STUDY OF SUSTAINABILITY PARAMETERS RELATED TO CEMENT PRODUCTION IN INDIA

A THESIS

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THESIS CERTIFICATE

This is to certify that the thesis titled **STUDY OF SUSTAINABILITY PARAMETERS RELATED TO CEMENT PRODUCTION IN INDIA**, submitted by **Sanoop Prakasan (CE14S018)**, to the Indian Institute of Technology Madras, for the award of the degree of **Master of Science**, is a bonafide record of the research work carried out by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Globally, the cement industry is the third largest energy consuming industrial sector (7% of the total industrial energy use) and the second largest CO_2 emitter (7% of the industrial CO_2 emissions). The global cement production is projected to increase by 12-23% by 2050. India is predicted to be one of the major contributors towards the predicted rise in global cement production. India is expected to produce 646 - 742 million tons of cement annually by 2030 and 780 - 1360 million tons by 2050. Despite being one of the significant cement-producing countries, there are no proper inventory databases and embodied energy and embodied CO_2 data related to cement production in India. This literature gap is studied and a set of data towards inventory, energy use and CO_2 are prepared for clinker (main ingredient of all types of cement), OPC, and PPC (more than 90% market share) based on two typical cement plants. Life Cycle Assessment (LCA) is used as a base methodology for determining sustainability metrics. A template is developed for the application of LCA based on ISO 14040 and ISO 14044.

The energy use and CO_2 emissions for Case Study 1 and Case Study 2 are as follows: (i) Energy use for clinker: 3990 and 3626 MJ/ton; (ii) CO_2 emissions for clinker: 849 and 868 kg CO_2/ton; (iii) Energy use for OPC: 4015 and 3821 MJ/ton; (iv) Energy use for PPC: 3077 and 2733 MJ/ton; (v) CO_2 emissions for OPC: 802 and 855 kg CO_2/ton; and (vi) CO_2 emissions for PPC: 606 and 595 kg CO_2/ton. The fuel and the electricity used for clinker production in both case studies are found to be higher than the similar values reported for other geographical regions across the world. The energy used for the production of OPC and PPC is within the range of similar data reported for other geographical regions across the world. However, the energy use for OPC production is around the higher end of the range and the energy used for PPC production is around the lower end of the range reported in the international databases.

Major contributors of CO_2 emissions for clinker, OPC and PPC production are direct CO_2 emissions from raw meal and fuel and the indirect CO_2 emissions of electricity production. CO_2 emissions due to major contributors for clinker and OPC production for Case Study 1 are lower compared to values reported for other geographical regions across the world. For case study 2, this is around the average of emissions reported for other geographical regions. CO_2 emissions due to major contributors for PPC production is around the lower range of values reported for other geographical regions.

Replacement of clinker with pozzolans such as fly ash and slag are proven measures to reduce the energy use and CO_2 emissions of cement production in India. Studies show that a combination of calcined clay and limestone has a higher clinker replacement level of up to 60%.

This study evaluates the potential of utilizing this material in detail in order to reduce the energy use and CO_2 emissions of cement production. Inventory, energy consumption and CO_2 emissions of Limestone Calcined Clay Cement (LC^3) are estimated using the LCA template developed. The data sources are case studies, laboratory experiments and literature. Based on the TGA/DSC results of clay samples, a set of parameters like specific heat capacity, calcination energy per kaolinite content and the total theoretical calcination energy for two calcination process scenarios (with heat recovery and without heat recovery) are calculated.

A total of 12 possible scenarios for LC^3 production is presented. Among these scenarios, a processing system is selected based on the trial industrial production reported in the literature. Four scenarios are considered to determine the energy use and emissions of clay calcination namely – S1: high calcination energy without heat recovery, S2: low calcination energy without heat recovery, S3: high calcination energy with heat recovery and S4: low calcination energy with heat recovery. These four scenarios are considered for Case Study 1 and Case Study 2. Hence, there are a total of eight scenarios related to inventory, energy use and CO_2 emissions of LC^3 production. The trends observed in the comparison of energy use and emissions of LC^3 production scenarios with OPC and PPC are similar for Case Study 1 and Case Study 2.

The energy use for LC^3 is less compared to OPC in all scenarios except the scenario - 'without heat recovery and high calcination energy'. CO_2 emissions due to LC^3 production is 15-37% less compared to OPC depending upon the variations in clay calcinations scenarios. The energy use for LC^3 is less compared to PPC in one scenario - 'with heat recovery and low calcination energy'. The energy use for PPC is less compared to LC^3 in the other three clay calcinations scenarios. CO_2 emissions of LC^3 production are lower compared to PPC in three clay calcinations scenarios namely S2, S3 and S4. For scenario S1, CO_2 emissions of LC^3 production are higher compared to PPC. The relative comparison of energy use and emissions of LC^3 production and PPC is influenced by the choice of clay calcination scenarios and supply chain parameters related to clay calcination.

This research evaluates the sustainability parameters like energy use and CO_2 emission related to production of Clinker, OPC and PPC in India. The results are useful to assess the the quality of cement production in India and compare with other countries. The potential of limestone and calcined clay as an additive to the cement is also studied. It is concluded that there is potential to reduce CO_2 emissions of cement production through the use of LC^3.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ATILH –	Association Technique de l'Industrie des Liants Hydrauliques
CKD –	Cement kiln dust
CSI –	Cement Sustainability Initiative
EPER –	European Pollutant Emission Register
ESP –	Electro Static Precipitator
GHG –	Green House Gas
Govt. –	Government
ILCD –	International Reference Life Cycle Data System
LCA –	Life Cycle Assessment
LCI –	Life Cycle Inventory
LCIA –	Life Cycle Impact Assessment\
NGO –	Non Governmental Organisation
RoW –	Rest of the World
SEC –	Specific Energy Consumption
SoCP –	Source of Calcination Process
SoGP –	Source of Grinding Process
SP –	Suspended Particles
SPM –	Suspended Particulate Matter
TARA –	Technology and Action for Rural Advancement
USGS –	United States Geological Survey
WBCSD –	World Business Council for Sustainable Development

CHAPTER 1

INTRODUCTION

1.1 Overview

The industrial revolution is one of the prominent steps undertaken towards development. This resulted in a lot of advantageous and disadvantageous consequences. One of the apparent issues was the depletion or over-consumption of non-renewable natural resources. The industrial revolution grew regardless of the consequential environmental issues. The world started to experience the harmful consequence evidently, in the form of climate change. Climate change was predominantly due to global warming, and the later was primarily due to the greenhouse gas emission. This global phenomenon changed the overview towards the development

The environmental issues drive a global notion to seek sustainable development. The World Commission on Environment and Development under United Nation, form a definition for sustainable development, "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs"(WCED 1987). The three pillars of sustainability are economic sustainability, social sustainability, and environmental sustainability. Satisfaction of all three components results in sustainable development. Environmental sustainability concept is defined by Goodland (1995) as "maintenance of natural capital" with set of input/output rules. There are many indicators or metrics for measuring environmental sustainability such as embodied energy, operating energy, indicators of potential environmental impacts (e.g. ozone layer depletion and Global warming potential), eco-efficiency (e.g. ratio of environmental impact and economic performance), environmental footprints (e.g. ecological footprint, carbon footprint, and water footprint) and sustainability indexes (e.g. environmental indicators – Relative environmental index) (Cucek et al. 2015).

Energy consumption is one of the primary features of industrialization which can cause resource depletion of non-renewable fuel. The cement industry is one of the important energy-intensive industrial sectors related to civil engineering. Globally the cement industry is the third largest energy consuming industrial sector (7% of industrial energy use) and the second largest CO_2 emitter (7% of industrial CO_2 emission) (IEA 2018). The global cement production is about 4000 million tons in 2014 (USGS, 2016). The global cement production is expected to increase by 12% – 23% by 2050 (IEA, 2018). According to Imbabi et al. (2012), cement production is expected to reach 5500 million tons by 2050. This expected increase in the cement production, and associated energy consumption and CO_2 emission demands a comprehensive assessment of the sustainability aspect of this sector.

Life Cycle Assessment (LCA) is most widely used as a sustainability assessment method. LCA is conducted on cement production for past few decades. Through the application of LCA, most of the developed countries have their, own Life Cycle Inventory (LCI) databases. A reliable set of LCI data, enable practitioners to calculate the potential environmental impact indicators. This helps in the assessment of the environmental aspects of a product. Thus LCI related to cement production enables to understand the environmental aspects of manufacturing operations. It also helps to evaluate the potential of measures to reduce energy consumption and CO_2 emissions.

LCI of clinker and cement production includes primarily raw materials (limestone, clay etc), fuels, electricity, CO_2, SO_2, NO_x, and PM. These emissions are harmful for climate and human health. In literature, there is a geographical gap in the LCA assessment studies reported across the world with respect to cement production. Not much data on LCI, energy and CO_2 emission are reported from developing countries. India despite being the second largest cement producer, does not have properly reported LCI data, embodied energy and embodied CO_2. Imbabi et al. (2012) mentioned that the developing nations like China and India will be the major contributors towards the rise of global cement production. Morrow et al. (2014) had projected that India's cement industry is anticipated to produce between 646-742 million tons cement per year by 2030, and Fonta et al. (2013) has projected the same for 2050 between 780-1360 million tons (considering the low and high demand). Thus, the associated energy consumption and CO_2 emissions will be increasing along with the production boom. This predicted increase in cement production emphasizes the need, importance and the relevance, of an LCA study on the Indian cement industry and its energy consumption and CO_2 emissions. This research focusses on LCA studies on Indian cement plants to produce data on inventory, energy use and CO_2 emissions.

There are several global programmes aimed at the reduction of energy consumption and CO_2 emissions related to cement industries. IEA's Blue map scenario has CO_2 level targets and sectoral approach to achieve the same. Globally, the annual CO_2 emissions from the cement industry are expected to be reduced from 1.88 GT in 2006 to 1.55 GT in 2006 by using methods like energy efficiency, use of alternative fuels (using biomass), clinker substitution and carbon capture and storage. The technique of clinker replacement is a proved method in India. The production of cement by replacement of clinker with fly ash is popular in India, in the name of Pozzolana Portland Cement (PPC). PPC covers about 70% of the Indian cement market (PSCC 2011). India relies heavily on coal-based thermal power plants for electricity. This serves as a source to meet the fly ash requirement. Similar to fly ash, there are a lot of pozzolans like slag, silica fume, metakaolin, rice husk ash, and bagasse ash. According to Antoni (2013), the additive which is a combination of calcined clay and limestone has a higher clinker replacement level of up to 60%. The clay and the limestone used for the same need not to be pure. Since India has good limestone and clay reserves, there is a potential material which can enable the CO_2 cut down in an efficient way. But the primary concern is that the clay is calcined before usage and there is an additional component of energy consumption and consequential CO_2 emission. Thus, the net effect of clinker cut down and calcination decides the advantage of this material. There exists a gap in quantifying the net effect of the energy use and CO_2 emissions related to cement production based on this additive (calcined clay and limestone). This gap is studied and addressed in this thesis.

1.2 Need for the study

The purpose of this research work is to address the following literature gaps.

- Lack of study on sustainability aspects of cement production in India.
- Lack of understanding of the sustainability aspects of limestone and calcined clay as a cement additive.

1.3 Objectives and scope

The two primary objectives of this study are,

1) To assess the sustainability aspects like inventory, energy use, and CO_2 emissions of clinker and conventional cement like Ordinary Portland Cement (OPC) and Pozzolana Portland Cement (PPC).
2) To assess the sustainability aspects like energy use and CO_2 emission of cement made using limestone and calcined clay as additives, which is also called Limestone Calcined Clay Cement (LC^3)

LCA is planned to be conducted based on the data collected from typical Indian cement plants. Ordinary Portland Cement (OPC) and Pozzolana Portland Cement (PPC) are the two types of cement selected for this study due to their highest market share (PSCC 2011). The functional unit is 1 ton. They are selected because this cement has the highest market share. Gate to gate system boundary condition is used as the majority of direct energy consumption and CO_2 emission is happening within the gate to gate system boundary.

Clay calcination process is studied based on lab scale experiments. Clay samples with kaolinite content ranging from 40-90 % are considered. Clay calcination process is considered in two cases - with heat recovery and without heat recovery. The results from clay calcination process, related objective one and literature are used to estimate energy use and CO_2 emissions related to LC^3.

1.4 Research methodology

The research methodology followed in this study is shown in Figure 1.1.

1.5 Thesis structure

The structure of the thesis is presented as follows:

1) Introduction: Overview of the topic, need for the study, objectives, scope, research methodology and thesis structure

2) Literature review: A set of results on inventory, energy, and CO_2 related to different unit processes in the manufacturing of clinker, OPC, and PPC across different geographical areas.

3) Methodology: A detailed description of LCA methodology based on ISO 14040 and ISO 14044

4) Case study 1: Estimation of inventory, energy use, and CO_2 emissions for clinker, OPC and PPC., based on a study at Cement Plant - 1

5) Case Study 2: Estimation of inventory, energy use, and CO_2 emissions for clinker, OPC and PPC, based on a study at Cement Plant - 2

6) Discussion of the case studies: Discussion and conclusion on the inventory, energy use, and CO_2 emissions for clinker based on two case studies, and comparison with CSI data.

7) Limestone Calcined Clay Cement (LC^3): Literature review, estimation of theoretical energy for clay calcination process, product systems for production of LC^3, and

estimation of energy use and CO_2 emissions with LC^3 and comparison with OPC and PPC.

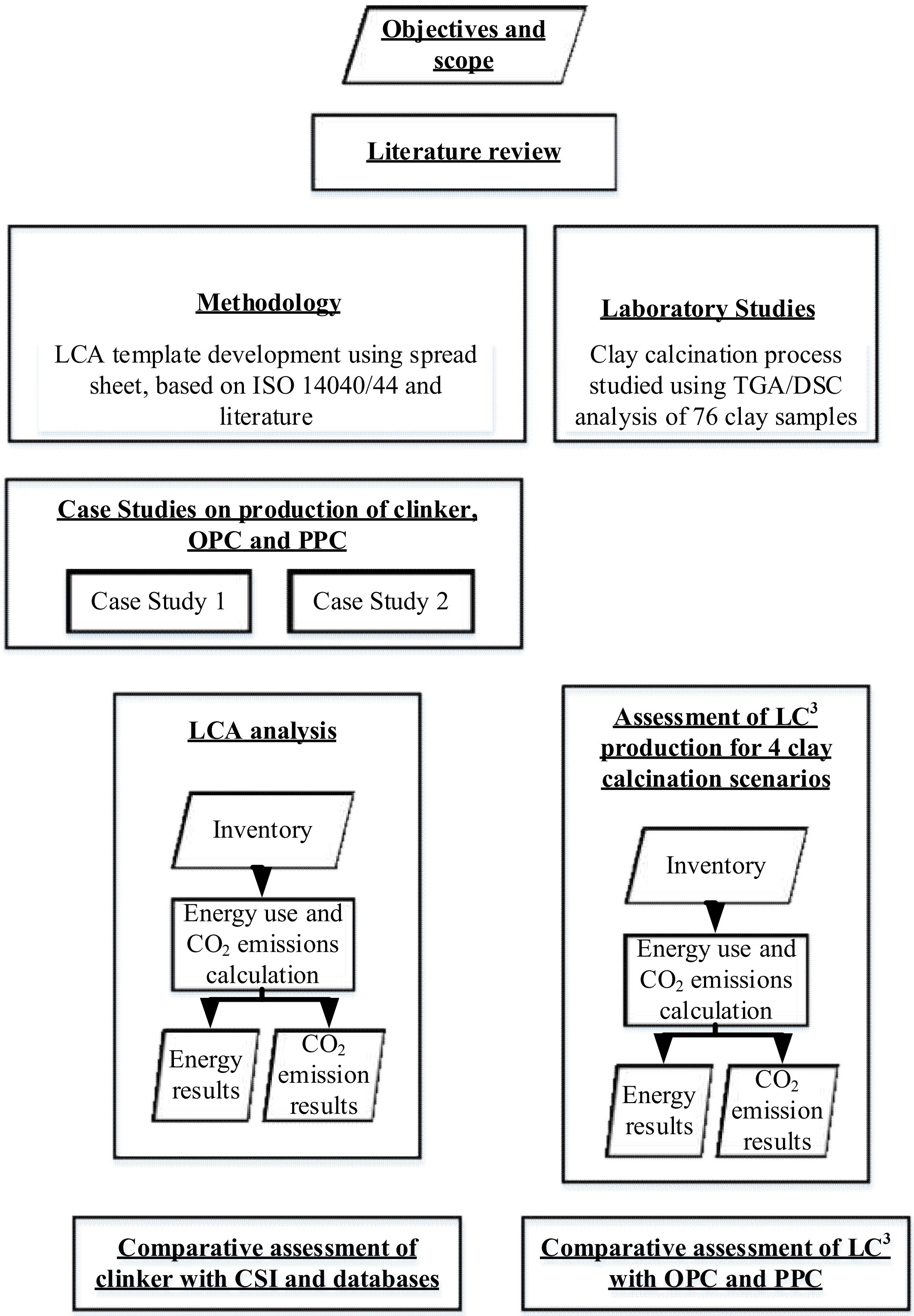

Figure 1.1: Research methodology

8) Conclusion: Generic conclusions, specific conclusions, and recommendations and future scope.

Annexure A: Tables related to Chapter 4

Annexure B: Energy use and CO_2 emissions calculation related to electricity production in Case Study 1

Annexure C: Tables related to Chapter 5

Annexure D: Energy use and CO_2 emissions related to limestone preparation in Case Study 1

Annexure E: Energy use and CO_2 emissions related to limestone preparation in Case Study 2

Annexure F: Preliminary analysis on energy use and CO_2 emissions of the transportation process, outside gate to gate system boundary.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the literature related to the sustainability assessment of cement production is discussed. Currently, the most widely used sustainability assessment method is Life Cycle Assessment (LCA). LCA gives a holistic assessment of the life cycle of a product, devoid of offsetting any processes involved. Even though LCA started from simple applications like analysis of beverage containers, it has expanded to complex processes like building materials (Hou et al. 2015). After the standardization of the LCA in 1997, journal articles published on this topic increased rapidly (Chen et al. 2014; Hou et al. 2015).

The major cement-producing countries in the world are China, India, and the United States. Since the cement industry is globally one of the biggest energy users and CO_2 emission generators, it is expected to have studies related to cement from these countries. Considering the number of publications, it is understood that most studies related to sustainability aspects of cement and concrete are from Europe, followed by China and the United States. Despite reporting studies based on energy auditing, energy benchmarking, energy efficiency, kiln efficiency, specific energy consumption etc. no exclusive LCA study has been conducted on cement production in India.

Two expected results of LCA are life cycle inventory and environmental impact related to the product. For cement production, literature provides a good quality inventory and environmental impacts related to production. Most European countries (ecoinvent 2018) and United States (Marceau et al. 2006) have developed life cycle inventory databases of cement. There is software available that compile different databases of life cycle inventory (LCI) from different areas. Life Cycle Impact Assessment (LCIA) results are also available in the literature. Usually, studies on LCIA uses predefined or established impact assessment methods through software.

2.2 LCI Study

Since the inventory data form the basis for the quality of LCA, studies are conducted to create good quality databases. Good quality LCI enable accurate prediction of environmental impacts. LCI results are beneficial to a wide range of audience like industrialists, academicians, policy makers, etc. LCI results enable the identification of the intensity of different data with respect to the unit process, which improves the understanding of the audience and thus proper measures can be taken.

The processing system considered in the publications are integrated cement production systems, and hardly grinding units and clinkerization units (Josa et al. 2004; Marceau et al. 2006; Huntzinger and Eatmon 2009; Chen et al. 2010; Li et al. 2014; MoP 2015). Mostly, 1 ton of the cement or clinker is usually considered as a functional unit, whereas 1 kg is also reported. LCI data are mostly reported in terms of cement followed by clinker. System boundaries mostly considered are Cradle to Gate and Gate to Gate, with later being more common. Even though most studies consider Gate to Gate, the limestone mining and transportation is to be included in the system boundary. Most of the inventory data are collected or monitored for several years, or for at least 1 year. The main technological aspect considered in cement production is the clinkerization technology. Different clinkerization techniques are wet processing, semi-dry processing, dry processing and dry processing with preheater precalciner technology. Dry processing and dry processing with preheater precalciner technology is considered in most of the studies. Most of the literature provides the main input data like raw material consumption, fuel and electricity. Raw material will be consumed for the clinker and cement production, fuel use corresponds to the clinkerization process and electricity use for limestone, raw material, fuel preparation, clinkerization, and grinding. The ancillary inputs like oil, water, cement bag, refractory, and other physical inputs like infrastructure, machinery, truck are rarely reported. Sources of data are direct measurement through case studies, Govt. databases (say, pollution control board), and NGO databases (ecoinvent 2018). Mostly data are reported as single values, without mentioning the variability of the data. Thus, it can be assumed that uncertainty analysis is hardly considered.

Some inventory values reported in the literature are discussed here process-wise. The conventional processes considered for the cement production is obtained from the literature. The processes are reported as the smallest possible unit processes. The input-output value related to the unit processes are mentioned, along with some data quality parameters like country, time period, associated technology and source of data.

2.2.1 Clinker

The inventory values from the literature are reported here process wise. The unit processes considered are limestone extraction, transportation of limestone, limestone preparation (crushing stacking and reclaiming), raw meal preparation, fuel preparation, clinkerization (also include cooling and storing), transportation of onsite vehicle, transportation of other inputs (raw materials and fuel), other processes (miscellaneous processes). Of the unit processes considered above, the data related to the fuel preparation, transportation of limestone and other inputs, onsite vehicles and other processes were not commonly found in the literature. The input-output values related to the unit processes are reported, along with some data quality parameters like country, time period, associated technology, and source of data. Most of the values are reported in terms of cement, which are converted in terms of clinker using suitable clinker to cement ratio.

2.2.1.1 Limestone extraction

Limestone extraction usually includes overburden values also and thus the limestone consumed by the cement plant will be less compared to the extracted amount. However, in the literature, the limestone consumed by the cement plant is only reported. The following are the limestone consumption values from the literature:

- Li et al. (2014) have reported limestone consumption of 1.15 ton/ton of cement, which when converted in terms of clinker is 1.53 ton/ton of clinker (converted using clinker to cement ratio of 0.75, as proposed in the article). The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- According to USGS (2014b), calcareous minerals like limestone, cement rock, lime and others are consumed at 1.44 ton/ton of clinker, based on the 2013 yearly report.

- Huntzinger and Eatmon (2009) reported a value of limestone consumption of 1.41 ton per ton of cement. The value, when calculated in terms of clinker (using clinker to cement ratio), is around 1.48 ton/ton of clinker. The value corresponds to the United States and dry technology (Preheater). The data source is the SimaPro library and databases.

- Calcareous marl, crushed limestone, and lime are consumed at 1.31 ton/ton of clinker as per Ecoinvent 3.2 database (accessed on 17-01-2018, using SimaPro 8.4.0.0). The value geographically corresponds to the rest of the world (except Canada and Europe).

The value of the limestone consumption depends on the mineral content of the same. From the above values, it can be understood that the expected limestone use can be in the range of 1.53-1.31 ton/ton of clinker.

2.2.1.2 Limestone preparation, raw meal preparation, fuel preparation and clinkerization

For all processes sequentially needed to prepare the raw material and fuel for clinkerization, mostly literature provide aggregated inventory value instead of inventory related to each unit process individually. The values are provided below starting from a group of processes to the smallest individual unit process.

2.2.1.2.a Limestone preparation, raw meal preparation, and fuel preparation

- Li et al. (2014) have reported the electricity required for the raw material and fuel preparation in terms of cement, which when converted per ton of clinker will be 42.41 kWh/ton of clinker (converted using clinker to cement ratio of 0.75, as proposed in the article). The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- Huntzinger and Eatmon (2009) have also reported the electricity required for the raw material preparation in terms of traditional Portland cement, which when converted to clinker will be 337 MJ/ton of clinker or 94 kWh/ton of clinker (using clinker to cement ratio of 0.95). It can be understood that it represents the secondary energy or the direct energy consumed. The value corresponds to the United States, and dry technology (Preheater). The data source is the SimaPro library and databases.
- Li et al. (2014) have reported water consumption in terms of cement which when calculated in terms of clinker is 0.520 m^3/ton of clinker. The water consumption of the plant has a recycling rate of 95-99%. The value temporally corresponds from 2004 to 2007, corresponds to China, and dry technology (New Suspension Preheater).

2.2.1.2.b Raw meal preparation, fuel preparation and clinkerization

- The electricity use is reported as 59.31 kWh/ton of clinker in Ecoinvent 3.2 database (accessed on 17-01-2018, using SimaPro 8.4.0.0). The data corresponds to the world average (except Canada and Europe), and includes all the processes from material preparation (except limestone crushing) till clinkerization.
- In the Ecoinvent 3.2 database (accessed on 16-01-2018, using SimaPro software), it is reported that particulate matter is produced at 0.038 kg/ton of clinker. The data corresponds to the rest of the world (except Canada and Europe).

- According to the Ecoinvent 3.2 database (accessed on 17-01-2018, using SimaPro software), SO_2 is produced at 0.39 kg/ton of clinker.
- According to the Ecoinvent 3.2 database (accessed on 17-01-2018, using SimaPro software), NO_x is produced at 1.092 kg/ton of clinker.

2.2.1.2.c Raw meal preparation

Usually, raw materials other than limestone are added to meet the required level of compounds like SiO_2, Al_2O_3 and Fe_2O_3. Clay for SiO_2, Haematite for Fe_2O_3, and Bauxite for Al_2O_3. The amount of raw materials depends on its mineral content. Sometimes, the limestone, marl, lime etc., consumed contain impurities like SiO_2 and Al_2O_3. Thus, the mineral requirement other than CaO will be satisfied and other raw materials are added only if there is any further mineral requirement.

- Li et al. (2014) reported the electricity required for the raw material grinding as 36.60 kWh/ton of clinker and 21.75 kWh/ton of raw material. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- The clinker inventory corresponding to the different geographical areas is analysed from the Ecoinvent database. The limestone consumed for processes for raw meal preparation to clinkerization was reported as 1315 kg for RoW, 1311 kg for Europe without Switzerland, 1311 kg for the US, 1546 kg for Switzerland and 1406 kg for Canada. Five values are reported ranging from 1311-1546 kg, where three of them are near 1311 and two above 1400 kg.
- Li et al. (2014) reported the addition of sandstone and ferrous tailing in terms of cement which when calculated in terms of clinker will be 0.063 ton/ton of clinker. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- Huntzinger and Eatmon (2009) reported clay, sand and iron ore consumption in terms of cement, which is converted to clinker (clinker to cement 0.95) as 0.198 ton/ton of clinker. The value geographically corresponds to the United States and technologically corresponds to dry technology (Preheater). The data source is the SimaPro library and databases.
- According to USGS (2014b) siliceous, aluminous and ferrous minerals like clay, shale, schist, iron ore, mill scale, sand, sandstone etc., are consumed. The value is calculated in terms of clinker as 0.16 ton/ton of clinker. All the values are from the 2013 yearly report.
- Marceau et al. (2006) reported other raw material consumption in terms of cement which is 0.241 ton when converted per ton of clinker. It includes shale clay, bottom

ash, fly ash, foundry sand, sand, blast furnace slag, iron ore, slate and other materials. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- The clinker inventory corresponding to different geographical areas can be analysed from the ecoinvent database. The minerals other than limestone consumed for raw meal preparation to clinkerization was reported as 336 kg for RoW, 340 kg for Europe without Switzerland, 340 kg for the US, 2.7 kg for Switzerland and 305 kg for Canada. Five values are reported, in which one value of 2.7 kg seems to be the exception, rest of them is ranging from 305 - 340 kg.

2.2.1.2.d Fuel preparation

Li et al. (2014) have reported a value of 5.81 kWh/ton of clinker and 39.8 kWh/ton of coal. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

2.2.1.2.e Clinkerization

- Li et al. (2014) reported 21.37 kWh/ton of clinker. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- Li et al. (2014) reported a consumption of 128 kg coal equivalent/ton of clinker. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- According to USGS (2014b), different fuels are used in the US for clinker production using the dry process. Coal and petcoke together are consumed around 106 kg/ton of clinker. Along with the same, other fuels like tyre and solid waste (21.9 kg/ton of clinker), oil (0.216 litres/ton of clinker), natural gas (9.51 m^3/ton of clinker) and liquid waste (9.78 litres/ton of clinker) are consumed. All the values are based on the 2013 yearly report.
- Marceau et al. (2006) reported solid fuel consumption in terms of cement, which when converted in terms of clinker will be of 131 kg/metric ton of portland cement (using clinker to cement ratio 0.95). The break-up of the individual fuels are as follows: solid fuel includes coal (106.3 kg), Petroleum coke (14.1 kg) and wastes (10.8 kg). Waste fuels include tire-derived waste, waste oil, solvents, other solid wastes and other wastes. Beyond the solid fuels, there is consumption of liquid and gaseous fuel like residual oil (0.065 litres/ton of cement), LPG (0.016 litres/ton of cement) and natural gas (7.635 m^3/ton of cement). Gasoline and middle distillates are also consumed but it is stated that they are assumed to be used for transportation. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- The clinker inventory corresponding to the different geographical areas is analysed from the ecoinvent database accessed on 17-01-2018, using SimaPro 8.4.0.0. The fuel consumed for processes for raw meal preparation to clinkerization was reported as 66 kg for RoW, 65 kg for Europe without Switzerland, 65 kg for the US, 47 kg for Switzerland and 136 kg for Canada. Five values range from 47-136 kg, with three of them in range of 65±1 kg. It is not mentioned exclusively, but it is obvious that the fuel is for the clinkerization process. A mixture of fuel for RoW contains hard coal, petroleum coke, light and heavy fuel oil, petrol, LPG and diesel.

- According to USGS (2014b), pozzolans like fly ash, bottom ash, slags, and natural and other pozzolans are added at a rate of 0.061 ton/ton of clinker, for the siliceous content of the clinker. All the values are based on the 2013 yearly report.

- The refractories and castable are not much seen in literature: 0.40 kg/ton of clinker refractories are consumed according to the Ecoinvent 3.2 database (accessed on 17-01-2018, using SimaPro software). The data geographically corresponds to the rest of the world

- Marceau et al. (2006) reported refractory consumption in terms of portland cement, which when converted in terms of clinker will be 0.46 kg/metric ton of clinker. The data corresponds to the US. The technology considered is preheater precalciner technology.

- Li et al. (2014) reported water consumption in terms of cement, which when calculated in terms of clinker is 1.207 m^3/ton of clinker. The water consumption of the cement plant has a recycling rate of 95-99%. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Li et al. (2014) reported PM emission of 0.087 kg/ton of clinker, during incineration. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Huntzinger and Eatmon (2009) reported particulate matter emission of 21 gm/ton of clinker. The value geographically corresponds to the United States and technologically corresponds to dry technology (Preheater). The data sources considered are the SimaPro library and databases.

- Li et al. (2014) reported SO_2 production of 0.048-0.150 kg/ton of clinker. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Li et al. (2014) reported NO_x emission of 0.90-2.20 kg/ton of clinker. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Grover et al. (2015) reported radiation and convection losses of heat from 3 cement plants as 51.7 kcal/kg of clinker or 216.31 kJ/kg of clinker, 52.4 kcal/kg of clinker or 219.24 kJ/kg of clinker, and 53.8 kcal/kg of clinker or 225.10 kJ/kg of clinker. The value geographically corresponds to India, temporally corresponds to 2012-13 and technologically corresponds to preheater precalciner technology.
- Virendra et al. (2015) reported radiation and convection heat loss of 27.41 and 16.64 kcal/kg clinker, respectively (or 114.68 and 69.62 kJ/kg clinker, respectively). The value geographically corresponds to India.

2.2.2 Cement

Grinding and packing are the two main processes involved in the production of cement after clinkerization. There are also processes like onsite transportation and other processes. Other processes are those miscellaneous processes which are not incorporated in the main processes for the production of cement or processes which are happening concurrently with respect to the mainstream processes. The values reported for processes till clinkerization are not reported here. The following are unit processes and associated inventory.

2.2.2.1 Grinding

- Li et al. (2014) reported 22.99 kWh/ton of P.O.cement. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- Virendra et al. (2015) reported 29.25 kWh/ton of cement for cement grinding. The data geographically corresponds to India and technologically corresponds to preheater precalciner technology. The data corresponds to generic cement including OPC, PPC, PSC and other cement.
- The cement portland data corresponding to the different geographical regions is analysed from the ecoinvent database (Version 3.2). The grinding electricity energy per ton of cement is 37.6 kWh for RoW, 54.2 kWh for Canada, 37.6 kWh for Europe without Switzerland and 55.8 kWh for the USA.
- The inventory of the cement, pozzolana and fly ash are analysed from the ecoinvent database (Version 3.2) for different geographical areas. The electricity for grinding is 32.9 kWh for Switzerland, 32.9 kWh for Europe without Switzerland, 32.9 kWh for RoW and 47.5 kWh for the USA.
- Li et al. (2014) reported consumption of gypsum at a rate of 0.05 ton/ton of P.O.cement. The admixtures like slag and fly ash are added at a rate of 0.155-0.200 ton/ton of P.O. cement. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- The inventory of 1 ton of cement portland corresponding to the different geographical regions is analysed from the ecoinvent database (Version 3.2). The clinker content is 902.5 kg for RoW, 920 kg for Canada, 902.5 kg for Europe without Switzerland and 902.5 kg for the US.

- The inventory of 1 ton of cement portland corresponding to the different geographical regions is analysed from the ecoinvent database (Version 3.2). The limestone content is 50 kg for RoW, 30 kg for Canada, 50 kg for Europe without Switzerland and 50 kg for the US.

- The inventory of 1 ton of cement portland corresponding to the different geographical regions is analysed from the ecoinvent database (Version 3.2). The gypsum content is 47.5 kg for RoW, 50 kg for Canada, 47.5 kg for Europe without Switzerland and 47.5 kg for the US.

- The inventory of the cement, pozzolana and fly ash are analysed for different geographical areas. The clinker content is 731.5 kg for Switzerland, 731.5 kg for Europe without Switzerland, 731.5 kg for RoW and 688.75 kg for the US.

- The inventory of the cement, pozzolana and fly ash are analysed for different geographical areas. The gypsum content is 38.5 kg for Switzerland, 38.5 kg for Europe without Switzerland, 38.5 kg for RoW and 36.25 kg for the US.

- Li et al. (2014) reported water consumption of 0.310 m^3/ton of P.O.cement. The water consumption of the plant has a recycling rate of 95-99%. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Marceau et al. (2006) reported particulate emission of 0.025 kg/metric ton of portland cement. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- Li et al. (2014) reported PM emission of 0.02 kg/ton of P.O.cement. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).

- Huntzinger and Eatmon (2009) have reported particulate matter emission of 5.4 gm/ton of cement. The value geographically corresponds to the United States and technologically corresponds to dry technology (Preheater). The data source is the SimaPro library and databases.

2.2.2.2 Packing

- Virendra et al. (2015) reported 1.65 kWh/ton of cement for cement grinding. The data geographically corresponds to India and technologically corresponds to preheater precalciner technology. The cement includes OPC, PPC, PSC and other cement.

- Marceau et al. (2006) reported cement bag consumption of 0.68 kg/metric ton of portland cement. The data geographically corresponds to the US. The technology considered is Preheater precalciner technology.

The literature values reported across different geographical areas and technology help us to have an overview of the inventory associated with the production of clinker and cement. This understanding of the inventory enables the reader to assess the inventory results provided in the case study chapters.

2.3 Energy use and CO_2 emissions

LCIA studies consider a lot of environmental issues like global warming, eutrophication, acidification, carcinogenicity, and ozone layer depletion. Most of the LCIA studies uses predefined impact assessment methods like Eco-Indicator 99, CML 2001, Impact 2002+, and ReCiPe Endpoint. In relation to the energy demand, the impact assessment method used in literature is Cumulative Energy demand (CED). Similarly, in relation to global warming and CO_2 emissions, the most common impact assessment method is IPCC 2013 GWP (100a). With respect to other impact assessment methods such as Eco-indicator 99, the impact category called climate change are present, which also accounts for global warming effect due to Green House Gas (GHG) emissions. There are less reported studies using CED and IPCC method on cement production. The energy use is calculated based on the embodied and direct energy of inputs. Mostly, the energy use from electricity and fuel used for clinkerization are only reported. More literature is available in relation to CO_2 emissions compared to energy calculation, which reports direct CO_2 emissions and emissions in terms of CO_2 equivalent. CO_2 emissions are not measured but mostly estimated from the use of raw material and fuel composition.

In this thesis, the direct energy use and CO_2 emission related to the cement production is only considered. Conceptually, in LCA, the measurement of input or output need to be extrapolated to impact indicator by understanding the scientific mechanism the data can undergo. And this impact indicator shows the intensity of environmental issue or impact on the category endpoint of the environment. In other words, in order to state the study as impact assessment the effect of energy consumption and CO_2 emissions on nature needs to be measured with proper scientific understanding. The energy consumed in the form of fuel extracted from earth can lead to environmental issues like depletion of natural resource (fossil fuel resources). Emission of more CO_2 can result in increased CO_2 intensity in the atmosphere. CO_2 has the property of entrapping the heat. Thus, increasing the concentration of CO_2 can result in entrapping of more heat and thus enhancing global warming. This extrapolation of energy use and CO_2 towards impact indicator of its corresponding environmental issue is not carried out in this study. For energy, even in literature, such extrapolation is not conducted, but for CO_2 emission the inventory results are converted to CO_2 equivalent which indicates the environmental issues of climate change (based on relative infrared radiative forcing with respect to CO_2). The software related studies mostly report values with cradle to gate system boundary. In studies other than those based on software, the energy and emission data are calculated based on databases, such studies are mostly corresponding to gate to gate system boundary. Certain values reported in the literature on the energy and CO_2 are provided as follows.

2.3.1 Energy use associated with clinker and cement

In literature and databases, the energy use results are presented as contributions from different data or from different processes. Comparatively, the results presented in the form of contribution from different data type are more than in the form of unit process wise. Thus, the literature values are reported data type-wise in this section. Thus, the results are provided here in terms of contribution from a set of data or individual data. The results till clinkerization reported in terms of clinker can be converted in terms of cement based on suitable clinker to cement ratio.

2.3.1.1 Considering contribution from all data or whole inventory

- From the analysis of 1 ton of clinker inventory (cradle to gate) from ecoinvent V3 using the impact assessment method Cumulative Energy Demand (V1.09), the amount of embodied energy is found to be 3710 MJ/ton for Rest of the World, 3720 MJ/ton for Canada, 2970 MJ/ton for Switzerland, 3810 MJ/ton for Europe without Switzerland and 3760 MJ/ton for USA.
- Hammond and Jones (2008) reported energy use of 4.6 MJ/kg of cement for the cradle to gate system boundary. If the cement is added with 25% fly ash (for which some embodied carbon is considered), the value changes to 3.52 MJ/kg of cement.

2.3.1.2 From electricity, fuel and raw material

Praseeda et al. (2015) reported energy consumption values of 2.91 and 4.32 MJ/kg of cement for two cement plants in India. The energy consumed is a sum of embodied energy of raw material (including limestone), transportation of raw materials (including limestone), mixing and grinding of raw material, clinker production, grinding of clinker, and packing. This work takes into account the energy use of electricity in terms of primary energy. An energy use range of 4.67–8.05 MJ/kg of cement is also reported based on Input-output LCA analysis of input-output transaction tables within the geographical representation of India.

2.3.1.3 From electricity and fuel

- Marceau et al. (2006) report energy consumption of 4220 MJ/ton of cement. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.
- From the analysis of clinker inventory from ecoinvent V3.2 using impact assessment method Cumulative Energy Demand (V1.09), the amount of energy from fuel and electricity is 3067 MJ/ton of clinker for RoW, 3556 MJ for Canada, 2770 MJ for Switzerland, 3139 MJ for Europe without Switzerland, and 3095 MJ for the US.
- MoP (2015) has reported normalized energy consumption for cement preparation in different cement plants whose primary products are PPC, OPC, PSC and clinker. Grinding units alone are also considered. The effect of electricity supply and purchase to the grid are also considered with suitable conversion factors to accommodate the primary energy value. The energy associated with the thermal treatment of clinker bought and the grinding energy of clinker sold are also considered.
    - PPC (55 plants): 712–1227 kcal/kg equivalent cement or 2979–5137 kJ/kg of equivalent cement,
    - OPC (16 plants): 965–1368 kcal/kg equivalent cement or 4038–5724 kJ/kg equivalent cement,
    - PSC (7 plants): 700-968 kcal/kg equivalent cement or 2929–4050 kJ/kg equivalent cement,
    - Grinding unit (2 plant): 139–201 kcal/kg of equivalent cement or 582–841 kJ/kg equivalent cement
    - Clinkerization (1 plant) – 1257 kcal/kg of equivalent cement or 5259 kJ/kg of equivalent cement.

  The values in kcal are converted to kJ using factor 4.184 joule/calorie. The data geographically corresponds to India and temporally corresponds to 2007-2010.
- Reddy and Jagadish (2003) reported energy consumption of 4.2 MJ/kg of cement. The energy of cement arises from the use of coal in the rotary kilns and energy needed for crushing and grinding the clinker. This study geographically corresponds to India.

2.3.1.4 From electricity and raw material

- The LCI of cement portland from the ecoinvent V3.2 database is analysed using Cumulative Energy Demand (CED) in order to find the embodied energy. The sum of the embodied energy of clinker and electricity consumed for processes after clinkerization in relation to the production of 1 ton of cement is compiled. The energy is 3800 MJ with respect to the geographical area of Rest of The World, 4047 MJ for the US, 3877 MJ for Europe without Switzerland, 3668 MJ for Canada and 3144 MJ for Switzerland.

