Cluster West production system has already implemented forms of Industrial Symbiosis and is a relatively synergistic cement production system.

### 7.1.2 What can CEMEX learn from Cluster West?

Considering the performance indicators of the Cluster West (Table 29), it is obvious that Cluster West portfolio cement requires much less energy than clinker from Kollenbach clinker. This is due to clinker substitution by GBFS has much less CO₂ emissions compared to clinker. This shows the value and strength of a production system, which is not enclosed in “plant level” improvements and even, though internally, improves its overall performance through inter-plant exchanges and cooperation.

**Figure 19. “Complexity of business approach” and “existing level of implementation of various CO₂ improvement measures in Cluster West”**

![Diagram](image)
Cluster West has demonstrated considerable initiatives in harmony with the principles of Industrial Ecology and symbiosis. The production system in Cluster West (based on 2009 data) is a relatively synergistic already. Therefore transferring the organizational knowledge (regarding finding the sources of alternative fuels and using them; and clinker substitution) which has been developed in Cluster West and translate it into more generic approaches that can be utilized in many other contexts (such as other CEMEX cement production sites) is a great challenge and opportunity for CEMEX.

7.2 Future of CO₂ emission reduction measures in cement industry

On a general level, based on the result of Part I of the assessment (section 5) it is possible to speculate on the most viable measures for reducing CO₂ emissions from cement production. For this purpose, the relation between “CO₂ emission reduction potential” and “complexity of business approach” of the measures are considered in Figure 23.

![Figure 20. “Complexity of business approach” and “CO₂ emission reduction potential” of various improvement measures](image-url)
As it is depicted in this figure, most of the measures, which require both mature technologies, and less complex business approaches have low potential for CO₂ reduction. Most of such measures are occurring inside a production plant. 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 or plant or corporation 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 few exceptions (high potential and mature technologies) which worth mentioning:

- Clinker substitution (PPC) is a mature technology and has high CO₂ improvement potential.
- Improved blended cements’ properties (PPB)

More complicated solutions requiring more complex business approaches 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)
8 CONCLUSIONS

In this thesis a framework for assessing various CO₂ improvement measures for cement production was developed. This assessment framework is composed of two main parts. The first part of the assessment is designed for generic study of existing CO₂ improvement measures available in academic or industrial literature. The second part is designed to be applied on an actual cement-producing site and evaluate the feasibility of improvement measures for that site.

After development of this assessment framework, both parts of it were executed. A generic study of CO₂ improvement measures in cement industry was performed. In addition, Cluster West as an actual cement production system to be studied was sleeved.

The main findings and conclusions of this thesis are summarized in the following sub-headings:

8.1 Conclusions regarding the assessment framework

Most of the existing CO₂ emission, reduction measures are limiting their options to “system optimization”. Often the “system re-design” and “system innovation” measures are less considered, or at least are not systematically evaluated. The “system optimization” measures are important due to their incremental nature and relatively quick payback time. They are essential and their utilization and development must be continuously pursued. However, it is also important to look beyond those measures and consider radical innovations regarding improving CO₂ performance of cement production.

The framework developed in this thesis is based on the concepts of Industrial Ecology and Industrial Symbiosis and facilitates systematic collection, classification, and evaluation of wide range of CO₂ improvement measures for cement industry. This framework can be used in different ways. It can be used as a system for performing literature study and categorizing the state-of-the-art of CO₂ improvement measures for cement production. It can also be sued to assess individual cement production sites. The results of the generic study (Part I) of the assessment can be used for several site-specific assessments. Therefore, a large international company that has tens or hundreds cement production sites in many countries can use this assessment to evaluate CO₂ improvement options of all its cement production plants under a unified and standard framework (Figure 21).
Figure 21. The application of the framework in large cement producing companies with several cement production systems

For easier analysis of the results, a software tool (based on Microsoft Excel) is developed. Data regarding different steps of the assessment can be entered in this tool and it can be used for creating different diagrams and tables for further evaluation.

8.2 Conclusions of the generic assessment

- High potential CO2 improvement measures have to address one or more of the following emissions sources: (1) emissions due to calcination, (2) emissions due to incineration of fuels, and (3) emissions due to high-energy demand for cement production. The final method is to (4) replace CO2 emissions elsewhere. In the generic study of the CO2 improvement measures in cement production, the following measures were considered to have relatively high potential:
  - Group of measures that cause less usage of clinker such as clinker substitution, and improving the properties of blended cements.
  - Group of measures are focusing on producing new cement-like products, which does not require clinker.
  - Group of measures that do approach CO2 emissions by utilizing (or capturing) it when it exits the cement plant. These groups include carbon sequestration or capture and storage, using excess heat and CO2 for biological production, and
New and innovative measures such as production of clinkerless or no-calcine cement products, carbon sequestration or carbon capture and storage technologies, synergies involving producing biological products from the excess heat and CO₂ of cement plant may also be part of the vision of future cement production and are emerging.

8.3 Conclusions of the Cluster West assessment

Cluster West has already implemented many effective CO₂ improvement measures in its production system. In addition to improving the production efficiency of the plants themselves, Cluster West has extended its search for using alternative fuels and materials to the extent that has caused it to have a relatively high performance indicators in areas such as utilization of alternative fuels and the rate of clinker substitution. These efforts are in line with the visions of Industrial Ecology and symbiosis regarding the importance of viewing industrial activities in integration with surrounding industrial ecosystem.

However, there are still many opportunities for further development in Cluster West. The result of the assessment shows that Cluster West can improve its CO₂ emissions by:

- **Cement plant:** Increase production efficiency by improving the thermal efficiency of the kiln system (improving cooling system, adding more pre-heating stages, adding precalciner), or producing electricity from excess heat (co-generation).
- **Products:** Increase clinker substitution rate, improve properties of blended cements such as slag cement types (CEM III).
- **Inputs:** Use higher rates of renewable or carbon neutral fuels (such as fuels with higher biogenic fractions).
- **Other outputs:** Except the major cooperation with a neighboring steel manufacturing company (in Schwelgern plant) that exists in Cluster West, other measures related to external synergies are not developed yet in the Cluster West. Improvement in this area may require medium or long-term planning due to lack of existing organizational knowledge and level of implementation.
9 REFERENCES


Arundel, A., Kemp, R., Parto, S., 2006. 21 Indicators for environmental innovation: what and how to measure. The international handbook on environmental technology management 324.