- The LCI of cement pozzolana and fly ash from the Ecoinvent V3.2 database is analysed using Cumulative Energy Demand in order to find the embodied energy. The embodied energy of electricity and clinker consumed is 3108 MJ with respect to the geographical area of Rest of The World, 3165 MJ for Europe without Switzerland, 3144 MJ for the US and 2514 MJ for Switzerland.

2.3.1.5 From electricity

- The Ecoinvent V3 has provided the electricity consumed for raw meal preparation, fuel preparation and clinkerization. Analysing the same with impact assessment method Cumulative Energy Demand (Version 1.09), the embodied energy of electricity consumed is calculated. The calculation carried out in software SimaPro 8.4.0.0. Results are reported for different geographical areas. 450MJ/ton of clinker is reported for Canada, 1230 MJ/ton of clinker for Switzerland, 643 MJ/ton of clinker for Europe without Switzerland, 663 MJ/ton of clinker for rest of the world, and 652 MJ/ton of clinker for the US. The system boundary considered is cradle to gate.
- The LCI of Portland cement from Ecoinvent V3 database is analysed using Cumulative Energy Demand in order to find the embodied energy from electricity (corresponding to grinding and packing). The embodied energy of electricity used for processes after clinkerization is 420 MJ with respect to the geographical area of Rest of The World. Other values calculated are 627 MJ for the US, 417 MJ for Europe without Switzerland, 228 MJ for Canada and 444 MJ for Switzerland.
- The LCI of Pozzolana and fly ash cement from Ecoinvent V3 database is analysed using Cumulative Energy Demand in order to find the embodied energy of electricity (corresponding to grinding and packing). The embodied energy of electricity used for processes after clinkerization is 368 MJ with respect to the geographical area of Rest of The World. Other values calculated are 365 MJ for Europe without Switzerland, 534 MJ for the US and 334 MJ for Switzerland.

2.3.1.6 From fuel

- Li et al. (2014) reported a thermal energy consumption of 2814 MJ/ton of P.O.cement. The value temporally corresponds from 2004 to 2007, geographically corresponds to China, and technologically corresponds to dry technology (New Suspension Preheater).
- Marceau et al. (2006) reported energy consumption of 3657 MJ/metric ton of portland cement. Fuel includes coal (2658 MJ), Petroleum coke (471 MJ), wastes (240 MJ), residual oil (2.6 MJ/ton of cement), LPG (0.4 MJ/ton of cement) and natural gas (276

MJ/ton of cement). Gasoline and middle distillates are also consumed but it is stated that they are assumed to be used for transportation. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- Virendra et al. (2015) reported 730 kcal/kg of clinker or 3054 kJ/kg of clinker as thermal specific energy consumption. The data geographically corresponds to India and technologically corresponds to preheater precalciner technology. The cement includes OPC, PPC, PSC, and other cement.

- MoP (2015) reported thermal energy consumption for clinker preparation in different cement plants whose primary products are PPC, OPC, PSC and clinker. The values are as follows.

  - PPC (55 plants) – 658–1074 kcal/kg of clinker or 2753–4494 kJ/kg of clinker,
  - OPC (16 plants) – 727–1001 kcal/kg of clinker or 3042–4188 kJ/kg of clinker,
  - PSC (7 plants) – 701–1208 kcal/kg of clinker or 2933–5054 kJ/kg of clinker,
  - Clinkerization (1 plant) – 869 kcal/kg of clinker or 3636 kJ/kg of clinker.

  The values in kcal are converted to kJ using factor 4.184 joule/calorie. The data geographically corresponds to India and temporally corresponds to 2007-2010.

- Grover et al. (2015) reported that in India the thermal energy consumption from fuel towards clinkerization is varying widely from 680 to 850 kcal/kg clinker or 2845 to 3556 kJ/kg clinker, where the best plants are with values 675–685 kcal/kg clinker or 2824–2866 kJ/kg clinker. Three case studies were conducted at cement plants with preheater precalciner technology during 2012-2013, and the thermal energy obtained from fuel is as follows: 762.8 kcal/kg of clinker or 3192 kJ/kg of clinker, 747.8 kcal/kg of clinker or 3129 kJ/kg of clinker and 806 kcal/kg of clinker or 3372 kJ/kg of clinker.

- Saidur et al. (2012) have reported specific heat energy consumption (SEC) of a plant with respect to the time period. The values in GJ/ton are 3.24 (2005-06), 2.85 (2006-07), and 2.81 (2007-08). Usually, the SEC for thermal energy is reported in terms of clinker so the unit is assumed to be per ton of clinker. The study geographically corresponds to Madhya Pradesh, India and technologically corresponds to dry processing technology.

- From the analysis of clinker inventory from Ecoinvent V3 using impact assessment method Cumulative Energy Demand (V1.09) the amount of energy from fuel is 2404 MJ/ton of clinker for RoW, 3106 MJ for Canada, 1540 MJ for Switzerland, 2496 MJ for Europe without Switzerland, and 2443 MJ for the US is also obtained.

2.3.1.7 From raw material

- From the analysis of clinker inventory from Ecoinvent V3 using impact assessment method Cumulative Energy Demand (V1.09), the amount of embodied energy from raw material is 592.88 MJ/ton of clinker. The raw material considered are lime, calcareous marl, lime hydrated, limestone, sand, bauxite and iron ore. Lime contributes the most with 501 MJ/ton of clinker. The value corresponds to cradle to gate system boundary and rest of the world geographically.
- The LCI of 1 ton of portland cement from Ecoinvent V3 database is analysed using Cumulative Energy Demand in order to find the embodied energy. The embodied energy of clinker is 3380 MJ with respect to the geographical area of Rest of The World. Other values calculated was 3420 MJ for the US, 3460 MJ for Europe without Switzerland, 3440 MJ for Canada and 2700 MJ for Switzerland.
- The LCI of 1 ton of pozzolana and fly ash cement from Ecoinvent V3 database is analysed using Cumulative Energy Demand in order to find the embodied energy. The embodied energy of clinker is 2740 MJ with respect to the geographical area of Rest of the World, 2800 MJ for Europe without Switzerland, 2610 MJ for the US and 2180 MJ for Switzerland.

2.3.1.8 From ancillary input

From the analysis of clinker inventory from ecoinvent V3.2 using the Cumulative Energy Demand (V1.09) impact assessment method, the amount of embodied energy from the ancillary material is 12.21 MJ/ton of clinker. The ancillary inputs are tap water, lubricating oil and refractory lining. The value geographically corresponds rest of the world and to Cradle to Gate system boundary.

2.3.1.9 From other physical input

From the analysis of clinker inventory from Ecoinvent V3 using impact assessment method Cumulative Energy Demand (V1.09) the amount of embodied energy from other physical input is 9.04 MJ/ton of clinker. The other physical inputs are cement factory, steel and industrial machines. The value geographically corresponds to rest of the world and to Cradle to Gate system boundary.

2.3.1.10 From transportation

Marceau et al. (2006) reported the average transportation energy of the off-site quarried material, post-industrial raw material and fuel transportation energy in terms of cement which when converted in terms of clinker are 5.35, 41.24, and 27.98 MJ/ton of clinker respectively.

2.3.2 CO_2 emissions associated with clinker and cement

Similar to the energy, CO_2 emission is also reported corresponding to data type or processes. CO_2 emission is found to be reported mostly in association with a data or group of data. CO_2 results are provided in terms of clinker and cement. The data till clinkerization in terms of clinker can be converted in terms of cement, using suitable clinker to cement ratio. Thus, the results are provided here in terms of contribution from a set of data or individual data

2.3.2.1 From all sources (inventory) of CO_2 emissions

- Hammond and Jones (2008) reported emission of 0.83 kg CO_2/kg of general cement for cradle to gate system boundary. If the cement is added with 25% fly ash (for which some embodied carbon is considered), the value changes to 0.62 kg CO_2/kg of cement.
- Chen et al. (2014) reported emission of CO_2 (from inventory) and CO_2 equivalent (from LCIA) respectively for two inventory data. LCIA was done using impact characterization method CML01 in SimaPro software. CO_2 emissions of 0.69 kg CO_2/kg of cement and 0.782 kg CO_2 equivalent/kg of cement is reported corresponding to 15 cement plant inventory data collected from European Pollutant Emission Register (EPER). CO_2 emissions of 0.81 kg CO_2/kg of cement and 0.899 kg CO_2 equivalent/kg of cement corresponding inventory data from Association Technique de l'Industrie des Liants Hydrauliques (ATILH).
- Fonta et al. (2013) stated that the Indian cement industry's efforts to reduce its carbon footprint by adopting the best available technologies and environmental practices are reflected in the achievement of reducing total CO_2 emissions to an industrial average of 0.719 tCO_2/t cement in 2010 from a substantially higher level of 1.12 tCO_2/t cement in 1996.

2.3.2.2 From electricity, fuel and raw material

- OPC, PPC and PSC have an estimated total CO_2 emission of 1.071, 0.961 and 0.632 ton/ton of cement (Das and Kandpal 1997). CO_2 comes from fuel for captive generation, fuel for thermal treatment and from raw material. This geographically corresponds to India and technologically corresponds to dry processing.
- Using the inventory from the Ecoinvent V3 and using a modified version of impact assessment method IPCC 2013 GWP 100a, the direct CO_2 emission and embodied CO_2 of electricity for 1 ton of clinker is quantified. The embodied CO_2 of the electricity is 878.1 kg CO_2 for geographical area Rest of the World. Similarly results are 847.1 kg CO_2 for the US, 864.4 kg CO_2 for Canada, 864.4 kg CO_2 Europe without Switzerland and 779.2 kg CO_2 for Switzerland.

2.3.2.3 From electricity and raw material

- The LCI of 1 ton of cement Portland (from the ecoinvent V3.2 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of clinker and electricity consumed. The values obtained for different geographical regions are 877 kg CO_2 for RoW, 877 kg CO_2 for the US, 850 kg CO_2 Europe without Switzerland, 804 kg CO_2 for Canada and 725 kg CO_2 for Switzerland.

- The LCI of 1 ton of cement pozzolana and fly ash (from the ecoinvent V3.2 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of clinker and electricity. The value obtained for different geographical regions are 712.3 kg CO_2 for RoW, 689.5 kg CO_2 Europe without Switzerland, 671.4 kg CO_2 for US and 586.79 kg CO_2 for Switzerland.

2.3.2.4 From fuel and raw material

- Marceau et al. (2006) calculated and reported CO_2 emissions in terms of cement as 863 kg/metric ton of portland cement, which when converted in terms of clinker will be 907.47 kg/ton of clinker. Carbon dioxide emissions from combustion are calculated from the carbon contents of the kiln fuels and CO_2 emissions from calcination are calculated from the proportion of calcium carbonate ($CaCO^3$) in the raw meal. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- Barcelo et al. (2014) have stated that according to the Cement Sustainability report in 2006, the embodied carbon of portland cement clinker is 866 kg CO_2/ton of clinker. And the direct emission has 60% contribution from raw material decomposition and 40% contribution from fuel used for heating. Barcelo et al. (2014) have also estimated the theoretical CO_2 emission as 816 kg/ton of clinker. CO_2 is estimated by calculating the process CO_2 from chemical composition and fuel CO_2 from calculated theoretical energy consumption.

- According to the GNR report of CSI (2014), the global average of gross CO_2 emission is 842 kg CO_2/ton of clinker. It primarily includes direct emission from raw material, kiln fuels and non-kiln fuels (except biomass fuels).

- According to GNR report of CSI (2014), in India, the average gross CO_2 emission is 828 kg CO_2/ton of clinker. It primarily includes direct emission from raw material, kiln fuels and non-kiln fuels (fuel excludes biomass fuels).

- Clinker inventory from ecoinvent database 8.4.0.0 reports direct CO_2 emission. The values corresponding to different geographical areas are as follows: 838 kg CO_2/ton of clinker for rest of the world, 846 kg CO_2/ton of clinker for Canada, 769 kg CO_2/ton of clinker for Switzerland, 839 kg CO_2/ton of clinker for Europe without Switzerland, and 839 kg CO_2/ton of clinker for the US.

2.3.2.5 From electricity

- According to IPCC 2013 GWP 100a, CO_2 embodied with respect to the electricity consumed for production of 1 ton of clinker (from ecoinvent V3.2 LCI database, corresponding to raw meal preparation, fuel preparation and clinkerization) is calculated for different geographical areas. The values are as follows: 40.1 kg CO_2 for Rest of World, 1.1 kg CO_2 for Canada, 10.2 kg CO_2 for Switzerland, 25.4 kg CO_2 for Europe without Switzerland and 35.9 kg CO_2 for the US. The system boundary considers is cradle to gate.

- Das and Kandpal (1997) estimated CO_2 emission from fossil fuels for a captive generation as 0.028 ton/ton of generic cement. Technological coverage considered is dry processing technology.

- The LCI of 1 ton of portland cement (from Ecoinvent V3 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of electricity. The value obtained for different geographical regions are 25.4 kg CO_2 for RoW, 34.5 kg CO_2 for the US, 16.5 kg CO_2 for Europe without Switzerland, 0.55 kg CO_2 for Canada and 3.7 kg CO_2 for Switzerland.

- The LCI of Pozzolana and fly ash cement (from Ecoinvent V3 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of electricity. The value obtained for different geographical regions are 22.3 for RoW, 14.5 Europe without Switzerland, 29.4 for US and 2.79 for Switzerland.

2.3.2.6 From fuel

- Marceau et al. (2006) reported CO_2 emission of 303 kg/metric ton of portland cement, which when converted in terms of clinker will be 318.61 kg/ton of clinker. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- Das and Kandpal (1997) estimated CO_2 emission from fossil fuels for clinkerization – 0.313 ton/ton of generic cement.

    - OPC: the CO_2 emission estimated from fuel combustion is 0.325 ton/ton of cement.

    - PPC: the CO_2 emission estimated from fuel combustion is 0.294 ton/ton of cement.

    - PSC: the CO_2 emission estimated from fuel combustion is 0.200 ton/ton of cement.

  Fuel combustion includes thermal treatment and captive generation. For generic cement data, about 10% is the total fuel is only used for the captive power plant.

- The inventory corresponding to 1 ton of clinker from different geographical areas is analysed from the Ecoinvent database. The carbon dioxide, from fossil fuels, non-biomass fuel (Alternative fossil fuel) and biomass fuel emitted from processes for raw meal preparation to clinkerization are reported as 854 kg CO_2 for RoW, 854 kg CO_2 for Europe without Switzerland, 854 kg CO_2 kg for the US, 817 kg CO_2 for Switzerland and 861 kg CO_2 for Canada. Five values are reported ranging from 817–861 kg CO_2, where four of them are above 854 kg CO_2. Even though it is not mentioned the fuel will be primarily used for clinkerization

2.3.2.7 From raw material

- Marceau et al. (2006) report a calculated value of 553 kg/metric ton of portland cement, which when converted to clinker becomes 581.49 kg/ton of clinker. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- CO_2 emission values reported by Das and Kandpal (1997) are as follows.

    - OPC: the CO_2 emissions estimated from raw material is 0.746 ton/ton of cement.

    - PPC: the CO_2 emissions estimated from raw material is 0.667 ton/ton of cement.

    - PSC: the CO_2 emissions estimated from raw material is 0.432 ton/ton of cement.

  Technological coverage considered is dry processing technology.

- The LCI of 1 ton of cement portland (from the ecoinvent V3.2 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of clinker. The results obtained for different geographical regions are 852 kg CO_2 for RoW, 842 kg CO_2 for the US, 853 kg CO_2 Europe without Switzerland, 803 kg CO_2 for Canada and 721 kg CO_2 for Switzerland.

- The LCI of 1 ton of cement pozzolana and fly ash (from the ecoinvent V3.2 database) is analysed (using IPCC 2013 GWP 100a) in order to find the embodied CO_2 of clinker. The values obtained for different geographical regions are 690 kg CO_2 for RoW, 675 kg CO_2 Europe without Switzerland, 642 kg CO_2 for the US and 584 kg CO_2 for Switzerland.

2.3.2.8 From transportation

- Marceau et al. (2006) have calculated CO_2 emission values as 3.93 kg/metric ton of Portland cement, from plant mobile equipment. Values are calculated assuming that gasoline and middle distillates are used in mobile equipment (limestone transportation and internal transportation) and applying transportation emission factors. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

- Marceau et al. (2006) have calculated CO_2 emission values as 7.64 kg/metric ton of portland cement. The value corresponds to the transportation of fuels and raw material (other than limestone). Values are calculated using transportation mode and distance data (PCA unpublished) and transportation emission factors. The data geographically corresponds to the US. The technology considered is preheater precalciner technology.

The two sustainability parameters like the energy use and CO_2 emissions can serve as indicators of environmental issues like resource depletion and global warming. It is also observed in the database and literature that apart from geographical areas like Switzerland, the United States, Europe, Canada and China, other countries are not much reported.

2.4 Lack of energy use and CO_2 emission data related to clinker and cement production in India

This literature coverage emphasizes that limited data are only reported on LCI, energy use and CO_2 emission corresponding to the Indian context. It supports the importance of objective 'on assessing the sustainability aspects, like inventory, energy use and CO_2 emission, of clinker and conventional cement' as mentioned in the 'Introduction' chapter.

Indian cement plants mostly (93%) use dry technology, which is currently the best technology available globally. Statistically, the cement industry has changed progressively from 1 % dry process plants in 1960 to over 77% dry process capacity as on 1990, and 93% in 2014-15. It is, therefore, appropriate that dry technology is the basis of the analysis in this work (Kumar 2015). It is hypothesised that the energy use and CO_2 emissions of Indian cement plants will be on par with developed countries as India uses dry technology.

CHAPTER 3

METHODOLOGY

3.1 Introduction

There are different types of LCA guidelines available in the world. Most of them are generic where some of them are more aligned to a particular goal. ISO 14044 and ILCD (International Life Cycle Database) (ies 2010a) are popular known LCA guidelines that provide an in-detail description of how to conduct an LCA. There are also guidelines that are intended to a particular application of the LCA, like PAS 2050 (BSI 2008), Greenhouse Gas Protocol and ISO 14067.

The International Organization for Standardization (ISO) is an internationally accepted organisation that provide standards. They give world-class specifications for products, services and systems, to ensure quality, safety and efficiency (ISO 2017). From 1997 onwards ISO provided standards on LCA through the ISO 14040 series, which deals with different aspects of LCA, like principles, framework, requirements, and phases of LCA. The ISO 14040 and 14044 were revised in 2006 and adopted by the Bureau of Indian Standards on the recommendation of the Environmental Management Sectional Committee and approval of the Chemical Division Council (IS 14044 2006). The IS/ISO 14044 focus on the requirements and guidelines of LCA. It also supersedes the ISO 14041, 14042 and 14043. The IS/ISO 14040:2006 and 14044:2006 are considered as the base for the development of a methodology framework for the current study. A detailed description of the development of LCA template is provided as follows.

3.2 Development of detailed LCA template based on ISO 14040 guidelines

The ISO standards on LCA have detailed descriptions of the terminologies, principles, requirements, guidelines etc. When studied in detail, it is found that most of the explanation in the code is generic. This observation is obvious since the code is meant to meet a wide range of application. Also, the code explains LCA in a descriptive and theoretical way as it helps the reader understand the concept behind the procedure. Thus, it is required to adopt the same from a generic form to a specific and simplistic form, and also from conceptual form to user-friendly practicable form for the present study. The four major phases of the LCA are:

1) Goal and Scope Definition
2) Life Cycle Inventory (LCI)
3) Life Cycle Impact Assessment (LCIA)
4) Interpretation

Figure 3.1: Stages of LCA (IS 14040 2006) shows interlinks among the four phases of LCA as in ISO 14040. The figure also shows the iterative nature of the LCA. In the first phase (goal and scope) a detailed description of the LCA to be conducted is provided. Here, the primary objective and the detail to which it needs to be studied are defined distinctly. In the second phase (LCI phase), the data collection and analysis are conducted as per the requirements in the goal and scope. In the third phase (LCIA phase), the effect of inventory in the form of environmental issues/impact is found and evaluated. In the fourth and final phase (Interpretation), the results of LCI and LCIA phase is assessed with respect to the requirements defined in the goal and scope phase, and also conclusions, limitation and recommendations are drawn.

Each phase has many steps in it, which can be called items or elements or sections. The terminology element is been used in the IS/ISO standard but the terminology "Section" will be used throughout in this thesis. For further classification, the terminology "Sub-section" is used. Based on the understanding from standard and prior experience of trial LCA conducted on the template developed by Ms. Sofia Sánchez Berriel (Faculty of Economic Sciences, Central University of Las Villas, Santa Clara, Cuba), an attempt has been made to develop a template for LCA, using a spreadsheet. The spreadsheet has four primary worksheets corresponding to the four phases of the LCA and some secondary worksheets related to the compilation of different factors required in LCI and LCIA. Sections of each phase are made in such a way that following the same enables the practitioner to perform LCA of a product or process in a standardised way. These steps can be descriptive, data analysis etc. Most of the sections in the main worksheets are in the form of tables with four columns. The first column is the index, the second column contains the name of the section or sub-section, the third column is blank for the practitioner to provide information related to his/her study, and the fourth column is for remarks, which provides some guidelines in relation to that section. This helps the practitioner about what kind of information needs to be provided in the description column (along with some sample information).

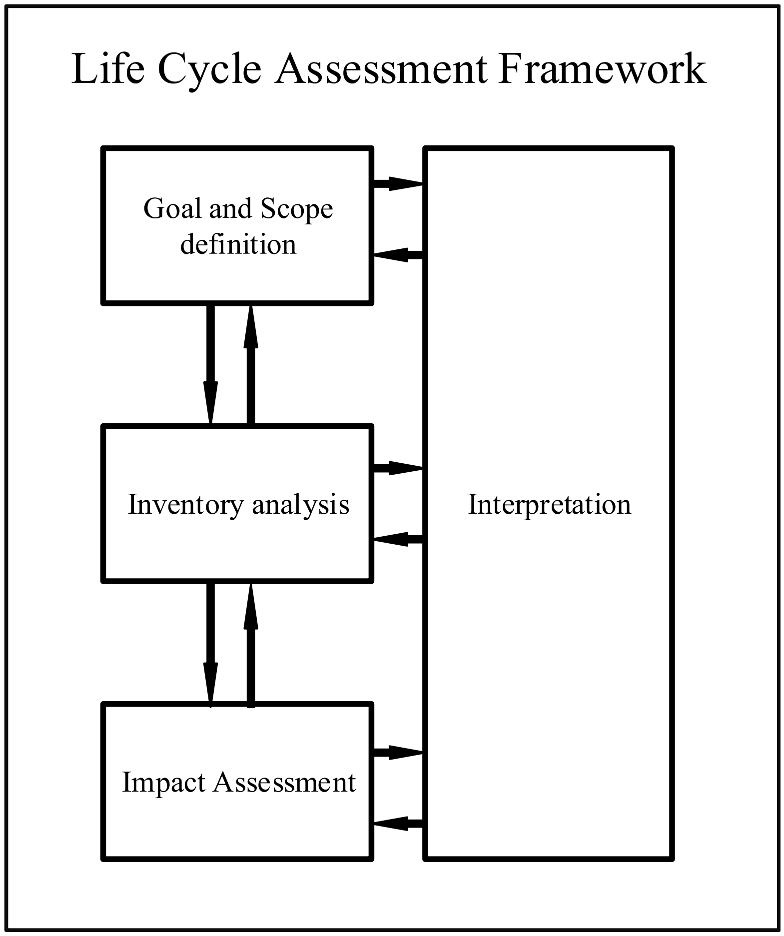

Figure 3.1: Stages of LCA (IS 14040 2006)

This template is then used for two LCA case studies on cement production in order to understand the applicability of template. Based on the feedback during the analysis, the template can be modified. The modification includes organisation of section, in which new sections or sub-sections are incorporated or existing sections are modified. Feedback and related information (from literature) are to be added in the remarks columns. A brief description of every section and sub-section of the four phases of LCA, which has been used in the template, are provided as follows.

3.3 Goal and scope

The goal and scope are similar to the planning phase in construction practices. Here, we plan the LCA study to be conducted or the structure of LCA. This phase should technically and unambiguously define the objective and the level of detail in which the objective should be met. By level of detail, it means a description of the product/process (in relation to LCA), how LCI and LCIA need to be conducted, and how the interpretation needs to be done. This detailed description can also help estimate time, and resources such as data required and cost of the project to meet the same. As the study moves into the later phases of the LCA, and if the study is subjected to unexpected change (few examples are changing in scope, addition or cut down of objective, and change in impact considered), it should be properly addressed in the Goal and Scope (in an iterative way). "Goal" and "Scope" can be distinctively called as two sub-phases. Each sub-phase consists of sections to be addressed. Since the LCA method is an iterative concept, there are also sections that need to be addressed as the study progresses in other phases.

Figure 3.2, shows the sections of goal and scope definition. A brief description of each section is provided, including the basic information a practitioner should know to perform that section during an LCA study. It also includes a sample of information the practitioner needs to provide with respect to the section.

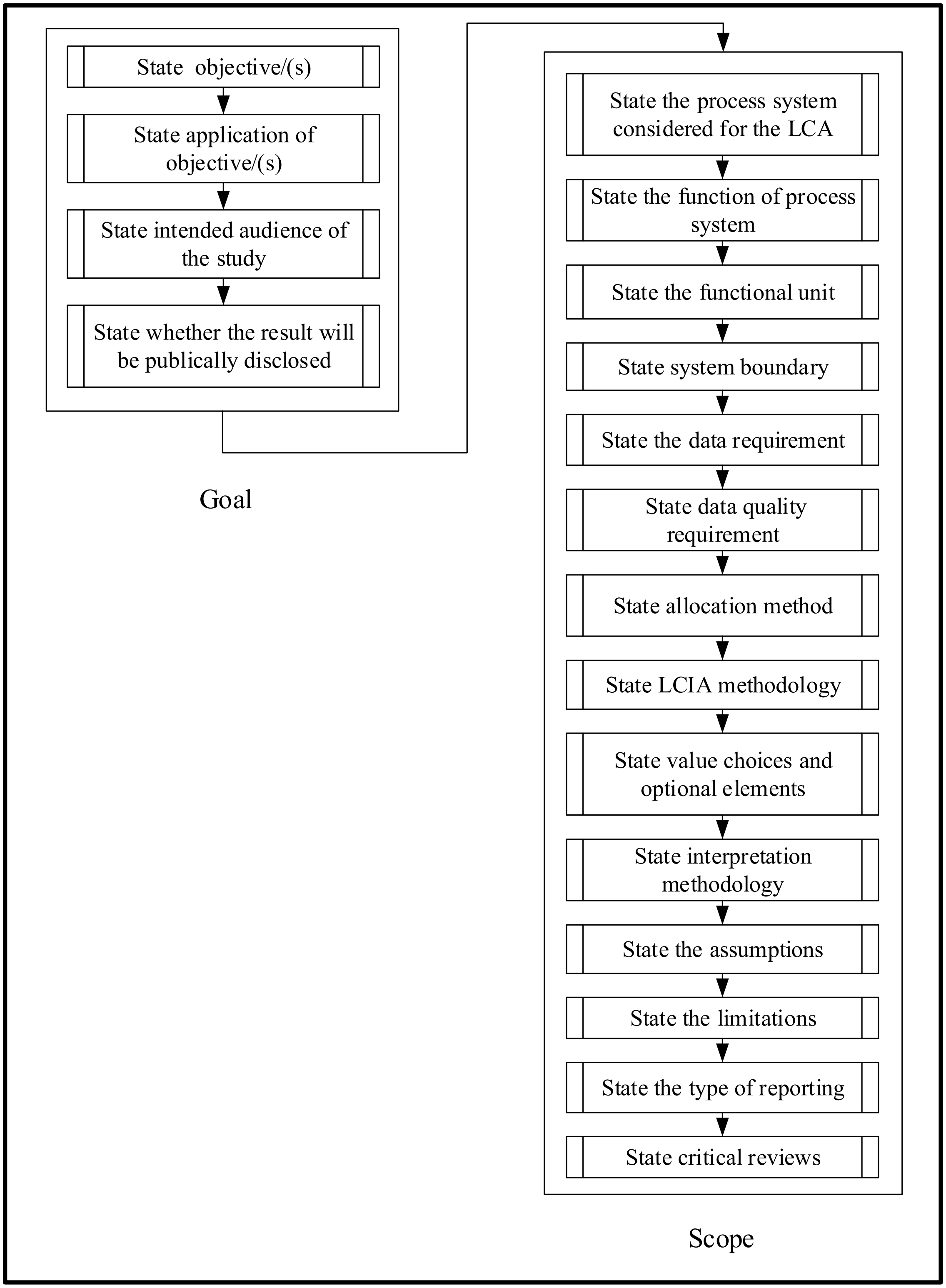

Figure 3.2: Sections of goal and scope definition

3.3.1 Goal – Objective of the study

LCA is conducted to assess the environmental sustainability of a product or process. Two common objectives are the development of life cycle inventory and assessment of environmental impacts. Other objectives are finding the hotspot unit process and a comparison of two or more products or processes. Thus, in this section, the LCA practitioner states the objective of the study with maximum detail. Few examples of information that can be provided is as follows: 1) To quantify the life cycle inventory of the cement production; 2) The main objective of this analysis is to find the energy consumption and CO_2 emissions due to the production of different types of cement; and 3) To find the most energy-intensive process in the production of steel.

3.3.2 Goal – Application of the objective

The practical application of the objective is described in this section. Generally, it includes the development of the inventory database and studying the effect of using alternative inputs/process such as raw material, fuel and new technologies, for comparative assessment with similar products. Examples: 1) To understand the current energy consumption and CO_2 emission of clinker production in an Indian cement plant and to compare it with respect to other reported values, and 2) To develop life cycle inventory for clinker production in India.

3.3.3 Goal – Intended audience of the study

The intended audience of the study is stated here. Few examples the intended audience could be academicians, industrialists, public policy maker, government organisations, intergovernmental organisation (environmentalists, e.g. WHO), and non-governmental organisations. Academicians can understand the process/input contribution in detail, which enable them to assess possibilities of improvement of major input or process and suggest a solution if needed. Even the hypothetical methods for improvement can be analysed. The industrialists can understand the area of potential improvement from the study and take decisions to improve the same. Public policy makers (say Government) can initiate a study to understand the environmental impact from a process or product.

3.3.4 Goal – Decision regarding public disclosure of comparative assertion

Decisions regarding public disclosure of comparative assertion are to be stated here. If it is decided to disclose the result in a public forum, more clarity and transparency should be provided to the LCA (e.g.: proper definition of the data quality requirement). In the interpretation phase, sensitivity analysis should be conducted and statement based on the same should be provided. If it is decided not to disclose, the same should be stated in the description cell.

3.3.5 Scope – Product system

Product system consists of a collection of unit processes with elementary and product flow, performing one or more defined functions, and which models the life cycle of a product. The product system associated with the study is mentioned here. The processing system can be defined in the name of the technological classification of the same. It is better to define the product system in detail if two or more product systems are compared. Examples are (1) comparison of hand drying system in the form of paper towel and an air dryer system, and (2) An integrated cement plant using dry processing for clinkerization. The plant use preheater precalciner unit along with the rotary kiln.

3.3.6 Scope – Function of a product system

It is a statement of performance characteristics, or in simple words, it is the process performed by the system. The process related to the process system which is being studied needs to be mentioned here. It is usually required if two or more functions are performed by the process system and only a few out of the same are considered for analysis. E.g. diesel production from crude oil using fractional distillation. Here, the processes associated with other products like gasoline, petrol, and furnace oil are not considered.

3.3.7 Scope – Functional unit of product/product system

The functional unit is a quantified performance of a product system for use as a reference unit. The functional unit should be a measurable quantity which serves the purpose of the process. The functional unit related to the study is stated here, e.g.: 1) one ton of clinker is considered as the functional unit for clinker production, 2) one truckload of sand (because the sand is practically available on the truck unit) is mined from the river bank and 3) one bag of cement.

3.3.8 Scope – System boundary

According to ISO 14044, the system boundary is a set of criteria specifying which unit processes are part of a product system. The system boundary is defined in detail in five subsections.

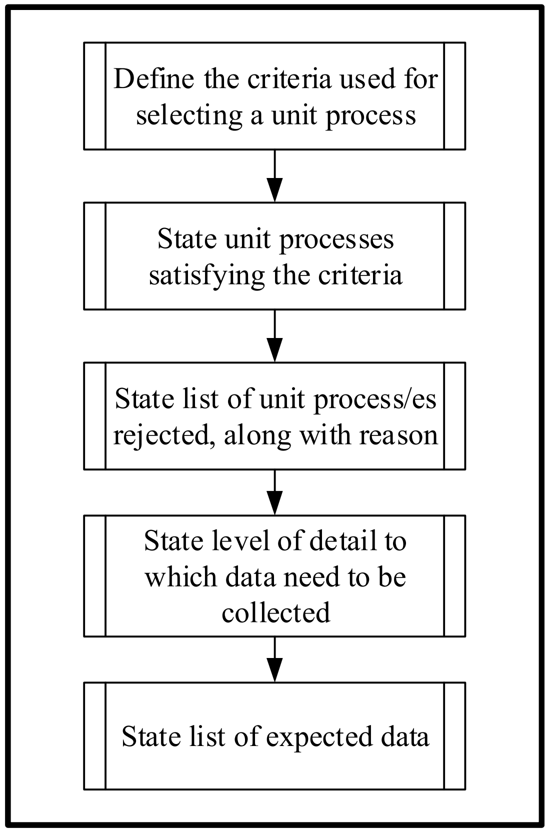

Figure 3.3: Subsections under system boundary

System boundary is defined using a set of five sub-sections as shown in Figure 3.3, a detailed explanation of each sub-section is provided below:

3.3.8.1 Criteria used for selecting the unit processes

Set of criteria which specify, out of all the unit processes (by default as per life cycle concept all unit process from cradle to grave should be considered), the unit processes to be considered as a part of product system is defined here. There are commonly known system boundaries like Cradle to Gate, Cradle to Grave, Cradle to Cradle, Gate to Gate, Gate to Grave, Gate to Cradle, and Well to Wheel. For example Gate to Gate: Every process starting from the entry gate to the exit gate in a factory is considered. In case of customised system boundaries, for a set of processes of interest, the detailed description of the same should be provided. This usually happens if the study is intended to align any database or organisation specified system boundary. For example, CSI system boundary: It is a system boundary followed by Cement Sustainability Initiative program to develop a database on energy and CO_2 performance of cement production across the world.

3.3.8.2 List of unit process

The processes to be considered according to the system boundary criteria are provided along with a brief description of the activities undergoing in the same. The process description should be provided in the logical order or in the order in which processes occur. It will be better if input, description of activities and output is described with a process flowchart. A process called "others" should be defined to take care of inputs and outputs that belong to less significant processes. Few examples are internal transportation in cement plant, electricity for the colony, cement plant office, and fuel for canteen cooking.

3.3.8.3 Deleted unit process and the reason for deletion

In this step, the processes that should be considered according to system boundary criteria but avoided due to some other reason are mentioned. Along with the process, the reason for the deletion of the same should be also mentioned. The deletion of the process can be due to different reasons like lack of data availability and negligible impact. The information regarding the deletion of the unit process and the reason for the same needed to be reported in the limitation section of the scope phase.

3.3.8.4 Cut-off criteria

Cut off criteria used towards the data collection is defined here. Few cut off criteria are mass limit, energy limit, and limit based on environmental significance. In the mass limit, the input/output should satisfy a cut-off % of the total mass input modelled, or % cut-off of a reference mass input value (from literature), e.g. the input should be at least 1gm or at least 1/1000 of the mass of functional unit. Zero or no cut off can also be used. In energy limit, the input/output should satisfy a cut-off % of the total energy input or cut off % of a reference energy value input. For example, the input should be at least 1kJ or 1/1000th of reference embodied energy value of the functional unit (found from literature). Zero or no cut off can also be used. For environmental significance, the input/output should satisfy a minimum additional % of the estimated environmental significance of the product system or of a reference environmental significance value (from literature). For example, for any output gas with at least minimum CO_2 equivalency of 1gm/kg of output, zero or no cut off can also be used.

3.3.8.5 List of expected input/output

Here, the list of expected inputs and outputs related to each unit processes should be provided. Every unit process considered according to the system boundary should be detailed with inputs and outputs. The inputs and outputs are preferably elementary. Inputs are raw material, energy (e.g. fuel, electricity, feedstock energy), ancillary input, other physical input (e.g. transportation trucks, machinery, and infrastructure), others and outputs are products, co-products, by-products, waste – emission to air (such as CO_2, CO, SO_2, NO_x, Radiation, and Noise), waste - emission to water (such as wastewater), waste - emission to soil (such as solid waste dumping) and others. In both input and output, there is a data category called "other" to report values which do not belong to the defined data categories. E.g., raw material extraction: the inventory (inputs and outputs) related to extraction of raw material for calculating its reference flow,

Input: Explosives, fuel consumed by equipment, electricity consumed, lubricant consumed by equipment, water consumed, equipment consumables, equipment, and the limestone extracted

Output: Limestone, overburden limestone, CO_2, and Dust.

3.3.9 Scope - Data requirement

Here, the inventory required for the study is reported process category-wise. This is to ensure that at least the inventory required to meet the objective will be collected. The expected inventory (Input and Output) listed in the system boundary, along with the inventory found in literature, books, reports, and preliminary studies should be compiled at this stage. E.g. Clinkerization – fuel, electricity, raw meal, hot air, oil, equipment (E.g. rotary kiln, transporting equipment, and fan), clinker, waste (brick lining etc.), CO_2, SO_2, NO_x, dust, hot air, radiation etc..

3.3.10 Scope – Data quality requirement

In this section, few qualities regarding the data are defined. This should be defined based on the required accuracy of the study. It is defined based on following defined qualities. As shown in Figure 3.4, the requirement of each quality like time period coverage, geographical coverage, technological coverage, precision, completeness, consistency, reproducibility, the source of data and uncertainty need to be defined based on the requirement of the LCA study. A brief description of each quality parameter is provided as follows.

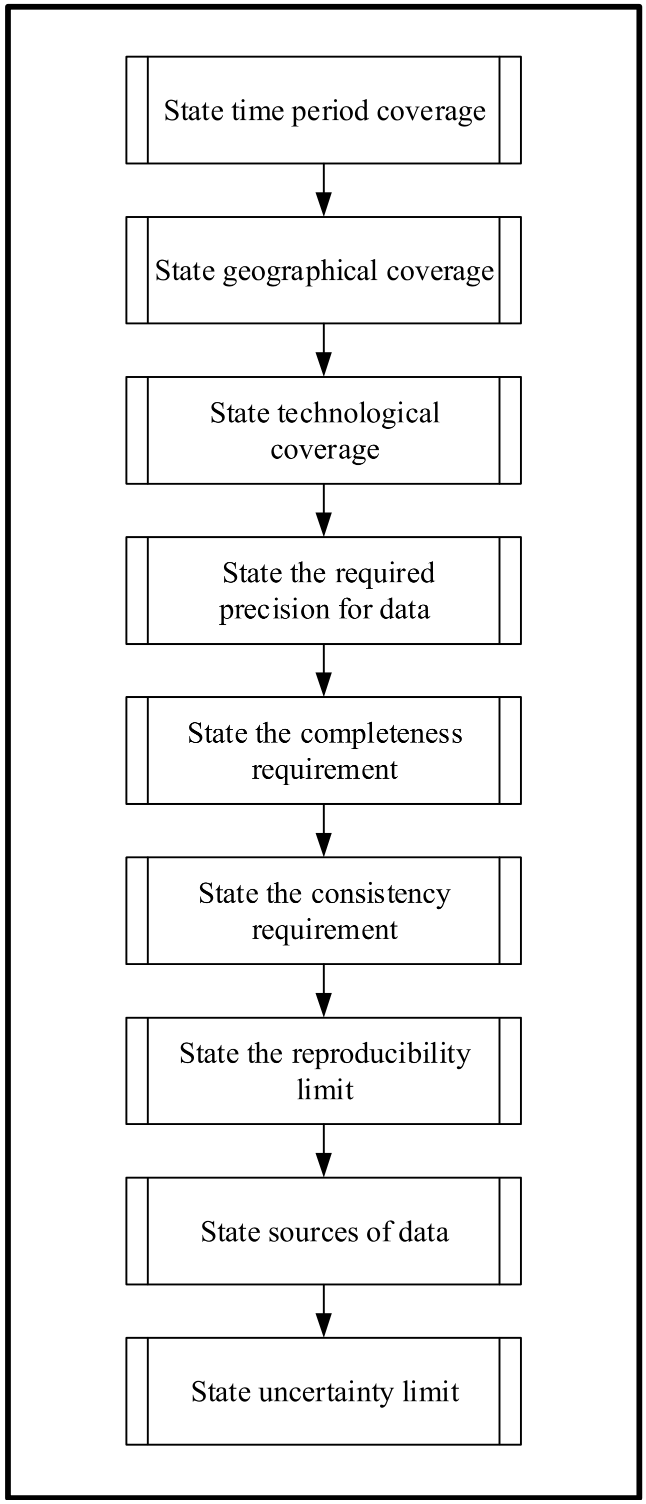

Figure 3.4: Subsections of data quality requirement

3.3.10.1 Time period coverage

Here, the time period and age corresponding to the data is defined. The time period should be when all the activities related to product system will occur repeatedly as a cycle. Age of the data can be selected based on the requirements of the study. E.g. time period: 2 years and age of the data: recent. The age of data can be represented more clearly as a range of years, e.g. 2012-2013.

3.3.10.2 Geographical representation

If the study should represent the scenario in any defined location, it is mentioned in this step. E.g.1) South India, 2) typical cement plants in India are situated near limestone mines so the plant should be next to limestone bed, 3) hilly area and 4) cold region.

3.3.10.3 Technological coverage

Here the type of technology the study aims for is stated. E.g. 1) clinker production through wet processing, 2) integrated cement factory with dry processing technology, and 3) any pilot plant.

3.3.10.4 Precision

Here, the permissible measure of variability is stated. For example, 1) coefficient of variation should be <0.2, and 2) data precise to one's position.

3.3.10.5 Completeness

Here, the degree of completeness required is defined. It is mentioned in the literature that completeness check is to ensure all relevant information and data needed for interpretation is available and complete (Cooper and Kahn 2012). It can be represented as the percentage of data that should be measured (measured according to the mass, energy and environmental significance limit defined, number of input), excluding estimation. One thumb rule in checking inventory completeness is that the input or output of a process should meet mass and energy balance. E.g. 1) all the data described in the data requirement should be met, and 2) 90% of the inventory in the data requirement should be met.

3.3.10.6 Consistency

In this section, the required level of consistency for the methodology is defined. By methodology, it is meant about the assumptions, data and methods followed. Data attributes are accuracy, age, time-related coverage, geographical coverage, technological coverage, and data source. Methods are system boundary, cut-off value, allocation, impact category, impact category indicator, characterization model and value choices. Few terminologies for consistency levels are fully consistent, partially consistent and not consistent.

3.3.10.7 Reproducibility

The extent to which the result need to be extrapolated is defined here, or to how much the data or result can be extrapolated by an independent practitioner need to be defined here. Reproducibility depends on the completeness and further technology correlation categories (Cooper and Kahn 2012). For the data or result to be reproducible, it should be transparent. E.g. 1) factory unit level data can be extrapolated to state-level data, and 2) to extrapolate to Indian average value.

3.3.10.8 Sources of data

Mostly the sources of data will be: 1) data measured by a practitioner (e.g. measured with equipment during study, sample collection, measurement, and analysis after study, and interview); 2) internal monitoring files of company (e.g. documents, presentations, and third-party survey reports (consulted by the company for monitoring certain data)); 3) data provided to Govt. bodies and public survey data sheets; 4) published articles (e.g. annual report of factories, and websites); and 5) Databases. Among these sources the best representative data should be selected and mentioned as a required source of data, e.g. the data should be site measured etc...

3.3.10.9 Uncertainty

Uncertainty is the change in result due to variation in the data (Inventory), model (characterization model) and assumptions. Here, a limit to the affordable uncertainty needs to be defined. E.g. $< \pm 10\%$ of a reference literature value

3.3.11 Scope - Allocation procedure

Mass allocation and economic allocation are commonly followed. There are other allocations like energy basis, hydrogen content basis allocation (Abella et al. 2016). The allocation should reflect the underlying physical relationship between the inputs and outputs with respect to the functional unit of product (sometimes a product, co-product and by-product), e.g. the mass allocation is being followed in the study (as seen in literature). Since there is only one major product (clinker), every input and output is proportionated with respect to the 1 ton of clinker.

3.3.12 Scope - LCIA methodology and types of impact

This is to select the right impact category related to the process system and associated impact category indicator and characterization model. Mostly these impact characteristics are recognised from previous studies, or else it can be found by the practitioner itself using preliminary studies. In preliminary studies, it is better to go step by step to find all three sequentially in the order impact category, impact category indicator and characterization model.

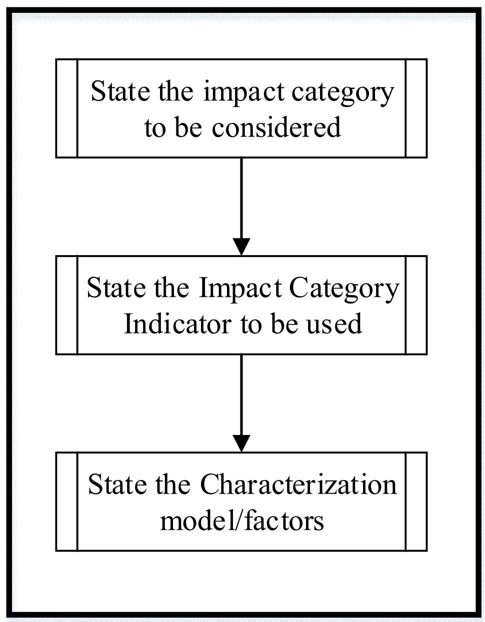

Figure 3.5: Sub-sections of LCIA methodology

3.3.12.1 Impact category

Here, the impact category to be considered for the study is defined. In the first step, it is required to select or define the impact category of interest to be studied in the LCA. Few steps to identify the impact category is as follows, attribute or aspect of the natural environment, human health, or resources, identifying an environmental issue giving cause for concern is called category endpoint (IS 14044 2006). There are lot of physically recognisable attributes of category endpoint which enable us to understand the environmental issue (Human health – eye irritation, asthma due to high amount of pollution, cancer in humans, Natural environment - extinction of plant species, dying of fish etc., Resource - Change in temperature, reduction of water level etc.). First, the category endpoints are recognised (E.g. skin, breath (human health), forest and crops (natural environment), water bodies, mineral ores, and mountain (resources)) on which the identifiable environmental issue/s related to the product system is observed. Based on the category endpoint all the environmental issue/s related to the product system are identified and compiled (E.g. global warming, increase of UV-B radiation, change in aquatic species composition, acidification, eutrophication etc.). A class of environmental issues of concern are called impact category (IS 14044 2006). The suitable impact category/ies (already existing) which reflect the comprehensive set of environmental issues found is selected for the study, E.g. Climate change, Ozone layer depletion, Eutrophication. If suitable impact category corresponding to the identified environmental issues are not found, a new impact category is defined.

There are few recommendations which the ISO standard insist on the impact category selection.

1) It should represent the aggregated impacts of inputs and outputs of the product system on the category endpoint through a category indicator,

2) It should be internationally accepted (if you are defining one logically and doing calculations, still the result is valid, but it should be understood and reported in limitation section that it does not satisfy this condition of international acceptance).

3) This step is a suggestion rather than a recommendation. The impact category should have an accurate or descriptive name. The related information and source of the impact category should be provided.

4) Minimised assumptions and value choices.

5) Avoid double counting unless insisted in the goal and scope, e.g. human health and carcinogenicity.

An example of the information to be provided in the description box related to impact category is as follows: 1) "The impact category considered is climate change. the environmental issues associated with the same is global warming and its side effects like melting of glaciers, the rise of sea level, frequent droughts, and uneven precipitation. The natural environment is the category endpoint", 2) "Impact category considered is stratospheric ozone depletion. The environmental issues are higher UV -B radiation on earth due to holes in the ozone layer. The category endpoint is human health, e.g. skin cancer", 3) "A defined Mid-point impact category called Cumulative Energy Demand is used for the analysis". An example considering all impact category, impact category indicator and characterization model are as follows "Impact Category: Climate change, Impact category indicator: kg CO_2equivalent, Characterization model: IPCC 2013 GWP 100a".

3.3.12.2 Impact category indicator

In the second step, a suitable impact category indicator corresponding to the impact category is selected. Impact category indicator is a quantifiable representation of impact category. Generally, the criteria for selection will be the ability to represent the environmental issue. The impact category indicator that can represent the environmental issue more precisely should be selected. There are few recommendations ISO 14044 insists, as follows. 1) International acceptance, 2) minimal assumptions and value choices, 3) avoid double calculation, and 4) environmentally relevant. If there is any uncertainty of linkages between category indicator and environmental issue, it is mentioned. Few examples of Impact category indicators are 1) "The impact indicator considered for Climate change is infrared radiative forcing (measured in kg CO_2 equivalent)", 2)"The Ozone depletion potential is considered as the impact category indicator for impact category Midpoint level stratospheric ozone depletion", 3)"The impact category is Ozone depletion and the Impact category indicator is DALY".

3.3.12.3 Characterization model

In the third step, the characterization model is selected. The selection of the characterization model will be based on its ability to convert the inventory result to impact category indicator using suitable characterization factor. Characterization factor for a data is created based on the distinct scientific mechanism and reproducible empirical observation between the data and impact category indicator. There are few recommendations for characterization model as follows: 1) International acceptance, 2) Minimal assumptions and value choices, 3) Avoid double counting unless mentioned in the goal and scope, and 4) It should have a distinct scientific mechanism and reproducible empirical observation. Even though it is not recommended, mention about the reversibility of environmental mechanism if present. It also needs to be understood that there is a trade-off between simplicity and accuracy of the characterization model. Other suggestions are,

1) Temporally and spatially valid with the goal and scope. Temporally properties are duration, residence time, persistence time etc... Spatial properties are geographical area etc...

2) The uncertainty on the linkages between the category indicator and category endpoints are mentioned.

An example for the information to be provided in the description cell is as follows: 1) The characterization model used for the study is "IPCC 2013 GWP 100a", with "kg CO_2 equivalent" as unit of impact category indicator for the impact category climate change, 2) Characterization model "Ozone layer" is been used (of Impact assessment method "Eco-indicator 99 (E) V2.10") with impact category indicator "DALY" and impact category "Ozone layer depletion", 3) The characterization factors are compilation of factors from data shared by cement plant, experimentally found by practitioner and from databases.

3.3.13 Scope - Value choices and optional elements

Here, the value choices related to the characterization factor or model are selected. The value choices are simply the values chosen for the calculation of the characterization factors related to the LCIA. This selection depends on the perspective or concern towards the environment. Three social perspectives used are an individualist, hierarchies and egalitarian. Individualist considers only short-term effect, hierarchist considers mid-term effects also and the egalitarian considers even long-term effect. According to Schryver (2010), the individualist perspective has a link with opinions from industry, the hierarchist perspective has a link with the Environmental Protection Agency, and the egalitarian perspective has a link with environmentalists. By default, if we are considering every effect from an input, the corresponding value choice is Egalitarian.

3.3.14 Scope - Interpretation

In this section, details of the different types of analysis and evaluation techniques to be used in the interpretation phase are provided.

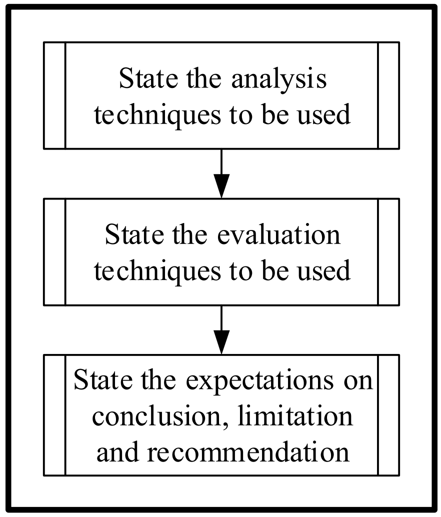

Figure 3.6: Subsection of interpretation

3.3.14.1 Analysis techniques

Different types of analysis techniques which are required to be applied to the results from LCI and LCIA are defined here. Few of these analysis techniques are contribution, dominance, influence, anomaly, uncertainty and sensitivity analysis.

3.3.14.2 Evaluation techniques

The evaluation techniques used in the interpretation phase is defined in this section. Evaluation techniques are used in order understand the reliability and stability of the result obtained from LCI and LCIA phase. Two evaluation techniques which can be used are completeness check and consistency check.

3.3.14.3 Conclusion, limitation, recommendation

The expected conclusions, limitations, and recommendations are defined here. The expected conclusion is that the define objectives in goal are complete. The study should be completed with no or zero limitation with respect to the scope defined. The recommendation can be on the application of the result (application is already defined in goal), measures to tackle possible consequence observed as environmental issues and measures to rectify the case-specific limitations faced in the study.

3.3.15 Scope – Limitations

Limitations is a section where all the limitations experienced during the study are documented. The known limitations in the goal and scope should be reported initially in this section and as the study progress in other phases like LCI, LCIA the calculation may face more limitations and it should be added in this section. Few generic limitations of goal and scope are lack of suitable characterization model and lack of clarity on associated impact category. Some examples of limitation faced as study progress are: 1) for some material the diesel consumption data for transportation is estimated; 2) the energy and emission characterization factor for the electricity was not calculated due to lack of data. The characterization value used in the calculation is taken from another source.

3.3.16 Scope – Assumptions

Assumptions made during goal and scope (before the study) and the assumptions made as the study progress are reported in this section. The assumptions can be rectified in the upcoming iterations (say, assumed data can be collected by conducting another iteration of data collection). Few examples of the assumption are: 1) The assumed inventory data; 2) Assumed conversion factors; 3) In case of data redundancy (2 or more different values of), priority is given to the sources of LCI data based on some assumed condition. For example, based on the time coverage the priority followed is: Sum of Monthly break up > Yearly break up. Based on type of data source a priority order given is: measured data> factory internal monitoring files> report submitted to the government.

3.3.17 Scope – Type of reporting

Here the type of reporting required for the study is provided. There are three types of reporting, the normal reporting of the practitioner (E.g. research purpose report, and industrial purpose), report for the third party and for public disclosure (for comparative assertion). The information to be incorporated into each type of report is provided in detail in ISO 14044.

3.3.18 Scope – Critical review

Critical review improves the credibility of the study by showing adherence to the Standard. The requirement of critical review is mentioned here (Yes or No). The details like how to perform the same and the level of expertise of the practitioner can also be defined. The more details are provided in the ISO 14044. It can be an internal reviewer, external reviewer, or a panel of an external reviewer.

3.4 Life Cycle Inventory (LCI)

It is the second phase of the LCA. According to ISO 14044, Life Cycle Inventory Analysis is "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle". Inventory means a collection of inputs and outputs related to the process system. Main input categories are energy, raw material, ancillary material, other physical inputs and others. Main outputs categories are products, co-products, by-products, waste - emission to air, waste – emission to water, waste – emission to soil and others. Examples of inputs and outputs are as follows.

1) Inputs
   a) Energy –
      i) Heat (MJ) – sunlight, and steam
      ii) Electricity (kWh) - electricity
      iii) Fuel (kg) – coal, petcoke and lignite
   b) Raw material – limestone (ton), and crude oil (ton)
   c) Ancillary material – lubricating oil, catalyst, and water
   d) Other physical inputs – infrastructure, machinery, and transportation equipment (truck)
   e) Others – Inputs which does not belong to any of the above categories. The material used for repairing the machinery, etc.
2) Outputs
   a) Products – cement, and steel
   b) By-products – fly ash
   c) Co-products – diesel, petcoke, and furnace oil
   d) Waste – wastewater, broken machinery, and overburden
      i) Releases to air – CO_2, CO, SO_x, NO_x, radiation, and noise
      ii) Releases to water – sludge, oil, wastewater
      iii) Releases to soil – overburden limestone, bio-waste, and vibration
   e) Others – output which does not belong to any of the above categories, E.g. broken machinery, and broken packets

In a simpler form, in this phase, all the input and output related to the life cycle of the product is collected and normalised to a functional unit of the product or process (analogous to goods and services). This is one of the most time and resource consuming phase of the LCA (Curran 2012; Sakai 1998) The LCI result itself can give a lot more understanding about the product or process. LCI results are sometimes enough for product comparison. The LCI result should be accurate and complete as this serves as the base values for the calculation in LCIA where the same will be converted into an impact indicator of a specific impact category. Thus the assumptions and calculations used in this phase should be scientific and logical.

In LCI due to numerous inputs and outputs, and variations in its magnitude, unit, source and similar other parameters, the results may have high uncertainty. The inventory data will be presented in a different unit of measurement, calculating of inventory results of required form, demands effort. For example, if an input data shows 2 or more values in different sources, then it can cause ambiguity on selecting one among them, or whether a range of value based on the same should be selected. Thus suitable and logical selection criteria should be assumed (which need to be stated in the Goal and Scope - assumptions section) and based on this criteria, the value of data should be selected. The further calculation can proceed with that value. In order to avoid similar ambiguities and to have a structured way of calculation, guidelines are provided in ISO 14044. The guidelines are studied thoroughly and it is been converted to a series of steps as provided in the Figure 3.7. There are basically six main steps. Details of these main steps are provided in the following section.

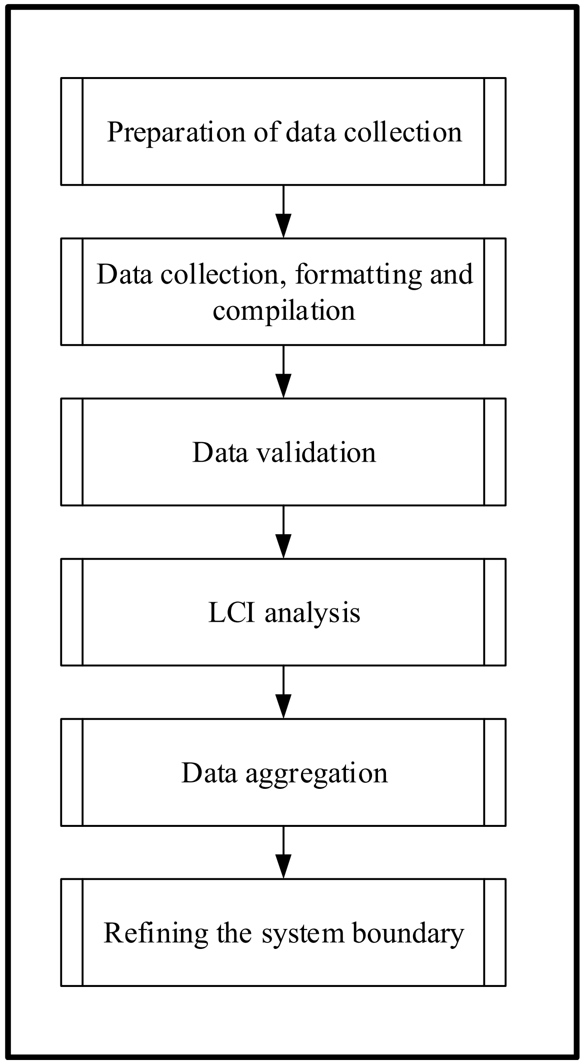

Figure 3.7: The sections in LCI phase

3.4.1 Preparation of data collection

This section acts as a final step of the planning of LCA. Here preparation is conducted on how to collect the expected life cycle inventory. The Figure 3.8 shows sub sections of the preparation required.

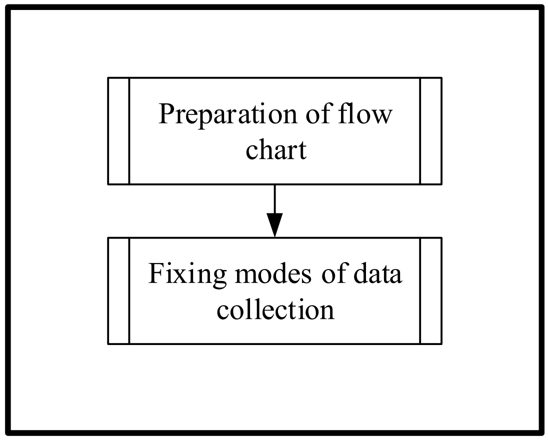

Figure 3.8: Sub-sections in preparation of data collection

3.4.1.1 Preparation of rough process flow chart

A process flowchart is prepared based on the processes, input and output considered (which is already described in the Goal and Scope phase). This process flowchart gives a complete understanding of the data that should be collected in the study. Flowchart also enables the data providers easy comprehension of the data requirement. Or even it can help the LCA practitioner to find the data from literature in an ordered manner. This can smoothen the data collection process.

3.4.1.2 Fixing modes of data collection

There are numerous ways of data collection, based on the data quality requirement. One or more suitable methods are chosen in this sub-section. Care must be taken to at least collect the data defined in the scope (with desired data quality). Else it can lead to cutting down of scope, repetition of data collection, the assumption of missing values etc... Use the process flowchart and the expected input/output data defined in the scope as a reference for data collection. Following are few modes of data collection, conducting questionnaire survey, interviews and hand notes, collecting soft copy files (E.g. internal monitoring document, third-party survey reports, and reports submitted to govt), hardcopy reports, photos, physical samples of input or output, referring official company websites, journals, reports, databases, existing LCI models, and software. For data collection using survey sheets, model data collection sheets are provided in the ISO 14044, which can be considered as a reference to prepare case-specific data collection sheets. To collect samples, the equipment required for the sampling should be specified. During data collection for every data, provision should be provided to mention the value, unit of measurements, and data quality requirement (E.g. time coverage, and source) defined in scope. Data collected can be quantitative or qualitative. The data can mainly be in measured, calculated and estimated. Select possible data collection methods which can be easily executed and can met desired data requirement and quality. After this step, the data collection should be conducted.

The examples of information obtained from this subsection are as follows: 1) Site visit and direct data collection via questionnaire are been selected as the mode of data collection. A list of materials and data to be collected and questions to be asked is been prepared; 2) The Govt reports on building construction (E.g. CPWD documents in govt projects) is been selected as the mode of data collection; 3) Based on Ecoinvent database and literature.

3.4.2 Data collection, compilation and formatting

This step describes details of data collection undergone and the way to format and compile the data obtained. The Figure 3.9 shows the required steps .

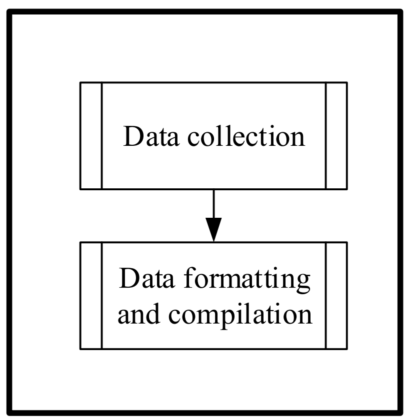

Figure 3.9: Sub-section of data collection, compilation and formatting

3.4.2.1 Data collection

This step should be started after the completion of data collection with the help of process flowchart and prepared modes of data collection. In the description box, information on the conducted data collection procedure is provided. Few examples for the same are as follows: 1) Case study, interview, sampling and collection of internal monitoring files are modes of data collection. A site visit is conducted to cement plant “A”. During the site visit, the different stages of processing of cement are well explained by the officials, especially General Manager of quality control. This enables the validation and modification of process flow chart prepared. Different officials were interviewed and hand notes were made on the same. The data requirement and study importance are been convinced during the interview. The factory's documentation having similar data which the LCA demands is been shared by the officials through the mail as soft copy files. Samples of fuels and raw material were also been provided. 2) The databases and literature (Journal, reports, conference papers, presentations and posters) are chosen as the source for inventory. The ecoinvent database is been used mostly. The data set corresponding to India's geographical coverage is not provided. Thus the next best representative region and corresponding dataset named RoW (Rest of the World) is selected to obtain data.

3.4.2.2 Data formatting and compilation

The data collected using different modes and from different sources will have an inconsistent format. These data need to be compiled and formatted to a uniform manner. In this subsection, the data collected is formatted and compiled. Usually the data can be in absolute values (E.g. limestone - 12000ton, and diesel - 145kl, corresponding to the time period defined in scope), data with respect to reference flow values (Mostly flow rates E.g. electricity 12.5kWh/ton of intermediate product, CO_2 - 23.6 kg/ton of limestone, and machine energy consumption rate), and miscellaneous data (E.g. Vehicle = mass × distance = 50ton × 5km = 250tkm). In order for easy comprehension and comparison, each data (input or output) is logged in a unique table format. Column 1 has Input or output "Name". Column 2 has "Value" of input or output. Column 3 has "Unit" of input or output measurement. Column 4 has "Remarks", here all the known details related to the input or output data should be provided. Few general information which can be provided is the definition of input or output, usage of input or output, the source of the data, time period of the data, and any assumptions related to data. This formatting of data facilitates the comparison and thus enables data validation of the later (in following sections). This formatted data needs to be sorted within itself. The sorting will enable easy location of required input or output from the inventory list and it also ensures that all data collected is considered for analysis. It can be sorted in either input and output category-wise, or process-wise. In input and output category-wise classification the input and output categories used are as follows. The Input categories are 1) Energy (heat, electricity, and fuel) 2) Raw material 3) Ancillary inputs 4) other physical inputs (transportation, and infrastructure) and 5) others. The output categories are 1) Products, 2) Co-products, 3) By-products, 4) Waste - Releases to air, 5) Waste - Releases to water, 6)Waste - Releases to the soil, and 6)others. If the well-established input and output categories are followed in literature related to the topic of study that can be also followed.

The input and output category-wise LCI compilation can be further classified into three subsections based on the quality of data. One with absolute values (cumulative, raw, and basic data corresponding to time period mentioned in the goal and scope), second will be data with respect to reference flow (data measured in relation to the intermediate product or product) and third can be miscellaneous data (E.g. assumed, estimated, and multiple data). It is preferred to have data mostly in absolute value followed by, data with respect to a reference value and miscellaneous data.

A sample of data that should be provided by the practitioner is as follows "Every data is presented in a unique format with four parts, as follows, Name of data, the value of data, unit of data, remarks about the data. Every data collected is provided in three tables, one contains absolute data, second is of data with respect to reference flow and third with miscellaneous data. Each table has a set of inputs and a set of outputs belonging to that sub-section. The inputs have categories like energy, raw material, ancillary inputs, other physical inputs and others, similarly, output has categories like product, by-product, co-product, waste - releases to air, waste - releases to water, waste - releases to land and others. All the data collected is reported in the following table in the format as explained earlier".

3.4.3 Data validation

In this step, the data compiled in the previous section is reported again and validated. The suitable data for Life Cycle Inventory Analysis is selected after analysis and reported. A check on data validity shall be conducted during the process of data collection to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled (IS 14044 2006). Or else, all data available can be collected and validated later. It is done in two steps. In the first step, all the data is reported, and the data which can be selected and rejected are distinguished. In the second step, the selected data is reported in another table.

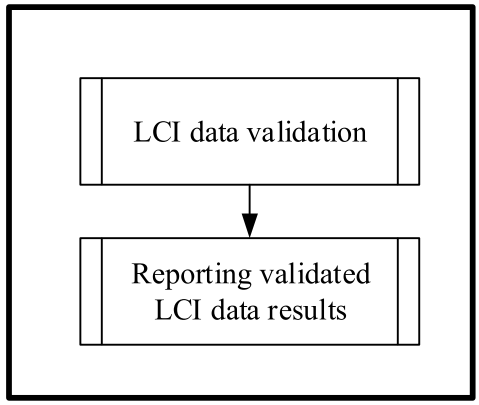

Figure 3.10: Sub-sections of data validation

3.4.3.1 LCI Data validation

The compiled data is subjected to checking for its reliability and data quality. After checking the data is marked as either selected or rejected. If the data is meeting the quality leave the data as such and if it is not, turn the text of data into italic. For the validation, any logical condition can be used. If a data is selected or rejected, the logical reason behind the same should be mentioned in remarks. Any logical condition can be used to validate the data, few checks are provided as follows,

1) Check data quality is met - Check the collected data had met the quality requirement defined in the Scope if no try to collect better data set.
2) Check the values are in the expected range - Check values are in the same range reported in the literature. If the values are found to be not matching with the literature, check and find the reason and report the same. If the reason for the mismatch is justifying, it is mentioned in the remark and used for analysis. If the reason is not justifiable, withheld the data.
3) Check for data redundancy - If the same data is reported in different sources with a different value, compare the data value with those reported in the literature and select one. If more than one data lies in the literature range, make a priority order for the different sources of data based on reliability. This priority order is mentioned in the assumption section of the goal and scope phase, and also the logical reason/assumption behind the order (E.g. priority order: internal monitoring files> third party reports > Govt reports. The assumption here is that when the data is monitored by the industries for their internal requirements it will be of best precision

and precision gets reduced as monitoring is carried by a third party, govt and so on). Select the data which belongs to the source which has higher priority. Care should be taken to consistently use the same priority order throughout the validation. If exceptional data is there (which is improperly following the defined priority order) the data can be used after mentioning the same in the remarks.

4) Mass and energy balancing - It is a good check to ensure the data related to unit process is complete.
5) If a new data is found during data collection (which is not found in any literature), check for the usage of the same in the processes, and if a proper explanation is found using the same for analysis. If this data is reported in two or more sources that are also an indication of trusting and using the data. The logic of data selection should be provided in the description cell.

A sample information to be provided at the end of this subsection is as follows "All the data from the inventory collection will be validated here. Few checks like data quality, data reliability (E.g. comparing with literature, checking mass and energy balance), and data redundancy are been conducted here."

3.4.3.2 LCI validated result

Here the validated data from the previous sub-section is reported. The value from this table is only used for the LCI analysis. Thus every data which is validated and needed to be used in the LCI analysis should be reported here. A sample information to be provided after this sub-section is as follows: "The validated data for LCI analysis is provided in the following table. The validation is conducted primarily for the data redundancies and by comparing the value with literature."

3.4.4 LCI analysis

In this step, the data validated in the previous section is analysed and LCI results are obtained. To be specific in LCI analysis, the validated input and output data is proportioned with respect to the functional unit. The functional unit data is necessary for all calculation at this phase. Thus if there is an issue with the functional unit value, it should be sorted out to a consistent value before the analysis. The details on sorting out of the functional unit should be reported in the assumption section. E.g. "As the amount of OPC and PPC produced is not provided separately it is calculated from the clinker to cement ratio of OPC and PPC, and clinker and cement production value. And the value of OPC produced is 0.4 million ton per annum". There are five steps involved in the LCI analysis as shown in Figure 3.11.

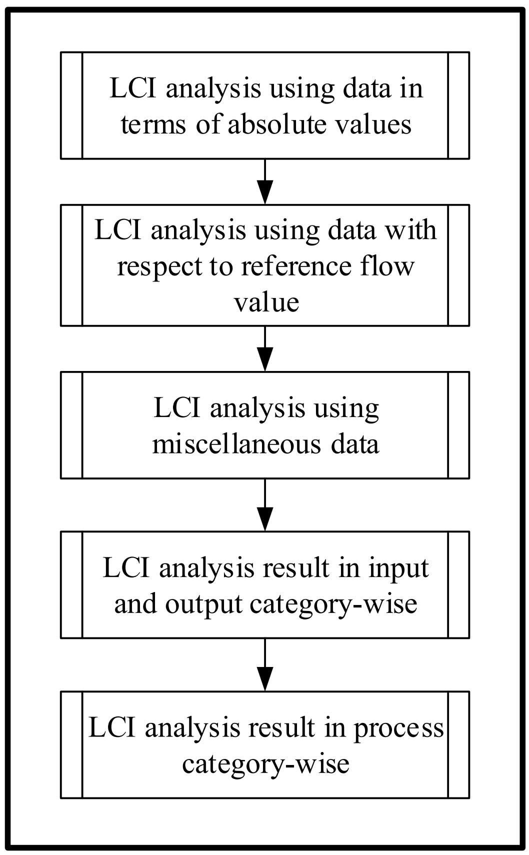

Figure 3.11: Subsections of LCI analysis

The first three subsections are an analysis of data belonging to three categories to which data is reported. And, the last two subsections are the compiled reporting of all these result in two different forms. A detailed explanation of these sub-sections are provided as follows,

3.4.4.1 LCI analysis - Using data in terms of absolute values

Here LCI analysis using absolute value is conducted. The absolute value of the input or output is divided by the absolute value of the functional unit.

3.4.4.2 LCI analysis - Using data with respect to the reference flow

Here the calculations using the reference flow are conducted, step by step. The input or output reported with respect to reference flow is converted to input or output with respect to the functional unit. A general formula is provided in Equation 3.1 (Eq 3.1). Details of calculation procedure and each variable should be reported under "remarks".

$$LCI\ result = \frac{Input\ or\ Output}{Reference\ flow} \times \frac{Reference\ flow}{Functional\ unit} \qquad \textbf{Eq 3.1}$$

3.4.4.3 LCI analysis using miscellaneous data

Here LCI analysis using miscellaneous data (say, assumed/estimated/multiple data) is conducted. If the certain input or output data is required and it is not available as an absolute value or reference flow, the calculation is done to obtain that data, based on assumed data, estimated data or calculated using multiple data. Data of any type can be used at this step. Based on logic or any scientific principles the required data can be calculated. Details of every data used, assumptions and steps of calculation should be provided in the remarks.

3.4.4.4 LCI analysis result (Input and output category-wise)

Here the results of LCI analysis are compiled and presented in a table in input and output category-wise.

3.4.4.5 LCI analysis result (Process-wise for clinker)

Here the results of LCI analysis are compiled and presented in the consequential order of processes considered (defined in the system boundary). Each process has an input section were the inputs LCI results related to that process are reported and followed by output section were the output LCI results associated with that process should be presented.

3.4.5 LCI data aggregation

Aggregation is the consolidation of inventory of equivalent data type or of similar environmental significance. (ies 2010b) Confidential and proprietary information can be protected by aggregation to LCI results dataset. The important specific inputs and outputs which is small magnitude can be excluded from aggregation as its significance will be lost when clubbed with similar data of higher magnitude. At the end of this section, a table of LCI result from is obtained in input and output category-wise.

3.4.6 Refining the system boundary

This section is an option to modify the existing system boundary based on the LCI analysis experience. In this section, the system boundary and its associated inputs, outputs and processes are revised as needful. Sometime at the end of the LCI analysis, it will be found that either the data collected is insufficient to meet the data required or the data collected way more than the data requirement. Few cases of lack of suitable data are as follows: 1) if the data does not meet the data quality mentioned in the scope and thus rejected at data validation; 2) all the required data related to the unit process is not collected. There are two ways to tackle the same either addition of more data to make completion or omission of few more data or process so that removal of a data set make the remaining data consistent and complete. For addition of data, measures should be taken to the iteration of data collection. During the iteration of data collection, the data collection sheet can be modified in order to meet the data lacking (E.g. redoing survey, and revisiting industry). Data can be collected from reliable databases, and reports. Estimation or assumption of data is also a way if the data is necessary to be included. In case of data or process deletion, the system boundary section of the scope phase remove that process from "List of unit process" and report the same in the subsection "Deletion of unit process" with reason (E.g. lack of data). Later reject those data (corresponding to that process) in data validation stating that they are beyond the system boundary. If the data is more than sufficient it can be reported in section "data collection, compilation and formatting" however need not necessarily to be used for validation and analysis. But if the data is sufficient enough for a process which is not included in the current system boundary. System boundary can also be expanded. In that case expand the system boundary section in the goal and scope phase followed by validation of corresponding data, LCI analysis and the addition of new results to the existing LCI analysis results.

3.5 Life Cycle Impact Assessment (LCIA)

LCIA is the third phase of LCA. According to ISO 14044, the definition is “Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product". In other words, the inventory result obtained in the LCI phase is converted to the impact indicator, which represents the magnitude of impact over category endpoints. Where the impact indicator is a quantifiable representation of Impact category (E.g. kg CO_2 equivalent). The impact is a set of environmental issues of concern (E.g. climate change), to which the inventory would have contributed. Category endpoints are where the environmental issues are identified (E.g. human health, Natural Environment, and Resources). ISO standard has a set of mandatory and optional elements or section or steps for performing LCIA. These sections are explained in a descriptive manner. The mandatory elements are studied thoroughly. As shown in Figure 3.12, three major sections are present in LCIA, with the subsections. A brief description of these sections is provided as follows.

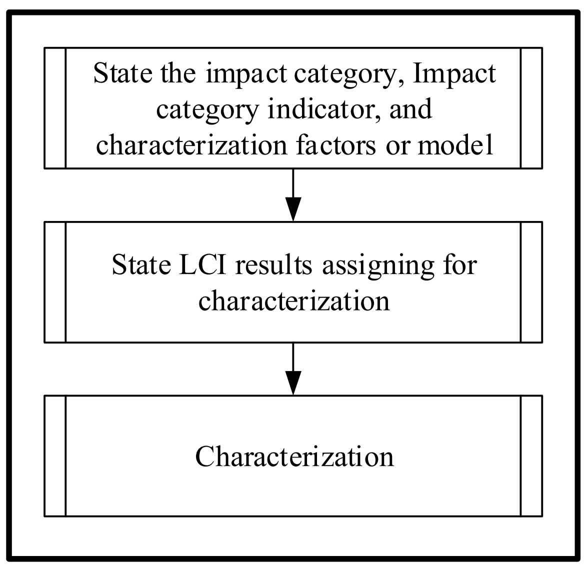

Figure 3.12: Sections of LCIA

3.5.1 Impact category, Impact category indicators and characterization factors/models used

As the name indicates, the impact category, impact category indicator and characterization factor or models to be used in the LCIA are to be defined. Based on the literature, all three would have been defined in the Goal and scope phase but the experience of LCI conducted and understanding from the LCI result can reflect changes. The logic for defining those three are as follows.

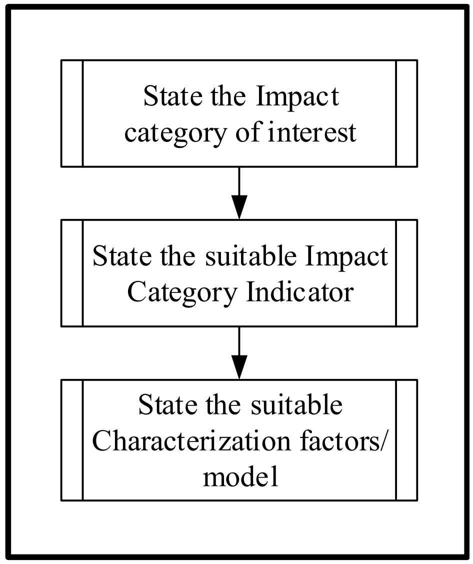

Figure 3.13: Sub-sections impact category, impact category indicator, and characterization factors/model

3.5.1.1 Impact category

Here the impact category to be considered is found and mentioned. First, find the category endpoint. In order to identify the impact category, impact category indicator and characterization model, the process system and its surroundings should be sequentially analysed. For example, check whether there is any issues on nearby, natural environment (E.g. Trees, forest, species around like birds, small animals, fish), human health of employees, surrounding people (E.g. breathing issues, viral issues, skin issue), resources (E.g. Water bodies, mines, air) experienced after product or product system is installed. Once the environmental issues are found check whether if there is any predefined impact category (by international bodies, educational institution etc.) which address the identified environmental issue/s. If suitable impact categories are found, select the same for study. If not, define a new impact category based on the identified environment issue/s and use the same for the study, by defining it is meant to give a name to the set of environmental issues to be studied.

3.5.1.2 Impact category indicator

Here a proper unit of measurement is chosen for each environmental issue. A quantifiable representation of impact category is called impact category indicator or impact indicator (IS 14044 2006). There is literature available which discuss different types of impact indicator and how appropriately it will reflect the impact category. The established environmental issues will be having a defined impact indicator (E.g. kg CO_2 equivalent, and Phosphate equivalent). If the impact category is newly defined one, identify and define a quantifying unit for the same. By identify it is meant to find a measurement way to quantify the change in the attributes of surrounding natural environment, human health, or resource (E.g. change of water pH, density, colour, dust in air measured as ppm, species number reducing in an area, and change in the oxygen level in the blood of human being).

3.5.1.3 Characterization factors or model

It is required to find the contribution of different inputs and outputs (of the inventory result) towards each impact category, in terms of the impact indicator. By understanding the environmental mechanisms, certain factors called characterization factors are derived and applied to particular data to convert the same into an equivalent impact indicator. A collection of such characterization factors can be called as a model. For example: 1 kg of Methane is equal to 25.4 kg of CO_2equivalent according to characterization model IPCC 2013 GWP 100a. There are many popular characterization models, which are collections of characterization factors for a set of inputs and outputs contributing to an impact category.

3.5.2 Classification of LCI results

This is the second section of LCIA: here, the inventory results obtained from the phase LCI are been classified for characterization. It is done in three steps as shown below in Figure 3.14 A detailed explanation of the subsections is provided as follows.

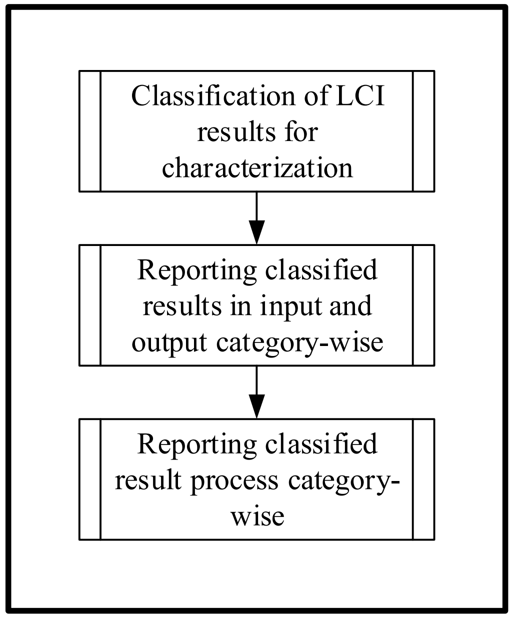

Figure 3.14: Subsections of LCI classification

3.5.2.1 Classification of LCI result

Through classification, the inventory result is separated into a set of data assigned for characterization and remaining data as a non-assigned set or rejected set. The reason for the selection or rejection of data should be properly stated, as a remark. Usually, data is assigned for characterization if the same is found to be contributing to the impact category. In order to identify the contribution towards impact category, a good understanding of the system of physical, chemical, biological processes related to the impact is required. A simple example is: for the impact category "climate change" (due to global warming), the data like CH_4, N_2O, CFCs etc. can be assigned for characterization. These data have global warming potential due to radiative forcing (measured in kg CO_2 equivalent), whereas the outputs like radiation, PM, SO_x, wastewater, solid waste etc. are not assigned for characterization as they do not have any radiative forcing. Sometimes, even though there is a contribution from the data, practical difficulties can be a hindrance for characterization, for example, the lack of knowledge of the contribution of data towards impact. In such cases, the reason for the rejection of the data (for characterization) needs to be reported also in the limitation section of the goal and scope phases. When data is not considered for analysis we are deviating from the defined goal and scope, which becomes a limitation. This step of classification enables properly documenting the assigned and non-assigned parts of LCI results for characterization. If there is a later iteration of the analysis to get the unassigned data characterised, this classification will be advantageous. The selection of a proper characterization model, which is capable of characterising the whole inventory, is essential.