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.


CEMEX-DE, 2010b. Data collected from CEMEX Germany Cluster West.


Fiksel, J., 2002. Substudy 5: Key Performance Indicators. WBCSD.


INECE, 2011. Training Course for Multimedia Inspectors, Section VII - Industrial Processes, Chapter 6 - Cement Industries.


LIU, 2011. CEMEX industrial ecology project.


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 CO2 emissions in the EU27 cement industry and the relationship with the capital budgeting decision criteria. Journal of Cleaner Production 19, 1207-1215.


PCA, 2008. Carbon Dioxide Control Technology Review.


Schneider, M., Romer, M., Tschudin, M., Bolio, H., 2011. Sustainable cement production--
present and future. Cement and Concrete Research 41, 642-650.
Seaden, G., 1996. Viewpoint: Economics of innovation in the construction industry. Journal of
Infrastructure Systems 2, 103.
Semadeni, M., 2003. Energy storage as an essential part of sustainable energy systems. CEPE
Working paper series.
170–182.
Renewable and Sustainable Energy Reviews 14, 2596-2610.
the Rate of Strength Development of Slag Cement.
Applied Thermal Engineering 26, 1420-1426.
Stolaroff, J.K., Lowry, G.V., Keith, D.W., 2005. Using CaO- and MgO-rich industrial waste
to portland cement. Clean Techn Environ Policy 12, 503-516.
336-338, 1895-1897.
Svensson, N., Roth, L., Eklund, M., Mårtensson, A., 2006. Environmental relevance and use of
energy indicators in environmental management and research. Journal of Cleaner
Production 14, 134-145.
Environment Program.
Manufacturing - background documentation [WWW Document].
from the portland cement industry.
USGS, 2005. Background facts and issues concerning cement and cement data. US Geological
Survey.
Zementwerke e.V.
Residues recycling: Reducing costs and helping the environment. JOM 62, 41-45.
cogeneration power plants in cement industry. Applied Energy 86, 941-948.


10 ACRONYMS

**BAT**: Best Available Technologies

**CP**: Cleaner Production

**EE**: Eco-efficiency

**IE**: Industrial Ecology

**IS**: Industrial Symbiosis

**ISO**: International Organization for Standardization

**KPI**: Key Performance Indicator

**LCA**: Life Cycle Assessment

**PF**: Primary fuels (Traditional Fuels, fossil fuels)

**RM**: Raw Meal

**SD**: Sustainable Development

**SF**: Secondary fuels, Alternative Fuels
11 GLOSSARY

**Aggregates:** Aggregates are sand and gravel, which are mined from quarries. They give ready-mix concrete its necessary volume and add to its overall strength. Under normal circumstances, one cubic meter of fresh concrete contains two metric tons of gravel and sand.

**Alternative Fuels:** refer to “secondary fuels”.

**Alternative Raw Materials:** Cementitious materials used as substitutes for conventional cement raw materials.

**Alternative Fuels and Raw Materials (AFR):** Inputs to cement production derived from industrial, municipal, and agricultural waste streams.

**By-product:** Secondary product of an industrial process.

**Calciner:** An air stream reactor that is connected between the rotary kiln and the cyclone preheater that makes it possible to already deacidify the kiln feed under optimum conditions upstream of the rotary kiln. To achieve this, up to 60% of the fuel is shifted from the rotary kiln burner to the calciner (CEMEX-DE, 2010d).

**Clinker:** Clinker is an intermediate cement product made by sintering limestone, clay, and iron oxide in a kiln at around 1,450 degrees Celsius. One tonne of clinker is used to make approximately 1.1 tonnes of gray Portland cement (CEMEX, 2011).

**Cyclone preheater:** A fuel saving process of producing cement clinker according to the dry method in which the raw meal passes through multiple cyclone stages arranged one above the other and is preheated to approximately 850 degC using the hot kiln exhaust gas (CEMEX-DE, 2010d).

**Fluffy materials:** Lightweight and high-caloric fractions of commercial or residential wastes (such as paper, cardboard, textiles, timber, plastics) that are suitable for the production of alternative fuels (CEMEX-DE, 2010d).

**Fossil fuel:** A general term for combustible geological deposits of carbon in reduced (organic) form and of biological origin, including coal, oil, natural gas, and oil shale.

**Granulated blastfurnace slag (GBFS):** Granulated blastfurnace slag (GBFS) is obtained by rapidly cooling (quenching) molten iron slag (which is a by-product of iron and steel manufacturing) from a blast furnace in water or steam, to produce a glassy, granular product that can be grounded into a fine powder which is called ground granulated blastfurnace slag (GGBFS).

**Greenhouse gases (GHG):** Greenhouse gases (GHG) absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H₂O),
carbon dioxide (CO$_2$), nitrous oxide (N$_2$O), methane (CH$_4$) and ozone (O$_3$) are the primary greenhouse gases in the Earth’s atmosphere (IPCC, 2007b)

**Kiln:** Large industrial oven for producing clinker used in manufacture of cement.

**Marl:** Sedimentation rock composting a mixture of clay and carbonates. If a deposit is favorable located, marl is an ideal raw material for cement production (CEMEX-DE, 2010d).

**Ordinary Portland Cement (OPC):** Cement that consists of approximately 95 percent ground clinker and 5 percent gypsum.

**Pyroprocessing:** Pyroprocessing is a process in which materials are subjected to high temperatures (typically over 800°C) in order to bring about a chemical or physical change. Calcination and sintering process in cement kiln are examples of pyroprocessing.

**Ready-mix concrete:** Ready mix concrete is a mixture of cement, aggregates, and water that is manufactured in a plant, according to a certain recipe, and then delivered to customer by truck mounted transit mixers (CEMEX, 2011).