3.5.2.2 Reporting classified inventory result (input and output category-wise)

In this sub-section, the result of data classification is provided. The accepted and rejected data for classification is reported separately in input and output category-wise

3.5.2.3 Reporting classified inventory results (process-wise)

In this sub-section, the result of data classification is provided. The accepted and rejected data for classification is reported separately process category-wise

3.5.3 Characterization

In this section, the characterization of assigned life cycle inventory data is conducted. It is carried out in two sub section as shown in Figure 3.15. A detailed explanation of the two subsections is provided in as follows.

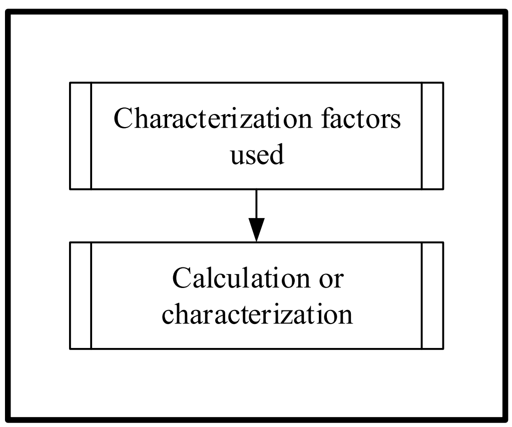

Figure 3.15: Sub-sections of characterization

3.5.3.1 Characterization factors used

In this section, characterization factors corresponding to each data in the inventory result should be reported. Characterization factors should be selected from the characterization model/(s) or the set of characterization factors mentioned in the first section. Here, if the suitable characterization factor cannot be found, it needs to be indicated in the limitation section of goal and scope phase, as it would result in the omission of the contribution of that data towards the impact category. Once the respective characterization factors are selected and reported the second section begins.

3.5.3.2 Characterization calculation

In the second section, the assigned inventory is characterised by the suitable characterization factor. It is carried out in 2 ways, first, the assigned result is characterised for input and output, category-wise. Secondly, the characterization is conducted process-wise where the same assigned inventory is categorised based on the processes considered and characterised.

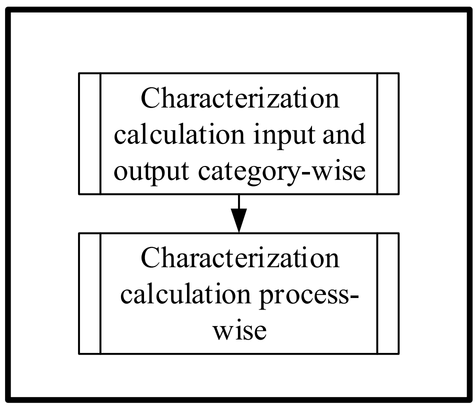

Figure 3.16: Sub-sections of characterization calculation

In the first section, the inventory assigned is multiplied with the selected characterization factors in input and output category-wise. The result thus obtained is then presented in three forms:

1) Characterization results (in detail for every data) – Every input and output and the corresponding results are presented
2) Characterization results (aggregated for each input-output type) – Each input and output data category and sum of the characterization results of all the data in that category
3) Characterization results (final result) – Sum of all the characterization results reported in terms of the product

In the first section, the inventory assigned is multiplied with the selected characterization factors process category-wise. The result thus obtained is then presented in three forms:

1) Characterization results (in detail for every data) – Every input and output, and the corresponding results are presented

2) Characterization results (aggregated for each process category) – Each process and sum of the characterization results of all the data in that process
3) Characterization result (final result) – Sum of all the characterization results reported in terms of product

Both ways, the result would remain the same but different ways of characterising help in analysis during interpretation phase.

3.6 Interpretation

This is the fourth and last phase of the LCA. Interpretation and the goal and scope are two phases which structure the LCA. The LCI and LCIA are the phases of execution, which collect and produce information. In the interpretation phase, the information produced during the LCI and LCIA phases is analysed with respect to a defined goal and scope. To be more precise, different observations and conclusion are drawn from the LCI and LCIA results, within the limitations of the accuracy in meeting defined goal and scope. Recommendations are also provided based on the conclusions, and also to reduce the limitations. This is carried out in three sections. The first section is the identification of significant issues, the second is evaluation and third is conclusions, limitations and recommendations. A detailed explanation of the sections are provided as follows.

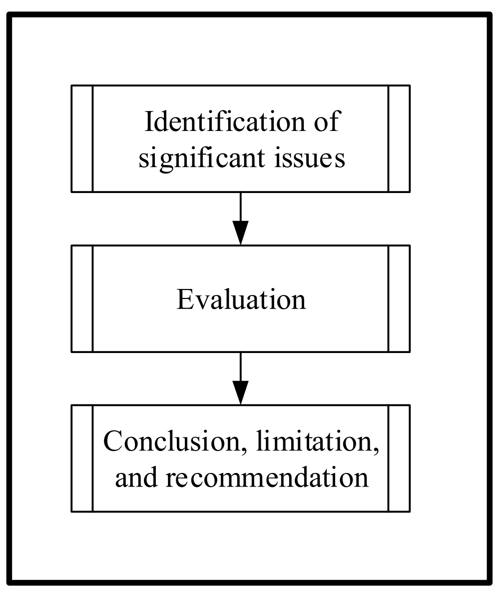

Figure 3.17: Sections of interpretation phase

3.6.1 Identification of significant issues

In this section, the significant issues are identified and observations are made through different analysis. This section has two sub-sections as shown in Figure 3.18. A detailed description of the two subsections is provided as follows.

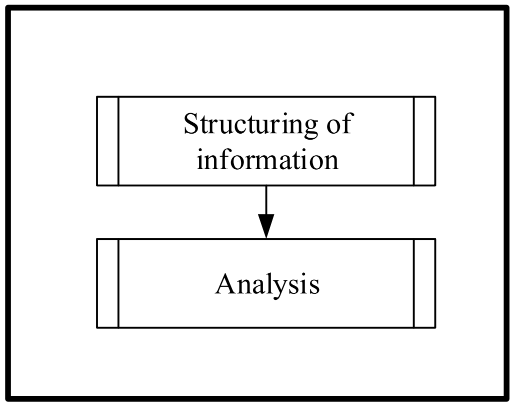

Figure 3.18: Subsections of identification of significant issues

3.6.1.1 Structuring of information

In this subsection, the results from the LCI or LCIA are structured. It is structured as a table where columns are unit processes and rows are inputs and outputs types. The column and row can be clubbed or divided further based on requirement. The unit processes can be clubbed to a group of similar type unit processes (E.g. grinding, thermal treatment and transportation), life cycle stages, a group of the unit process with similar managerial influence etc. The rows can be divided into individual input and output or clubbed to the category of inputs and outputs.

This structuring should be applied to both LCI and LCIA results for complete analysis. However, based on the requirements it can be limited to one of them also. First. this structuring should be applied to the LCI result. Here one more column can be added at right end, to report the total values of inputs or outputs in each row. Similarly, while structuring the LCIA results a row should be added at the bottom and a column should be added at the right end in order to report the sum of values in a corresponding column and rows respectively. This structuring gives a holistic and comprehensive representation of LCI and LCIA result.

3.6.1.2 Analysis

In this sub-section, the structured results are analysed using different techniques to draw different observations and conclusions. Few of the analysis techniques provided in the ISO 14044 have been used here. ISO 14044 does not provide sensitivity analysis and uncertainty analysis under, analysis section. A detailed description of each analysis is provided as follows.

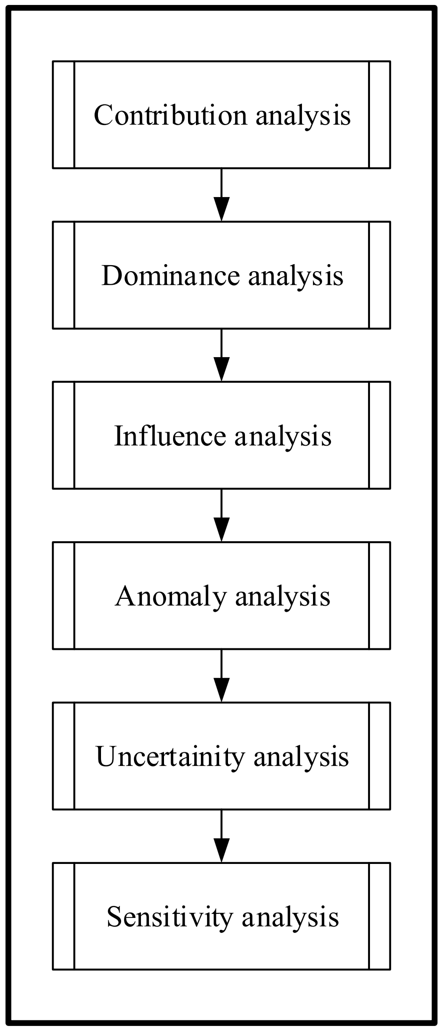

Figure 3.19: Sub-section of analysis

Contribution analysis

In this subsection, the results in the structured table are converted in terms of percentage with respect to the total value. The LCI results are represented in terms of percentage with respect to total values reported in the last column of the structured table of LCI result whereas for

LCIA results are reported as the percentage value of each data with respect to the aggregated value of all LCIA result. This analysis enables understanding of the major and minor contributing individual data, data type, data category, unit processes, and life cycle stages in terms of percentage.

Dominance analysis

In this subsection, the results reported in the contribution analysis are assigned to different ranks, categories, or classes either by specific ranking procedure, scientific conditions, logical condition, as per requirement of client etc. For example, a contribution can be divided into different ranges (100%-91%, 90%-81% etc.) and each range can be assigned to different classes (A, B, C etc.). Such classification enables the client of LCA to easily identify the input, output, data type, data category, unit process, life cycle stages, etc. belonging to their required category.

Influence analysis

In this subsection, the values in the structured table with result are replaced with classes, where each class represents the degree of control of management over that particular data corresponding to the unit process (if the table is of data as a row and unit process as a column). The benefit of this classification is that the management can understand which data can be changed by them and the degree of the same. Sample classifications are like full control, partial control, and no control. If the highly contributing data is under full control, the management can rectify the issue by taking direct measures. If the highly contributing data is of less or no control, the management cannot directly rectify the same. They should try indirect methods like switching the data to a controlled source or requesting the current source of the data to rectify the issue.

Anomaly analysis

In this subsection, the abnormality of the result is analysed. The data is compared with literature and the classified based on the deviation from the literature values. The values in the structured result are been classified into 3 classes, each with a symbol like #,* and O. The first symbol (#) is mentioned for a new data or an unexpected data. The second symbol (*) is used if the value of data is having high variation from the expected result. The third symbol (O) is used if the value of the result is of the expected range.

Uncertainty analysis

In this subsection, uncertainty analysis is conducted to quantify the uncertainty in the results due to variability in data, model imprecision, and input uncertainty (IS 14044 2006). In simple terms, it is the range within which the results can vary due to various reasons, and thus shows how reliable the final result is. For example, the LCI result of a data type or data category will be a sum of individual inputs and outputs. Each input and output may have a variation in their value or it can be a range. If this variation is considered, the sum of LCI result belonging to a data type or data category will be also a range (by adding the minimum value and maximum value of constituent input and output separately). The difference between the maximum and minimum value of the aggregated LCI result, represented in percentage with respect to initial aggregated LCI result, is also a measure of uncertainty.

Sensitivity analysis

In this subsection, the influence of an input or output towards the final result is analysed. In the uncertainty analysis, the variation in the value of all inputs and outputs are considered. Thus the variation details of each data are already available. By varying the numerical value of one input or output from its minimum to maximum value it is possible to find the difference it can cause to the final result (say on the LCI result of a data type or LCIA result). This difference expressed in percentage with respect to the initial aggregated value of LCI or LCIA result is known as sensitivity. The sensitivity concept can be even applied to assumptions and methods.

3.6.2 Evaluation

The objectives of this section are to establish and enhance confidence in, and the reliability of, the results of the LCI or the LCIA study. Basically, this phase is to check whether the analysis has met the requirements (data and method) in the defined goal and scope phase. It has two subsections, one is completeness check (for data) and other is consistency check (for methods). If the data or methods used in the study is found to be different from the defined goal and scope, then the result observed in the section "Identification of the significant issue" are less reliable or it is meant that these results are valid only within the limitation found in the evaluation section. This can lead to a reiteration of the study or any other solutions, to attain the requirements in goal and scope defined. If such measures cannot be applied, the goal and scope are adjusted to the current level of study and the changes are mentioned, in the limitation section of the goal and scope phase. Every adjustment and the reason for the same is mentioned individually. The details of completeness check and a consistency check is provided as follows.

3.6.2.1 Completeness check

In this subsection, the completeness of data collected for the study is compared with the data requirement mentioned in the goal and scope phases. It is checked by analysing one by one, for each unit process considered for the study. Each unit process and the inventory collected for the same is compared with the expected value in the defined goal and scope. It is mentioned as “complete” if the data is found to be complete after checking. If found to be incomplete, “partially complete” or “not complete” is mentioned. This incompleteness can reduce the reliability of result and this is a limitation.

3.6.2.2 Consistency check

In this subsection, the consistency of the methods used in the study is compared with the defined goal and scope. By “methods” different aspects are meant like system boundary, limits of data collection, data quality requirement, allocation methods, impact category, impact category indicator, characterization model, value choices, assumptions and classification for LCI study. These aspects are checked with respect to the defined goal and scope (except classification which is conducted based on data contribution towards defined Impact category). Based on the degree of consistency observed during analysis “consistent”, “partially consistent” or “not consistent” is mentioned. This inconsistency needs to be mentioned when the results are reported. If a number of inconsistent methods are present it is a limitation and reiteration of LCA can be suggested or the goal and scope need to be redefined based on the limitation.

3.6.3 Conclusion, limitation and recommendation

In this section, the conclusions, limitations and recommendations based on the LCA study need to be mentioned. An outline for the information to be provided in each subsection is provided as follows.

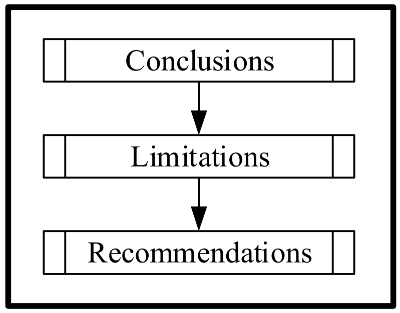

Figure 3.20: Subsections of conclusion, limitation and recommendation

3.6.3.1 Conclusion

In this subsection, primarily the degree to which the goal met is defined. It can be mentioned either in a quantitative or qualitative way. Conclusions are made and reported based on the observation obtained during the analysis conducted in the section "Identification of significant issue". From standard structured information and contribution analysis the major and minor contributing, data or unit process can be identified. The classification results can be obtained from the dominance analysis based on conditional ranking. The results can be reported in terms of the managerial influence, from the observations of the Influence analysis. If any new data is observed or if any data value seems to be anomalous, those details can be reported from the result of anomaly analysis. The most influential factors can be found through sensitivity analysis. And the variation in the final result due to inconsistency in data can be obtained through uncertainty.

3.6.3.2 Limitation

As the LCA study progress, the limitation experienced would have been reported in the limitation section of the goal and scope phase. Here, that information from the limitation section is reported. Similarly, the incompleteness of data in unit processes found in the completeness check is reported here. Also, the inconsistency of data and methods found in the inconsistency check is also reported here. When the result of an LCA needs to reported anywhere, the conclusion and limitation together need to be reported as it gives the complete understanding of the analysis. This can also serve as the future scope of work.

3.6.3.3 Recommendation

Recommendations can be based on the conclusions obtained and related to the limitation of the study. First, the recommendations to rectify the limitation need to be stated, till the result can reach the required quality. Since LCA is an iterative method, a reiteration of the study is most common and obvious measure to rectify limitation. The application of the goal will be mentioned in the goal and scope phase. The recommendation can be made by mentioning how to use the conclusions obtained for the application. In case of comparative LCA, the recommendations can be made in the advantage of one product/product system over other with explicit reason (conclusions within the limitation of study). Then, the possible measures are given for the client of the LCA study to rectify the issues (found in conclusion). Recommendations should be derived unambiguously and in a stepwise manner for the logical and reasonable consequence of the conclusions (ies 2010a; IS 14044 2006). Recommendations and suggestions can be based on the literature related to the issues found, or self-proposed ideas. For example, suggestions can be made to improve the major or most sensitive inputs or unit process, which the intended client of LCA study should take into consideration. If the important data or unit process are not under the management control of the client, measures can be suggested to improve the control over the same. Practical solutions can be found in the literature.

CHAPTER 4

CASE STUDY 1

4.1 Introduction

A case study has been conducted in order to calculate the inventory, energy consumption and CO_2 emissions related to clinker and cement production. The case study was conducted in UltraTech cement plant at Reddipalayam district, Tamil Nadu. Field visits were conducted twice, first a preliminary visit followed by a detailed visit. During the visit, interactions were made with the concerned officials and the data required for the study is conveyed. Different types of data available with the cement plant which can help in the LCA was shared by the officials.

The LCA was conducted for 3 products, first clinker was analyzed followed by Ordinary Portland Cement (OPC) and Pozzolano Portland Cement (PPC). The template developed is used for the calculation of inventory results, energy use, and CO_2 emissions of all three product. The results are thus provided product wise under following sections. The case study 1 is abbreviated as CS 1 in the following text.

4.2 LCI for clinker production

As defined in the methodology chapter a detailed and structured analysis was carried out. Three sections and the key information from the LCI analysis are provided as follows.

4.2.1 Goal and scope

The goal and scope are defined initially before the LCA. This will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. The final goal and scope after the analysis is reported here.

1) **Goal:**
    a) **Objective** - To develop the life cycle inventory of clinker.
    b) **Application** - Life cycle inventory for Indian clinker can be added to the life cycle database of building materials.
    c) **Intended audience** - Academicians and industrialists.

d) **Public disclosure** - Yes, the study is intended to disclose to the public.

2) **Scope**

a) **Process system** - The processes involved in clinker production in an integrated cement plant using dry processing technology for clinkerization. The plant uses 5 stage preheater precalciner unit along with the rotary kiln.

b) **Function** - Production of clinker.

c) **Functional unit** - 1 ton of clinker is considered as the functional unit. Functional unit considered in most of the literature are in tons and the production of the clinker is measured in tons by cement plant (daily).

d) **System boundary**

i) **Criteria used:** "Gate to Gate" - All the processes happening between the entry and exit gate of the cement plant are considered. Here exceptional processes like the extraction and transportation of limestone (raw material) are also considered. The addition of processes resulted in a set of processes under the complete managerial influence of the company. In other words, gate to gate system boundary of a cement plant, where the limestone mine is considered to be within the physical boundary of the cement plant.

ii) **Processes considered:** Processes considered according to Gate to Gate system boundary are as follows.

(1) **Limestone extraction and transportation:**

Extraction of limestone from the quarry and loading the same to the truck. Limestone is extracted using equipment like ripper dozer, and rock breaker. The loader is used to load the extracted limestone to the trucks for transportation. The limestone loaded truck is transported from mines to limestone deposits in the cement plant and unloaded.

(2) **Limestone crushing, stacking and reclaiming:**

The limestone is fed into a dumper, from which it is then transferred to a crusher. In the crusher, the limestone chunks are crushed into mixture of small pieces and powder. The crushed limestone is transferred to stacker unit, where it is stacked layer by layer. The heap is cut vertically by reclaimer and transferred to silos.

(3) Raw meal preparation:

The raw materials other than limestone, like clay, ferrite and bauxite required for the raw meal preparation is consumed and loaded to the respective silos. The materials are consumed from silo in the respective mass ratio and transferred to the vertical roller mill for grinding. The ground material is transferred to the cyclone separator. Where the mixture of hot gas and raw meal powder gets separated. The raw meal particles are collected at the bottom of the cyclone separator. Using air slides and bucket elevator the collected powdered raw meal is transported and fed into the continuous flow silo. Here the material gets mixed thoroughly as it gets interacted with the air currents produced by high power fans. This raw meal is mixed to a level of uniformity required for the kiln processes.

(4) Fuel preparation:

Fuels are grounded to the required fineness in coal mill. This mixture is passed through a cyclone separator and fine coal is been collected.

(5) Clinkerization, cooling and storing:

The raw meal collected from the continuous flow silo is transferred to the top of the preheater set (5 stage preheating system). From the highest preheater chamber, it moves to succeeding chambers and continues till the end of second last preheating chamber. During this movement, it interacts with upstream moving hot air current and gets heated up to (300-900 ^{o}C). This hot air current is exhaust air coming from the rotary kiln and cooler. The heated raw material from the 4th or second last chamber of the preheater is transferred near to the entry of the kiln, where it is blown to the precalciner unit by the hot air coming from the kiln and cooler. Around 20% of the mass is flowing back along with the hot air. Fuel is fed into the precalciner where it gets ignited and the raw meal gets calcined around 60%. This partially clinkerized raw meal from the precalciner is transferred to 5th or last chamber of preheater from where it is fed to the rotary kiln. The clinkerization process continues, as the raw material move from higher end to the lower end (on the slope) of the rotary kiln. Using a fuel spraying jet a mixture of hot air and fuel powder is injected from the lower end of rotary kiln. In the rotary kiln, raw meal is exposed to a temperature range from 900 ^{o}C to 1450 ^{o}C along its length. Raw meal gradually gets converted to clinker as it reaches the lower end of the kiln. This hot clinker is then dropped into the cooling chamber where the clinker is cooled. Water is sprayed and the air is blown (7 fans) to cool down the clinker. The clinker is then transferred to deep pan conveyor. The hot air from the cooling tank/chamber is carried to the preheater and precalciner unit, where it is used for the heating raw meal. After the cooling process, the clinker is carried in a conveyor belt to the clinker silo.

(6) Others (services etc):

All miscellaneous processes beyond the previous processes, happening simultaneously in a non-continuous way are included under the process named 'others'. It can be processes like onsite transportation, factory infrastructure requirement, colony daily activities, and maintenance of the electric network.

iii) Deleted processes: There are also processes which satisfy the condition of system boundary but not included due to some reason say to mismatch with an existing system boundary, no related data was obtained. A process as such are provided as follows.

(1) Electricity production - In literature, electricity production is not seen as a part of the cement production process system. So in order to make system boundary more compatible with literature, electricity production is not considered in LCI calculation. However, the data collected during the case study is used to calculate the energy use and CO_2 emissions related to electricity produced. The results are used later in calculation as energy and CO_2 emission factor.

iv) Cut off criteria: Mass limit - Zero limit, Energy limit - Zero limit, Environmental significance - Zero limit.

e) Expected inventory:

i) Limestone extraction and transportation: Diesel (for excavator, and loader), electricity (for buildings in mines), limestone (extracted), oil (for equipment), water (for equipment and dust removal), spare parts (for equipments), trucks, office buildings, electricity network, limestone (extracted), overburden limestone, CO_2, PM, dust, noise, water. Diesel (for transportation), limestone (loaded), truck, limestone (unloaded), CO_2, CO, NO_x, PM, and dust.

ii) **Limestone crushing, stacking and reclaiming:** Fuel (for backhoe and tipper), electricity (for crusher, conveyor belts, stacker and reclaimer), limestone chunks, oil (for loading equipment, crusher, and stacking machines), equipment (crusher, conveyor belt, stacker, and reclaimer), infrastructure, crushed limestone, CO_2 (from loading equipment), PM (from loading equipment), and dust (loading and stacking).

iii) **Raw meal preparation:** Electricity (for vertical roller mill, transferring equipment, and fans), limestone, clay, ferrite, bauxite, air current, oil (for conveyor system), silo, vertical raw mill, infrastructure, raw meal, dust and exit air current.

iv) **Fuel preparation:** Electricity (for the mill and conveyor system), fuels (as raw material), oil (for conveyor system), mill, infrastructure, powdered fuel and dust.

v) **Clinkerization, cooling and storing:** Fuel (for kiln), electricity, raw meal, hot air, water, oil (for motors used for rotation kiln etc), preheater-precalciner unit, rotary kiln, fuel spraying jet, conveyor systems, fans, silo, infrastructure, clinker, CO_2, dust, NO_x, SO_x, water vapour, hot air, radiation, noise.

vi) **Others (services etc):** Diesel (internal transportation), electricity (for plant lighting, colony, and transmission losses), electricity network, infrastructure (colony, and offices), CO, CO_2, NO_x, and PM**.**

f) **Data quality:**

i) **Time period coverage:** Time period - 1 year; Age of data - Recent. A year is a cyclic period where all the activities take place in the cement plant. Say, the repairing of the equipment used to take place at the end of a year.

ii) **Geographical representation:** According to a report by PSCC (2011) most of the cement plant is situated in the raw material prone area. The major raw material for clinker and cement is limestone. Thus, a cement plant which is situated next to limestone quarry will be representative. Thus, a cement plant which is situated next to limestone mine needs to be studied.

iii) **Technological coverage:** According to Kumar (2015) 93% of the Indian cement are made based on dry processing technology, and thus, a cement plant with dry processing technology is required to be studied.

iv) **Precision:** Raw material mass in kg, electricity in kWh, CO_2, NO_x in kg, SO_2, and dust in grams. Other data are required in a unit such that the numerical value is greater than the numerical value of the product in a functional unit. This is based on values reported in the literature.

v) **Completeness:** All the data described in the data requirement with respect to the processes should be met.

vi) **Consistency:** The data, methods and assumptions used in the study should be consistent throughout the study.

vii) **Reproducibility:** The data can be extrapolated to region level data.

viii) **Sources of data:** Data monitored by the cement plant.

ix) **Uncertainty of the information:** The inventory results should have no uncertainty.

g) **Allocation procedure:** Since the study is related to a single product all the data were allocated to the same product.

h) **Interpretation to be used:**

i) Analysis considered: Contribution analysis and anomaly analysis.

ii) Evaluation considered: Completeness and consistency.

iii) Conclusion, limitation, recommendation.

i) **Limitation**

i) The fuel for unloading and transferring materials to the silos are not considered.

ii) Electricity production is happening within the cement plant. In order to make the system boundary inline with literature, the electricity production process is not considered. However, the data related to the same has been studied separately. Based on the results the energy and CO_2 factors of electricity are calculated. These factors are used for calculation thus the energy use and emission calculation results are representative and suitable.

iii) The electricity for reclaiming of limestone is included in the electricity for raw meal section as it was monitored in this manner in the company.

iv) The source of SO_2 and NO_x, in the fuel preparation section is not clear.

v) The electricity consumed for services like plant lighting, colony lighting, quarters lighting and transmission losses are not accounted in the electricity consumed till clinkerization.

vi) The limestone consumed data is used instead of limestone extracted. Thus, the overburden losses are not considered. Similarly, the limestone crushed is assumed to be completely used for raw meal preparation, raw meal produced is assumed to be completely used for clinkerization, fuel consumed is assumed to be completely used for fuel preparation, and powdered fuel is assumed to be completely used for clinkerization. All the losses happening between the product flow between the consequential processes are not considered.

vii) The diesel consumption for extraction and transportation is reported as single values, thus break up is not available.

j) Assumptions

i) The limestone mine is assumed to be within the cement plant boundary. Thus, the processes like extraction and transportation of limestone are considered under gate to gate analysis.

ii) Truck for transportation of limestone and onsite transportation is assumed to be owned by the cement plant.

iii) The truck itself unload the limestone and there is no external equipment used for the same.

iv) The electricity is consumed from the captive power plant.

v) In the case of data redundancy, priority order is given to LCI data based on reliability of its source. Data source priority condition followed is: Internal monitoring documents > Third party survey sheets (For the public database, E.g. "CSI protocol") > Values reported to Govt. If there are discrepancies within the internal monitoring documents the value from the file exclusively discussing the required data type will be considered, E.g. "EN -14-15". If within the same source, variation are observed, then data with the most breakup (based on the time period of measurement) needs to be considered, say: Sum of Monthly break up > Yearly break up.

vi) The electricity of the kiln section includes the electricity for intermediate material transferring during cooling and storage.

vii) The diesel for onsite transportation can be assigned to clinker or cement. Usually, the generic inputs which belong to miscellaneous or 'other' processes (other than the main unit process with product flow) will be assigned to cement as it is the final product. But it is assumed here that the onsite transportation will be mostly happening till clinkerization and thus it is logical that the diesel for onsite transportation can be assigned to clinker.

k) **Type of reporting:** Reporting as a part of MS research work, with no comparative assertions.

l) **Critical review**: No critical review.

4.2.2 Life Cycle Inventory (LCI)

As explained in the methodology a set of 6 steps are conducted to find LCI results.

1) **Preparation of data collection**

   a) **Preparing rough process flow chart**: A basic process flow chart is being made based on the discussions with Mr. Jayasankar Kentinkara (Industrialist), and Dr. Anjan K Chatterjee (academician as well as industrialist).

   b) **Fixing modes of data collection**: Site visits and interviews are preliminarily decided as a method of data collection. But after a preliminary site visit and interaction with officials, other modes of data collections like questionnaire, a collection of data monitored by the plant, and collection of samples are also considered as a mode of data collection.

2) **Data collection, formatting and compilation**

   a) **Data collection:** A preliminary site visit was conducted to the cement plant where the processes of cement production were observed in detail. Interviews are conducted with many officials of the cement plant which help to understand data available with the cement plant. The preliminary process map created is subjected to correction by the official to make it more representative of the plant. Based on the processes seen in the cement plant a list of inputs and outputs required for the study is been listed out. A questionnaire is conducted later to collect some information (using e-mail). Another site visit is conducted with the list of required information and samples. Different officials were interviewed. The data requirement and study importance are convinced during the interview. The documentation having data similar to required data is been shared by the officials. Samples of fuels and raw material were also shared. The data collected includes hand notes of interview, Internal monitoring files (Presentations, screenshots images of presentation, soft copy (excel files) of data documentation, hard copy print out, photos of hard copy reports, log book, schematic flowcharts, and software's user interphase), Public survey report on their production (E.g. CSI Protocol), samples of raw material and fuels, and data from public site (Cements website).

b) **Data formatting and compilation:** The data from the different sources is been listed out as input-output category wise. The category of the input was fuels, electricity, raw material, transportation, and others (where the inputs which do not belong to any of above categories can be added. E.g. Other ancillary inputs, other physical inputs). These categories are followed as the LCI results are found to be categorised like this in the literature. The output can be categorised as products, coproducts and emission to air, water and soil. As mentioned in the methodology chapter every data is listed in tables with an order of input/output name, the value of measurement, unit of measurement, and remarks. The data are classified as an absolute value, reference flow value and miscellaneous value.

3) **Data validation**

a) **Data validation:** The data collected is thus validated for the LCI analysis. By validation, it means reliable data which can be used for LCI analysis are selected at this stage. Few data out of collected were rejected due to data redundancy, the unreliability of source of data, and miscellaneous data which cannot be used to make life cycle inventory data.

b) **Data validated result:** The validated data results are provided in annexure in the classification of absolute value (Table A. 1), reference flow value (Table A. 2) and miscellaneous values (Table A. 3).

4) **LCI analysis:** The three types of validated data are then used for corresponding analysis like LCI analysis using absolute data, reference flow data and miscellaneous data. The three LCI result thus obtained is compiled and reported as input-output category wise and process wise in Table 4.1 and Table 4.2 respectively.

5) **Data aggregation:** The data type aggregated result is provided in the annexure (Table A. 7).

6) **Refining system boundary:** No change in system boundary.

Table 4.1: CS 1: LCI for production of clinker (input-output category-wise)

Input	Value	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section	1.02	kWh / ton of clinker
Electricity consumed by raw mill section	23.16	kWh / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut	1.34	kWh / ton of clinker

Input	Value	Unit
down		
Energy - Fuel		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg/ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg/ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg/ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg/ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg/ton of clinker
De oiled Rice Bran	0.797	kg/ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Raw material		
Limestone and marl	1.453	ton/ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton/ton of clinker
Other physical inputs - Transportation		
Diesel oil	0.783	kg / ton of clinker
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker
Others		
Refractories and castable	0.426	kg / ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1	ton / ton of clinker
Waste - Releases to air		
SPM - Kiln main stacks	0.102	kg/ton of clinker
SPM - Coal mill stacks	0.023	kg / ton of clinker
SPM - Cooler stacks	0.031	kg / ton of clinker
SO_2 - Kiln Main Stacks	0.026	kg/ton of clinker
SO_2 - Coal Mill Stacks	0.008	kg / ton of clinker
NO_x - Kiln Main Stacks	1.843	kg/ton of clinker
NO_x - Coal Mill Stacks	0.035	kg / ton of clinker
Radiation and Convection losses from cooler	25.1	MJ / ton of clinker

Input	Value	Unit
Radiation and Convection losses from kiln	82.0	MJ / ton of clinker
Radiation and Convection losses from preheater	70.3	MJ / ton of clinker
Radiation and convection losses from tertiary air duct	8.8	MJ / ton of clinker

Table 4.2: CS 1: LCI for production of clinker (process-wise)

Process	Value	Unit
Limestone extraction and transportation		
Input		
Limestone and marl	1.453	ton/ton of clinker
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker
Output		
Limestone and marl	1.453	ton/ton of clinker
Limestone crushing, stacking and reclaiming		
Input		
Limestone and marl	1.453	ton/ton of clinker
Electricity consumed by limestone crushing section	1.02	kWh/ton of clinker
Output		
Limestone and marl	1.453	ton/ton of clinker
Raw meal preparation		
Input		
Limestone and marl	1.453	ton/ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Electricity consumed by raw mill section	23.16	kWh/ton of clinker
Output		
Raw meal	1.508	tons/ton of clinker
Fuel preparation		
Input		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg/ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg/ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg/ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg/ton of clinker

Process	Value	Unit
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg/ton of clinker
De oiled Rice Bran	0.797	kg/ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Output		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
SPM - Coal mill stacks	0.023	kg / ton of clinker
SO_2 - Coal Mill Stacks	0.008	kg / ton of clinker
NO_x - Coal Mill Stacks	0.035	kg / ton of clinker
Clinkerization, cooling and storing		
Input		
Raw meal	1.50762	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton / ton of clinker
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily	0.048	kg / ton of clinker

Process	Value	Unit
cotton waste)		
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Refractories and castable	0.426	kg / ton of clinker
Output		
Clinker	1.0	ton / ton of clinker
SPM - Kiln main stacks	0.102	kg / ton of clinker
SPM - Cooler stacks	0.031	kg / ton of clinker
SO_2 - Kiln Main Stacks	0.026	kg / ton of clinker
NO_x - Kiln Main Stacks	1.843	kg / ton of clinker
Radiation and Convection losses from cooler	25.1	MJ / ton of clinker
Radiation and Convection losses from kiln	82.0	MJ / ton of clinker
Radiation and Convection losses from preheater	70.3	MJ / ton of clinker
Radiation and convection losses from tertiary air duct	8.8	MJ / ton of clinker
Others (services etc)		
Inputs		
Diesel oil	0.783	kg / ton of clinker

4.2.3 Interpretation

As explained in the methodology chapter. The significant issues are found here, followed by evaluation of results with goal and scope and arriving at conclusions and recommendations (within the limitations of the study).

1) Identification of significant issues

- **a) Structured information:** The LCI results obtained in the study is structured process wise along column and data type wise along the row. The result is provided in Table 4.3.

Table 4.3: CS 1: LCI for clinker production (structured)

Unit process / Data category	Limestone extraction and transportation	Limestone crushing, stacking and reclaiming	Raw meal preparation	Fuel preparation	Clinkerization, cooling and storing	Others (services etc)	Total
Energy -Electricity (kWh/ton of clinker)	-	1.02	23.16	5.95	29.79	-	59.92
Energy - Fuel (kg/ton of clinker)	-	-	-	-	114.97	-	114.97
Raw material (kg / ton of clinker)	1452.50	-	55.12	-	8.22	-	1515.85
Other physical inputs - Transportation (Diesel, in kg / ton of clinker)	1.723	-	-	-	-	0.783	2.51
Others (refractories and castable, gm/ton of clinker)	-	-	-	-	425.59	-	425.59
Waste - release to air - Emission (SPM, gm/ton of clinker)	-	-	-	22.67	133.55	-	156.22
Waste - release to air - Emission (SO2, gm/ton of clinker)	-	-	-	7.73	25.95	-	33.68
Waste - release to air - Emission (NOx, gm/ton of clinker)	-	-	-	35.04	1843.44	-	1878.48
Waste - release to air - Radiation (MJ/ton of clinker)	-	-	-	-	186.19	-	186.19

b) Analysis – Different analysis is conducted as mentioned in the Chapter 3 - methodology. The dominance analysis is not conducted as there is no categorization or classification for the inventory data based on its percentage contribution.

i) Contribution analysis

The percentage contribution of inventory results are discussed here. Raw meal preparation and clinkerization process are the most electricity consuming processes with a percentage contribution of 38.65 and 49.73. Followed by fuel preparation 9.93% and limestone crushing and stacking with 1.70%. The major raw material for clinker is limestone which contributes 96% of the raw material considered. The remaining contribution is from clay, ETP sludge and fly ash. The extraction and transportation of limestone consumes 69% and the internal transportation consumes remaining 31% of the total diesel consumption. SPM is released from fuel preparation and clinkerization process with 15% and 85% contribution respectively. Similarly, SO_2 is also found to be reported in fuel preparation and clinkerization process with 23% and 77% contribution respectively. NO_x is also reported to be produced in fuel preparation and clinkerization process with 2% and 98% contribution respectively. Other inputs like fuel, refractories and castable, and output like radiation and convection is completely (100%) from the clinkerization process.

ii) Anomaly analysis

The degree to which the data is in line with the literature is discussed here. 59.31 kWh/ton of clinker is reported in Ecoinvent database Version 3.2 (accessed on 17-01-2018, using SimaPro 8.4.0.0), corresponding to the processes from material preparation (except limestone crushing) till clinkerization. And the value reported in the study, 58.90 kWh/ton of clinker matches with the literature. Considering unit process wise the Li et al. (2014) has reported the electricity required for the raw material grinding as 36.60 kWh/ton of clinker. The value calculated in literature 23.16 kWh seems to be lower with respect to the literature. For fuel preparation process Li et al. (2014) have reported a value of 5.81 kWh/ton of clinker, the value calculated in the study is 5.95 kWh/ton of clinker which is matching with the literature. For clinkerization Li et al. (2014) has reported 21.75 kWh/ton of clinker. And the value obtained in the study seems to be higher by around 30%. Thus, it can be concluded that the sum of electricity values for raw material preparation, fuel preparation and clinkerization is matching with the literature. Considering individually the process fuel preparation has similar values that in literature, raw meal preparation has lower and clinkerization has a higher value.

The amount of fuel consumption reported in literature or estimated from literature varies from 106 – 131 kg (Li et al. 2014; Marceau et al. 2006; USGS 2014b). The value obtained in the study 114.97 kg matches with the literature.

Limestone consumption reported and estimated from literature is varying from 1.31-1.53 ton/ton of cement (ecoinvent 2018; Huntzinger and Eatmon 2009; Li et al. 2014; USGS 2014b). The value of limestone consumption is 1.453 which is matching with the expected value from literature.

The value of other raw material consumed reported in the literature varies from 0.0475-0.34 ton/ton of clinker (ecoinvent 2018; Huntzinger and Eatmon 2009; Li et al. 2014; Marceau et al. 2006; USGS 2014b). The value obtained in the study is 0.06 ton/ton of clinker. Even though the value lies within the range of the literature, it seems to be very low compared to literature values. From the conversation with the cement plant official, it was informed that mostly the additional raw materials are consumed less as the limestone consumed contain impurities which meet the mineral requirement other than CaO.

In literature the consumption of no raw material as reported at the kiln feed stage. Here in the plant, the fly ash is reported to be added at the kiln feed stage. There is no raw material expected to be added in kiln other than a raw meal, thus the fly ash seems to be an unexpected input. Usually, fly ash is consumed as raw material to meet the siliceous content requirement. In (USGS 2014b) it is reported that many pozzolans like fly ash, bottom ash, slags, natural and other pozzolans are consumed for preparing the clinker but the stage at which it is been added is not reported.

Li et al. (2014) have reported on average quarrying/mining represents 1% and Transportation/distribution represents 3% of total energy consumption (Cradle to gate). According to the database Ecoinvent 3 (accessed on 16-01-2018, using SimaPro 8.4.0.0), 18 MJ/ton of limestone extracted is been consumed from diesel. 18 MJ can be around 0.42 litre of the diesel (considering the calorific value 43

MJ/kg, Source: 2006IPCC guidelines for national greenhouse gas inventories). The value obtained in the study is a sum of extraction and transportation. If the total diesel consumption is divided based on the percentage contribution mentioned in (Li et al. 2014), the diesel will be 0.43 kg for extraction and 1.29 kg for transportation. According to this breakup value the diesel required for extraction matches with the literature values.

2) Evaluation

a) Completeness check

The comparison and the reporting of completeness of inventory data are conducted. All the processes contain few important data as seen in literature, but the data does not meet completely the required list of inventories defined in the goal and scope

b) Consistency check

The attributes like cut off value, data accuracy, geographical coverage, technological coverage, data allocation, and assumptions are consistent with the defined goal and scope. The system boundary is partially consistent as the electricity production process happening within the gate to gate system boundary is not considered in the study in order to make it more suitable with literature. In temporal coverage of data, except radiation values, all other values are consistent with the required time period. The data source is partially consistent as few data measured by the third party is been used.

3) Conclusion, limitation and recommendation

a) Conclusion:

i) The life cycle inventory of the clinker production is quantified. The inventory data like electricity, fuel, raw material, other ancillary inputs, SPM, SO_2, NO_x, and radiation and convection losses are calculated with respect to their corresponding unit processes.

ii) Raw meal preparation and clinkerization process are the highest electricity consuming processes with consumption of 38.65% and 49.73% respectively. The major raw material for clinker is limestone which contributes 96% of the total raw material considered. In extraction and transportation processes, the extraction and transportation of limestone consume the 69% and the internal transportation consumes the remaining 31% of the total diesel consumption. 85 % of total SPM, 77% of SO_2 and 98% of NO_x was released from clinkerization and remaining from the fuel preparation. Other inputs like fuel, refractories and castable, and output like radiation and convection is completely (100%) from the clinkerization process.

iii) The values of electricity for fuel preparation seems to be matching with literature. Whereas electricity for limestone preparation and raw meal preparation values are low and clinkerization is high with respect to literature. The fuel consumption for clinkerization seems to match with the literature. Among raw materials consumed, limestone is matching with the literature, the other raw materials like clay and ETP sludge is very low compared to other raw material consumption in literature. The fly ash is reported to be added as kiln feed which is an unexpected data and not seen reported in the literature. The diesel consumed for extraction and transportation is matching with a value estimated from literature. The diesel consumed for onsite transportation is found in the study which is not seen reported in the literature thus it is an unexpected data. The castable refractories consumed is as expected, based on values reported in the literature. The NO_x value seems to be in line with values reported in the literature but at the higher end of values reported in the literature. The particulate matter emission seems to be higher than the literature values and SO_2 emissions seem to be lower than literature values. The radiation and convection losses are found as expected in the literature but comparatively in the lower range of value reported in the literature.

b) Limitation:

i) From analysing the data completion for each unit processes with respect to the expected inventory data defined in goal and scope. It is understood that only a few data are collected. Most of the process related raw material and energy were only able to collect, other inputs like ancillary inputs and other physical inputs where not able to collect. Similarly, assumption as made that output of a process is transferred to the consequent process without losses. CO_2 one of the main output of the cement industry was not able to measure. The releases to water and soil were also not collected. Thus, it is understood that the inventory is partially complete, and it is a limitation with LCI data collection. More data can be collected for exclusive inventory data set.

ii) A consistency check is carried out to understand the consistency of data, method and assumption associated with the analysis. Cut off value, data accuracy, temporal coverage, geographical coverage, technological coverage, and assumptions used in the study are consistent with the defined goal and scope. System boundary seems to be partially consistent because few processes are included and excluded beyond the system boundary condition. Limestone extraction in quarry and transportation to plant is happening outside cement plant premises but it is assumed to be happening within the cement plant boundary and these processes are included. Similarly, the electricity production happening in the cement pant boundary is been excluded. Data sources which have data measured and reported by cement plant officials are aimed to be collected for analysis. But data measured by the third party are also used for analysis. Thus, data source considered is partially consistent. And thus, partial consistency of system boundary and data source are the limitation of the study.

iii) Beyond the completeness and consistency issues the limitation met during analysis are reported in the goal and scope, it is also applicable.

c) Recommendation

i) Few recommendations based on the study are as follows. The dataset inventory has met most of the data quality requirement and thus can be reported to as a set of LCI data related to clinker production in a typical Indian cement plant. Still, an iteration of data collection can be conducted in order to improve the completeness of data collection with respect to all unit process considered. Evidently the inventory data on the equipment (e.g. electrostatic precipitator and bag house filter) and infrastructure (e.g. buildings for equipment, office buildings and colony) was not obtained. The data collection can be completely done from plant monitored data.

4.3 Energy use for clinker production

In this section, the extrapolation of the LCI analysis toward the energy is been discussed.

4.3.1 Goal and scope

All the details defined in the goal and scope of LCI analysis (Section: 4.2.1) is valid here except few updations and additions. The changed and added information are as follows.

1) Goal:

a) Objective - To quantify the energy consumption related to the production of clinker in a typical integrated cement factory in India.

b) **Application** - To understand the current value of energy consumption of Indian clinker. This can serve as a new data to life cycle database on the energy use of clinker in India. This can also be used in predicting energy related to normal and blended cement.

2) **Scope:**

   a) **System boundary:** Even though the electricity production is not considered as one of the processes in the analysis, the energy consumed in electricity production is considered as energy use of electricity.

   b) **Energy calculation methodology**: The energy consumed within the system boundary is planned to calculate. The energy will be calculated in MJ. The inputs from which energy is produced within gate to gate system boundary is fuel. Calorific value is used to estimate the energy produced from the inventory result of fuel. The calorific value of the fuels burned is planned to obtain from cement plant itself in order to have the same data quality and representativeness. If the factors are not available from cement plant factors from other sources are planned to use. The other sources are provided in the order of their priority, based on the representativeness of the input.

      i) **Characterisation factors obtained from the cement plant**,

      ii) **Bomb calorimetry results of fuel sample collected**,

      iii) **Emission Factors for Greenhouse Gas Inventories (2014)** (Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf),

      iv) **2006 IPCC Guidelines for national Greenhouse gas inventory** (Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > Chapter 1 > Table 1.2, http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html)"

4.3.2 Life Cycle Inventory (LCI)

The life cycle inventory analysis for this section is same as in section 4.2.2. LCI result tables are provided as input-output category-wise in Table 4.1 and process-wise in Table 4.2.

4.3.3 Energy calculation

Here the LCI result is converted into energy values, using energy factors within the system boundary.

1) **Energy calculation:** Same as defined in goal and scope (Section 4.3.1), the energy use related to inventory within Gate to Gate system boundary is calculated (in MJ). The

inputs from which energy is produced within gate to gate system boundary is fuel. The calorific value of the fuel is used to estimate the energy produced from the inventory value. The calorific value of the fuels burned is obtained from the cement plant itself. The emission factor for electricity is calculated separately and cited.

2) **Classification**: The LCI results are classified based on energy consumption. The data is selected if there is a contribution of energy from the data or else it is rejected. The selected LCI results for energy calculation are provided input-output category-wise in Table 4.4.

Table 4.4: CS 1: LCI selected for calculating energy use for clinker production (input-output category-wise)

Input	Value	Unit
Energy – Fuel		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Energy – Electricity		
Electricity consumed by limestone crushing section	1.02	kWh / ton of clinker
Electricity consumed by raw mill section	23.16	kWh / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Other physical inputs – Transportation		

Input	Value	Unit
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker
Diesel oil	0.783	kg / ton of clinker

The outputs are not considered as they are not contributing energy to the system and the excess energy taken by the outputs are assigned to the product itself. The rejected data are as follows.

1) **Input**
   a) **Raw material:** Limestone and marl, white clay, ETP sludge, and fly ash.
   b) **Other:** Refractory and castable.
2) **Output**
   a) **Waste** – Release to air: SPM, SO_2, NO_x, radiation and convection.

The selected data is used for energy calculation.

3) **Energy Calculation**:

Here the LCI results are converted to the energy produced using suitable energy factor,

   a) **Energy factor**

   The suitable energy factors are selected from the data shared by cement plant and provided in Table 4.5.

Energy factor of the electricity is calculated based on the thermal power plant inventory data obtained from the cement plant (Table B. 2).

   b) **Calculation of energy consumption**

   The selected inventory (Table 4.4) is multiplied with factor (Table 4.5) and the energy consumed is calculated. Results are provided in Table 4.6 and Table 4.7 as input-output category-wise and process-wise respectively.

Table 4.5: CS 1: Energy factors for calculation (clinker)

Input	Value	Unit
Energy – Fuel		
Petcoke(Imported)	33.33	MJ/kg
Petcoke(Indigenous)	33.52	MJ/kg
Coal	25.62	MJ/kg
Lignite	20.06	MJ/kg
Diesel (HSD)	42.68	MJ/kg
RDF (Refuse derived fuel) including plastics	16.96	MJ/kg
Tyres	27.49	MJ/kg
Solvents (Paint Sludge)	13.26	MJ/kg
Footwear scrap	21.75	MJ/kg
AF Hard rubber	27.04	MJ/kg

Input	Value	Unit
Mixed industrial waste (Carbon Powder, Coal ash)	15.98	MJ/kg
Other fossil-based wastes and mixed fuels (oily cotton waste)	18.85	MJ/kg
Others (UNL waste, Fibre waste)	15.42	MJ/kg
Agro based	12.18	MJ/kg
Coir pith	10.34	MJ/kg
Cashew nut Shell	18.98	MJ/kg
Coffee Husk	13.56	MJ/kg
DORB (De oiled rice bran)	12.62	MJ/kg
Other Bio Mass Fuel (E.g. Wooden Dust)	9.18	MJ/kg
Energy – Electricity		
Electricity	13.40	MJ/kWh

Table 4.6: CS 1: Energy use for production of clinker (input-output category-wise)

Input/output	Energy	Unit
Energy – Fuel		
Petcoke (imported)	1174.524	MJ / ton of clinker
Petcoke (indigenous)	845.160	MJ / ton of clinker
Coal	28.230	MJ / ton of clinker
Lignite	733.981	MJ / ton of clinker
Diesel	2.125	MJ / ton of clinker
RDF (Refuse derived fuel) including plastics	143.745	MJ / ton of clinker
Tyres	43.887	MJ / ton of clinker
Solvents (Paint Sludge)	35.099	MJ / ton of clinker
Foot wear scrap	26.625	MJ / ton of clinker
Hard rubber	10.195	MJ / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	11.444	MJ / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.904	MJ / ton of clinker
Others (UNL waste, Fibre waste)	1.912	MJ / ton of clinker
Agro based	4.116	MJ / ton of clinker
Coir pith	0.567	MJ / ton of clinker
Cashew nut	6.794	MJ / ton of clinker
Coffee husk	0.023	MJ / ton of clinker
De oiled Rice Bran	10.052	MJ / ton of clinker
Other biomass fuel (wooden dust)	0.182	MJ / ton of clinker
	3079.563	
Energy - Electricity		
Electricity	13.63	MJ / ton of clinker
Electricity	310.28	MJ / ton of clinker
Electricity	79.72	MJ / ton of clinker
Electricity	381.31	MJ / ton of clinker
Electricity	17.91	MJ / ton of clinker
	802.85	
Other physical inputs - Transportation		
Diesel	73.51	MJ / ton of clinker
Diesel oil	33.42	MJ / ton of clinker
	106.94	
Total	**3989.35**	**MJ / ton of clinker**

Table 4.7: CS 1: Energy use for the production of clinker (process wise)

Process and inputs	Energy	Unit
Limestone extraction and transportation		
Input		
Diesel	73.51	MJ / ton of clinker
	73.51	**MJ / ton of clinker**
Limestone crushing, stacking and reclaiming		
Input		
Electricity consumed by limestone crushing section	13.63	MJ / ton of clinker
	13.63	**MJ / ton of clinker**
Raw meal preparation		
Input		
Electricity consumed by raw mill section	310.28	MJ / ton of clinker
	310.28	**MJ / ton of clinker**
Fuel preparation		
Input		
Electricity consumed by coal mill section	79.72	MJ / ton of clinker
	79.72	**MJ / ton of clinker**
Clinkerization, cooling and storing		
Input		
Petcoke (imported)	1174.52	MJ / ton of clinker
Petcoke (indigenous)	845.16	MJ / ton of clinker
Coal	28.23	MJ / ton of clinker
Lignite	733.98	MJ / ton of clinker
Diesel	2.12	MJ / ton of clinker
RDF (Refuse derived fuel) including plastics	143.74	MJ / ton of clinker
Tyres	43.89	MJ / ton of clinker
Solvents (Paint Sludge)	35.10	MJ / ton of clinker
Foot wear scrap	26.62	MJ / ton of clinker
Hard rubber	10.19	MJ / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	11.44	MJ / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.90	MJ / ton of clinker
Others (UNL waste, Fibre waste)	1.91	MJ / ton of clinker
Agro based	4.12	MJ / ton of clinker
Coir pith	0.57	MJ / ton of clinker
Cashew nut	6.79	MJ / ton of clinker
Coffee husk	0.02	MJ / ton of clinker
De oiled Rice Bran	10.05	MJ / ton of clinker
Other biomass fuel (wooden dust)	0.18	MJ / ton of clinker
Electricity consumed by kiln section	381.31	MJ / ton of clinker
Electricity consumed by kiln section for kiln shut down	17.91	MJ / ton of clinker
	3478.78	**MJ / ton of clinker**
Others (services etc)		
Input		
Diesel oil (onsite transportation)	33.42	MJ / ton of clinker
	33.42	MJ / ton of clinker
Total	**3989.35**	**MJ / ton of clinker**

The discussion on the energy consumption results will be provided in the following Interpretation phase.

4.3.4 Interpretation

1) **Identification of significant issues**: The energy consumed results are structured and analysed.

   a) **Structured information**

      The energy results are structured as unit process along the column and data category along the row. The structured results are provided in Table 4.8.

Table 4.8: CS 1: Energy use for production of clinker (structured)

Unit process / Data category	Limestone extraction and transportation	Limestone crushing, stacking and reclaiming	Raw meal preparatio n	Fuel preparation	Clinkerization, cooling and storing	Others (services etc)	Total
Energy -Electricity (MJ/ton of clinker)	-	13.63	310.28	79.72	399.22	-	802.85
Energy - Fuel (MJ/ton of clinker)	-	-	-	-	3079.56	-	3079.56
Other physical inputs - Transportation (MJ / ton of clinker)	73.512	-	-	-	-	33.42	106.94
Total	73.51	13.63	310.28	79.72	3478.78	33.42	3989.35

Note: All the results are in MJ/ton of clinker

b) Analysis

i) Contribution analysis

The percentage contribution from the different data is discussed here. The most contributing input is fuel consumed for the clinkerization with 77.19% of total energy consumption followed by electricity for clinkerization and raw meal preparation with 10.01% and 7.78% respectively. The smallest energy contributing inputs are electricity for limestone preparation and diesel consumed for onsite transportation, which contributes 0.34% and 0.84% respectively. Amount processes the most contributing processes are a clinkerization process which consumed 87.20% of total energy followed by raw meal preparation with 7.78% and fuel preparation with 2%. These 3 processes consumed around 97% of the total energy and thus focus on energy-related study can be more oriented towards these processes. Analysing data type wise the electricity (20.12%) and fuel (77.19%) consumes 97.32%. Thus, if data collection is carried out data type wise the fuel and electricity data should be given highest priority.

ii) Anomaly analysis

The energy consumption values are discussed here in the context of previously reported literature values. The embodied energy of electricity consumed for clinker production is calculated in SimaPro software for different geographical areas. The values vary from 450-1230 MJ/ton of clinker, where the value corresponding to the Geographical area "Rest of the World" which is the most comparable value to this study, is 663 MJ/ton clinker. Comparing to the literature value the total electricity energy obtained in the study seems to be higher than the literature value. There are few thermal energy consumption values available in literature corresponding to the Indian cement production scenario. The energy from fuel for clinkerization is reported in MoP (2015) as 658-1074 kcal/kg of clinker or 2753-4494 kJ/kg of clinker. The value reported by Virendra et al. (2015), which is 730 kcal/kg of clinker or 3054 kJ/kg of clinker, Grover et al. (2015) which is 680 to 850 kcal/kg clinker or 2845 to 3556 kJ/kg clinker and Saidur et al. (2012) which is 2.81 - 3.24 MJ/kg of clinker also lies in this range. Values 2800-3200 MJ/ton of clinker is common in most of the above-mentioned literature. Comparing with the value obtained in the literature the energy from fuel for clinkerization obtained in the study lies in the expected range. Li et al. (2014) have mentioned on average quarrying/mining represents 1% and transportation/distribution represents 3% of total energy consumption (Cradle to the gate). Splitting the energy consumption found in the study according to Li et al. (2014) the extraction and transportation energy will be 18.38 and 55.13 MJ/ton of clinker. According to the database Ecoinvent 3 (accessed on 16-01-2018, using SimaPro 8.4.0.0), 18 MJ/ton of limestone extracted is been consumed from diesel. Considering the limestone to clinker ratio, 1.453 the limestone extraction energy will be 26.15 MJ/ton of clinker. Marceau et al. (2006) have reported average onsite quarried material transportation energy in terms of cement which when converted in terms of clinker is 36.89 MJ/ton of clinker. Considering the estimated values extraction value seems to be low compared to the literature and the transportation energy seems to be higher with literature. The energy for extraction and transportation depends on factors like type of quarry, and transportation distance. Thus, the values can vary geographically. Total value seems to be higher than the sum of literature values (63 MJ). From the analysis of clinker inventory from Ecoinvent V3 using impact assessment method Cumulative Energy Demand (V1.09), the amount of embodied energy is found to be 3710 MJ/ton of clinker. The value corresponds to cradle to gate system boundary and rest of the world geographically. Similarly, a value corresponding to other geographical areas is 3720 MJ/ton of clinker for Canada, 2970 MJ/ton of clinker for Switzerland, 3810 MJ/ton of clinker for Europe without Switzerland and 3760 MJ/ton of clinker for the US. Comparing with the literature, the value obtained in the study seems to be higher. It is to be noted that despite the literature values reported are corresponding to Cradle to gate system boundary the values in the study which belong to the gate to gate system boundary is showing high values.

2) Evaluation

a) Completeness check

The completeness issues mentioned in the completeness section of LCI analysis are also applicable here (Section: 4.2.3). Beyond the same, during characterization, there is no incompleteness happened. Incompleteness in energy calculation can happen due to a lack of suitable energy factor.

b) Consistency check

The consistency issues mentioned in the LCI analysis (Section: 4.2.3) is also applicable here. The energy consumption calculation methodology was consistent.

3) Conclusion, limitation and recommendation

a) Conclusions

i) The energy contribution from different LCI results is calculated and reported. The total energy consumed within gate to gate system boundary is 3989 MJ/ton of clinker (Table 4.8).

ii) The most and least contributing inputs are fuel for clinkerization with 77.19% and electricity for limestone preparation with 0.34%. The electricity and fuel consume about 97.32% and the processes like raw meal preparation, fuel preparation and clinkerization consume around 96.98%.

iii) Comparing to the literature value the total electricity energy obtained in the study seems to be higher than literature value, energy from fuel for clinkerization obtained in the study lies in the expected range. And estimated values of extraction energy seem to be low compared to the literature and the transportation energy seems to be higher with literature. Comparing the literature, the total energy obtained in the study seems to be higher.

b) Limitation

All the limitation reported in the LCI analysis (Section: 4.2.3) are also applicable here. There is no completion issue due to the classification of inventory result for characterization. And the energy calculation methodology seems to be consistent along the study.

c) Recommendation

This can serve as a new data to life cycle database on the energy use of Indian clinker (within gate to gate system boundary). This can also be used in predicting energy and emission related to normal and blended cement. As recommended in LCI analysis the reiteration data can also be conducted to improve the completeness and to collect data completely measured by the cement plant.

4.4 CO_2 emission for clinker production

The LCI result reported in the LCI analysis does not contain the data related to CO_2 emission. CO_2 is an important inventory result related to clinker production as 5% of the global anthropogenic CO_2 emission is said to be produced from cement production. And since the climate change due to global warming is a concern across the world, the quantification of CO_2 is important in LCI analysis of clinker. In this section, the CO_2 emission associated with clinker production within the gate to gate system boundary is been calculated.

4.4.1 Goal and scope

All the details defined in the goal and scope of LCI analysis (Section: 4.2.1) is valid here except few updations and addition. The changed and added information are as follows.

1) **Goal:**
   a) **Objective**: To quantify the CO_2 emission related to the production of clinker in a typical integrated cement factory in India.
   b) **Application**: To understand the current value of CO_2 emission associated with Indian clinker. This can serve as a new data to life cycle database on Carbon dioxide emission of building materials in India. This can also be used in predicting CO_2 emission related to normal and blended cement.
2) **Scope:**
   a) **System boundary:** Even though the electricity production is not considered as one of the processes in the analysis, the CO_2 emission associated with electricity production are considered.
   b) **CO_2 emission calculation methodology**: Here the steps to estimate the CO_2 from the unit process considered is explained. The CO_2 from the different inputs are reported in the literature. The CO_2 is primarily from decarbonisation of raw meal, from burning of fuel (heating in the kiln, and for equipment used in extraction and transportation). Thus, the suitable CO_2 emission factors are calculated or cited from data shared by the cement plant. CO_2 emission factors for a raw meal is calculated based on the CaO and MgO content of the raw meal and the stoichiometric ratio (molar mass ratio) of CaO and MgO with CO_2. The CO_2 emission factor for fuels is obtained from cement plant data. If the CO_2 emission factor is not available from different sources. Based on the representativeness with the fuel, the priority order of sources is provided as follows.
      i) **CHNS (Carbon, Hydrogen, Nitrogen and Sulphur) analysis results of fuel samples from the cement plant.**
      ii) **Emission Factors for Greenhouse Gas Inventories (2014)** (Source: Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emissithe on-factors_2014.pdf).

iii) **CSI protocol 2013** (Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors").

iv) **2006 IPCC Guidelines for national Greenhouse gas inventory** (Source: Table 1.4, website - http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html, Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > chapter 1 Introduction).

c) **CO_2 calculation methodology:** The amount of CO_2 generated within gate to gate system boundary is calculated, thus it includes the direct CO_2 from the unit processes considered and the embodied CO_2 from the inputs within the system boundary. Here, in this case, electricity is the only input data which has embodied CO_2 within the gate to gate system boundary. But it is not accounted as the electricity production process. Considering the embodied CO_2 of electricity, and direct CO_2 emission, the total CO_2 of the clinker is found. The CO_2 is measured in kg. The CO_2 factor of electricity is calculated based on captive power plant data of cement plant. (Table B. 3).

d) **Limitation**

i) For certain fuels suitable CO_2 emission factors were not found and thus emission factor of similar fuel is used for calculation.

4.4.2 Life Cycle Inventory (LCI)

The life cycle inventory results provided in for clinker LCI analysis (Section 4.2.2) are used here. The CO_2 is one of the major direct output of the process system, however the same was not able to measure. Thus the CO_2 related to different input is calculated and added to the existing LCI result. In the first step, LCI result which is probable to produce CO_2 is classified. In the second step, CO_2 emission factor suitable for the classified data identified from cement plant data or from other sources, are multiplied with LCI results and the CO_2 emissions are obtained. In the third step, the new CO_2 results obtained is added with previous LCI results.

1) **Classification of LCI result**

a) **Classification:** The LCI data which produce CO_2 is been selected from the whole LCI result set.

b) **Classified results:** The data which is associated with CO_2 production is provided in Table 4.9.

Table 4.9: CS 1: LCI selected for calculating direct CO_2 emissions for clinker production (input-output category-wise)

Input	Value	Unit
Raw material		
Limestone and marl	1.453	ton / ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Energy - Electricity		
Electricity consumed by limestone crushing section	1.02	kWh / ton of clinker
Electricity consumed by raw mill section	23.16	kWh / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Energy - Fuel		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Other physical inputs - Transportation		
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker
Diesel oil	0.783	kg / ton of clinker

2) CO_2 estimation

a) Selecting CO_2 emission factor: The selection of suitable CO_2 emission factor is carried over in this subsection. The CO_2 emission factor data was not obtained from the cement plant. For raw material, the factor is calculated using CaO and MgO content shared by the cement plant. It is assumed that there is no free CaO and MgO present in the raw meal thus all the CO_2 is assumed to be produced from the complete decarbonation of $MgCO_3$ and $CaCO_3$ present in the raw meal. Thus, based on the stoichiometric ratio the CO_2 from the raw meal is calculated. The Equation used in this study is provided in Equation 4.1 (Eq 4.1).

$$CO_2 = \left(\frac{Molar\ mass\ of\ CO_2}{Molar\ mass\ of\ CaO} \times \frac{Amount\ of\ CaO\ from\ CaCO_3}{Amount\ of\ raw\ meal} + \frac{Molar\ mass\ of\ CO_2}{Molar\ mass\ of\ MgO} \times \frac{Amount\ of\ MgO\ from\ MgCO_3}{Amount\ of\ raw\ meal}\right) \quad Eq.\ 4.1$$

For fuels the CO_2 emission factors were not obtained from the cement plant, thus it is obtained from a couple of sources like

i) **CHNS (Carbon, Hydrogen, Nitrogen and Sulphur) analysis results of fuel samples from the cement plant**
ii) **Emission Factors for Greenhouse Gas Inventories (2014)** (Source: Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf)
iii) **CSI protocol 2013** (Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors")
iv) **2006 IPCC Guidelines for national Greenhouse gas inventory** (Source: Table 1.4, website - http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html, Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > chapter 1 Introduction)

For few data, the suitable emission factors were found. Table A. 8 contain emission factors with a suitable unit and Table A. 9 contains emission factors in other units. For certain data, the corresponding CO_2 emission factors were not found and thus the CO_2 emission factor of the similar data is used (Table A. 10). Among these selected factors few are of in different unit (kg CO_2/MJ) and thus they are multiplied with suitable calorific value (MJ/kg) (Table A. 11) to make the unit of a factor to kg CO_2/kg of fuel. The final and compiled set of CO_2 emission factors for the calculations are provided in Table 4.10.

Table 4.10: CS 1: CO_2 emission factors for calculating direct CO_2 emissions (clinker)

Input	Value	Unit
Energy - Fuel		
Petcoke	3.06	kg CO_2 / kg
Coal	2.27	kg CO_2 / kg
Lignite	1.36	kg CO_2 / kg
Diesel	3.16	kg CO_2 / kg
RDF (Refuse derived fuel) including plastics	1.21	kg CO_2 / kg
Tyres	2.24	kg CO_2 / kg
Solvents (Paint Sludge)	0.98	kg CO_2 / kg
Foot wear scrap	1.80	kg CO_2 / kg
Hard rubber	2.24	kg CO_2 / kg
Mixed industrial waste (Carbon powder, Coal ash)	1.33	kg CO_2 / kg
Other fossil-based wastes and mixed fuels (oily cotton waste)	1.51	kg CO_2 / kg
Others (UNL waste, Fibre waste)	1.28	kg CO_2 / kg
Agro based	1.34	kg CO_2 / kg
Coir pith	1.14	kg CO_2 / kg
Cashew nut	2.09	kg CO_2 / kg
Coffee husk	1.49	kg CO_2 / kg
De oiled Rice Bran	1.39	kg CO_2 / kg
Other biomass fuel (wooden dust)	1.01	kg CO_2 / kg
Raw material		
Raw meal	0.34	kg CO_2 / kg

b) **CO_2 emission estimation:** The selected LCI results are multiplied with the suitable CO_2 emission factors and the CO_2 emission results were obtained. The results are provided in Input-output category-wise and process wise as follows.

Table 4.11: CS 1: Direct CO_2 emissions calculated for clinker production (Input-output category-wise)

Input/output	CO_2 emission result	Unit	Remark
Energy - Fuel			
CO_2 from Petcoke (imported)	107.83	kg CO_2/ton of clinker	Fuel used for the thermal treatment in the kiln, preheater and precalciner
CO_2 from Petcoke (indigenous)	77.14	kg CO_2/ton of clinker	
CO_2 from Coal	2.50	kg CO_2/ton of clinker	
CO_2 from Lignite	49.76	kg CO_2/ton of clinker	
CO_2 from Diesel	0.16	kg CO_2/ton of clinker	
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2/ton of clinker	
CO_2 from Tyres	3.58	kg CO_2/ton of clinker	
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2/ton of clinker	
CO_2 from Foot wear scrap	2.21	kg CO_2/ton of clinker	
CO_2 from Hard rubber	0.85	kg CO_2/ton of clinker	
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2/ton of clinker	
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2/ton of clinker	
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2/ton of clinker	
CO_2 from Agro based	0.45	kg CO_2/ton of clinker	
CO_2 from Coir pith	0.06	kg CO_2/ton of clinker	
CO_2 from Cashew nut	0.75	kg CO_2/ton of clinker	
CO_2 from Coffee husk	0.00	kg CO_2/ton of clinker	
CO_2 from De oiled Rice Bran	1.11	kg CO_2/ton of clinker	
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2/ton of clinker	
	260.40	**kg CO_2/ton of clinker**	
Raw material			
CO_2 from raw meal	514.86	kg CO_2/ton of clinker	CO_2 emission due to decarbonisation of raw meal
	514.86	**kg CO_2/ton of clinker**	
Other physical inputs - Transportation			
CO_2 from Diesel (Limestone extraction and transportation process)	5.45	kg CO_2/ton of clinker	Diesel consumed for limestone extraction and transportation process.
CO_2 from Diesel oil	2.48	kg CO_2/ton of clinker	Diesel consumed for internal transportation
	7.92	**kg CO_2/ton of clinker**	
Total	**783.18**	**kg CO_2/ton of clinker**	

3) **Updated LCI result**

The estimated CO_2 results are added to the previously reported LCI result (Table 4.1 and Table 4.2). The results are provided in input-output category-wise and process-wise in Table 4.12 and Table 4.13 respectively.

Table 4.12: CS 1: Updated LCI for production of clinker (input-output category–wise)

Input	Value	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section	1.02	kWh / ton of clinker
Electricity consumed by raw mill section	23.16	kWh / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Energy - Fuel		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Raw material		
Limestone and marl	1.453	ton / ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton / ton of clinker
Other physical inputs - Transportation		
Diesel oil	0.783	kg / ton of clinker
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker

Input	Value	Unit
Others		
Refractories and castable	0.426	kg / ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1	ton / ton of clinker
Waste - Releases to air		
CO_2 from diesel	5.45	kg CO_2 / ton of clinker
CO_2 from diesel oil (onsite transportation)	0.00	kg CO_2 / ton of clinker
CO_2 from Petcoke (imported)	107.83	kg CO_2 / ton of clinker
CO_2 from Petcoke (indigenous)	77.14	kg CO_2 / ton of clinker
CO_2 from Coal	2.50	kg CO_2 / ton of clinker
CO_2 from Lignite	49.76	kg CO_2 / ton of clinker
CO_2 from Diesel	0.16	kg CO_2 / ton of clinker
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2 / ton of clinker
CO_2 from Tyres	3.58	kg CO_2 / ton of clinker
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2 / ton of clinker
CO_2 from Foot wear scrap	2.21	kg CO_2 / ton of clinker
CO_2 from Hard rubber	0.85	kg CO_2 / ton of clinker
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2 / ton of clinker
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2 / ton of clinker
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2 / ton of clinker
CO_2 from Agro based	0.45	kg CO_2 / ton of clinker
CO_2 from Coir pith	0.06	kg CO_2 / ton of clinker
CO_2 from Cashew nut	0.75	kg CO_2 / ton of clinker
CO_2 from Coffee husk	0.00	kg CO_2 / ton of clinker
CO_2 from De oiled Rice Bran	1.11	kg CO_2 / ton of clinker
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2 / ton of clinker
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker
SPM - Kiln main stacks	0.102	kg / ton of clinker
SPM - Coal mill stacks	0.023	kg / ton of clinker
SPM - Cooler stacks	0.031	kg / ton of clinker
SO_2 - Kiln Main stacks	0.026	kg / ton of clinker
SO_2 - Coal Mill Stacks	0.008	kg / ton of clinker
NO_x - Kiln Main Stacks	1.843	kg / ton of clinker
NO_x - Coal Mill Stacks	0.035	kg / ton of clinker
Radiation and Convection losses from cooler	25.1	MJ / ton of clinker
Radiation and Convection losses from kiln	82.0	MJ / ton of clinker
Radiation and Convection losses from preheater	70.3	MJ / ton of clinker
Radiation and convection losses from tertiary air duct	8.8	MJ / ton of clinker

Table 4.13: CS 1: Updated LCI for production of clinker (process–wise)

Process	Value	Unit
Limestone extraction and transportation		
Input		
Limestone and marl	1.453	ton / ton of clinker
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker
Output		
Limestone and marl	1.453	ton / ton of clinker
CO_2 - Diesel	5.45	kg CO_2 / ton of clinker
Limestone crushing, stacking and reclaiming		
Input		
Limestone and marl	1.453	ton / ton of clinker
Electricity consumed by limestone crushing section	1.02	kWh/ton of clinker
Output		
Limestone and marl	1.453	ton / ton of clinker
Raw meal preparation		
Input		
Limestone and marl	1.453	ton / ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Electricity consumed by raw mill section	23.16	kWh/ton of clinker
Output		
Raw meal	1.508	tons/ton of clinker
Fuel preparation		
Input		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Output		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker

Process	Value	Unit
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
SPM - Coal mill stacks	0.023	kg / ton of clinker
SO_2 - Coal Mill Stacks	0.008	kg / ton of clinker
NO_x - Coal Mill Stacks	0.035	kg / ton of clinker
Clinkerization, cooling and storing		
Input		
Raw meal	1.50762	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton / ton of clinker
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Refractories and castable	0.426	kg / ton of clinker
Output		
Clinker	1.0	ton / ton of clinker

Process	Value	Unit
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker
CO_2 from Petcoke (imported)	107.83	kg CO_2 / ton of clinker
CO_2 from Petcoke (indigenous)	77.14	kg CO_2 / ton of clinker
CO_2 from Coal	2.50	kg CO_2 / ton of clinker
CO_2 from Lignite	49.76	kg CO_2 / ton of clinker
CO_2 from Diesel	0.16	kg CO_2 / ton of clinker
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2 / ton of clinker
CO_2 from Tyres	3.58	kg CO_2 / ton of clinker
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2 / ton of clinker
CO_2 from Foot wear scrap	2.21	kg CO_2 / ton of clinker
CO_2 from Hard rubber	0.85	kg CO_2 / ton of clinker
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2 / ton of clinker
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2 / ton of clinker
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2 / ton of clinker
CO_2 from Agro based	0.45	kg CO_2 / ton of clinker
CO_2 from Coir pith	0.06	kg CO_2 / ton of clinker
CO_2 from Cashew nut	0.75	kg CO_2 / ton of clinker
CO_2 from Coffee husk	0.00	kg CO_2 / ton of clinker
CO_2 from De oiled Rice Bran	1.11	kg CO_2 / ton of clinker
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2 / ton of clinker
SPM - Kiln main stacks	0.102	kg / ton of clinker
SPM - Cooler stacks	0.031	kg / ton of clinker
SO_2 - Kiln Main stacks	0.026	kg / ton of clinker
NO_x - Kiln Main stacks	1.843	kg / ton of clinker
Radiation and Convection losses from cooler	25.1	MJ / ton of clinker
Radiation and Convection losses from kiln	82.0	MJ / ton of clinker
Radiation and Convection losses from preheater	70.3	MJ / ton of clinker
Radiation and convection losses from tertiary air duct	8.8	MJ / ton of clinker
Others (services etc)		
Inputs		
Diesel oil	0.783	kg / ton of clinker
Output		
CO_2 from diesel oil (onsite transportation)	2.48	kg CO_2 / ton of clinker

4) Aggregated LCI result

The updated LCI results are aggregated and reported in annexure (Table A. 13).

4.4.3 CO_2 emission calculation

The CO_2 associated with the existing inventory data (within the gate to gate) is calculated as follows.

1) **CO_2 emission calculation methodology:** As explained in the goal and scope the CO_2 associated with electricity and direct CO_2 emission is calculated and added to a total of

CO_2 emission associated with clinker. The CO_2 is calculated in kg. The emission factors used for direct CO_2 is 1 kg CO_2/kg and for electricity the factor is 1.09 kg CO_2/kWh (as calculated from captive power plant data (Table B. 3).

2) **LCI result assigning**

The LCI result which contributes to CO_2 within gate to gate is selected from updated LCI result. The selected LCI results are provided in Table 4.14.

Table 4.14: CS 1: LCI data selected for calculating CO_2 emissions for clinker production (Input–output category–wise)

Input	Value	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section	1.02	kWh / ton of clinker
Electricity consumed by raw mill section	23.16	kWh / ton of clinker
Electricity consumed by coal mill section	5.95	kWh / ton of clinker
Electricity consumed by kiln section	28.46	kWh / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh / ton of clinker
Output	**Value**	**Unit**
Waste - Releases to air		
CO_2 from diesel	5.45	kg CO_2 / ton of clinker
CO_2 from diesel oil (onsite transportation)	0.00	kg CO_2 / ton of clinker
CO_2 from Petcoke (imported)	107.83	kg CO_2 / ton of clinker
CO_2 from Petcoke (indigenous)	77.14	kg CO_2 / ton of clinker
CO_2 from Coal	2.50	kg CO_2 / ton of clinker
CO_2 from Lignite	49.76	kg CO_2 / ton of clinker
CO_2 from Diesel	0.16	kg CO_2 / ton of clinker
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2 / ton of clinker
CO_2 from Tyres	3.58	kg CO_2 / ton of clinker
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2 / ton of clinker
CO_2 from Foot wear scrap	2.21	kg CO_2 / ton of clinker
CO_2 from Hard rubber	0.85	kg CO_2 / ton of clinker
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2 / ton of clinker
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2 / ton of clinker
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2 / ton of clinker
CO_2 from Agro based	0.45	kg CO_2 / ton of clinker
CO_2 from Coir pith	0.06	kg CO_2 / ton of clinker
CO_2 from Cashew nut	0.75	kg CO_2 / ton of clinker
CO_2 from Coffee husk	0.00	kg CO_2 / ton of clinker
CO_2 from De oiled Rice Bran	1.11	kg CO_2 / ton of clinker
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2 / ton of clinker
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker

The inputs like fly ash, and refractories and castable are not selected as they have no direct CO_2 emission nor have embodied CO_2 within gate to gate system boundary. Similarly, the outputs like SP, SO_2, NO_x, radiation and convection losses are also rejected for CO_2 estimation.

3) CO_2 emission calculation

Here the CO_2 emission factor suitable for the classified inventory is been selected and the CO_2 emission is calculated.

a) CO_2 emission factor

Only two data are present CO_2 and electricity. The CO_2 is considered as such, thus factor is 1 and the CO_2 factor of electricity is 1.09 kg CO_2/kWh (Table B. 3).

Table 4.15: CS 1: CO_2 factor for calculation (clinker)

Input/s	Value	Unit
Energy - Electricity		
Electricity	1.09	kg CO_2 / kWh
Output/s	**Value**	**Unit**
Waste - Emission to air		
CO_2	1.00	kg CO_2 / kg

b) CO_2 emission calculation

The classified inventory is multiplied with the CO_2 emission factor. The result thus obtained is provided as input-output category-wise and process-wise in Table 4.16 and Table 4.17 respectively.

Table 4.16: CS 1: CO_2 emissions for production of clinker (input-output category-wise)

Input/output	CO_2 emissions	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section	1.11	kg CO_2 / ton of clinker
Electricity consumed by raw mill section	25.18	kg CO_2 / ton of clinker
Electricity consumed by coal mill section	6.47	kg CO_2 / ton of clinker
Electricity consumed by kiln section	30.94	kg CO_2 / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.45	kg CO_2 / ton of clinker
	65.14	**kg CO_2 / ton of clinker**
Energy - Fuel		
CO_2 from Petcoke (imported)	107.83	kg CO_2 / ton of clinker
CO_2 from Petcoke (indigenous)	77.14	kg CO_2 / ton of clinker
CO_2 from Coal	2.50	kg CO_2 / ton of clinker
CO_2 from Lignite	49.76	kg CO_2 / ton of clinker
CO_2 from Diesel	0.16	kg CO_2 / ton of clinker
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2 / ton of clinker

Input/output	CO_2 emissions	Unit
CO_2 from Tyres	3.58	kg CO_2 / ton of clinker
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2 / ton of clinker
CO_2 from Foot wear scrap	2.21	kg CO_2 / ton of clinker
CO_2 from Hard rubber	0.85	kg CO_2 / ton of clinker
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2 / ton of clinker
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2 / ton of clinker
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2 / ton of clinker
CO_2 from Agro based	0.45	kg CO_2 / ton of clinker
CO_2 from Coir pith	0.06	kg CO_2 / ton of clinker
CO_2 from Cashew nut	0.75	kg CO_2 / ton of clinker
CO_2 from Coffee husk	0.00	kg CO_2 / ton of clinker
CO_2 from De oiled Rice Bran	1.11	kg CO_2 / ton of clinker
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2 / ton of clinker
	260.40	**kg CO_2 / ton of clinker**
Raw material		
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker
	514.86	**kg CO_2 / ton of clinker**
Other physical inputs - Transportation		
CO_2 from Diesel (Limestone extraction and transportation process)	5.45	kg CO_2 / ton of clinker
CO_2 from Diesel oil	2.48	kg CO_2 / ton of clinker
	7.92	**kg CO_2 / ton of clinker**
Total	**848.32**	**kg CO_2 / ton of clinker**

Table 4.17: CS 1: CO_2 emissions for production of clinker (process-wise)

Process and inputs	CO_2 emissions	Unit
Limestone extraction and transportation		
Output		
CO_2 - Diesel	5.45	kg CO_2 / ton of clinker
	5.45	**kg CO_2 / ton of clinker**
Limestone crushing, stacking and reclaiming		
Input		
Electricity consumed by limestone crushing section	1.11	kg CO_2 / ton of clinker
	1.11	**kg CO_2 / ton of clinker**
Raw meal preparation		
Input		
Electricity consumed by raw mill section	25.18	kg CO_2 / ton of clinker
	25.18	**kg CO_2 / ton of clinker**
Fuel preparation		
Input		
Electricity consumed by coal mill section	6.47	kg CO_2 / ton of clinker
	6.47	**kg CO_2 / ton of clinker**

Process and inputs	CO_2 emissions	Unit
Clinkerization		
Input		
Electricity consumed by kiln section	30.94	kg CO_2 / ton of clinker
Electricity consumed by kiln section for kiln shut down	1.45	kg CO_2 / ton of clinker
Output		
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker
CO_2 from Petcoke (imported)	107.83	kg CO_2 / ton of clinker
CO_2 from Petcoke (indigenous)	77.14	kg CO_2 / ton of clinker
CO_2 from Coal	2.50	kg CO_2 / ton of clinker
CO_2 from Lignite	49.76	kg CO_2 / ton of clinker
CO_2 from Diesel	0.16	kg CO_2 / ton of clinker
CO_2 from RDF (Refuse derived fuel) including plastics	10.22	kg CO_2 / ton of clinker
CO_2 from Tyres	3.58	kg CO_2 / ton of clinker
CO_2 from Solvents (Paint Sludge)	2.60	kg CO_2 / ton of clinker
CO_2 from Foot wear scrap	2.21	kg CO_2 / ton of clinker
CO_2 from Hard rubber	0.85	kg CO_2 / ton of clinker
CO_2 from Mixed industrial waste (Carbon powder, Coal ash)	0.95	kg CO_2 / ton of clinker
CO_2 from Other fossil-based wastes and mixed fuels (oily cotton waste)	0.07	kg CO_2 / ton of clinker
CO_2 from Others (UNL waste, Fibre waste)	0.16	kg CO_2 / ton of clinker
CO_2 from Agro based	0.45	kg CO_2 / ton of clinker
CO_2 from Coir pith	0.06	kg CO_2 / ton of clinker
CO_2 from Cashew nut	0.75	kg CO_2 / ton of clinker
CO_2 from Coffee husk	0.00	kg CO_2 / ton of clinker
CO_2 from De oiled Rice Bran	1.11	kg CO_2 / ton of clinker
CO_2 from Other biomass fuel (wooden dust)	0.02	kg CO_2 / ton of clinker
	807.65	**kg CO_2 / ton of clinker**
Others (services etc)		
Output		
CO_2 from diesel oil (onsite transportation)	2.48	kg CO_2 / ton of clinker
	2.48	**kg CO_2 / ton of clinker**
Total	**848.32**	**kg CO_2 / ton of clinker**

4.4.4 Interpretation

The CO_2 emission results are interpreted here. As mentioned in methodology the first the significant issues are found, followed by evaluation and then a description of conclusion, limitation and recommendations.