**Secondary Fuels (Alternative Fuels):** Energy containing wastes used to substitute for conventional thermal energy sources. (Fiksel, 2002)

**Waste:** A by-product material having no or minimal economic value derived from a process or activity.

*Note:* Glossary definitions are from various sources and references (Fiksel, 2002; CEMEX, 2011).
12 APPENDIX

12.1 Introduction to Cleaner production and Eco-efficiency

Eco-efficiency (EE) is a preventive environmental management strategy that seeks “the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the Earth’s carrying capacity” (WBCSD, 2000). EE strategies demand manufacturing, trade, and service sectors to decrease their material intensity, energy intensity, dispersion of toxic substances while increasing their recyclability, use of renewables, product durability, and service intensity. In summary EE have three main goals (WBCSD, 2000):

EE goal#1 – Decrease the consumption of resources

EE goal#2 – Decrease impact on nature

EE goal#3 – Increase product or service value

Another environmental management concept, which is relatively close to EE, is cleaner production that is defined as “continuous application of an integrated preventative environmental strategy to processes, products, and services to increase efficiency and reduce risks to humans and the environment” (UNEP, 1994). Five prevention measures aimed by CP are product modification, input substitution, technology modification and plant improvement, good housekeeping, and reuse/recovery/recycling.

EE and CP can be seen as two relatively close and complementary concepts. CP is more oriented toward “operational side of business (production)” while EE is focuses on “strategic side of business (value creation)” (Van Berkel, 2007b).

12.2 Introduction to Industrial Ecology

Industrial ecology (IE) is a discipline that is formed around the idea of looking at industrial systems as a form of ecosystem. Although general understanding of the concept can be as old as 300 hundred years, the official birth of “Industrial Ecology” is an article by Frosch and Gallopolos (1989) when they defined the concept of industry ecology as:

“In an industrial ecosystem the traditional model of industrial activity, in which individual manufacturing take in raw materials and generate products to be sold plus waste to be disposed of, is transformed into a more integrates system, in which the consumption of energy and materials is optimized and the effluents of one process serve as the raw material for another process.”

Graedel and Allenby (2003) describe the essence of Industrial Ecologyas:

“Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and
technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.”

And finally according to Boons & Howard-Grenville (2009) Industrial Ecology is:

“Industrial ecology is the study of the material and energy flows resulting from human activities. This study provides the basis for developing approaches to close cycles in such a way that ecological impact of these activities is minimized.”

In Industrial Ecology the concept of “waste” is not welcomed. Waste is a useless or worthless material; however, in nature (the source of inspiration for IE) no material is permanently unusable and eventually all materials are somehow reused. Therefore, according to Industrial Ecology “wastes” are potentially useful “residues” which we have not yet learned to use efficiently (Graedel and Allenby, 2003).

Industrial Ecology concept can be applied to various scales. It can focus on individual products and study their environmental impacts through various stages of their life cycle. Industrial Ecology can also study the production site of those products. Raw and processed materials along with energy are going into the plant and products along with residues and various emissions to land, water and air and low-grade energy forms such as heat and noise are leaving the plant. Industrial Ecology studies such a manufacturing plant by quantifying and budgeting its input and output streams and identifying solutions to minimize unwanted residues and emissions by recycling them internally or by feeding them into another facilities. (Figure XX) In full scales, Industrial Ecology can be even applied to the entire economic activities (Graedel and Allenby, 2003).
Figure 22 – Industrial Ecology seeks system improvement by considering “all” input and output streams and discarding the notion of “waste”

In the last two decades, the discipline of Industrial Ecology has grown considerably as an umbrella for many subjects, methods, and concepts, which have emerged inside this field. Industrial Ecology provides substantial set of concepts and tools for the “study of the flows of material and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, and social factors on the flow, use, and transformation of resources” (Allenby, 1994).

12.3 Introduction to Industrial Symbiosis

Industrial Symbiosis (IS) as a key concept in the field of Industrial Ecology (IE) promotes cyclical flows of energy (based on the energy principle), materials, by-products, utilities, and other types of resources via business networks, which are trying to approach sustainable industrial activities through increased cooperation (Chertow and Lombardi, 2005). The collective and collaborative approach by “traditionally separate” by “geographically close” entities with aim of utilizing synergistic possibilities is a key element of Industrial Symbiosis (Chertow, 2000).

As mentioned before, Industrial Ecology can be applied at various spatial scopes: facility or firm-level, inter-firm level, and regional or global level. Industrial Symbiosis is one of the ways that Industrial Ecology at inter-firm level operates as depicted in figure XX (Chertow, 2000).
Industrial Symbiosis consists of local/regional exchanges among different entities that yield a collective benefit greater than the sum of the individual benefits that could be achieved by acting alone. It is often assumed that these symbiotic relationships provide environmental benefits, however only rarely these benefits have been carefully evaluated (Chertow, 2007).

Chertow (1999) identifies five types of material exchange patterns as follows:

**Type 1- through waste exchange:** While potentially beneficial in accomplishing various input/output savings, these approaches are not identified as IS, because in most of the cases they are one-way relations happening at the end-of-life stages. They tend to occur on a trade-by-trade basis and not consciously.

**Type 2- inside a facility or firm:** Several forms of material exchange can happen inside large organizations and although they are happening internally, they can similar to multi-firm (or inter-firm) forms of IS. The larger organization can significantly benefit from these internal symbiotic material exchanges.

**Type 3- between firms, which are co-located in a defined eco-industrial park:** Various forms of energy, water, material, information, service, and utility exchanges between several firms or organizations that are located inside the borders of a defined industrial park or with “over the fence” partners.

**Type 4- between local firms, which are not co-located:** These exchanges are happening between firms located within an area. They are not particularly inside a well-defined industrial

![Figure 23 – Relation of Industrial Symbiosis with Industrial Ecology](image-url)
park (like type 3 Industrial Symbiosis), but considering their relative geographical nearness, seek to benefit from the already generated material, energy, or other streams.

**Type 5- between firms, which are virtually organized across a wider region:** Synergistic collaborations can be shaped beyond co-located (type 2) or local (type 3) firms and expand into include regional economic actors. This allows wider options for by-product exchange and can lead to formation of virtual networks of diverse types of industries.