1) **Identification of the significant issue**

a) **Structured table**

The result of CO_2 emission calculation is consolidated and presented in a structured table. CO_2 from electricity is indirect CO_2 whereas from other inputs it is direct CO_2. The result in the form of structured table is provided in Table 4.18.

Table 4.18: Structured result

Unit process / Data category	Limestone extraction and transportation	Limestone crushing, stacking and reclaiming	Raw meal preparation	Fuel preparation	Clinkerization, cooling and storing	Others (services etc)	Total
Electricity	-	1.11	25.18	6.47	32.39	-	65.14
CO_2 from Fuel	-	-	-	-	260.40	-	260.40
CO_2 from raw material	-	-	-	-	514.86	-	514.86
CO_2 from diesel	5.45	-	-	-	-	2.48	7.92
Total	5.45	1.11	25.18	6.47	807.65	2.48	848.32

Note: All the results are in kg CO_2 / ton of clinker

b) Analysis

The results are analysed to obtain observations and conclusions.

i) Contribution analysis

The most CO_2 contributing input is a raw meal with 60.69%, followed by fuel in clinkerization with 30.70%, the lowest values are indirect CO_2 of electricity for limestone preparation with 0.13% and other (services) with 0.29%. Clinkerization unit process contributes the most with 95.21%, followed by raw meal preparation with 2.97%, and the remaining each process contributes less than 1%. Analysing data type wise, CO_2 from raw material and fuel contribute most with 60.69% and 30.70% respectively. Followed by electricity with 7.68% and diesel for extraction and transportation with 0.93%. Thus, for CO_2 emission calculation, the study of the clinkerization process alone gives a coverage of 95.21% if the raw meal preparation is also considered the coverage becomes 98.18%. Similarly, for CO_2 estimation based on data type the raw material and fuel for clinkerization produces 91.39% coverage.

ii) Anomaly analysis

According to clinker inventories from Ecoinvent 8.4.0.0 analysed with IPCC 2013 GWP 100a, the embodied CO_2 from the electricity varies from 1.1 - 40.1 kg CO_2/ton of clinker. Comparing with the same the embodied CO_2 of electricity (65 kg CO_2) in the study seems to be high. CO_2 from fuel is reported by Marceau et al. (2006) in terms of cement which when converted to clinker will be 318.61 kg/ton of clinker. The value obtained in the study (260.40) seems to be low with respect to the same. The amount of CO_2 from raw material is reported by Marceau et al. (2006) in terms of cement which when converted in terms of clinker will be 581.49 kg CO_2/ton of clinker. The value obtained in the study (514.86) seems to be low compared to the same. Marceau et al. (2006) have calculated CO_2 from plant mobile equipment with respect to cement produced when the results are converted in terms of clinker the value will be equal to 4.13 kg/ton of clinker. Compared to the same the value obtained in the study (2.48) is low.

Barcelo et al. (2014) have cited the Cement Sustainability report in 2006, for CO_2 emission from raw material and fuel as 866 kg CO_2/ton of clinker. Barcelo et al. (2014) have also estimated the theoretical CO_2 emission as 816 kg /ton of clinker from fuel and raw material. Compared to those literature values the value obtained in the study (775.25 kg CO_2/ton of clinker,) is very low. The direct CO_2 emission from cement plant associated with clinker production are 769, 838, 839, 839 and 846 kg according to Ecoinvent database 8.4.0.0 for different geographical conditions. The global average as per GNR reports CSI (2014) is 828 kg. Thus, the value obtained in the study 783.18 kg seems to be low with the literature values.

2) **Evaluation**

The confidence over the result obtained in the analysis is evaluated here with respect to the goal and scope defined. Completeness check and consistency check are conducted to understand the degree to which the results are matching with the goal and scope.

a) **Completeness**

Beyond the incompleteness in the LCI data, during CO_2 estimation there was lack of suitable CO_2 emission factor for certain fuels. Thus, the emission factor of similar fuel is used for calculation.

b) **Consistency**

As same as during energy calculation, the CO_2 emission calculation methodology is consistent. The assumptions considered in the calculation are also consistent.

3) **Conclusions, limitations and recommendations**

a) **Conclusions**

i) The CO_2 associated with different data like electricity, fuel, and the raw meal is calculated. The total CO_2 calculated from the inventory is 848.32 kg CO_2 / ton of clinker.

ii) From contribution analysis, it is understood that for CO_2 calculation the study of the clinkerization process alone gives a coverage of 95.21% if the raw meal preparation is also considered the coverage becomes 98.18%. Similarly, for CO_2 calculation based on data type the raw material and fuel for clinkerization produces 91.39 % coverage.

iii) Comparing with literature the value of indirect CO_2 from electricity seems to be higher, whereas the direct emission from fuel for clinkerization, from raw material decarbonisation and onsite transportation seems to be low. The sum of direct CO_2 from fuel and raw material is also low with respect to the aggregated values reported in literature. The sum of direct CO_2 from fuel for clinkerization, onsite transportation and raw material is also low compared to total values reported in the literature.

b) Limitations

Apart from limitations faced in the LCI analysis, there is an incompletion issue of CO_2 emission factor was faced. For certain fuels, CO_2 emission factors are not found and thus the CO_2 emission factors of similar fuels are used.

c) Recommendations

This can serve as a new data to life cycle database on CO_2 emission, corresponding to clinker in India. This can also be used in predicting CO_2 related to Portland and blended cement. An iteration of data collection can be conducted in order to improve the completeness of data with respect to all unit process considered. Also, other greenhouse gases associated can also be estimated and added to inventory.

4.5 LCI for OPC production

As defined in the methodology chapter a detailed and structured analysis is been carried out in order to find the inventory of OPC. The 3 sections and the key information from the same is provided as follows.

4.5.1 Goal and scope

The goal and scope are defined initially before the LCA. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is been reported here.

1) Goal

The goal and scope are same as that of clinker for LCI analysis (Section: 4.2.1) except few changes like the change of functional unit from clinker to OPC and change in processes considered. The details of subsection which differs from goal and scope defined for clinker is provided as follows.

a) Objective

To obtain the inventory data related to OPC production.

b) Application

A set of inventory data of Indian OPC can be reported in life cycle databases of building material.

2) **Scope**

The scope of OPC is also similar to that of the scope defined for clinker for LCI analysis (Section: 4.2.1), except for few details. The sub-elements which differ from the scope of clinker is provided as follows.

a) **Product/process system to be considered:** The processes involved in cement production after clinkerization in Indian cement plant.

b) **Functions of the product system/systems:** Production of cement.

c) **Functional unit:** 1 ton of cement is considered as the functional unit.

d) **System boundary**

   i) **Criteria:** Gate to gate.

   ii) **List of the unit process:**

      (1) **Grinding of cement:** The grinding of clinker, gypsum, filler limestone, and grinding aid into the cement of required fineness.

      (2) **Packing of cement:** The packing of cement into plastic/paper bags.

      (3) **Transportation:** The transportation of limestone.

      (4) **Others (services etc):** All miscellaneous processes excluded in the previous processes or happening simultaneously in a non-continuous way.

e) **Data required:**

   i) **Grinding of cement:** Clinker, filler limestone, gypsum, grinding aid, electricity, oil, water, steel balls, ball mill, cement, dust, and radiation and convection losses.

   ii) **Packing of cement:** Cement, electricity, packing bags, oil, ink, equipment, infrastructure and packed cement bags.

   iii) **Transportation:** The transportation of filler limestone.

   iv) **Others (services etc):** Electricity consumed for other processes like lighting plant area, office and colony, water for colony area, other equipment, and fuels for the canteen.

f) **Allocation:** Since two products are produced, an allocation criterion is required for the allocation of data towards each product. If the break-up of an input consumed or output released, in relation to the production of OPC and PPC is known, the same breakup values are followed for calculation. If a data contribution towards each product is unknown the mass allocation is followed. By mass allocation, it is meant that the data will be proportioned towards each product based on the mass proportion of each product produced with a total mass of products.

g) Interpretation methodology:

i) Identification of significant issues.

(1) Structured result.

(2) Analysis: Contribution and anomaly.

ii) Evaluation: Completeness and consistency.

iii) Conclusion, limitation and recommendation.

h) Limitation:

i) The plant is not an exclusive grinding unit but an integrated cement plant unit, of which process after clinkerization is been studied to simulate cement production unit.

i) Assumption

i) The electricity is assumed to be produced completely in the plant.

ii) In the case of data redundancy, the priority order is given to the reliability of LCI data. Reliability is determined based on the data source and the time duration of data breakup. For source priority followed is: Internal monitoring documents> Values reported to Govt> Third party survey sheets (For the public database, E.g. "CSI protocol"). If within the internal monitoring documents if there are discrepancies, the value from the file exclusively discussing the required data type will be used, E.g. "EN -14-15". If within the source there is a redundancy based on the time period the priority followed is: Sum of Monthly break up > Yearly break up.

iii) The filler limestone is obtained from the quarry of the cement plant limestone mines.

iv) The recycled water is assumed to be released back to the water source

v) The clinker breakup towards OPC and PPC is not provided. Total clinker is divided towards OPC and PPC based on the ratio of estimated clinker for OPC and PPC. The clinker is estimated using clinker to cement ratio of OPC and OPC produced, clinker to cement ratio of PPC and PPC produced.

4.5.2 Life Cycle Inventory

As per methodology, the 6 methods are conducted to find the LCI analysis.

1) **Preparation of data collection:** Same as that for clinker analysis as data collection is done at same site visits (Section: 4.2.2).

2) **Data collection, formatting and compiling:** Same as that for clinker analysis as data collection is done at same site visits (Section: 4.2.2).
3) **Data validation:** It is conducted as per defined methodology (Table A. 14).
4) **LCI analysis:** It is conducted as per the methodology defined. The LCI analysis is conducted with absolute data (Table A. 15) and reference flow data (Table A. 16). The results are compiled and provided in Table 4.19.
5) **LCI data aggregation:** LCI result aggregated is also calculated (Table A. 17).
6) **Refining the system boundary:** No change in system boundary.

Table 4.19: CS 1: LCI for production of OPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.906	ton/ton of OPC
Limestone (as performance improver)	0.051	ton/ton of OPC
Gypsum	0.042	ton/ton of Cement
Electricity		
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Electricity consumed for services	3.15	kWh/ton of cement
Ancillary inputs		
Water - Cement plant (including mines)	0.060	m^3/ton of cement
Water – Colony	0.021	m^3/ ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Others		
Grinding media	1.30E-05	ton/ton of Cement
Output	**Value**	**Unit**
Product		
OPC	1.00	ton/ton of OPC
Waste - Release to air		
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
R-134A	4.86E-07	ton/ton of Cement
Waste - Release to water		
Recycled water	4.57E-02	m^3/ton of Cement
Waste - Release to soil		
Solid waste	1.04	ton/ton of Cement

Table 4.20: CS 1: LCI for production of OPC (process–wise)

Process	Value	Unit
Grinding of cement		
Inputs		
Clinker	0.906	ton/ton of OPC
Limestone (as performance improver)	0.051	ton/ton of OPC
Gypsum	0.042	ton/ton of Cement
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Grinding media	1.30E-05	ton/ton of Cement
Output		
OPC	1	ton/ton of OPC
Packing of cement		
Inputs		
OPC	1	ton/ton of OPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Output		
OPC	1	ton/ton of OPC
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
Others		
Inputs		
Electricity consumed for services	3.15	kWh/ton of cement
Water - Cement plant (including mines)	0.060	m^3/ton of cement
Water – Colony	0.021	m^3/ ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Output		
R-134A	4.86E-07	ton/ton of Cement
Recycled water	0.046	m^3/ton of Cement
Solid waste	1.037	ton/ton of Cement

4.5.3 Interpretation

1) Identification of significant issues

a) Structured results

The LCI results structured data type and process wise is presented in Table 4.21.

Table 4.21: CS 1: LCI for production of OPC (structured)

Unit processes / Data category	Grinding of cement	Packing of cement	Others	Total
Raw material - Clinker (kg /ton of OPC)	906.10			906.10
Raw material - Limestone (kg/ton of OPC)	50.62			50.62
Raw material - gypsum (kg/ton of cement)	41.57			41.57
Energy - Electricity (kWh/ton of OPC)	26.00	0.65	3.15	29.80
Ancillary input - Bags - Plastic (Polypropylene) (kg/ton of cement)		1.047		1.047

Data category / Unit processes	Grinding of cement	Packing of cement	Others	Total
Ancillary input - Bags - paper (kg/ton of cement)		0.801		0.801
Ancillary input - Water (litre/ton of cement)			81.34	81.341
Ancillary input - Oil (gm/ton of cement)			130.32	130.32
Ancillary input - Grease (gm/ton of cement)			6.92	6.92
Other - Grinding media (gm/ton of cement)	12.95			12.95
Waste - Release to air - SPM (gm/ton of cement)	3.21			3.21
Waste - Release to air - R-134A (gm/ton of cement)			0.49	0.49
Waste - Release to water - Recycled water (litre/ton of cement)			45.73	45.73
Waste - Release to soil - Solid waste			1.037	1.04

b) Analysis

i) Contribution analysis:

Except for electricity, all data corresponds to a single process. And thus 100% contribution will be in that process. For electricity, the 87% of the electricity is consumed in grinding. Followed by other processes with 11% and 2% for packing.

ii) Anomaly analysis:

The clinker (906 kg) and gypsum (42 kg) content are in line with values reported by Josa et al. (2004) and Li et al. (2014). The limestone content is within expected range as per IS 12269 (2013). The grinding energy of OPC is reported as 23 kWh/ton of OPC by Li et al. (2014) and 29.25 kWh/ton of generic cement (a mixture of OPC, PPC , PSC and other cements) by Virendra et al. (2015) Comparing with those the value (26 kWh) obtained in the study is within the expected range. Virendra et al. (2015) have reported 1.65 kWh/ton of cement for cement grinding, with respect to the same the value (0.65 kWh) in the study seems to be low. Virendra et al. (2015) have reported 0.25 kWh/ton of cement for plant stoppage units and 4.06 kWh/ton of cement for miscellaneous electricity consumption, with respect to the same the value obtained in the study (3.15 kWh) seems to be low. Marceau et al. (2006) have reported cement bag consumption of 0.68 kg/metric ton of Portland cement, compared to this the cement bag consumed (1.8 kg) seems to be high. Marceau et al. (2006) have reported water consumption of 537 kg/metric ton of Portland cement and Li et al. (2014) has reported water consumption of 1.605 m^3/ton of P.O.cement. Compared to those the value (81 litres) seems to be very low. Marceau et al. (2006) have reported oil and grease consumption as 0.13 kg/ton of cement, the value obtained in the study (0.137 kg) is similar to this value. Marceau et al. (2006) have also reported consumption of grinding media as 0.14 kg/ton of cement compared to which the value obtained in the study (0.013 kg) seems to be very low. The PM emission is reported as 25 gm by Marceau et al. (2006), 20 gm by Li et al. (2014), and 0.012 lbs or 5.4 gm by Huntzinger and Eatmon (2009) compared to these values the value (3.21 gm) obtained in the study seems to be very low. The refrigerant data seems to be new data. The wastewater released data is available in literature were the water recycled is not commonly seen in literature. Marceau et al. (2006) have cited and reported a generic CKD production value of 38.6 kg/metric ton of Portland cement which is a solid release to land. But the solid waste found in the study includes a lot of solid waste release to land like Metal Scrap, Burst Bags, Refractory, Rubber/cables/wires Scrap, fly ash + Bed Ash, Rejected Screening Material from mines, which seems to be a new data.

2) Evaluation

a) Completeness check: The data from the unit processes are complete.

b) Consistency check: The data, methods, and assumptions considered in the study are consistent.

3) Conclusions, limitations and recommendations

a) Conclusions

i) The LCI result of the OPC is calculated and reported. Apart from conventional inventory data like clinker (906 kg), filler limestone (50 kg), gypsum (41 kg) and electricity (30 kWh), LCI result shows a set of ancillary inputs, other inputs and waste releases. The materials like grinding media, oil, grease, bags (plastic and paper), SPM, ozone-depleting agent (R-134A), recycled water, and solid waste is being identified and reported. All these inputs or outputs are having very less contribution with respect to mass, except Solid waste which is having a contribution of around 1 ton per ton of cement. Here solid waste includes, rejected screening material from mines, fly ash + bed Ash, metal scrap, burst bags, refractory, rubber/cableswires, and scrap. The water consumption is reported to be 81 litre/ton of cement, this includes the water consumed in mines, cement plant and workers colony. The source of the water is groundwater. It is also reported that 45 litre water is recycled from the total water consumed (including for TPP).

ii) Except for electricity, all data corresponds to a single process. And thus 100% contribution will be in that process. For electricity, the 87% of the electricity is consumed in grinding. Followed by other processes with 11% and 2% for packing.

iii) According to anomaly analysis the data like clinker, limestone, gypsum, electricity (for grinding), and oil and grease seems to be in line with the literature. Whereas the data like electricity for packing and other processes, cement bags, water, grinding media, PM are having a value which is not in line with respect to the literature. Cement bags was consumed in high amount whereas other data is having low value with respect to the literature. The data like R-134A, recycled water and solid waste seems to be new or unexpected data.

b) Limitations

No consistency or completeness issues, other significant limitations encountered during the analysis.

c) Recommendation

The data can be used as an inventory data corresponding to Ordinary Portland cement in India. The inventory data on the equipment (e.g. ball mill and cyclone separator) and infrastructure (e.g. buildings for equipment, office buildings, and colony) was not obtained. Thus further data collections can improve the completeness of inventory. More analysis can be conducted on the current LCI results.

4.6 Energy use for OPC production

As defined in the methodology chapter a detailed and structured analysis is been carried out. The 4 sections and the key information from the same is provided as follows.

4.6.1 Goal and scope

The goal and scope are defined initially before the analysis. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is been reported here.

1) Goal

The goal and scope are the same as that of LCI analysis of OPC, except few sub-elements like objective, and application, which is provided below.

a) Objective

To quantify the energy related to the production of OPC (Ordinary Portland cement) in a typically integrated cement factory in India.

b) Application

The value can be reported in the energy database of building materials in India. It has an application like estimation of the energy of cement-based products like cement concrete.

2) Scope

a) Energy calculation methodology

The energy is calculated by considering the indirect energy and direct energy of all the data within the system boundary. Energy is calculated in MJ/ton of clinker. The energy associated with clinker and electricity is already calculated such values are used in the calculation. The suitable energy factor (which reflects the direct energy or embodied energy) of the data is used for calculation.

4.6.2 Life Cycle Inventory

The life cycle inventory result provided in the OPC - LCA for inventory section is used here (Section: 4.5.2).

4.6.3 Energy calculation

1) **Energy calculation methodology:** The input which contributes to the energy of the OPC is selected from LCI results and multiplied with suitable energy factor. The energy is calculated in unit MJ. The suitable energy factors are calculated from cement plant data.

2) **Classification**

The inventory results obtained is classified into selected and rejected data for energy calculation. The selected data is those which contribute towards the energy use of OPC within gate to gate analysis, and the remaining data are rejected. The result tables are provided in Table 4.22.

Table 4.22: CS 1: LCI selected for calculating energy use for production of OPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.91	ton/ton of OPC
Energy – Electricity		
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Electricity consumed for services	3.15	kWh/ton of cement

As explained before few LCI results are rejected as it is not contributing to energy consumed within gate to gate system boundary. Such data are provided below.

- **Input**:
    a) **Raw material**: Limestone and gypsum.
    b) **Ancillary inputs**: Water, Oil (Lubricant), Grease, Bags PP, Bags (Paper).
    c) **Others**: Grinding media.
- **Output**
    a) **Emission to air:** SPM - Cement Mill Stacks, R-134A.
    b) **Emission to water**: Recycled water.
    c) **Emission to soil**: Solid waste.

3) Energy calculation

The energy is calculated using the suitable energy factors.

a) Energy factors

The energy factor of selected inventory data are provided in Table 4.23.

Table 4.23: CS 1: Energy factors for calculation (OPC)

Input	Value	Unit
Raw material		
Clinker	3.99	MJ/kg
Energy - Electricity		
Electricity	13.40	MJ/kWh

The value of clinker is from section Table 4.6 and electricity is from Table B. 2.

b) Energy calculation

The selected inventory result is multiplied with energy factor to get the total energy for the OPC. The results are provided input-output category-wise and process-wise in Table 4.24 and Table 4.25 respectively.

Table 4.24: CS 1: Energy use for production of OPC (input-output category–wise)

Inventory	Energy	Unit
Raw material		
Clinker	3614.73	MJ/ton
Electricity		
Electricity consumed by cement mill section	348.33	MJ/ton
Electricity consumed by packing plant section	8.73	MJ/ton
Electricity consumed for services	42.24	MJ/ton
Total	**4014.03**	**MJ/ton**

Table 4.25: CS 1: Energy use for the production of OPC (process–wise)

Unit process	Energy	Unit
Grinding of cement		
Input		
Electricity consumed by cement mill section	348.33	MJ/ton
Clinker	3614.73	MJ/ton
	3963.06	**MJ/ton**
Packing of cement		
Input		
Electricity consumed by packing plant section	8.73	MJ/ton
	8.73	**MJ/ton**
Others		
Input		
Electricity consumed for services	42.24	MJ/ton
	42.24	**MJ/ton**
Total	**4014.03**	**MJ/ton**

4.6.4 Interpretation

The results obtained in the energy calculation is been interpreted here with respect to the goal and scope.

1) Identification of the significant issues

The energy consumed is analysed to identify the significant issues. The structured table are provided in Table 4.26.

a) Structured result

Table 4.26: CS 1: Energy use for production of OPC (structured)

Unit process / Data type	Grinding of cement	Packing of cement	Others	Total
Clinker	3614.73	-	-	3614.73
Electricity	348.33	8.73	42.24	399.30
Total	3963.06	8.73	42.24	4014.03

Note: All values are in MJ/ton of cement

b) Analysis

i) Contribution analysis: The major contribution is from clinker with 90.05% contribution and electricity contributes 9.95%. Among processes, the grinding of cement contains 98.73% of the total energy use.

ii) Anomaly analysis: The embodied energy of Portland cement corresponding to five different geographical regions is calculated using LCI from Ecoinvent V3 database and impact assessment method "Cumulative Energy Demand". The embodied energy of clinker varies from 2700-3460 MJ, where four of them are above 3350 MJ. The corresponding value obtained in the study (3615 MJ) seems to be higher. The embodied energy of electricity is in range of 228-627 MJ where three of them are in the range of 430 ± 14 MJ. Compared to this the corresponding value obtained in the study (399 MJ) seems to be lower. The total embodied energy of electricity and clinker is in range of 3144-4047 MJ, where three of them are in the range of 3780 ± 100 MJ. The corresponding value of the study is (4014 MJ) which seems to be at the high within the expected range.

2) **Evaluation**

   a) **Completeness check:** The data corresponding to the unit process is meeting the requirement of goal and scope.

   b) **Consistency check:** The energy calculation seems to be calculated as methodology defined in the goal and scope.

3) **Conclusions, limitations and recommendation**

   a) **Conclusions:**

      i) The energy use of the OPC is been calculated as 4014 MJ/ton of OPC.

      ii) The major contribution is from clinker with 90.05% contribution and electricity contributes 9.95%. Among processes, the grinding of cement contains 98.73% of the total energy use.

      iii) The energy associated with clinker seems to be higher than the expected range. The electricity seems to be at the lower end of the expected range. The total energy from clinker and electricity seems to be having value at the higher end of the expected range.

   b) **Limitations:** The completeness and consistency check is satisfactory and no limitation is encountered during energy calculation.

   c) **Recommendation:** The value can be reported in Life cycle energy database, corresponding to the energy of Indian OPC within gate to gate system boundary. More analysis can be conducted to draw observations from the results.

4.7 CO_2 emissions for OPC production

4.7.1 Goal and Scope

The goal and scope are same as defined in the LCI analysis of the OPC (section: 4.5.1), few subsections which are different is provided as follows.

1) Goal

- **a) Objective**: To compute the CO_2 emission related to the OPC production within gate to gate system boundary
- **b) Application**: The CO_2 emission of the Indian OPC can be reported in the LCA databases. This can also be used to calculate the CO_2 contributed from cement towards products like concrete.

2) Scope

- **a) CO_2 emission calculation methodology**

  The direct and indirect CO_2 emitted associated with the production of OPC within the gate to gate analysis is been quantified here. The CO_2 is estimated in kilogram as a unit. The suitable CO_2 factors corresponding to the inventory results are used for the calculation

4.7.2 Life Cycle Inventory

The life cycle inventory result provided in the OPC - LCA for inventory section is used here (Section: 4.5.2)

4.7.3 CO_2 emission calculation

The inventory results are classified and the selected inventory result which contains direct and indirect CO_2 is used for calculation. The selected inventory and suitable CO_2 factors are used for calculation,

1) **CO_2 calculation methodology**: The inventory which is associated with CO_2 emission is selected from the LCI results and multiplied with the suitable CO_2 factor. The CO_2 is calculated in unit kg CO_2. The factors are calculated based on cement plant data.

2) **Classification**

   The classified inventory results and discussion are same as provided in the classification of inventory for energy calculation (Table 4.22)

3) **CO_2 emission calculation**

   The CO_2 is calculated using the suitable CO_2 factors

a) CO_2 factors

The CO_2 factor of selected inventory data is provided below

Table 4.27: CS 1: CO_2 factors for calculation (OPC)

Input	Value	Unit
Raw material		
Clinker	0.85	kg CO_2 / kg
Electricity		
Electricity	1.09	kg CO_2/kWh

b) CO_2 emission calculation

The selected inventory result is multiplied with CO_2 factors to get the total CO_2 associated with OPC. The results are provided as input-output category-wise and process-wise in Table 4.28 and Table 4.29 respectively.

Table 4.28: CS 1: CO_2 emissions for production of OPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	768.66	kg CO_2/ton of OPC
Electricity		
Electricity consumed by cement mill section	28.26	kg CO_2/ton of OPC
Electricity consumed by packing plant section	0.71	kg CO_2/ton of OPC
Electricity consumed for services	3.43	kg CO_2/ton of cement
Total	**801.06**	**kg CO_2/ton of OPC**

Table 4.29: CS 1: CO2 emissions for production of OPC (process-wise)

Process and inputs	Value	Unit
Grinding of cement		
Input		
Clinker	768.66	kg CO_2/ton of OPC
Electricity consumed by cement mill section	28.26	kg CO_2/ton of OPC
	796.92	**kg CO_2/ton of OPC**
Packing of cement		
Input		
Electricity consumed by packing plant section	0.71	kg CO_2/ton of OPC
	0.71	**kg CO_2/ton of OPC**
Others		
Input		
Electricity consumed for services	3.43	kg CO_2/ton of Cement
	3.43	**kg CO_2/ton of Cement**

Process and inputs	Value	Unit
Total	**801.06**	**kg CO_2/ton of OPC**

4.7.4 Interpretation

The results obtained in the CO_2 emission calculation is been interpreted here with respect to the goal and scope

1) Identification of the significant issues

The CO_2 emissions are analysed to identify the significant issues. The structured results are provided in Table 4.30.

a) Structured result

Table 4.30: CS 1: CO_2 emissions for production of OPC (structured)

Unit process / Data type	Grinding of cement	Packing of cement	Others	Total
Clinker	768.66			768.66
Electricity	28.26	0.71	3.43	32.40
Total	796.92	0.71	3.43	801.06

Note: All values are in kg CO_2/ton of OPC

b) Analysis

i) **Contribution analysis:** The clinker consumed around 96% and electricity consumed the remaining 4% of embodied CO_2. Comparing process wise the grinding process contains 99.5% of the total embodied CO_2.

ii) **Anomaly analysis:** The embodied CO_2 of Portland cement is calculated using the LCI from Ecoinvent V3 database and a modified version of Impact assessment method IPCC 2013 GWP 100a. The embodied CO_2 of clinker varies from 721-853 kg, where three of them are above 840 kg. The corresponding value obtained in the study (769 kg) seems to be low. The embodied CO_2 of electricity is in range of 0.55-34.5 kg where the values are dispersed across the range. Compared to this the corresponding value obtained in the study is 32.40 kg, which seems to be at the higher end of the expected range. The total embodied CO_2 of electricity and clinker is in range of 725-877 kg, three of them are above 850 kg. The corresponding value in the study (801 kg) seems to be at the lower end compared to other values.

2) **Evaluation**

   a) **Completeness check:** The data corresponding to the unit process is meeting the requirement of goal and scope.

   b) **Consistency check:** The CO_2 calculation seems to be calculated as methodology defined in the goal and scope.

3) **Conclusions, limitations and recommendation**

   a) **Conclusions:**

      i) The embodied CO_2 of the OPC is been calculated as 801.06 kg CO_2/ton of OPC.

      ii) The clinker consumed around 96% and electricity consumed the remaining 4% of embodied CO_2. Comparing process wise the grinding process contains 99.5% of the total embodied CO_2.

      iii) The clinker value seems to be low and electricity seems to be high with literature, however, both lies in the expected range. The total value also seems to be less but within the expected range.

   b) **Limitations:** The completeness and consistency check is satisfactory and no limitation is encountered during energy calculation.

   c) **Recommendation:** The value can be used to report as embodied CO_2 of Indian OPC. More analysis can be conducted to draw observations from the results.

4.8 LCI for PPC production

As defined in the methodology chapter a detailed and structured analysis is been carried out. The 3 sections and the key information from the same is provided as follows.

4.8.1 Goal and scope

The goal and scope are defined initially before the LCA. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is been reported here.

1) **Goal**

   The goal and scope are same as that of OPC for LCI analysis (Section 4.5.1) except few changes like the change of functional unit from OPC to PPC, and change in data requirement.

   a) **Objective**

      To get inventory data for PPC production.

b) **Application**

A set of inventory data of Indian PPC can be reported in life cycle databases of building material.

2) **Scope**

The scope of PPC is also similar to that of the scope defined for clinker for LCI analysis (Section: 4.5.1), except for few details. The sub-elements which differs from the scope of clinker is provided as follows.

a) **System boundary**

i) **List of the unit process:**

(1) **Grinding of cement:** The grinding of clinker, gypsum, supplementary cementitious material, and grinding aid into the cement of required fineness.

(2) **Packing of cement:** The packing of cement into plastic/paper bags.

(3) **Others (services etc):** All miscellaneous processes excluded in the previous processes or happening simultaneously in a non-continuous way.

b) **Data required:**

i) **Grinding of cement:** Clinker, SCM, Gypsum, Grinding aid, electricity, Oil, Water, steel balls, ball mill, cement, dust, and radiation and convection losses.

ii) **Packing of cement:** Cement, electricity, packing bags, oil, ink, equipment, and packed cement bags.

iii) **Others (services etc):** Electricity consumed for other processes like lighting plant area, office and colony, water for colony area, other equipment, and fuels for the canteen.

c) **Allocation:** Since two products (OPC and PPC) are produced the inventory is divided based on the mass of each cement produced. Thus, the mass allocation is followed in the study.

4.8.2 Life Cycle Inventory

As per methodology, the six steps are conducted to find the LCI analysis. The step like

1) **Preparation of data collection:** Same as that for clinker analysis as data collection is done at same site visits (Section: 4.2.2)

2) **Data collection, formatting and compiling:** Same as that for clinker analysis as data collection is done at same site visits (Section: 4.2.2)

3) **Data validation:** Is conducted as per defined methodology and results are obtained (Table A. 14).

4) **LCI analysis:** The LCI is analysed and results were obtained. In the first step, the analysis is conducted for absolute data. The results obtained is same as that of OPC (Table A. 15) except for the replacement of limestone data with fly ash data (0.278ton/ton of PPC). In the second step LCI analysis of reference, flow data is conducted. The results were same as OPC (Table A. 16) results except for clinker (0.679 ton/ton of PPC) and electricity for grinding (23.74 kWh/ton of PPC). Thus, except the amount of clinker, fly ash, and electricity for grinding other values are same as LCI results for OPC. The LCI result of PPC is provided as input-output category-wise and process-wise in Table 4.31 and Table 4.32 respectively.
5) **LCI data aggregation:** LCI result aggregated is also calculated
6) **Refining the system boundary:** No change in system boundary

Table 4.31: CS 1: LCI for production of PPC (input-output category–wise)

Input	Value	Unit
Electricity		
Electricity consumed by cement mill section	23.74	kWh/ ton of PPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Electricity consumed for services	3.15	kWh/ton of cement
Raw material		
Clinker	0.679	ton/ton of PPC
Fly ash (in cement plant)	0.278	ton/ton of PPC
Gypsum	0.042	ton/ton of Cement
Ancillary inputs		
Water - Cement plant (including mines)	0.060	m^3/ton of cement
Water – Colony	0.021	m^3/ ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Others		
Grinding media	1.30E-05	ton/ton of Cement
Output	**Value**	**Unit**
Product		
PPC	1	ton/ton of PPC
Waste - Release to air		
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
R-134A	4.86E-07	ton/ton of Cement
Waste - Release to water		
Recycled water	0.046	m^3/ton of Cement
Waste - Release to soil		
Solid waste	1.037	ton/ton of Cement

Table 4.32: CS 1: LCI for production of PPC (process–wise)

Process	Value	Unit
Grinding of cement		
Inputs		
Clinker	0.68	ton/ton of PPC
Fly ash (in cement plant)	0.28	ton/ton of PPC
Gypsum	0.04	ton/ton of Cement
Electricity consumed by cement mill section	23.74	kWh/ ton of PPC
Grinding media	1.30E-05	ton/ton of Cement
Output		
PPC	1.00	ton/ton of PPC
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
Packing of cement		
Inputs		
PPC	1.00	ton/ton of PPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Output		
PPC	1.00	ton/ton of PPC
Others		
Inputs		
Electricity consumed for services	3.15	kWh/ton of cement
Water - Cement plant (including mines)	0.060	m^3/ton of cement
Water – Colony	0.021	m^3/ ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Output		
R-134A	4.86E-07	ton/ton of Cement
Recycled water	0.046	m^3/ton of Cement
Solid waste	1.037	ton/ton of Cement

4.8.3 Interpretation

1) Identification of significant issues

a) Structured results

The LCI results are structured here data type and process wise. The structured table is provided in Table 4.33.

Table 4.33: CS 1: LCI for production of PPC (structured)

Data category \ Unit processes	Grinding of cement	Packing of cement	Others	Total
Raw material - Clinker (kg /ton of OPC)	678.67			678.67
Raw material - Fly ash (kg/ton of OPC)	278.40			278.40
Raw material - Gypsum (kg/ton of cement)	41.57			41.57
Energy - Electricity (kWh/ton of OPC)	23.74	0.65	3.15	27.54
Ancillary input - Bags - Plastic		1.047		1.047

Data category \ Unit processes	Grinding of cement	Packing of cement	Others	Total
(Polypropylene) (kg/ton of cement)				
Ancillary input - Bags - paper (kg/ton of cement)		0.801		0.801
Ancillary input - Water (litre/ton of cement)			81.34	81.341
Ancillary input - Oil (gm/ton of cement)			130.32	130.32
Ancillary input - Grease (gm/ton of cement)			6.92	6.92
Other - Grinding media (gm/ton of cement)	12.95			12.95
Waste - Release to air - SPM (gm/ton of cement)	3.21			3.21
Waste - Release to air - R-134A (gm/ton of cement)			0.49	0.49
Waste - Release to water - Recycled water (litre/ton of cement)			45.73	45.73
Waste - Release to soil - Solid waste			1.037	1.04

b) Analysis

i) Contribution analysis

Except for electricity, all other materials are consumed by a particular unit process or in other words 100% contributions is towards a single unit process. The 86% of electricity consumed is in the grinding process, 11% for other processes and 2% for packing. The data like clinker, fly ash, gypsum, grinding media, PM emission are completely associated with the grinding process. Bags are associated with the packing process. The data like water, oil, grease, R-134A, recycled water and solid waste are associated with other processes.

ii) Anomaly analysis

The inventory of the Cement, pozzolana and fly ash is analysed from the Ecoinvent database for different geographical areas. The clinker content varies from 731.5 kg to 688.75 kg. Compared to this the clinker (679 kg) obtained in the study seems to be less. The gypsum content is varying from 38.5-36.25 kg. Compared to this the gypsum content in the study (42 kg) is high. The fly ash amount (278 kg) reported lies in the range (15-35 %) provided in IS 1489 Part 1 (1991). Virendra et al. (2015) have reported 29.25 kWh/ton of generic cement for cement grinding (OPC, PPC, PSC and other cement), in Ecoinvent database the electricity for the production of pozzolana and fly ash cement varies from 32.9 to 47.5 kWh. Compared to these literature values grinding value (23.74 kWh) and total electricity (27.54 kWh) obtained in the study is less. Compared to these literature values grinding value (23.74 kWh) and total electricity (27.54 kWh) obtained in the study is less. All other data obtained are same as for OPC and discussion is provided in the section 4.5.3.

2) Evaluation

a) Completeness check: The data from the unit processes are complete

b) Consistency check: The data, methods, and assumptions considered in the study are consistent.

3) Conclusions, limitations and recommendations

a) Conclusions

i) The LCI result of the PPC is calculated and reported. Apart from conventional inventory data like clinker (679 kg), fly ash (278 kg), gypsum (41 kg) and electricity (30 kWh), LCI result shows a set of ancillary inputs, other inputs and waste releases. Except for clinker, fly ash and electricity for grinding all the data are same as OPC and thus conclusions from OPC selection is also applicable here.

ii) Except for electricity, all other materials are consumed by a particular unit process or in other words 100% contributions is towards a single unit process. The 86% of electricity consumed is in the grinding process, 11% for other processes and 2% for packing. The data like clinker, fly ash, gypsum, grinding media, PM emission are completely associated with the grinding process. Bags are associated with the packing process. The data like water, oil, grease, R-134A, recycled water and solid waste are associated with other processes.

iii) Except for the clinker, fly ash, gypsum, and electricity for grinding, all other results are with respect to the generic cement (both OPC and PPC cement) and thus the anomaly result conclusions of OPC are applicable here also (Section: 4.5.3). The fly ash seems to be an expected range. The electricity for grinding and clinker seems to be low. Whereas the gypsum seems to be high.

b) Limitations

No consistency issues, completeness issues, or other significant limitations encountered during the analysis.

c) Recommendation

The data can be used as an inventory data corresponding to Portland Pozzolana Cement in India. The inventory data on the equipment (e.g. ball mill and cyclone separator) and infrastructure (e.g. buildings for equipment, office buildings and colony) was not obtained. Thus further data collections can improve the completeness of inventory. More analysis can be conducted on the current LCI results.

4.9 Energy use for PPC production

As defined in the methodology chapter a detailed and structured analysis is been carried out. The 4 sections and the key information from the same is provided as follows.

4.9.1 Goal and scope

The goal and scope are defined initially before the analysis. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is been reported here. Goal and scope defined

1) Goal

The goal and scope are same as that of energy consumption calculation of OPC, except few sub-elements like objective which is provided below

a) Objective

To quantify the embodied energy related to the production of PPC (Portland Pozzolana Cement) in a typically integrated cement factory in India

4.9.2 Life Cycle Inventory

The life cycle inventory result provided in the PPC - LCA for inventory section is used here (Section: 4.8.2)

4.9.3 Energy calculation

The embodied energy of PPC is calculated here,

1) **Embodied energy calculation methodology:** The step is same defined in OPC section for embodied energy calculation (Section: 4.6.3)

2) **Classification**

The inventory results obtained is classified into selected and rejected data for energy calculation. The selected data is those which contribute towards the embodied energy of PPC within gate to gate analysis, and the remaining data are rejected. The result tables are provided in Table 4.34.

Table 4.34: CS 1: LCI selected for calculating energy use for production of PPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.679	ton/ton of PPC
Energy – Electricity		
Electricity consumed by cement mill section	23.74	kWh/ ton of PPC
Electricity consumed by packing plant section	0.65	kWh/ ton of cement
Electricity consumed for services	3.15	kWh/ton of cement

As explained before from the LCI results few data are rejected as it is not contributing to the energy consumed within gate to gate system boundary. Such data are provided below.

1) **Input**:
   a) **Raw material**: Fly ash and gypsum.
   b) **Ancillary inputs**: Water, Oil (Lubricant), Grease, Bags PP, Bags (Paper).
   c) **Others**: Grinding media.
2) **Output**
   a) **Emission to air:** SPM - Cement Mill Stacks, R-134A.
   b) **Emission to water**: Recycled water.
   c) **Emission to soil**: Solid waste.

3) **Energy calculation**

The energy is calculated using the suitable embodied energy values.

a) **Embodied energy calculation methodology:** Same as for OPC provided in section 4.6.3.

b) **Embodied energy factors:** Same as given for OPC in Table 4.23.

c) **Energy calculation**

The selected inventory result is multiplied with energy factor to get the total embodied energy of the PPC. The results are provided as Input-output category-wise and process-wise in Table 4.35 and 4.36 respectively.

Table 4.35: CS 1: Energy use for production of PPC (input-output category–wise)

Inventory	Value	Unit
Raw material		
Clinker	2707.47	MJ/ton
	2707.47	**MJ/ton**
Electricity		
Electricity consumed by cement mill section	318.09	MJ/ton
Electricity consumed by packing plant section	8.73	MJ/ton
Electricity consumed for services	42.24	MJ/ton
	369.06	**MJ/ton**
Total	**3076.53**	**MJ/ton**

Table 4.36: Energy consumption results of PPC process–wise

Unit process	Value	Unit
Grinding of cement		
Input		
Clinker	2707.47	MJ/ton
Electricity consumed by cement mill section	318.09	MJ/ton
	3025.56	**MJ/ton**
Packing of cement		
Input		
Electricity consumed by packing plant section	8.73	MJ/ton
	8.73	**MJ/ton**
Others		
Input		
Electricity consumed for services	42.24	MJ/ton
	42.24	**MJ/ton**
Total	**3076.53**	**MJ/ton**

4.9.4 Interpretation

The results obtained in the energy calculation is been interpreted here with respect to the goal and scope

1) Identification of the significant issues

The energy consumed is analysed to identify the significant issues. The structured results is provided in Table 4.37.

a) **Structured result**

Table 4.37: CS 1: Energy use for production of PPC (structured)

Data type \ Unit process	Grinding of cement	Packing of cement	Others	Total
Clinker	2707.47			2707.47
Electricity	318.09	8.73	42.24	369.06
Total	3025.56	8.73	42.24	3076.53

Note: The values are provided in unit MJ/ton of PPC

b) **Analysis**

i) **Contribution**

The clinker has 88% and electricity has 12% contribution towards embodied energy. Considering process-wise grinding has 98.34% and remaining distributed across packing and other unit processes.

ii) **Anomaly**

The cement pozzolana and fly ash from the Ecoinvent database corresponding to the different geographical region is analysed with impact characterization method "Cumulative Energy Demand" to find the embodied energy. The embodied energy of clinker varies from 2180-2800 MJ, where three of them are above 2600 MJ. The value obtained in the study (2707 MJ) seems to be low. The embodied energy of electricity is in range of 334-534 MJ where three of them are below 370 MJ. Compared to this the corresponding value obtained in the study is 369 MJ, which seems to be low. The total embodied energy of electricity and clinker is in range of 2514-3165 MJ, where three of them are above 3100 MJ. The corresponding value in the study (3076 MJ) seems to be a higher limit of most of the expected values.

2) **Evaluation**

a) **Completeness check:** The data corresponding to the unit process is meeting the requirement of goal and scope.

b) **Consistency check:** The energy calculation seems to be calculated as methodology defined in the goal and scope.

3) **Conclusions, limitations and recommendation**

a) **Conclusions:**

i) The embodied energy of the PPC is been calculated as 3077 MJ/ton of PPC.

ii) The clinker has 88% and electricity has 12% contribution towards embodied energy. Considering process-wise grinding has 98.34% and remaining distributed across packing and other unit processes.
iii) The clinker value seems to be higher and electricity seems to be lower, but all lies within the expected range. The total value lies in the higher end of the expected range.

b) **Limitations:** The completeness and consistency check is satisfactory and no limitation is encountered during energy calculation.
c) **Recommendation:** The value can be used to report as the embodied energy of Indian OPC. More analysis can be conducted to draw observations from the results

4.10 CO_2 emissions for PPC production

4.10.1 Goal and Scope

The goal and scope are same as defined in the CO_2 emission calculation of the OPC (Section: 4.7.1), few sub-elements which are different is provided as follows.

1) **Goal**
   a) **Objective**: To compute the CO_2 emission related to the PPC production within the gate to gate system boundary.

4.10.2 Life Cycle Inventory

The life cycle inventory result provided in the PPC - LCA for inventory section is used here (Section: 4.8.2).

4.10.3 CO_2 emission calculation

The inventory results are classified and the selected inventory result which contains direct and indirect CO_2 is used for calculation. The selected inventory and suitable embodied CO_2 values are used for calculation,

1) **CO_2 emission calculation methodology**: Same as defined for OPC in section 4.7.3
2) **Classification**
   The classified inventory results and discussion are same as provided in the classification of inventory for energy calculation (Section: 4.9.3)
3) **CO_2 emission calculation**
   The CO_2 is calculated using the suitable embodied CO_2 values

a) CO_2 emission factors

The CO_2 emission factors values of selected inventory data are from Table 4.27

b) CO_2 emission calculation

The selected inventory result is multiplied with CO_2 emission factor to get the total CO_2 emissions related to production of PPC. The CO_2 emission results are provided input-output category-wise and process-wise in Table 4.38 and 4.39 respectively.

Table 4.38: CS 1: CO_2 emissions for production of PPC (input-output category-wise)

Input	Value	Unit
Raw material		
Clinker	575.73	kg CO_2/ton of PPC
	575.73	**kg CO_2/ton of PPC**
Energy - Electricity		
Electricity consumed by cement mill section	25.81	kg CO_2/ton of PPC
Electricity consumed by packing plant section	0.71	kg CO_2/ton of PPC
Electricity consumed for services	3.43	kg CO_2/ton of PPC
	29.94	**kg CO_2/ton of PPC**
Total	**605.68**	**kg CO_2/ton of PPC**

Table 4.39: CS 1: CO_2 emissions for production of PPC (process-wise)

Process and inputs	Value	Unit
Grinding of cement		
Input		
Clinker	575.73	kg CO_2/ton of PPC
Electricity consumed by cement mill section	25.81	kg CO_2/ton of PPC
	601.54	**kg CO_2/ton of PPC**
Packing of cement		
Input		
Electricity consumed by packing plant section	0.71	kg CO_2/ton of PPC
	0.71	**kg CO_2/ton of PPC**
Others		
Input		
Electricity consumed for services	3.43	kg CO_2/ton of PPC
	3.43	**kg CO_2/ton of PPC**
Total	**605.68**	**kg CO_2/ton of PPC**

4.10.4 Interpretation

The results obtained in the embodied CO_2 calculation is been interpreted here with respect to the goal and scope

1) **Identification of the significant issues**

The CO_2 emission consumed is analysed to identify the significant issues. The structured CO_2 emission results are provided in Table 4.40.

a) **Structured result**

Table 4.40: CS 1: CO_2 emissions for production of PPC (structured)

Unit process / Data type	Grinding of cement	Packing of cement	Others	Total
Clinker	575.73			575.73
Electricity	25.81	0.71	3.43	29.94
Total	601.54	0.71	3.43	605.68

Note: All values are in kg CO_2/ton of PPC

b) **Analysis**

i) **Contribution**

Clinker contributes to 95% and electricity contributes rest 5%. The grinding process contributes 99.3% and remaining is contributed by packing and other processes

ii) **Anomaly**

The cement pozzolana and fly ash belonging to the different geographical area is analysed using the Ecoinvent database and modified impact assessment method IPCC2013 GWP100a in order to understand the embodied CO_2. The embodied CO_2 of clinker varies from 584-690 kg, where three of them are above 640 kg. The value obtained in the study (576 kg) seems to be low. The embodied CO_2 of electricity is in range of 2.79-29.4 kg where three of the value is above 14 kg. The corresponding value obtained in the study (29.94 kg) seems to be higher than expected values. The total embodied CO_2 of electricity and clinker is in range of 587-712 kg, where three of them are above 670 kg. The corresponding value in the study (605.68 kg) seems to be at the lower end.

2) **Evaluation**

a) **Completeness check:** The data corresponding to the unit process is meeting the requirement of goal and scope

b) **Consistency check:** The CO_2 calculation seems to be calculated as methodology defined in the goal and scope

3) **Conclusions, limitations and recommendation**

a) **Conclusions:**

i) The embodied CO_2 of the PPC is been calculated as 605.68 kg CO_2/ton of PPC.

ii) Clinker contributes to 95% and electricity contributes rest 5%. The grinding process contributes 99.3% and remaining is contributed by packing and other processes

iii) The clinker value seems to be a lower expected range. The electricity seems to be higher beyond the expected range. The total value seems to be in a lower expected region.

b) **Limitations:** The completeness and consistency check is satisfactory and no limitation is encountered during energy calculation.

c) **Recommendation:** The value can be used to report as embodied CO_2 of Indian OPC. More analysis can be conducted to draw observations from the results

CHAPTER 5

CASE STUDY 2

5.1 Introduction

This chapter discusses the second case study conducted. The case study is conducted in an integrated cement plant of Dalmia Cements at Reddipalayam district, Tamil Nadu. A visit was conducted (during December 2015), and data requirement was shared. Some of the data were collected directly from the officials and remaining later via mail. Same as in the case study one the clinker, OPC, PPC are analysed for inventory, followed by embodied energy and embodied CO_2 are calculated based on the inventory. All the calculation were conducted based on the Gate to gate system boundary. The structure of this chapter and most of the descriptions are the same as that of Chapter 4: Case Study 1. The term 'case study 2' is abbreviated and used as CS 2.

5.2 LCI for clinker production

As defined in the methodology chapter, a detailed and structured analysis is carried out. The three sections and the key information from the same is provided as follows.

5.2.1 Goal and scope

The goal and scope are defined initially before the LCA. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is reported here.

1) **Goal :**
   a) **Objective** - To develop the life cycle inventory of Clinker.
   b) **Application** - Life cycle inventory for Indian clinker can be added to the life cycle database of building materials.
   c) **Intended audience** - Academicians and industrialists ;
   d) **Public disclosure** - Yes, the study is intended to disclose to the public.

2) **Scope**

a) **Process system** - The processes involved in clinker production in an integrated cement plant, using dry processing technology for clinkerization. The plant uses 6 stage preheater precalciner unit along with the rotary kiln;

b) **Function** - Production of clinker;

c) **Functional unit** - 1 ton of clinker is considered as the functional unit. Functional unit considered in most of the literature are in tons and the production of the clinker is measured in tons by cement plant (daily)

d) **System boundary**

i) **Criteria used:** "Gate to Gate" - All processes starting from the consumption of raw material through the entry gate, processing of the product, and exit of product through exit gate is considered in the analysis. Here exceptional processes like the extraction and transportation of limestone (raw material) are considered. Due to this addition of process, the processes under system boundary will look like the set of process under the complete managerial influence of the company. Or in other words, the limestone mine is considered to be within the boundary of the cement plant.

ii) **Processes considered:** Processes considered according to the gate to the gate system boundary are provided as follows.

(1) **Limestone extraction**: Extraction of limestone using extraction equipment or blasting of a limestone quarry. There will be loading equipment to load the limestone to trucks used for transportation.

(2) **Limestone crushing till clinkerization** - The crushing of limestone chunks to small size. Mixing of the raw meal ingredients (Say limestone, clay, hematite, bauxite etc.) in the required proportion. The raw meal is ground and blended uniformly. Preparation of fuel for kiln application. The process of thermal treatment of the raw meal to produce clinker.

(3) **Others (services etc.)** - All miscellaneous processes excluded in the previous processes or happening simultaneously in a non-continuous way e.g. onsite transportation, factory lighting, colony lighting, and transformer losses.

(4) **Transportation** - The transportation of limestone from the quarry.

iii) **Deleted processes:** There are also processes which satisfy the condition of system boundary but deleted due to some reason.

(1) **Electricity production -** In literature, the electricity production is not seen as a part of the cement production process system. So in order to make system boundary more compatible with literature, electricity production is not considered. The data collected during the case study is used to calculate the energy and CO_2 emission factor for the electricity separately.

iv) **Cut off criteria:** Mass limit - No limit; Energy limit - No limit; Environmental significance - No limit.

e) **Expected inventory:**

i) **Limestone extraction**: Explosives, fuel consumed for equipment, electricity consumed, lubricant consumed for equipment, water consumed, equipment, equipment consumables, the limestone extracted, and the emissions generated.

ii) **Limestone preparation till clinkerization**: Limestone preparation -Limestone chunks, electricity (related to each process), water(for cooler), lubricant for related equipment, crushing equipment, infrastructure, consumables for equipment, crushed limestone, noise, and emission; Raw meal preparation - Electricity for related equipment, limestone, clay (and other ingredients for raw meal), lubricants for equipment, infrastructure, raw mill, raw meal, PM, and noise; Clinkerization - Electricity, raw meal, lubricants for the equipment, water for cooling, equipment (preheater precalciner unit, kiln unit, transferring equipment), infrastructure, clinker, PM, CO_2, SO_2, NO_x, water vapour, radiation, and noise.

iii) **Transportation**: Diesel, the amount of material transported, and distance.

iv) **Others (services etc.):** Electricity (office), diesel (for small equipment), water (for an office building), oil (for equipment), equipment, infrastructure, PM (from small equipment), CO_2, and wastewater (from office, canteen etc.).

f) **Data quality:**

i) **Time period coverage:** Time period - 1 year; Age of data - Recent. A year is a cyclic period where all the activities take place in the cement plant. Say, the repairing of the equipment used to take place at the end of a year.

ii) **Geographical representation:** According to a report of PSCC (2011) most of the cement plant is situated in the raw material prone area. The major raw material for clinker and cement is limestone. Thus a cement plant which is situated next to limestone quarry will be representative. Thus a cement plant which is situated next to limestone mine needs to be studied.

iii) **Technological coverage:** Around 93% of the Indian cement are made based on the dry processing technology (Kumar 2015). And thus a cement plant with dry processing technology is studied.

iv) **Precision:** Raw material mass in kg, electricity in kWh, CO_2, NO_x in kg, SO_2, and dust in grams. Other data are required in a unit such that the numerical value is greater than the numerical value of the product in a functional unit. This is based on values reported in the literature.

v) **Completeness:** All the data described in the data requirement with respect to the processes should be met.

vi) **Consistency:** The data, methods (steps followed) and the assumptions used in the study should be consistent throughout the study.

vii) **Reproducibility:** The data should be extrapolated to region level data.

viii) **Sources of data:** Data monitored by the cement plant.

ix) **The uncertainty of the information:** The energy and CO_2 emission value should have no uncertainty.

g) Allocation procedure: Since the study is related to a single product all the data were allocated to the same product.

h) Interpretation to be used:

i) The analysis considered: Contribution analysis and anomaly analysis.

ii) The evaluation considered: Completeness and consistency.

iii) Conclusion, limitation, and recommendation.

i) Limitation

i) The plant considered is not a clinker production unit but an integrated cement plant unit, of which process till clinkerization is studied to simulate clinker production unit.

ii) The energy and CO_2 emission factor for the electricity is not calculated due to lack of data. The factor used in the calculation is taken from another source.

iii) The transportation of the feldspar is not considered due to lack of data.

j) Assumptions

i) The limestone is assumed from a quarry in the premises of cement factory. And thus, the extraction and transportation of limestone are included in the gate to gate system boundary. The limestone extraction and transportation are controlled by the cement plant officials and thus incorporation of these processes make the system boundary like a set of processes under control of cement plant officials.

ii) In the case of data redundancy (2 or more similar values), priority is given to the LCI data which has more detailed values (E.g. Monthly break up) and source. Based on the time coverage the priority followed is: Sum of Monthly break up > Yearly break up.

iii) The electricity production is assumed to be same as that of in 'Chapter 4: Case study 1'.

iv) It is assumed that the limestone produced is completely used as raw material for clinker and not as filler limestone. The reported diesel value for extraction and transportation of limestone is assigned to the limestone consumed for clinkerization.

k) **Type of reporting:** Reporting as a part of MS research work, with no comparative assertions.

l) **Critical review**: No critical review.

5.2.2 Life Cycle Inventory (LCI)

As explained in methodology a set of six steps are conducted to find LCI results.

1) Preparation of data collection

a) **Preparing rough process flow chart**: Process flow chart is not made.

b) **Fixing modes of data collection**: An integrated cement plant, named Dalmia cement, in Ariyalur of Reddipalayam district is located which satisfy the geographical and technological requirement. A site visit is planned and permission for the site visit is obtained. A list of materials and data to be collected and questions to be asked is prepared. The sampling kits are also taken in order to collect the raw material and fuel samples for later analysis.

2) Data Collection, Formatting and compilation

a) **Data collection:** During site visit, the different stages of processing of cement is well explained by the officials, especially Mr.Balakrishnan.P, General Manager, quality control. Different officials were interviewed. The data requirement and study importance were convinced during the interview. The documentation having similar data was shared by the officials through the mail. Samples of fuels and raw material were also provided.

b) **Data formatting and compilation:** The data from the different sources are listed as input and output category-wise. As mentioned in the methodology the data is formatted and compiled. All data are listed in a format with details like input/output name, the value of measurement, unit of measurement, and remarks. The input data is categorised as raw material, energy (fuels, electricity), ancillary materials, other physical inputs (transportation), and others. These categories like raw material, fuel, electricity, transportation and others are followed as the LCI results are found to be categorised as in the literature. The output data are categorised as products, co-products and emission to air, water and soil.

3) **Data validation**

a) **Data validation:** The validation is conducted preliminarily for the data redundancies. If the same input/output values are reported in different sources, the values which lie in the expected range (logically or from the literature) is selected. If all the value seems to be in the same range, based on the assumptions (provided in the assumption section goal and scope) regarding the reliability of the data, selection of input/output is made from most reliable source. Out of redundant data the elimination was also made as the data is incomplete (or reference flow is not provided).

b) **Data validated result:** The validated data results in the form of absolute data and reference flow are identified and reported in Annexure (Table C. 1). Since the data set is small all the results are reported in one table.

4) **LCI analysis:** The validated data is then used for analysis. As defined in methodology, initially LCI analysis of absolute data is conducted followed by LCI analysis of reference flow. The results are compiled and provided, in input-output category-wise and process-wise in Table 5.1 and Table 5.2 respectively.

5) **Data aggregation:** The aggregated LCI result are calculated and provided in the annexure (Table C. 4).

6) **Refining system boundary:** No change in system boundary.

Table 5.1: CS 2: LCI for production of clinker (input-output category–wise)

Input	Value	Unit
Raw material		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
Fuel		
Diesel (HSD)	0.202	kg/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternate fuel	0.010	Ton/ton of clinker
Electricity		
Electricity	0.089	kWh/ton of clinker
Electricity	49.8	kWh/ton of clinker
Transportation		
Diesel (for limestone)	0.712	kg/ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1.00	Ton/ton of clinker
Emission to air		
CO_2 (from raw material)	0.53	Ton/ton of clinker
Radiation loss	125.94	MJ/ton of clinker
Radiation loss	75.73	MJ/ton of clinker
Radiation loss	15.90	MJ/ton of clinker
Other		
Heat of PH Exit gases	531.37	MJ/Ton of clinker
Heat of PH Exit dust	32.64	MJ/Ton of clinker
Heat through Cooler Vent	414.22	MJ/Ton of clinker

Table 5.2: CS 2: LCI for production of clinker (process–wise)

Process	Value	Unit
Limestone extraction		
Input		
Limestone	1.383	Ton/ton of clinker
Diesel (HSD)	0.202	kg/ton of clinker
Electricity	0.089	kWh/ton of clinker
Output		
Limestone	1.383	Ton/ton of clinker
Limestone Crushing - clinkerization		
Input		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternate fuel	0.010	Ton/ton of clinker
Electricity	49.8	kWh/ton of clinker
Output		
Clinker	1.00	Ton/ton of clinker
CO_2 (from raw material)	0.53	Ton/ton of clinker
Radiation loss	125.9384	MJ/ton of clinker
Radiation loss	75.7304	MJ/ton of clinker
Radiation loss	15.8992	MJ/ton of clinker
Heat of PH Exit gases	531.37	MJ/ton of clinker
Heat of PH Exit dust	32.64	MJ/ton of clinker
Heat through Cooler Vent	414.22	MJ/ton of clinker
Transportation		
Inputs		
Diesel (HSD)	0.712	kg/ton of clinker

5.2.3 Interpretation

As explained in the methodology chapter. The significant issues are found here, followed by evaluation of results with goal and scope and arriving at conclusions and recommendations (within the limitations of the study).

1) Identification of significant issues

- **a) Structured information:** To get a holistic view the LCI results obtained in the study is structured process wise along column and data type wise along the row. The structured results are provided in Table 5.3.

Table 5.3: CS 2: LCI for production of clinker (structured)

Unit processes / data category-wise	limestone extraction	Limestone crushing - clinkerization	Transportation	Total
Raw material - limestone (kg/ton of clinker)	1383			1382.96
Raw material - fireclay (kg/ton of clinker)		21.24		21.24
Raw material - feldspar (kg/ton of clinker)		10.19		10.19
Energy - Fuel - Diesel (kg/ton of clinker)	0.20		0.712	0.91
Energy - Fuel - Coal (kg/ton of clinker)		1.70		1.70
Energy - Fuel - Pet coke (kg/ton of clinker)		56.06		56.06
Energy - Fuel - Lignite (kg/ton of clinker)		43.32		43.32
Energy - Fuel - Alternate fuel (kg/ton of clinker)		10.19		10.19
Energy - Electricity (kWh/ton of clinker)	0.089	49.8		49.89
Release to air - CO_2 (kg/ton of clinker)		529		813.11
Release to air - Radiation (MJ/ton of clinker)		218		217.57
Release to air - Heat (lost through gas and dust) (MJ/Ton of clinker)		978		978.22

b) **Analysis –** Different analyses are conducted as mentioned in the goal and scope.

i) **Contribution analysis**

All LCI data like fireclay, feldspar, coal, petcoke, lignite, alternate fuel, CO_2, radiation and convection, and heat loss are associated (100%) with a group of the unit process between limestone crushing and clinkerization. The limestone (100%) is initially produced in limestone extraction process and it is transferred till clinkerization. The electricity is consumed mostly between a group of processes from limestone crushing to clinkerization (99.82%) and remaining traces in limestone extraction (0.18%). Out of total diesel consumed the 78% is used for transportation of limestone and the remaining 22% is for limestone extraction.

ii) **Anomaly analysis**

The clinker inventory corresponding to five different geographical area is analysed from the Ecoinvent database. The electricity consumed for processes from raw meal preparation to clinkerization was reported as 59.31 kWh for Rest of the World, 58.00 kWh for Europe without Switzerland, 58.00 kWh for the US, 121 kWh for Switzerland and 107 kWh for Canada. The five values reported are ranging from 58-121, in which three of them are around lower limit and two around the higher limit. And the value reported in the study, 49.98 kWh/ton of clinker seems to be lower than expected range from the literature. It is to be understood that despite the additional process of limestone extraction and crushing, the value obtained in the study seems to be lower.

The clinker inventory corresponding to the different geographical area is analysed from the Ecoinvent database. The fuel consumed for processes for raw meal preparation to clinkerization was reported as 66 kg for RoW, 65 kg for Europe without Switzerland, 65 kg for the US, 47 kg for Switzerland and 136 kg for Canada. Five values are reported ranging from 47-136 kg, in which three of them are in the range of 65±1 kg. The amount of fuel consumption reported in the literature or estimated from literature varies from 106-131 kg (Li et al. 2014; Marceau et al. 2006; USGS 2014b). The value obtained in the study (111.28 kg) matches with the literature and lies in the higher range of literature value.

Limestone consumption reported and estimated from literature is varying from 1310-1530 kg/ton of clinker (ecoinvent 2018; Huntzinger and Eatmon 2009; Li et al. 2014; USGS 2014b). The value of limestone consumption, (1383 kg) is matching with the expected value from literature.

The value of other raw material consumed reported in the literature varies from 47.5-340 kg/ton of clinker (ecoinvent 2018; Huntzinger and Eatmon 2009; Li et al. 2014; Marceau et al. 2006; USGS 2014b). The value obtained in the study is (31.43 kg) lies lower than the range from the literature. During the interview with cement plant official, it was informed that mostly the additional raw materials are consumed less as the limestone consumed contain impurities which meet the mineral requirement other than CaO.

Li et al. (2014) have reported that average quarrying/mining represents 1% and Transportation/distribution represents 3% of total energy consumption (Cradle to gate). According to the quarrying process named "Limestone, unprocessed {RoW}- limestone quarry operation - Alloc Def, U" from ecoinvent (2018), 18MJ is consumed from diesel per ton of limestone extracted. 18 MJ can be around 0.42 litre of the diesel (considering the calorific value 43 MJ/kg, Source: 2006IPCC guidelines for national greenhouse gas inventories). The value obtained in the study is a sum of extraction and transportation. If the total diesel consumption is divided based on the percentage contribution mentioned in Li et al. (2014), the diesel will be 0.43 kg for extraction and 1.29 kg for transportation. According to this breakup value, the diesel obtained in the study for extraction (0.2 kg) and transportation (0.712 kg) seems to be very low.

CO_2 from raw material is reported by Marceau et al. (2006) in terms of cement which converted in terms of clinker is 581.49 kg/ton of clinker. CSI (2013) uses 525 kg CO_2/ton of clinker as emission from raw material decarbonisation. Compared to these values the value reported in the study (529 kg) seems to be the expected value.

Grover et al. (2015) have reported radiation and convection losses from three cement plants as 51.7 kcal/kg of clinker or 216.31 kJ/kg of clinker, 52.4 kcal/kg of clinker or 219.24 kJ/kg of clinker, and 53.8 kcal/kg of clinker or 225.10 kJ/kg of clinker. And Virendra et al. (2015) have reported radiation and convection heat loss as 27.41 and 16.64 kcal/kg clinker respectively (or 114.68 and 69.62 kJ/kg clinker respectively). Compared to these values the radiation and convection losses in the study (218 MJ) are in the higher range of expected values.

2) **Evaluation**

a) **Completeness check:** The data collected is not complete as per the data requirement provided in the goal and scope. The data like electricity is not provided in the separate unit processes, which eventually resulted in the clubbing of 4 unit process to a group of unit processes.

b) **Consistency check:** The system boundary is not consistent as the unit process of electricity production is not considered in the study, and the extraction and transportation of limestone are included.

3) **Conclusion, limitation and recommendation**

a) **Conclusion:**

i) The life cycle inventory of the clinker production is identified and quantified. The inventory data like electricity, fuel, raw material, other ancillary inputs, CO_2, radiation and convection losses, and heat are calculated with respect to their corresponding unit process/es.

ii) Except for limestone, diesel and electricity, all the other processes are completely associated with a group of processes from limestone crushing and clinkerization. Limestone is consumed (100%) at limestone extraction process. Electricity is distributed mainly to limestone crushing till clinkerization (99.82%) and negligible amount to limestone extraction (0.18%). Diesel is distributed to transportation (78%) and extraction (22%) of limestone.

iii) Compared to literature the limestone consumed, fuel consumed, CO_2 from raw material, radiation and convection loss values are as expected. The values of other raw materials like clay and feldspar, diesel for extraction and transportation of limestone, and electricity for processes from limestone extraction to clinkerization lies less than the expected value. The electricity for limestone extraction and heat loss seems to be unexpected or new data.

b) **Limitation:**

i) The data collected is not complete as per the data requirement provided in the goal and scope. The data like electricity is not provided in the separate unit processes, which eventually resulted in the clubbing of four unit process to a group of a unit processes.

- **ii)** The system boundary is not consistent as the unit process of electricity production is not considered in the study, and the extraction and transportation of limestone are included.

- **c) Recommendation**
  - **i)** The LCI result can be reported to LCI databases as LCI data for Indian clinker within gate to gate system boundary. This can serve as a base for calculating energy consumption or other environmental impact. The inventory data on the equipment (e.g. electrostatic precipitator and bag house filter) and infrastructure (e.g. buildings for equipment, office buildings and colony) was not obtained. Further data collections can be conducted to improve the completeness of inventory collected.

5.3 Energy use for clinker production

In this section, the extrapolation of the LCI analysis toward the energy is discussed.

5.3.1 Goal and scope.

All the details defined in the goal and scope of LCI analysis (4.2.1) is valid here except few updations or addition. The changed and added information are as follows.

1) **Goal:**
   - **a) Objective** - To quantify the energy consumption related to the production of clinker in a typically integrated cement factory in India;
   - **b) Application** - To understand the current value of energy consumption of Indian clinker. This can serve as a new data to life cycle database as embodied energy of Indian clinker. This can also be used in predicting energy related to normal and blended cement.
2) **Scope:**
   - **a) System boundary:** Gate to gate is system boundary criteria.
     - **i)** Even though the electricity production is not considered as one of the processes in the analysis, the energy consumed in electricity production is considered as embodied energy of electricity. And the embodied energy of electricity is accounted in the embodied energy calculation of clinker.
   - **b) Energy calculation methodology**: The energy consumed within the cement plant is planned to calculate. Direct energy consumption within the unit processes considered and embodied energy of all data within the system boundary are considered in the

calculation. The energy is calculated in MJ. The inputs from which energy is produced within unit processes is fuel. Calorific value is used to estimate the energy produced from the inventory result of fuel. The calorific value of the fuels is obtained from the following sources. The sources are provided in the order of their priority in representativeness with input.

(1) **The calorific value obtained from the cement plant,**

(2) **Bomb calorimetry results of sample collected,**

(3) **Emission factors for greenhouse gas inventories** - US EPA 2014 report (Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf),

(4) **2006IPCC Guidelines for national greenhouse gas inventories** (Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > Chapter 1 > Table 1.2, http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html)"

The embodied energy related to electricity within the considered system boundary was unable to calculate due to the lack of data from the thermal power plant. And thus the embodied energy of electricity is cited from Chapter 4: Case study 1.

5.3.2 Life Cycle Inventory (LCI)

The life cycle inventory analysis for this section is same as in section 4.2.2. Results table alone is provided as input-output wise in Table 4.1 and process wise in Table 4.2.

5.3.3 Energy calculation

Here the LCI result is converted into energy values, using suitable calorific or embodied energy values.

1) **Embodied energy calculation methodology:** As defined in goal and scope the energy consumed within the system boundary is calculated. The energy is calculated in MJ. The energy is calculated using suitable energy factor like calorific value for fuels and embodied energy factor for electricity. The calorific value of the fuels burned is obtained from the following sources. The sources are provided in the order of their priority in the representativeness of the input.

   i) **Energy factors obtained from the cement plant,**

   ii) **Bomb calorimetry results of sample collected,**

iii) **Emission factors for greenhouse gas inventories - US EPA 2014 report** (Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf),

iv) **2006IPCC Guidelines for national greenhouse gas inventories** (Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > Chapter 1 > Table 1.2, http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html)"

The embodied energy factor for electricity collected from the cement plant was not complete, thus the embodied energy factor from Chapter 4: Case study 1 is cited.

2) **Classification**: The LCI results are classified based on energy consumption. The data is selected if there is a contribution of energy from the input. The selected LCI data are provided in Table 5.4.

Table 5.4: CS 2: LCI selected data for calculating energy use for clinker production (input-output category–wise)

Input	Value	Unit
Fuel		
Diesel (HSD)	0.202	kg/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
AF	0.010	Ton/ton of clinker
Electricity		
Electricity	0.089	kWh/ton of clinker
Electricity	49.800	kWh/ton of clinker
Transportation		
Diesel (for limestone)	0.712	kg/ton of clinker

Certain inputs are not selected or considered as it neither contribute to the energy consumed for cement production, nor has embodied energy within gate to gate system boundary. The outputs are not considered as they are not contributing energy to the system and the excess energy taken by the outputs are assigned to the product itself. The data are as follows.

1) **Input**
   a) **Raw material:** Limestone and marl, white clay, ETP sludge, and fly ash
   b) **Other:** Refractory and castable
2) **Output**
   a) **Waste –** Release to air: SO_2, NO_x, radiation and convection.

3) **Energy Calculation**:

Here the LCI results are converted to direct energy or embodied energy using suitable embodied energy factor and calorific value,

a) Energy factor

The suitable factors selected are provided in table 5.5.

Table 5.5: CS 2: Energy factor for calculation (clinker)

Input	Value	Unit	Remark
Fuel			
Diesel (oil)	43.00	MJ/kg	Source: 2006IPCC guidelines for national greenhouse gas inventories.
Coal	22.61	MJ/kg	Average of 2 test values with standard deviation of 0.1 and COV 0.43%. The ash content and LOI average are 10.5 and 89.5 respectively. The results are obtained from bomb calorimetry test of sample collected from the cement plant
Petcoke	33.48	MJ/kg	Average of 2 test result values with standard deviation of 0.19 and COV 0.56%. The ash content and LOI average are 5 and 95 respectively. The results are obtained from bomb calorimetry test of sample collected from the cement plant
Lignite	20.79	MJ/kg	Average of 2 test result values with standard deviation of 0.05 and COV 0.24%. The ash content and LOI average are 4 and 96 respectively. The results are obtained from bomb calorimetry test of sample collected from the cement plant
Alternative Fuel	9.96	MJ/kg	It is reported that solid waste and spent wash is used as alternative fuels. Since the mass proportion is not provided with the average of the calorific value of both the fuel is used here.
Electricity			
Electricity	13.40	MJ/kWh	Sum of energy consumed from fuels in a thermal power plant. Source: Chapter 4: Case study 1
Transportation			
Diesel (oil)	43.00	MJ/kg	Source: 2006IPCC 2006 guidelines for national greenhouse gas inventories.

b) Calculation of energy consumption

The selected inventory (Table 5.4) is multiplied with suitable energy factor (Table 5.5) and the energy consumed is calculated. Results are provided as input-output category-wise and process-wise in Table 5.6 bad Table 5.7 respectively.

Table 5.6: CS 2: Energy use for production of clinker (input-output category–wise)

Inventory	Energy	Unit
Fuel		
Diesel (for limestone extraction)	8.69	MJ/ton of clinker
SA Coal	38.41	MJ/ton of clinker
Pet coke	1876.97	MJ/ton of clinker
Lignite	900.64	MJ/ton of clinker
AF	101.48	MJ/ton of clinker
	2926.19	**MJ/ton of clinker**
Electricity		
Electricity	1.20	MJ/ton of clinker
Electricity	667.27	MJ/ton of clinker
	668.46	**MJ/ton of clinker**
Transportation		
Diesel (HSD)	30.60	MJ/ton of clinker
	30.60	**MJ/ton of clinker**
Total	**3625.25**	**MJ/ton of clinker**

Table 5.7: CS 2: Energy use for production of clinker (process–wise)

Process	Energy	Unit
Raw material extraction		
Input		
Diesel (Limestone)	8.69	MJ/ton of clinker
Electricity	1.20	MJ/ton of clinker
	9.89	**MJ/ton of clinker**
Limestone Crushing - Clinkerization		
Input		
SA Coal	38.41	MJ/ton of clinker
Pet coke	1876.97	MJ/ton of clinker
Lignite	900.64	MJ/ton of clinker
AF	101.48	MJ/ton of clinker
Electricity	667.27	MJ/ton of clinker
	3584.76	**MJ/ton of clinker**
Transportation		
Inputs		
Diesel (for limestone)	30.60	MJ/ton of clinker
	30.60	**MJ/ton of clinker**
Total	**3625.25**	**MJ/ton of clinker**

5.3.4 Interpretation

1) **Identification of significant issues**: The energy consumed results are structured and analysed to identify significant issues

a) **Structured information**

The energy results are structured as unit process category-wise along the column and data category-wise along the row. . The structured form of results are provided in Table 5.8.

Table 5.8: CS 2: Energy use for production of clinker (structured)

Unit processes / Data category	Limestone extraction	Limestone Crushing - clinkerization	Transportation	Total
Electricity	1.20	667.27	-	668.46
Fuel	8.69	2917.50	-	2926.19
Other physical inputs - transportation	-	-	30.60	30.60
Total	9.89	3584.76	30.60	3625.25

Note: All the results are in MJ/ton of clinker

The energy calculation of the clinker production is conducted. The energy use from different inputs like electricity, fuel for thermal treatment and transportation is calculated. The energy use for production of clinker is found to be 3625.25 MJ/ton of clinker

b) **Analysis**

i) **Contribution analysis**

The highest contributing input towards embodied energy is fuel for clinkerization which is found to be 80.48%, followed by electricity consumed for limestone crushing till clinkerization with 18.41%. The remaining inputs like limestone extraction and transportation are having the negligible contribution of 0.27% and 0.84% respectively. The main contributor data type-wise is fuel and process wise are the process from limestone crushing till clinkerization. The unit process-wise data was not able to obtain due to lack of data breakup.

ii) **Anomaly analysis**

The main contributors to energy are fuel for thermal treatment and electricity for different processes. The contribution of different data towards embodied energy of clinker is found using Ecoinvent V3 inventory database, and impact assessment method "Cumulative Energy Demand V1.09". Unless specially mentioned, the comparative statements made in this section are based on the value obtained from the above analysis. The embodied energy from fuel is 2404 MJ for RoW, 3106 MJ for Canada, 1540 MJ from Switzerland, 2496 MJ from Europe without

Switzerland and 2443 MJ from the US. MoP (2015) has reported thermal energy consumption of clinkerization ranging 658-1074 kcal/kg of clinker, which is around 2753-4494 MJ/ton of clinker. The corresponding thermal energy (2918 MJ) obtained in the study, is in the higher range with respect to other geographical areas across the globe, but lower range compared to the values reported in India. The embodied energy of electricity values varies from 450 - 1230 MJ/ton of clinker. Of which three of the values are around 653 ± 10 MJ. The corresponding electricity value obtained in the study (668 MJ) lies in the expected range. In total, the energy values from fuel for thermal treatment and electricity are in the range of 2770-3556 MJ of which three of them are in the range of 3100 ± 40 MJ. The corresponding value (3595 MJ) obtained in the study seems to be higher than the expected range.

According to the database of Ecoinvent V 3.2 (accessed using SimaPro 8.4.0.0), 18 MJ is consumed per ton of limestone extracted (Product: Limestone unprocessed {RoW} - limestone quarry operation - Alloc Def, U) is been consumed from diesel. The data corresponds to the geographical area of the rest of the world. Considering limestone content of 1.383 ton/ton of clinker the energy consumed is 25 MJ. Compared to this, the energy obtained in the study (8.69 MJ) is very small. The electricity is reported as 0.0273 kWh or 0.098 MJ per ton of limestone. Considering 1.383 ton of limestone per ton of clinker the electric energy consumption is 0.038 kWh or 0.136 MJ. Compared to the literature the value obtained in the study (1.2 MJ) is very high.

Marceau et al. (2006) have reported average onsite quarried material transportation energy in terms of cement which when converted in terms of clinker is 36.89 MJ/ton of clinker. Compared to this the value obtained in the study seems to be small,

2) Evaluation

a) Completeness check

The LCI results are not complete compared to the requirements in the goal and scope. The limitation of LCI is provided in LCI analysis. Beyond the LCI incompleteness, the embodied energy factor of electricity produced in the cement plant was not obtained and thus the value from a previous case study is used for calculation. The calorific value of the fuels is not obtained from the data collected. Thus they are calculated from bomb calorimetric test results of fuel samples collected and few from the database. Since the alternate fuel value break up was not provided in the LCI result, the average of calorific values for the fuels are used for analysis

b) Consistency check

Apart from the inconsistency of LCI analysis, the additional sub-section of energy calculation methodology is consistent with respect to the defined goal and scope.

3) Conclusion, limitation and recommendation

a) Conclusions

i) The embodied energy calculation of clinker production is conducted within gate to gate system boundary. The energy comes from inputs like electricity and fuel. The energy from fuel used for the clinkerization contributes the most with 2918MJ/ton of clinker and the least is contributed by electricity consumed in the mining section which is 1.2MJ. It is important to be noted that electricity values reported expressing the embodied energy for the production of electricity also.

ii) The highest contributing input towards embodied energy is fuel for clinkerization which is found to be 80.48%, followed by electricity consumed for processes from limestone crushing till clinkerization with 18.41%. These two lie in the same set of unit processes from limestone crushing to clinkerization. And they almost accommodate the energy from total fuel consumption and electricity consumption.

iii) The energy from fuel for clinkerization (2918 MJ) seems to be high with respect to other countries, however, it lies within the expected range. The energy from electricity seems to be an average expected value. The total energy from electricity and fuel corresponding to a group of process from limestone crushing to clinkerization seems to be higher than expected values. The energy consumed for limestone extraction from fuel seems to be low whereas from the electricity it is very high. The energy for limestone transportation is comparable.

b) Limitation

i) Apart from the limitation faced in LCI analysis, the suitable calorific value of fuel and embodied energy factor of electricity was not able to be obtained or derived from cement plant data.

ii) Apart from the consistency status of LCI analysis, the additional sub-section of energy calculation methodology is consistent with respect to the defined goal and scope.

c) **Recommendation**

i) The study can be reported to different databases as embodied energy of Indian clinker within gate to gate system boundary.

ii) From the study, it is recommended that during LCA of clinker production, an inventory collection of electricity and fuels alone can provide a coverage of 98% of total energy. Or if the data collection is processes wise, the processes from limestone crushing till clinkerization can provide a coverage of 98% of total energy. The remaining inputs like limestone extraction and transportation are having the negligible contribution of 0.27% and 0.84% respectively.

iii) The value can be used to estimate the embodied energy of normal and blended cement.