### 12.4 Industrial Ecology and Symbiosis and levels of sustainability

Industrial Ecology and Symbiosis can be viewed in the context of sustainability. In order to be able to organize various environmental management efforts it is important to have an overall vision of how different approaches can contribute towards sustainability of the system of interest. From operational perspective (and not necessarily from value generation perspective) four levels of sustainability can be identified. First: (1) cleaner production (Baas, 2005) and eco-efficiency, (2) product and service system (PSS) (Sakao and Lindahl, 2009) and eco-effectiveness, (3) Industrial Ecology and symbiosis (Chertow, 2000; Baas, 2005; Wolf and Petersson, 2007), and (4) sustainability and renewable energy. These levels and short description of each are summarized in Table 26.

**Table 26. Levels of sustainability and environmental management concepts**

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
<th>Spatial scope</th>
<th>Temporal scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cleaner production and eco-efficiency</td>
<td>Cleaner production (Baas, 2005) strategies such as good-housekeeping, process and product improvement, risk reduction, de-materialization and efficient use of material and energy.</td>
<td>micro</td>
<td>short term</td>
</tr>
<tr>
<td>2</td>
<td>Product service system and eco-effectiveness</td>
<td>Broader perspective on products, their function and need through (re)design and service systems (Sakao &amp; Lindahl, 2009), cradle-to-cradle concept and design (McDonough &amp; Braungart, 2002) such as closing loops, or substitution of toxic materials.</td>
<td>micro-meso</td>
<td>short-medium term</td>
</tr>
<tr>
<td>3</td>
<td>Industrial ecology and symbiosis</td>
<td>Inter-firm integration, synergistic collaborations, and optimization by exchanging various forms of energy, water, material, information, service, and utility exchanges (Chertow 2000; Baas 2005; Wolf &amp; Petersson 2007).</td>
<td>meso-macro</td>
<td>medium-long term</td>
</tr>
<tr>
<td>4</td>
<td>Sustainability and renewable energy</td>
<td>Large scale utilization of renewable sources of energy and macro-level dissemination of social, economic, and environmental aspects of sustainability.</td>
<td>macro</td>
<td>long term</td>
</tr>
</tbody>
</table>

It is important to re-emphasize that there are overlapping areas between these key environmental management concepts. These concepts do not have clear-cut borders or scopes and tend to diffuse into several spatial and temporal scales. Therefore, promoting higher levels of sustainability does not mean that other approaches in lower levels of sustainability are less important or less necessary. In fact, in the vision of sustainability, all of these levels must be considered, each applied on different temporal or spatial scope (Figure 24).
Therefore, environmental management concepts are neither contradicting each other nor coming in sequential order. They can disseminate and develop concurrently and complement each other. For instance, meso-level dissemination of Industrial Ecology or symbiosis does not negate the importance of micro-level strategies of cleaner production and eco-efficiency. It may be useful to consider that these concepts are developed along each other, on top of each other, and into each other in various spatial and temporal scopes.

12.5 Cluster West site visit

Summary of main points and findings which were noticed during site visit are available in the following table:
### Table 27 - Summary of Cluster West site visit

<table>
<thead>
<tr>
<th>Plant</th>
<th>Topic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kollenbach</td>
<td>Bypass dust</td>
<td>In Cluster West, bypass dust is not considered as waste and is used in the production of intermediate or final products.</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Surrounding environment</td>
<td>The plant is located near the city of Beckum (less than 40000 inhabitants). Few other cement plants exist in the area; however, there is no other major industry in the nearby areas of the plant.</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Raw materials</td>
<td>Almost all of the required raw materials for cement production in Kollenbach plant is from quarries with less than 50km distance.</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Alternative fuels</td>
<td>Large share of required fuel energy is from alternative fuels mainly refused derived wastes (RDF) (such as different types of fluffy Materials), animal meal, shredded tyres, and etc.</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Alternative fuels</td>
<td>Year 2000 was a turning point in Kollenbach regarding use of AFR. They were used before since 1980s (In 1985 they were using about 5-10 % alternative fuels) however in 2000 new modifications lead to much wider usage of AFR. There are many parameters involved to make a certain material a usable AFR and these parameters may not be constant in time. For instance, the sudden availability of animal meat and bone was due to spread of mad cow disease in Europe that led to slaughtering lots of cattle. The future availability of these types of fuels may not be same due to potential changes in the price or demand or etc.</td>
</tr>
<tr>
<td>Cluster West</td>
<td>wastes</td>
<td>Except wasted heat and CO₂ emissions in the exhaust, there is no other considerable (relatively) waste stream generated from the production process.</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Waste heat</td>
<td>Main sources of waste heat are the vicinity of kiln (high temperature) and cooling system (mid-temperature) and pre-heater tower (low temperature).</td>
</tr>
<tr>
<td>Kollenbach</td>
<td>Waste heat</td>
<td>City of Beckum’s municipality does not have interest (or financial means) and the infrastructure for district heating and it is also non-existing; therefore, it would require CEMEX to take large part of the share in the</td>
</tr>
</tbody>
</table>
development of using waste heat in district heating project. However, as the core business of CEMEX is producing cement they are not willing to lose focus. Part of gypsum required in the production of cement is replaced by “REA gypsum” which is a byproduct of coal powered power plants desulphurization system.

<table>
<thead>
<tr>
<th>Location</th>
<th>Exchange</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kollenbach</td>
<td>Exchanges</td>
<td></td>
</tr>
<tr>
<td>Schwelgern</td>
<td>Surrounding environment</td>
<td>The plant is located inside Thyssen Krupp Steel plant.</td>
</tr>
<tr>
<td>Schwelgern</td>
<td>Surrounding environment</td>
<td>The plant is located near the Rhine river in a heavily industrial area. Many power plants and heavy industries (such as steel) are in the area.</td>
</tr>
<tr>
<td>Schwelgern</td>
<td>Exchanges</td>
<td>The plant is using coke gas from the neighboring steel plant. This fuel is used for drying the GBFS received from steel plant.</td>
</tr>
<tr>
<td>Schwelgern</td>
<td>Exchanges</td>
<td>The plant is continuously receiving the slag from iron production in granulated form (GBFS). These GBFS is used in Schwelgern and Dortmund plants for production of different types of slag cements (CEM III).</td>
</tr>
</tbody>
</table>
### 12.6 Workshop in Cluster West office

Summary of the ideas provided by attendees in the CEMEX workshop.

*Table 28 – List of CO₂ emission reduction measures proposed during Cluster West workshop*

<table>
<thead>
<tr>
<th>Description of measure</th>
<th>Category</th>
<th>Sub-category (code)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce thermal heat consumption by improving heat recovery in clinker cooler.</td>
<td>Production efficiency</td>
<td>Thermal efficiency (EEH)</td>
</tr>
<tr>
<td>Produce electricity from waste heat.</td>
<td>Resource recovery</td>
<td>Co-generation (ERE)</td>
</tr>
<tr>
<td>Make use of residue materials captured in exhaust filters.</td>
<td>Resource recovery</td>
<td>Recycle/reuse (ERR)</td>
</tr>
<tr>
<td>Use other alternative materials</td>
<td>Input substitution</td>
<td>Alternative materials for clinker production (IFM), clinker substitution (PPC)</td>
</tr>
<tr>
<td>Reduce dependency on single alternative material such GBFS</td>
<td>Input substitution</td>
<td>Clinker substitution (PPC)</td>
</tr>
<tr>
<td>Use more alternative fuels</td>
<td>Input energy change</td>
<td>Fuel diversification (IEF)</td>
</tr>
<tr>
<td>Use fuels with higher renewable or carbon neutral fractions.</td>
<td>Input substitution</td>
<td>Renewable energy (IER)</td>
</tr>
<tr>
<td>Develop admixtures to reduce clinker factor</td>
<td>Product development</td>
<td>Improve blended cements’ properties (PPB)</td>
</tr>
<tr>
<td>Develop admixtures to improve blended cements.</td>
<td>Product development</td>
<td>Improve blended cement’s properties (PPB)</td>
</tr>
<tr>
<td>Carbonization of construction and demolition waste concrete (C&amp;D wastes) by using CO₂ from plant.</td>
<td>External synergies</td>
<td>Carbon sequestration (SEC)</td>
</tr>
<tr>
<td>Utilize synergies (wastes, heat, CO₂, etc.) for producing biogas.</td>
<td>External synergies</td>
<td>Biological production (SEB), integration with waste treatment plant (SIW), synergies among co-located firms (SIC)</td>
</tr>
<tr>
<td>Produce bio-products or CO₂ products from waste CO₂.</td>
<td>External synergies</td>
<td>Biological production (SEB)</td>
</tr>
<tr>
<td>Use CO₂ and heat to produce biomass and use the biomass as fuel (close the loop).</td>
<td>External synergies</td>
<td>Biological production (SEB)</td>
</tr>
<tr>
<td>Instead of allowing heat to go to air, send it down to be stored in ground water aquifer.</td>
<td>External synergies</td>
<td>Synergistic heating (SEH)</td>
</tr>
<tr>
<td>Co-location of large-scale municipal waste-</td>
<td>External synergies</td>
<td>Integration with waste</td>
</tr>
<tr>
<td>Description of measure</td>
<td>Category</td>
<td>Sub-category (code)</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------------------</td>
<td>-------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>to-energy gasification plant and cement plant. Produce lean gas as kiln fuel as well as</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electricity for plant.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco-marketing of products to support improving product portfolio.</td>
<td>Management</td>
<td>Marketing, education, and public relations (MM)</td>
</tr>
<tr>
<td>Increase public awareness about various properties of different cement types.</td>
<td>Management</td>
<td>Marketing, education, and public relations (MM)</td>
</tr>
<tr>
<td>Use waste heat to dry raw materials and inlet fuels.</td>
<td>Production</td>
<td>Pre-heating/drying (ERH)</td>
</tr>
<tr>
<td>Improve blended cements such as CEM III while maintaining same performance as CEM I</td>
<td>Product</td>
<td>Improve blended cements’ properties (PPB)</td>
</tr>
<tr>
<td>(for example from early age strength development perspective).</td>
<td>development</td>
<td></td>
</tr>
<tr>
<td>CO₂ capture by calcine looping in synergy with power plant integration.</td>
<td>External synergies</td>
<td>Integration with power plant (SIP)</td>
</tr>
<tr>
<td>Produce new types of clinker and/or modify input raw materials to increase their</td>
<td>Input substitution</td>
<td>Low temperature clinker production (IFC)</td>
</tr>
<tr>
<td>combustion properties in order to achieve calcination and clinkerization at lower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperatures.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

12.7 Performance of cement production in the Cluster West

In order to summarize the performance of the cement production in Cluster West, a few key performance indicators (KPI) are considered and calculated:

- **Specific thermal energy consumption** (MJ/tonne): total amount of thermal energy required for production of one tonne of cement.
- **Specific electricity consumption** (kWh/tonne): total amount of electrical energy required for production of one tonne of cement.
- **Clinker-to-cement ratio** (tonne clinker/tonne cement): share of clinker in the cement product.
- **Share of secondary fuels from total fuels energy** (MJ/MJ): the fraction of the energy of the fuels that is coming from alternative fuels. The energy content of all alternative fuels used in the Cluster West (in 2009) were calculated and divided to the total energy content of all the fuels. Alternative fuels used in Cluster West are primarily used in Kollenbach plant as kiln fuel (Table 24).
- **Share of biogenic fuels from total fuels energy** (MJ/MJ): the fraction of the energy of the fuels that is coming from biogenic sources and therefore is considered carbon-neutral
in this report. The biogenic share of alternative fuels used in Cluster West is related to their composition and the type of wastes that they are derived from. This information was extracted from CO2 reporting of Cluster West to authorities.

- **Lifecycle CO\textsubscript{2} emissions (kg\textsubscript{CO2-eq}/tonne\textsubscript{cement})**: total amount of greenhouse gases (excluding the biogenic emissions) emitted during different phases of lifecycle of cement (cradle-to-gate\textsuperscript{14}).

These KPIs are calculated for the all the three plants inside the Cluster West. As the Cluster West produces several types of cement products, in order to make the calculations of KPI for possible, a pseudo product called “Cluster West portfolio cement” is defined. The KPIs for Cluster West (and for the clinker produced in the Kollenbach plant) are presented in Table 29. For comparison, similar KPIs for other countries are also presented.

**Table 29. Key performance indicators for the Cluster West cement production system and few other countries/regions**

<table>
<thead>
<tr>
<th>KPI</th>
<th>CEMEX Germany</th>
<th>Others (clinker or OPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kollenbach clinker 2009</td>
<td>XCW portfolio cement 2009</td>
</tr>
<tr>
<td>Specific thermal energy consumption (MJ/tonne)</td>
<td>3,915</td>
<td>1,782</td>
</tr>
<tr>
<td>Specific electricity consumption (kWh/tonne)</td>
<td>69</td>
<td>112</td>
</tr>
<tr>
<td>Clinker-to-cement ratio (Kg/Kg)</td>
<td>100%</td>
<td>42%</td>
</tr>
<tr>
<td>Share of secondary fuels from total fuels energy (M/M)</td>
<td>67%</td>
<td>65%</td>
</tr>
<tr>
<td>Share of biogenic fuels from total fuels energy (M/M)</td>
<td>41%</td>
<td>40%</td>
</tr>
<tr>
<td>CO\textsubscript{2} emissions (clinker production) (kg\textsubscript{CO2}/tonne)</td>
<td>840\textsuperscript{f}</td>
<td>990\textsuperscript{f}</td>
</tr>
<tr>
<td>Lifecycle CO\textsubscript{2} emissions (cradle-to-gate) (kg\textsubscript{CO2-eq}/tonne)</td>
<td>850\textsuperscript{f}</td>
<td>385\textsuperscript{f}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Ziegler et al. 2006
\textsuperscript{b} Ali et al. 2011
\textsuperscript{c} WBCSD 2002
\textsuperscript{d} LIU 2011
\textsuperscript{e} Clinker (Ecoinvent 2010)

\textsuperscript{14} In lifecycle study of a product, the term cradle-to-gate refers to studying different phases of its life cycle including extraction of raw materials, processing the materials, and production of the product. The full lifecycle study that is often referred to as cradle-to-grave study includes additional stages such as distribution, use, repair and maintenance, and recycling or final disposal.

12.8 Gross list of CO\textsubscript{2} emission reduction measures (unclassified list)

**Table 30 – Gross list of ideas for improvement of cement production**

---

\textsuperscript{14} In lifecycle study of a product, the term cradle-to-gate refers to studying different phases of its life cycle including extraction of raw materials, processing the materials, and production of the product. The full lifecycle study that is often referred to as cradle-to-grave study includes additional stages such as distribution, use, repair and maintenance, and recycling or final disposal.
<table>
<thead>
<tr>
<th>Category Code</th>
<th>Description</th>
<th>Primary Focus</th>
<th>Remarks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEE</td>
<td>Improve milling of finish products: Grind slag and clinker separately, then mix them together. Use roller mill.</td>
<td>Internal</td>
<td></td>
<td>(Liu &amp; Li, 2009)</td>
</tr>
<tr>
<td>EEE</td>
<td>Increase electrical efficiency: Implementing variable speed drive (VSD) for Low Tension (LT) and High Tension (HT) motors reduces wasting of energy.</td>
<td>Internal</td>
<td></td>
<td>(Thirugnanasambandam et al., 2011)</td>
</tr>
<tr>
<td>EEH</td>
<td>Improve thermal efficiency of kiln by adding a secondary shell around kiln surface</td>
<td>Internal</td>
<td>About 12% of total input energy can be saved.</td>
<td>(Engin &amp; Ari, 2005)</td>
</tr>
<tr>
<td>EEH</td>
<td>Reduce thermal heat consumption by improved heat recovery in clinker cooler.</td>
<td>Internal</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>ERH</td>
<td>Use waste heat to dry raw materials and inlet fuels.</td>
<td>Internal &amp; Output</td>
<td>In a case in Jordan it is proposed to use this heat for warming the heavy oil (fuel), the same concept can be applied for drying the fuels.</td>
<td>(CEMEX, 2011; Engin &amp; Ari, 2005; Al-Hinti et al., 2008)</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat.</td>
<td>Internal &amp; Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat by TE solid state heat engine.</td>
<td>Internal &amp; Output</td>
<td>The parameter $Z$ is the square of the Seebeck voltage per unit of temperature, multiplied by the electrical conductivity and divided by the thermal conductivity, and $T$ is the absolute temperature. In today's best commercial TE cooling/heating modules, $ZT$ is about 1.0. $ZT$ about 2 is required in order to be effective in cement waste heat recovery.</td>
<td>(Hendricks &amp; Choate, 2006; Bell, 2008)</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat by WHRSG.</td>
<td>Internal &amp; Output</td>
<td>About 30% of the electricity requirement of the plant and a 10% improvement in the primary energy efficiency of the plant. Payback time is 2 years. Major heat loss sources are kiln exhaust (19.15% of total input), cooler.</td>
<td>(Khurana et. al., 2002; Engin &amp; Ari, 2005)</td>
</tr>
<tr>
<td>Category code</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
<td>---------------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat by using Kalina cycle (Kalina process)</td>
<td>Internal &amp; Output</td>
<td>Due to low temp. of waste heat (200-400°C), efficiency is limited to 20-25%. 10 KWh/tonne of clinker from cooler waste air and 9-12 KWh/tonne clinker from kiln gasses = 22 KWh/Tonne of clinker</td>
<td>(Kalina &amp; Leibowitz, 1989; Mirolli, 2005; Wang et. al., 2009; Kalina, 2010)</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat by using organic rankine cycle (ORC)</td>
<td>Internal &amp; Output</td>
<td>29.1% CO2 reduction (related to electricity used in plant) and 2.63% related of total CO2 produced. example: converting 18% of cooler exhaust waste heat to electricity.</td>
<td>(Legmann, 2002)</td>
</tr>
<tr>
<td>ERE</td>
<td>Produce electricity from waste heat by cryogenic power generation cycle</td>
<td>Internal &amp; Output</td>
<td></td>
<td>(Wei-ping, 2007; Qiang et al., 2004)</td>
</tr>
<tr>
<td>ERR</td>
<td>Make use of residue materials captured in exhaust filters.</td>
<td>Internal &amp; Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>IFC</td>
<td>Produce new types of clinker and/or modify input raw materials to increase their combustion properties in order to achieve calcination and clinkerization at lower temperatures.</td>
<td>Input&amp;Internal</td>
<td>For instance it has been demonstrated that by applying combustion synthesis techniques the temperature requirement for clinker production can be decreased to about 1200°C. (Zapata, Bosch, 2009)</td>
<td>(CEMEX, 2011; Zapata, Bosch, 2009)</td>
</tr>
<tr>
<td>Category</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>---------------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>IFC, IEF</td>
<td>Use spent-pot-lining (SPL) waste from aluminum industry as coal-admixture.</td>
<td>Input</td>
<td>It has to be crushed properly and mixed with coal/coke. Ad the result of flour and carbon content, clinker production benefits from various aspects. Main is clinker is produced at lower temperature (80°C less). (Mikša, 2003; Venancio et al., 2010)</td>
<td>(Mikša et al., 2003; MES, 2007; Venancio et al., 2010)</td>
</tr>
<tr>
<td>IFM</td>
<td>Recycle/reuse concrete: Use concrete crusher sand as an alternative material in cement clinker manufacture. The chemical composition of the concrete crusher sands clearly indicates that these materials can primarily be utilized as a substitute for sand, and can account for an average of 3% of a typical raw material mix.</td>
<td>Input</td>
<td>list of more AFR is presented</td>
<td>(Schneider, 2011)</td>
</tr>
<tr>
<td>IFM</td>
<td>Use paper sludge waste to create blended cement.</td>
<td>Input</td>
<td></td>
<td>García, R. et al., 2008</td>
</tr>
<tr>
<td>IFM, PPC</td>
<td>Gas quenching (by nitrogen) steel slag in order to produce cement usable byproduct</td>
<td>Input</td>
<td></td>
<td>Long, Y. et al., 2011</td>
</tr>
<tr>
<td>IFM, SIW</td>
<td>Use cement kiln as scavanger of toxic organic materials, or hazardous elements. By &quot;selective removal of of Hg from exhaust gas&quot; or by both &quot;selective extraction of hazardous compounds from non-product outputs and forced extraction of unwanted substances from inputs&quot; can be even better.</td>
<td>Input</td>
<td></td>
<td>(Reijnders, 2007)</td>
</tr>
<tr>
<td>IEF</td>
<td>Use fly ash from large scale fluidised-bed (FB) biomass gasification plant as alternative fuel in the cement kiln.</td>
<td>Input</td>
<td></td>
<td>(Gómez-Barea et al., 2009)</td>
</tr>
<tr>
<td>IER</td>
<td>Use other alternative materials and not be too dependent on GBFS.</td>
<td>Input</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>IER</td>
<td>Use incineration ash residues as secondary material for clinker (MSWI fly and bottom ash, sewage sludge ash)</td>
<td>Input</td>
<td>More than 44% of MSW ash with the addition of very small amounts of silica and iron oxide can be used to produce cement clinkers. The amount of CaCO3 necessary to produce clinkers (approximately 50%) is also smaller than the same required for the conventional process (more than 70%). (Saikia, 2007)</td>
<td>(Lam et al., 2010)</td>
</tr>
<tr>
<td>Category Code</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>IER</td>
<td>Use more alternative fuels with higher renewable or carbon neutral fractions.</td>
<td>Input</td>
<td>Emissions from calcination is not reduced, however less fuel is required for kiln.</td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>IER</td>
<td>Use solar energy for calcinating limestone.</td>
<td>Input</td>
<td></td>
<td>(Meier et al., 2004, 2006; CEMEX, 2011)</td>
</tr>
<tr>
<td>PPC</td>
<td>Blended cements: substitute clinker with mineral components such as ground granulated blastfurnace slag or fly ash.</td>
<td>Internal &amp; Output</td>
<td></td>
<td>(Boesch &amp; Helliweg)</td>
</tr>
<tr>
<td>PPC, PPB</td>
<td>Develop admixtures to reduce clinker factor and improved blended cements</td>
<td>Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>PPB</td>
<td>Improve GBFS addition while maintaining same performance as CEM I (eg. from early age strength development perspective).</td>
<td>Internal &amp; Output</td>
<td>Improve GBFS cements: Improve early strength development of &quot;GBFS based binders&quot; by adding small quantities of gypsum and Anhydrite II. (adding these binder does not affect the later strength of cement)</td>
<td>(CEMEX, 2011; O’Rourke et al., 2009)</td>
</tr>
<tr>
<td>PPB</td>
<td>Mechanically activate GBFS in order to allow increased share of GBFS is slag cement without compromising on early strength development.</td>
<td>Input</td>
<td></td>
<td>Kumar, S. et al., 2008</td>
</tr>
<tr>
<td>PPB</td>
<td>Use spend catalyst from oil-cracking refineries as supplementary cementing material</td>
<td>Input, internal fluid catalytic-cracking catalyst (FCC)</td>
<td></td>
<td>(Antiohos et al., 2006)</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce cement based on MgO and special mineral additives. It requires lower temperature processing and causes less CO2 emissions. The cement hardens by absorbing atmospheric CO2. Performance of cement unknown.</td>
<td>Input, internal, output</td>
<td>Also see CeramiCrete (based on MgO), the prospect is long term.</td>
<td>(Gauthier 2009; Li et al., 2008) also : Novacem (a spin-out from Imperial College, London) developed this (prototype).</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce clinkerless cement: utilize sulfur dioxide removal waste products and fly ash to produce low energy clinkerless cement.</td>
<td>Input, internal, output</td>
<td></td>
<td>(Rust et al., 2009)</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce non-calcined cement by mixing ground limestone powder, blastfurnace slag, steel slag and gypsum without calcination.</td>
<td>Input, internal, output</td>
<td></td>
<td>(Lin &amp; Zhao, 2009)</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce calcium sulfoaluminate</td>
<td>Input, internal, output</td>
<td></td>
<td>(Pera &amp; Ambroise, 2004; Quillin, 2001; Gartner &amp; Quillin, 2007)</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce alkali-activated cement</td>
<td>Input, internal, output</td>
<td></td>
<td>Palomo et al., 1999</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce sialite cement.</td>
<td>Input, internal, output</td>
<td></td>
<td>Sun et al., 2007; Sun et al., 2009; Yi et al., 2009</td>
</tr>
<tr>
<td>PNC</td>
<td>Produce cement with Kalera process</td>
<td>Input, internal, output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------</td>
<td>-------------------------------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>SEC</td>
<td>Carbonization of construction and demolition waste concrete (C&amp;D wastes) by using CO2 from plant.</td>
<td>Output</td>
<td>Use or offset CO2</td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>SEC</td>
<td>CO2 capture by solar energy</td>
<td>Output</td>
<td></td>
<td>(Nikulshina et al., 2009)</td>
</tr>
<tr>
<td>SEC</td>
<td>Capture CO2 by Calera process: CO2 is bound into a product called &quot;calcium carbonate cement&quot;. This is a process which happens in nature. Corals get Ca and Mg from seawater in order to make their reefs and shells.</td>
<td>Output</td>
<td>For every tonne of cement, half of tonne of CO2 is sequestered.</td>
<td>(Biello, 2008)</td>
</tr>
<tr>
<td>SEC</td>
<td>Capture CO2 in cement plants (CCS) with Oxy-combustion CO2 Capture.</td>
<td>Output</td>
<td>Addition of oxygen to combustion and required flue gas recycling will alter process conditions. Additional research is required to provide a viable design.</td>
<td>(Barker et al., 2009; Zeman, F., 2009)</td>
</tr>
<tr>
<td>SEC</td>
<td>CO2 capture by calcine looping in synergy with power plant integration.</td>
<td>Input &amp; Output</td>
<td>Cement and power plants do not need to be co-located.</td>
<td>(CEMEX, 2011; Rodríguez et al., 2008; Romeo et al., 2011)</td>
</tr>
<tr>
<td>SEB</td>
<td>Utilize synergies (wastes, heat, CO2, ...) for producing biogas.</td>
<td>Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>SEB</td>
<td>Produce bio-products or CO2 products from waste CO2.</td>
<td>Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>SEB</td>
<td>Kollenbach: Use CO2 from exhaust to grow algae and use algae (after processing) as fuel.</td>
<td>Input &amp; Output</td>
<td>a consulting company has confirmed that the exhaust flue from kiln system in Kollebach can be used to produce algae site visit (more to be added)</td>
<td></td>
</tr>
<tr>
<td>DA2</td>
<td>Microalgae Cultivation Utilizing An Industrial Partnership</td>
<td>Input &amp; Output</td>
<td></td>
<td>ISIE2011, abstracts#146, ISIE2011, abstracts#146</td>
</tr>
<tr>
<td>SEB</td>
<td>Produce biofuel (ethanol) by blue-green algae.</td>
<td>Input &amp; Output</td>
<td>In comparison to gasoline, predicted values represent 67% and 87% reductions in the carbon footprint for ethanol fuel on a energy equivalent basis.</td>
<td>ISIE2011, abstracts#860</td>
</tr>
<tr>
<td>SEB</td>
<td>Use CO2 and heat to produce biomass and use the biomass as fuel (close the loop)</td>
<td>Output</td>
<td>For instance algae to biodiesel.</td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>Category</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>---------------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>SEH</td>
<td>Use waste heat from cement plant to dry sludge from WWTP and use (co-firing) the dried sludge as alternative fuel in cement kiln.</td>
<td>Input &amp; Output</td>
<td>Aside from fuel, 1 Tonne of dried sludge can replace up to 1/3 of raw material required for clinker production. Co-firing of sewage sludge in cement works using excess heat can be considered from energy, economic and environmental points of view, as one of the most appropriate solutions of sludge treatment both for WWTPs and cement works. (Stasta et. al., 2006)</td>
<td>(Stasta et. al., 2006)</td>
</tr>
<tr>
<td>SEH</td>
<td>Instead of allowing heat to go to air, send it down to be stored in ground water aquifer.</td>
<td>Output</td>
<td>Then use ground heat pumps to increase the temperature. Also can be combined with low temperature power generation cycles for geothermal power generation.</td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>SEH</td>
<td>Recycle waste cement: Extract calcium ions from waste cement particles by pressurized carbon dioxide and produce CaCO3 which can be used as a raw material for cement production.</td>
<td>Input &amp; Output</td>
<td>Recycle waste cement in order to capture CO2 and produce high quality CaCO3 which is a valuable products for many industries. High-purity calcium carbonate has been in demand for a wide range of applications such as fine chemicals, ceramics, and filler. High-purity calcium carbonate is also used in flue gas desulfurization processes to produce high-purity gypsum, which is required for the production of gypsum boards (Katsuyama, Y. et al., 2005)</td>
<td>(Iizuka et al., 2004; Katsuyama, Y. et al., 2005)</td>
</tr>
<tr>
<td>SIP</td>
<td>Calcium sorbent cycling for simultaneous CO2 capture and clinker production</td>
<td>Input &amp; Output</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>SIW</td>
<td>Colocation of large scale municipal waste-to-energy gasification plant and cement plant. Produce lean gas as kiln fuel as well as electricity for plant.</td>
<td>Input &amp; Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>Category</td>
<td>Description</td>
<td>Primary Focus</td>
<td>Remarks</td>
<td>References</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>SIC</td>
<td>Schwelgern: Dry GBFS more in steel plant before sending it to cement plant (ship it with lower moisture content).</td>
<td>Input</td>
<td></td>
<td>site visit</td>
</tr>
<tr>
<td>SIC</td>
<td>Schwelgern: Bringing heat from steel plant to dry GBFS in cement site.</td>
<td>Input</td>
<td></td>
<td>site visit</td>
</tr>
<tr>
<td>MM</td>
<td>Eco-marketing of products to support improving product portfolio.</td>
<td>Output</td>
<td></td>
<td>(CEMEX, 2011)</td>
</tr>
<tr>
<td>MM</td>
<td>Increase public awareness about various properties of different cement types.</td>
<td>Output</td>
<td>So the wider society (including deeper actors in customer chain) can recognize the benefits of blended cements.</td>
<td>(CEMEX, 2011)</td>
</tr>
</tbody>
</table>