5.4 CO_2 emissions for clinker production

Five percentage of the global anthropogenic CO_2 emission is said to be produced from cement production. And since the climate change due to global warming is a concern across the world, the quantification of embodied CO_2 is important. In this section, the embodied CO_2 emission associated with clinker production within the gate to gate system boundary is calculated.

5.4.1 Goal and scope

All the details defined in the goal and scope of LCI analysis (section: 4.2.1) is valid here except few update or addition. The changed and added information are as follows.

1) **Goal:**

a) **Objective**: To quantify the CO_2 emission related to the production of clinker in a typically integrated cement factory in India.

b) **Application**: This can serve as a new data to life cycle database on embodied Carbon dioxide of building material. This can also be used in predicting CO_2 emission related to normal and blended cement.

2) **Scope:**

a) **System boundary:** Gate to gate is the considered criteria

i) Even though the electricity production is not considered as one of the processes in the analysis, the CO_2 emission from the captive power plant is considered as embodied carbon dioxide of electricity.

b) CO_2 emission calculation methodology: The CO_2 from the different inputs are reported in the literature. The CO_2 is primarily from decarbonisation of raw meal, and from the burning of fuel (for electricity production, heating in the kiln, for equipment used in extraction and transportation). In this study, the data related to the CO_2 from fuel was not obtained. CO_2 from fuel is estimated from fuel inventory results and suitable CO_2 emission factor. The suitable CO_2 emission factors are calculated or cited from different sources. The CO_2 emission factor of fuel is expected to obtain from cement plant data. If not available CO_2 emission factor is cited from other sources also depending upon the representativeness with the LCI data. A set of such sources are provided below in the order of priority.

i) **CO_2 emission factor from cement plant data**

ii) **CHNS (Carbon Hydrogen Nitrogen Sulphur) results of fuel samples from the cement plant**

iii) **Emission factors for greenhouse gas inventories – US EPA 2014** (Source: Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf)

iv) **CSI protocol 2013** (Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors")

v) **2006 IPCC Guidelines for national Greenhouse gas inventory** (Source: Table 1.4, website - http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html, Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > chapter 1 Introduction)

c) CO_2 calculation methodology: The CO_2 of the LCI data within gate to gate system boundary is calculated. The CO_2 is a sum of direct CO_2 and embodied CO_2 within gate to gate system boundary. The value is calculated in kg CO_2. The direct CO_2 emission is considered as such and thus factor can be considered as 1. The inputs like electricity the embodied energy factor is required. It was not able to calculate the embodied energy factor from the data collected from the plant, due to incompleteness. Thus embodied energy factor from case study 1 is used.

d) Limitation

i) For certain fuels suitable CO_2 emission factors were not found and thus emission factor of similar fuel is used for calculation.

5.4.2 Life Cycle Inventory (LCI)

The life cycle inventory results are provided in clinker LCI analysis (section 4.2.2). The LCI result reported in the LCI analysis does not contain the data related to CO_2 emission from fuels. CO_2 is an important inventory result related to clinker production and thus it is calculated and added to the existing LCI result. The calculation is carried over in the following steps. In the first step, the data in existing LCI results which can produce CO_2 is selected. In the second step, the suitable CO_2 emission factor for the selected inventory results are found and used for the CO_2 emission calculation. In the third step, the new CO_2 inventory results are updated to existing LCI results. In the fourth step, the aggregated CI result is calculated.

1) Classification

- **a) Classification:** The data from which the CO_2 is produced is selected from existing LCI results.
- **b) Classified results:** The selected data for calculating the direct CO_2 emissions are provided in Table 5.9.

Table 5.9: CS 2: LCI selected for calculating direct CO_2 emissions for clinker production (input-output category-wise)

Input	Value	Unit
Fuel		
Diesel (HSD)	0.202	kg/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternative fuel (AF)	0.010	Ton/ton of clinker
Transportation		
Diesel (HSD)	0.712	kg/ton of clinker

The inventory data which is rejected is as follows

1) Input data

- **a) Raw material**: Limestone, fire clay and feldspar - The CO_2 from them are already accounted for and reported.
- **b) Electricity** – No direct CO_2

2) Output data

a) **Emission to air:** Radiation loss – No CO_2 emission

b) **Heat –** No CO_2 emission

2) **CO_2 estimation**

The CO_2 is estimated in two steps. In the first step, suitable CO_2 emission factor corresponding to the selected LCI result is chosen, followed by CO_2 estimation.

a) **CO_2 emission factors**

Except for diesel, the CO_2 emission factors of other fuel was not obtained from the cement plant. The diesel CO_2 emission factor obtained was in terms of the litre and thus it is converted to kg. Thus, as mentioned in the goal and scope, CO_2 emission factor corresponding to few data are obtained from other sources. Samples of fuels were collected from the cement plant, which is analysed (CHNS analysis) to obtain the CO_2 emission factor. The compiled set of CO_2 emission factors are provided in Table 5.10.

Table 5.10: CS 2: CO_2 emission factors for calculation (clinker)

Input	Value	Unit
Fuel		
Diesel	3.22	kg CO_2 / kg of fuel
Coal	2.45	kg CO_2 / kg of fuel
Petcoke	3.10	kg CO_2 / kg of fuel
Lignite	2.16	kg CO_2 / kg of fuel
AF	0.92	kg CO_2 / kg of fuel

b) **CO_2 estimation results**

The CO_2 is estimated with selected data and suitable CO_2 emission factors. The results obtained are provided as input-output category-wise and process-wise in Table 5.11 and Table 5.12 respectively.

Table 5.11: CS 2: Direct CO_2 emissions calculated for clinker production (input-output category–wise)

Input	CO_2 emissions	Unit
Fuel		
CO_2 from Diesel (HSD)	0.65	kg CO_2/ton of clinker
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
	281.51	**kg CO_2/ton of clinker**
Transportation		
CO_2 from Diesel (for limestone)	2.29	kg CO_2/ton of clinker
	2.29	**kg CO_2/ton of clinker**
Total	**283.80**	**kg CO_2/ton of clinker**

Table 5.12: CS 2: Direct CO_2 emissions calculated for clinker production (process-wise)

Process	CO_2 emissions	Unit
Raw material extraction		
Output		
CO_2 from Diesel (HSD)	0.651	kg CO_2/ton of clinker
	0.651	**kg CO_2/ton of clinker**
Limestone Crushing - Clinkerization		
Output		
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
	280.86	**kg CO_2/ton of clinker**
Transportation		
Output		
CO_2 from Diesel (for limestone)	2.29	kg CO_2/ton of clinker
	2.29	**kg CO_2/ton of clinker**
Total	**283.80**	**kg CO_2/ton of clinker**

3) Updated LCI result

The CO_2 emission results obtained are updated in the existing LCI results. The results are provided as input-output category-wise and process-wise in Table 5.13 and Table 5.14 respectively.

Table 5.13: CS 2: Updated LCI for production of clinker (input-output category–wise)

Input	Value	Unit
Raw material		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
Fuel		
Diesel (HSD)	0.202	kg/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternate fuel	0.010	Ton/ton of clinker
Electricity		
Electricity	0.089	kWh/ton of clinker
Electricity	49.8	kWh/ton of clinker
Transportation		
Diesel (for limestone)	0.712	kg/ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1.00	Ton/ton of clinker
Emission to air		
CO_2 from Diesel (for limestone extraction)	0.651	kg CO_2/ton of clinker
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
CO_2 from Diesel (for limestone transportation)	2.29	kg CO_2/ton of clinker
CO_2 (from raw material)	529.31	kg CO_2/ton of clinker
Radiation loss	125.94	MJ/ton of clinker
Radiation loss	75.73	MJ/ton of clinker
Radiation loss	15.90	MJ/ton of clinker
Other		
Heat of PH Exit gases	531.37	MJ/Ton of clinker
Heat of PH Exit dust	32.64	MJ/Ton of clinker
Heat through Cooler Vent	414.22	MJ/Ton of clinker

Table 5.14: CS 2: Updated LCI for production of clinker (process–wise)

Process	Value	Unit
Raw material extraction		
Input		
Limestone	1.383	Ton/ton of clinker
Diesel (HSD)	0.202	kg/ton of clinker
Electricity	0.089	kWh/ton of clinker
Output		
Limestone	1.383	Ton/ton of clinker
CO_2 from Diesel (HSD)	0.651	kg CO_2/ton of clinker
Limestone Crushing - clinkerization		
Input		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternate fuel	0.010	Ton/ton of clinker
Electricity	49.8	kWh/ton of clinker
Output		
Clinker	1.00	Ton/ton of clinker
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
CO_2 (from raw material)	529.31	kg CO_2/ton of clinker
Radiation loss	125.9384	MJ/ton of clinker
Radiation loss	75.7304	MJ/ton of clinker
Radiation loss	15.8992	MJ/ton of clinker
Heat of PH Exit gases	531.37	MJ/Ton of clinker
Heat of PH Exit dust	32.64	MJ/Ton of clinker
Heat through Cooler Vent	414.22	MJ/Ton of clinker
Transportation		
Inputs		
Diesel (HSD)	0.712	kg/ton of clinker
Limestone	1.383	Ton/ton of clinker
Output		
CO_2 from Diesel (for limestone)	2.29	kg CO_2/ton of clinker
Limestone	1.383	Ton/ton of clinker

4) Aggregated LCI result

The results obtained previously are aggregated data type-wise and reported in Annexure (Table C. 6)

5.4.3 CO_2 emission calculation

The embodied CO_2 associated with the existing inventory data (within the gate to gate) is calculated in three steps. In the first step, the calculation methodology is defined. In the second step, the LCI data required for the calculation is selected. In the third step suitable CO_2 factor is found and embodied CO_2 is calculated using LCI data.

1) **CO_2 emission calculation methodology**: The embodied CO_2 of clinker is calculated from the LCI. The embodied CO_2 is the sum of direct CO_2 and embodied CO_2 of data within gate to gate system boundary. The embodied CO_2 is calculated in kg. The direct CO_2 is considered as such and thus the factor for the same is 1. For electricity, the embodied CO_2 factor is required but the value could not be obtained from cement plant data due to the incompleteness of data collected. Thus the value from Chapter 4: Case study 1 is cited.
2) **LCI result assigning**:
   The LCI result which has embodied CO_2 within gate to gate system boundary is selected from LCI result and reported. The selected LCI data are provided in Table 5.15.

Table 5.15: CS 2: LCI selected for calculation of CO_2 emissions for production of clinker

Input	Value	Unit
Electricity		
Electricity	0.089	kWh/ton of clinker
Electricity	49.8	kWh/ton of clinker
Output	**Value**	**Unit**
Emission to air		
CO_2 from Diesel (HSD) (for limestone extraction)	0.651	kg CO_2/ton of clinker
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
CO_2 from Diesel (for limestone transportation)	2.29	kg CO_2/ton of clinker
CO_2 (from raw material)	529.31	kg CO_2/ton of clinker

The inputs like limestone, fire clay, feldspar, fuels, radiation, and heat loss are not selected as they do not have embodied CO_2 within gate to gate system boundary.

3) **CO_2 emission calculation**

Here the CO_2 emission factor suitable for the classified inventory is selected and the CO_2 emission is calculated.

a) CO_2 emission factor

The CO_2 emission factors used for calculation is provided in Table 5.16.

Table 5.16: CS 2: CO_2 emission factor for calculation (clinker)

Input	Value	Unit	Remark
Electricity			
Electricity	1.09	kg CO_2/kWh	Cited from Chapter 5: Case study 2
Output	**Value**	**Unit**	**Remark**
Emission to air			
CO_2	1.00	kg CO_2/kg CO_2	

b) CO_2 emission calculation

The classified inventory is multiplied with the compiled set of CO_2 emission factor. The CO_2 emissions result thus obtained is presented in input-output category-wise and process-wise in Table 5.17 and Table 5.18 respectively.

Table 5.17: CS 2: CO_2 emissions for the production of clinker (input-output category–wise)

Input	CO_2 emissions	Unit
Electricity		
Electricity	0.10	kg CO_2/ton of clinker
Electricity	54.14	kg CO_2/ton of clinker
	54.24	**kg CO_2/ton of clinker**
Emission to air		
CO_2 from Diesel (HSD) (for limestone extraction)	0.65	kg CO_2/ton of clinker
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
CO_2 from Diesel (for limestone transportation)	2.29	kg CO_2/ton of clinker
CO_2 (from raw material)	529.31	kg CO_2/ton of clinker
	813.11	**kg CO_2/ton of clinker**
Total	**867.35**	**kg CO_2/ton of clinker**

Table 5.18: CS 2: CO_2 emissions for the production of clinker (process–wise)

Process	CO_2 emissions	Unit
Limestone extraction		
Input		
Electricity	0.097	kg CO_2/ton of clinker
Output		
CO_2 from Diesel (HSD)	0.651	kg CO_2/ton of clinker
	0.748	**kg CO_2/ton of clinker**
Limestone crushing – clinkerization		
Input		
Electricity	54.14	kg CO_2/ton of clinker
Output		
CO_2 from SA Coal	4.16	kg CO_2/ton of clinker
CO_2 from Pet coke	173.79	kg CO_2/ton of clinker
CO_2 from Lignite	93.57	kg CO_2/ton of clinker
CO_2 from AF	9.33	kg CO_2/ton of clinker
CO_2 (from raw material)	529.31	kg CO_2/ton of clinker
	864.31	**kg CO_2/ton of clinker**
Limestone transportation		
Output		
CO_2 from Diesel (for limestone)	2.293	kg CO_2/ton of clinker
	2.293	**kg CO_2/ton of clinker**
Total	**867.347**	**kg CO_2/ton of clinker**

5.4.4 Interpretation

As mentioned in methodology, first the significant issues are found, followed by evaluation and then a description of conclusion, limitation and recommendations.

1) Identification of the significant issue

a) Structured table

The results of CO_2 emissions are consolidated and presented in a structured table. CO_2 from electricity is embodied CO_2, whereas from other inputs, it is direct CO_2. The CO_2 emission results are presented in Table 5.19.

Table 5.19: CS 2: CO_2 emissions for the production of clinker (structured)

Data category \ Unit process	Limestone extraction	Limestone Crushing - clinkerization	Transportation	Total
Energy - Electricity	0.10	54.14	-	54.24
Release to air - CO_2 (from fuel)	0.65	280.86	-	281.51
Release to air - CO_2 (from raw material)	-	529.31	-	529.31
Release to air - CO_2 (from diesel)	-	-	2.29	2.29
Total	0.75	864.31	2.29	867.35

All the results are in kg CO_2 / ton of clinker

The embodied CO_2 of clinker is calculated with respect to the gate to gate system boundary. The embodied CO_2 in electricity and direct CO_2 from fuels and raw meal are most contributing. The total CO_2 emissions of clinker are estimated as 867.35 kg CO_2/ton of clinker.

b) Analysis

i) Contribution analysis

The CO_2 emissions from a raw meal is highest with 61.03%, followed by CO_2 from fuel for clinkerization with 32.38% and electricity for a group of processes from limestone crushing till clinkerization 6.24%. The embodied CO_2 of electricity for limestone extraction is least with 0.01% contribution. Analysing the CO_2 emission process-wise, the processes between limestone crushing till clinkerization covers 100% of the CO_2 emission. In terms of data type, the major contributors are the raw meal, fuel for kiln and electricity with 61, 32 and 6 % of total emissions respectively.

ii) Anomaly analysis

The CO_2 associated with data is calculated using inventory from Ecoinvent database V3 and modified version of the impact assessment method "IPCC 2013 GWP100a" for five geographical area. The primary contributing data are direct CO_2 emission and embodied CO_2 of electricity. The value of direct CO_2 varies from 769-846 kg with four of them above 838 kg. The corresponding value obtained in the study (810 kg) is less. Similarly, the embodied energy of electricity is in the range of 1.1-40.1 kg, where three are above 25 kg. The corresponding value in the study (54.14 kg) seems higher than the literature value. The total direct CO_2 and embodied CO_2 from clinker production is coming in the range of 779-878 kg, where four of them are in the range of 862 ± 16 kg. The corresponding value in the study (864.31 kg) is an average value of the expected range of value.

2) Evaluation

The confidence over the result obtained in the analysis is evaluated here with respect to the goal and scope defined. Completeness check and consistency check are conducted to understand the degree to which the results are matching with the goal and scope.

a) Completeness

Apart from the incompleteness in LCI analysis, an incompleteness in finding suitable embodied CO_2 factor for electricity is faced. The data related to the production of electricity was incomplete and thus the embodied CO_2 could not be calculated. The embodied CO_2 factor of the electricity produced in Case study 1 is used in the analysis. Similarly, the CO_2 emission values of fuels (except diesel) were not obtained from the cement plant, thus they are calculated from test results of the collected sample fuel and from databases. Since the break-up of alternate fuel LCI value is not provided with the average CO_2 emission factors of alternate fuel is used.

b) Consistency

Apart from the consistency status of LCI analysis, the additional sub-elements of CO_2 estimation and embodied CO_2 calculation methodology seems to be consistent with respect to the defined goal and scope.

3) Conclusions, limitations and recommendations

a) Conclusions

i) The CO_2 emission with respect to the production of clinker within the gate is calculated and reported as 867.35 kg CO_2/ton of clinker.

ii) The most contributing data is CO_2 from raw material (61%), fuel (32%) and embodied CO_2 of electricity (6%). The group of processes from limestone crushing till clinkerization covers around 100%.

iii) The embodied CO_2 of electricity is higher than the values expected. The direct CO_2 from raw material and fuel is low, however within the expected range. Total direct and embodied CO_2 from processes limestone crushing to clinkerization lies around the average of expected result range.

b) Limitations

i) **Completeness check:** Apart from the incompleteness in LCI analysis, an incompleteness in finding suitable energy factor is faced.

ii) **Consistency check:** No consistency issues are faced.

c) Recommendations

The embodied CO_2 of Indian clinker can be reported in the LCA databases. It can also be used to estimate the embodied CO_2 of normal and blended cement. Also, it is recommended that during LCA of clinker production an inventory collection of CO_2 from the raw meal, fuels, and electricity can provide a coverage of ~100%. The effect of transportation is negligible. Or if the data collection is processes-wise the process from limestone crushing to the clinkerization process will give a coverage near to 100%.

5.5 LCI for OPC production

As defined in the methodology chapter a detailed and structured analysis is carried out. The three sections and the key information from the same is provided as follows.

5.5.1 Goal and scope

The goal and scope are defined initially before the LCA. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined is of adjusted form. This final goal and scope after the analysis is reported here.

1) Goal

The goal and scope are same as that of clinker for LCI analysis (section: 4.2.1) except few changes like the change of functional unit from clinker to OPC, and change in processes. The changes made are provided as follows.

a) Objective

To get inventory data for OPC production.

b) Application

A set of inventory data for production of OPC in India can be reported in life cycle databases of building material.

2) Scope

The scope of OPC is also similar to that of the scope defined for clinker for LCI analysis (section: 4.2.1), except for few details. The sub-elements which differs from the scope of clinker is provided as follows.

a) **Product/process system to be considered:** The processes involved in cement production after clinkerization in Indian cement plant

b) **Functions of the product system/systems:** Production of cement

c) **Functional unit:** 1 ton of cement is considered as the functional unit.

- d) **System boundary**
  - i) **Criteria:** Gate to gate
  - ii) **List of the unit process:**
    - (1) **Grinding of cement:** The grinding of clinker, gypsum, filler limestone, and grinding aid into the cement of required fineness.
    - (2) **Packing of cement:** The packing of cement into plastic/paper bags
    - (3) **Others (services etc.):** All miscellaneous processes excluded in the previous processes or carried out simultaneously in a non-continuous way
  - iii) **Deleted processes:**
    - (1) **Transportation:** The transportation of limestone. This process was deleted after LCI analysis. The process was deleted because no data corresponding to the process was found
- e) **Data required:**
  - i) **Grinding of cement:** Clinker, filler limestone, gypsum, electricity, oil, water, steel balls, grinding aid, ball mill, cement, dust, and radiation and convection losses.
  - ii) **Packing of cement:** Cement, electricity, packing bags, oil, ink, equipment, and packed cement bags.
  - iii) **Others (services etc.):** Electricity consumed for other processes like lighting plant area, office and colony, water for colony area, other equipment, and fuels for the canteen.
- f) **Allocation:** Since two products (OPC and PPC) are produced, the inventory is divided based on the mass of each cement produced. Thus mass allocation is followed in the study.
- g) **Interpretation methodology:**
  - i) Identification of significant issues
    - (1) Structured result
    - (2) Analysis: Contribution and anomaly.
  - ii) Evaluation: Completeness and consistency.
  - iii) Conclusion, limitation and recommendation

h) Limitation:

i) The OPC and PPC produced were not provided separately and thus was calculated using the clinker to cement ratio of OPC and PPC, total clinker produced, and total cement produced.

ii) The plant is not an exclusive grinding unit. Thus, the processes involved in and after the grinding section of the integrated cement plant is studied.

iii) The electricity for grinding and packing are not separately provided.

iv) The electricity required for the grinding of OPC and PPC is not provided separately.

i) Assumption

i) It is assumed that in OPC and PPC the gypsum percentage is the same. Based on this assumption amount of gypsum added in both types of cement are calculated.

ii) Gypsum consumption is reported as 31000 ton. With this amount of gypsum, the difference in OPC and clinker would not be filled. Thus, it is assumed that fillers are used in the OPC. Thus, the amount in OPC, other than clinker and gypsum is assumed to be filler.

iii) The unit of the electricity consumed after clinkerization is provided as kWh/ton. It is not mentioned that whether it indicates clinker or cement. Comparing with the literature it is understood that the OPC and PPC grinding energy lies in the same range as reported in data shared by the cement plant (even though OPC value will be of higher than PPC). Thus it is assumed that the value reported here will be the average electricity consumed by both OPC and PPC or in other words, the grinding and packing energy of the generic cement produced in the plant.

iv) In the case of data redundancy, priority is given to the reliability of LCI data based on some condition. For time period variation, the priority followed is: Sum of Monthly break up > Yearly break up. For different accuracies, the data with more accuracy is selected for calculation.

5.5.2 Life Cycle Inventory

As per methodology, six steps are conducted to find the LCI analysis. The step is as follows.

1) **Preparation of data collection:** It is the same as that for clinker analysis, as data collection is done at same site visits (Section: 4.2.2)

2) **Data collection, formatting and compiling:** Same as that for clinker analysis as data collection, formatting and compiling is done together (Section: 4.2.2)

3) **Data validation:** Same as defined in clinker analysis as the data validation is conducted together (Section: 4.2.2). The validated results are provided in Annexure (Table C. 6).
4) **LCI analysis:** The total clinker used for OPC and OPC produced was not provided. Thus, the calculation using miscellaneous data is carried out as the first step. It is found by solving two equations with clinker to cement ratio of OPC, PPC, total clinker and total cement produced. Thus, the clinker content for OPC and PPC are obtained. Using the respective clinker to cement ratio, OPC and PPC produced are also calculated. In the first step, the calculation using miscellaneous data is conducted. The data regarding the clinker content was only provided. Based on the assumption that gypsum content is the same for OPC and PPC (total cement), it is calculated. The remaining percentage apart from clinker and gypsum is assumed to be from the contribution of filler (Table C. 7). In the second step, the LCI analysis is conducted using absolute data (Table C. 8). In the third step, the LCI analysis is conducted using reference flow data (Table C. 9). All the LCI results are compiled and reported as input-output category-wise and process-wise in Table 5.20 and Table 5.21.
5) **LCI data aggregation:** The data present in data categories are different, thus the aggregated LCI result is same as LCI result Input-output category-wise.
6) **Refining the system boundary:** No change in system boundary.

Table 5.20: CS 2: LCI for production of OPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.950	Ton/ton of OPC
Gypsum	0.020	Ton/ton of cement
Filler	0.030	Ton/ton of OPC
Electricity		
Electricity	28.03	kWh/Ton of cement
Ancillary materials		
Water	47.1	kg/Ton of cement
Other physical inputs		
LPG	1.08E-05	Ton/ton of cement
Output	**Value**	**Unit**
Product		
OPC produced	1	Ton/ton of OPC
Emission to air		
CO_2	9.92E-08	Ton/ton of cement
Freon (R22)	1.18E-07	Ton/ton of cement

Table 5.21: CS 2: LCI for production of OPC (process–wise)

Process	Value	Unit
Grinding of cement - packing of cement		
Input		
Clinker	950	kg/ton of OPC
Gypsum	20.4	kg/ton of cement
Filler	29.6	kg/ton of OPC
Electricity	28.03	kWh/Ton of cement
Output		
OPC produced	1	Ton/ton of OPC
Others		
Input		
Water	47.1	kg/Ton of cement
LPG	10.77	gm/ton of cement
Output		
CO_2	99.2	mg/ton of cement
Freon (R22)	118.11	mg/ton of cement

5.5.3 Interpretation

1) Identification of significant issues

a) Structured results

The LCI results are structured as process-wise along the column and data category-wise along the row. The structured results are provided in Table 5.22.

Table 5.22: CS 2: LCI for production of OPC (structured)

Unit processes / Data category	Grinding to packing of cement	Other processes	Total
Clinker (kg/ton of OPC)	950		950.00
Gypsum (kg/ton of cement)	20.42		20.42
Filler (kg/ton of OPC)	29.58		29.58
Electricity (kWh/Ton of cement)	28.03		28.03
Water (kg/Ton of cement)		47.1	47.10
LPG (gm/ton of cement)		10.77	10.77
CO_2 (mg/ton of cement)		99.21	99.21
Freon (R22) (mg/ton of cement)		118.11	118.11

b) Analysis

i) Contribution

The products like clinker, gypsum, filler and electricity are completely consumed (100%) in the group of processes from grinding to the packing of cement. Data like water, LPG, CO_2, and Freon (R22) corresponds (100%) to other processes.

ii) Anomaly

According to Cement Portland LCI from Ecoinvent database V3, corresponding clinker content reported is 902.5 kg and 920 kg for four different geographical area across the globe. The clinker value (950 kg) obtained in the study seems to be a little higher than expected range. From the above-mentioned inventory, the gypsum content is reported as 47.5 kg and 50 kg for different geographical regions across the globe. The value obtained in the study (20.42 kg) is low than expected range. According to (IS 12269 2013) the filler should be of maximum 5% (50 kg). The filler value (29.58 kg) is within this limit thus the value was as expected. From the Ecoinvent database four electricity consumption values are found, and are in the range of 37.6-55.8 kWh, in which two values lies in the lower limit and two values lies around the higher limit. The value obtained in the study (28.03 kWh) seems to be lesser than the expected range. The water consumption per ton of Portland cement is in the range of 537-1605 kg as per values reported in the (Josa et al. 2004; Li et al. 2014; Marceau et al. 2006). Compared to this, the value in the study (47 kg) seems to be too low. Few new values like Freon, CO_2 from a fire extinguisher, and LPG for factory and canteen usage were identified, which is having negligible value.

2) Evaluation

a) Completeness check: The data from the unit processes are complete

b) Consistency check: The data, methods, and assumptions considered in the study are consistent.

3) Conclusions, limitations and recommendations

a) Conclusions

i) The inventory data like clinker (950 kg), gypsum (20 kg), filler (30 kg), electricity (28 kWh), water (47 kg), and some minor inventories are identified and reported. The minor items are miscellaneous items such as LPG for canteen (11 mg), CO_2 from fire extinguisher (99 mg), and Freon (R22) (118 mg) as a refrigerant.

ii) The products like clinker, gypsum, filler and electricity are completely consumed (100%) in the processes from grinding to the packing of cement. Data like water, LPG, CO_2, and Freon (R22) corresponds to other processes.

iii) The filler amount seems to be within the recommendation of Indian standards. The clinker content is higher with respect to the literature range. The inputs like gypsum, electricity and water seems to be low with respect to the expected values. The data like LPG, CO_2, and Freon (R22) are unexpected or new data observed.

b) Limitations

i) The data collected is incomplete. The basic data like clinker of OPC, OPC produced, gypsum content of OPC, and filler content were not provided.

ii) The electricity break-up towards grinding and packing processes were also not provided. Most of these issues are solved based on assumption and estimation.

iii) Except for data accuracy, every other section seems to be consistent.

c) Recommendation

The data can be submitted to the LCI database as the inventory for Indian OPC. It needs to be stated that the data is valid with the limitations of assumptions made during calculation. Inventory data can be used for impact assessments, estimation of energy and cost. There are a lot of assumptions made for the inventory calculation. Reiteration of data collection can be conducted to rectify these assumptions. The inventory data on the equipment (e.g. ball mill and cyclone separator) and infrastructure (e.g. buildings for equipment, office buildings and colony) was not obtained. Thus further data collections can improve the completeness of inventory. More analysis can also be conducted on the current LCI results.

5.6 Energy use for OPC production

As defined in the methodology chapter a detailed and structured analysis is carried out. The four sections and the key information from the same is provided as follows.

5.6.1 Goal and scope

The goal and scope are defined initially before the analysis. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is reported here.

1) **Goal**

The goal and scope are the same as that of LCI analysis of OPC, except few sub elements like objective, and application, which is provided below.

a) **Objective**

To quantify the energy consumption related to the production of OPC (Ordinary Portland cement) in a typically integrated cement factory in India.

b) **Application**

The value can be reported in the embodied energy database of building materials in India. It can be used for calculating embodied energy of Portland cement-based concrete.

2) **Scope**

a) **Energy calculation methodology**

The energy is calculated by considering the embodied energy and direct energy of all the data within the system boundary. By direct energy, it is meant that the energy is consumed in the considered unit processes and by embodied energy it is meant that the energy is embodied in the data within gate to gate system boundary which enters to unit processes as input e.g. clinker and electricity. Energy is calculated in MJ/ton of cement. The embodied energy of the data like clinker and electricity is already calculated and such values are used in the calculation. The calorific value of the fuels is obtained from following sources provide in the priority order. Priority order is provided based on representativeness.

i) **Characterisation factors obtained from cement plant,**

ii) **Bomb calorimetry results of sample collected,**

iii) **Emission factors for greenhouse gas inventories** - US EPA 2014 report (Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf),

iv) **2006IPCC Guidelines for national greenhouse gas inventories** (Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > Chapter 1 > Table 1.2, http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html)"

5.6.2 Life Cycle Inventory

The life cycle inventory result provided in the section 5.5.2 is used here

5.6.3 Energy calculation

The selected inventory results are converted to energy using suitable energy factors.

1) **Energy calculation methodology:** The energy within gate to gate system boundary is calculated using suitable LCI data and energy factors. The energy is calculated in MJ. The clinker energy is calculated in the section 4.3.3. The embodied energy of electricity was not obtained due to the incompleteness of data from the cement plant. Thus, the embodied energy of the electricity from 'chapter 4: Case study 1' is cited. The calorific value of LPG is cited from database.

2) **Classification**

   The inventory results obtained is classified into selected and rejected data for energy calculation. The selected data is those which contribute towards the embodied energy of the OPC within gate to gate analysis. The results are presented in Table 5.23.

Table 5.23: CS 2: LCI selected for calculating energy use for production of OPC

Input	Value	Unit
Raw material		
Clinker	0.950	Ton/ton of OPC
Electricity		
Electricity	28.03	kWh/ton of cement
Others		
LPG	1.08E-05	Ton/ton of cement

Few LCI results data are rejected as it is not contributing to energy consumption within gate to gate system boundary. Such data are provided below

1) **Input** :
   a) **Raw material**: Gypsum and filler.
   b) **Ancillary inputs**: Water
2) **Output**
   a) **Emission to air:** CO_2, Freon (R22)

3) **Energy calculation**

   The energy is calculated using the suitable embodied energy values.

   a) **Energy factor**

      The energy factors of selected inventory data are provided in Table 5.24.

   b) **Energy calculation**

The selected inventory result is multiplied with suitable energy factor to get the total energy for production of OPC. The results are provided as input-output category-wise and process-wise in Table 5.25 and Table 5.26.

Table 5.24: Energy factors for calculation (OPC)

Input	Value	Unit	Remark
Electricity			
Electricity	13.40	MJ/kWh	Sum of energy consumed from fuels in thermal power plant and fuel for transportation. Source: Case study 1
Fuel			
LPG	51.80	MJ/kg	Formula = Heating value / Density. The unit is converted from MJ/L to MJ/kg by dividing with density. Heating Value, Source: EPA 2014, fuel named: Liquefied Petroleum Gases (LPG). The density used in 0.495kg/litre, Source: http://www.elgas.com.au/blog/453-the-science-a-properties-of-lpg.
Raw material			
Clinker	3625	MJ/ton of clinker	The energy from processes like extraction of raw material, limestone crushing till clinkerization, and transportation, within gate to gate system boundary.

Table 5.25: CS 2: Energy use for the production of OPC (input-output category–wise)

Inventory	Embodied energy result	Unit
Raw material		
Clinker	3443.99	MJ/ton of OPC
Electricity		
Electricity	375.57	MJ/ton of cement
Other physical inputs		
LPG	0.56	MJ/ton of cement
Total	**3820.12**	**MJ/ton of OPC**

Table 5.26: CS 2: Energy use for the production of OPC (process–wise)

Process	Energy	Unit
Grinding of cement till packing		
Input		
Clinker	3443.99	MJ/ton of OPC
Electricity	375.57	MJ/ton of OPC
	3819.56	**MJ/ton of OPC**
Others		
Inputs		
LPG	0.56	MJ/ton of OPC
	0.56	**MJ/ton of OPC**
Total	**3820.12**	**MJ/ton of OPC**

5.6.4 Interpretation

The results obtained in the energy calculation is interpreted here with respect to the goal and scope

1) Identification of the significant issues

The energy consumed is structured and analysed to identify the significant issues. The structured results are provided in the Table 5.27.

a) Structured result

Table 5.27: CS 2: Energy use for the production of OPC (structured)

Unit process / Data category-wise	Grinding to packing of cement	Other processes	Total
Clinker	3443.99	-	3443.99
Electricity	375.57	-	375.57
LPG	-	0.56	0.56
Total	3819.56	0.56	3820.12

Note: All values are in MJ/ton of OPC

The energy use for OPC is calculated within gate to gate system boundary. The embodied energy of clinker and electricity consumed are the main contributor. The embodied energy of OPC is 3820.12 MJ/ton of OPC

b) Analysis

i) Contribution

The main contributor towards embodied energy of OPC is clinker with 90% contribution followed by electricity with 10% contribution and negligible traces from LPG. The embodied energy contribution belongs to processes grinding and packing of cement.

ii) Anomaly

Clinker and electricity are the primary contributing inputs. Embodied energy contribution from data is calculated using LCI (corresponding to five geographical area) from Ecoinvent database V3 and using impact assessment method "Cumulative energy Demand V1.09". The embodied energy of clinker varies from 2700-3460 MJ, where four of them are above 3350 MJ. The corresponding value obtained in the study (3444 MJ) is higher. The embodied energy of electricity is in range of 228-627 MJ where three of them are in the range of 430 ± 14 MJ. Compared to this, the corresponding value obtained in the study (376 MJ) is lower. The total embodied energy of electricity and clinker is in the range of 3144-4047 MJ, where three of them are in the range of 3780 ± 100 MJ. The corresponding value of the study is (3820 MJ) which is high, however within the expected range.

2) Evaluation

a) Completeness check: Apart from LCI incompleteness, the incompleteness met is lack of embodied energy factor for electricity and calorific values of LPG.

b) Consistency check: Apart from the LCI analysis the energy calculation methodology followed, assumptions, and characterization factor used was consistent.

3) Conclusions, limitations and recommendation

a) Conclusions:

i) The embodied energy of OPC is calculated as 3820 MJ/ton of OPC within the gate to gate system boundary.

ii) The main contributor towards embodied energy is clinker (90%) and electricity (10%). Both the inputs correspond to process grinding and packing of cement.

iii) The embodied energy of clinker lies at the higher end of the expected range. The electricity lies within the expected range however near to lower limit. The sum of the embodied energy of clinker and electricity also lies in the expected range, however at the higher end.

b) Limitations:

i) The incompleteness is met in finding suitable factor for electricity and LPG.

ii) The study is consistent with respect to goal and scope.

c) **Recommendation:**

The embodied energy value can be reported in an energy database as a value corresponding to Indian OPC. The value can be used in the estimation of the embodied energy of concrete. The reiteration of data can be conducted to get more data and also data with break-up value towards different unit processes. More analysis can be conducted to draw observations from the results.

5.7 CO_2 emissions for OPC production

5.7.1 Goal and Scope

The goal and scope are same as defined in the LCI analysis of the OPC (Section: 4.5.1), few sub-elements which are different is provided as follows.

1) **Goal**

   a) **Objective**: To compute the CO_2 emission related to the OPC production within gate to gate system boundary.

   b) **Application**: The embodied CO_2 of the Indian OPC can be reported in the LCA databases. This can also be used to calculate the embodied CO_2 contributed from cement towards concrete.

2) **Scope**

   a) **CO_2 emission calculation methodology**

   The direct CO_2 emitted and embodied CO_2 associated with the inventory for the production of OPC, within the gate to gate analysis is quantified here. The embodied CO_2 is estimated in kilogram as a unit. The embodied CO_2 values corresponding to the inventory results are used for the calculation.

5.7.2 Life Cycle Inventory

The life cycle inventory result provided in the section 5.5.2 is used.

5.7.3 CO_2 emission calculation

The inventory results are classified and the selected inventory result which is related to direct and indirect CO_2 is used for calculation. The selected inventory and suitable embodied CO_2 values are used for calculation,

1) **CO_2 emission calculation methodology:** The embodied CO_2 is calculated. The embodied CO_2 is the sum of direct CO_2 emission from unit processes and embodied CO_2

from the input of unit processes which possess embodied CO_2 within the gate to gate system boundary. The embodied CO_2 is calculated in kg CO_2. The inventory data which is direct CO_2 or has embodied CO_2 is selected and multiplied with a suitable CO_2 factor to obtain the embodied CO_2 results. The CO_2 emitted is considered as such thus the factor is 1 for CO_2. For clinker, the embodied CO_2 is obtained from the section 5.4.3. The embodied CO_2 of the electricity was not obtained due to incomplete data and thus cited from Chapter 4: Case Study 1. The calorific value of the fuel is obtained from any of the following sources. The sources are provided in the order of priority.

a) **The CO_2 emission factor from cement plant data**
b) **The CO_2 emission factor of samples measured through CHNS analyser**
c) **Emission factors for greenhouse gas inventories – US EPA 2014 (**Source: Table 1, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf**)**
d) **CSI protocol 2013 (**Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors")
e) **2006IPCC guidelines for national greenhouse inventories (**Source: Table 1.4, website - http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html, Volume 2 Energy, Draft 2006IPCC guidelines for national greenhouse gas inventories > chapter 1 Introduction**)**

2) **Classification**

The data associated with CO_2 emission is selected from LCI result for calculation. The selected data are presented n Table 5.28.

Table 5.28: CS 2: LCI selected for calculating CO_2 emissions for production of OPC

Input	**Value**	**Unit**
Raw material		
Clinker	0.950	Ton/ton of OPC
Electricity		
Electricity	28.03	kWh/Ton of cement
Other physical inputs		
LPG	1.08E-05	Ton/ton of cement
Output	**Value**	**Unit**
Emission to air		
CO_2	9.92E-08	Ton/ton of cement

3) CO_2 emission calculation

The CO_2 is calculated using the suitable embodied CO_2 values

a) CO_2 emission factors

The CO_2 emission factor values of selected inventory data are provided in Table 5.29.

b) CO_2 emission calculation

The selected inventory result is multiplied with a suitable CO_2 factor to get the total CO_2 emissions for the production of OPC. The results are presented as input-output category-wise and process-wise in Table 5.30 and Table 5.31.

Table 5.29: CS 2: CO_2 emission factors for calculation (OPC)

Input	Value	Unit	Remarks
Electricity			
Electricity	1.09	kg CO_2/kWh	Sum of CO_2 emission from fuels in a thermal power plant. Source: Case study 1
Raw material			
Clinker	867.35	kg CO_2/ton of clinker	CO_2 release due to decomposition of carbonates in raw material, burning of fuel for clinkerization, electricity production and transportation. Source: Case study 2, Dalmia cement plant.
Other physical input			
LPG	2.91	kg CO_2 /kg	The LPG kg CO_2 factor, Time Period: yearly, Source: File: Co2 emission.xls, Worksheet: co2 emissions, Table 5.1 SCOPE 1 Emissions, Cell address: E9. The unit is not provided checking with the value reported in the "Table 5.2, India: Greenhouse Gas Emissions 2007, INCCA, MoEF" and considering the density of 0.495kg/litre. The possible unit is kg CO_2/kg. Density value, source: http://www.elgas.com.au/blog/453-the-science-a-properties-of-lpg.
Output	**Value**	**Unit**	**Remark**
Emission to air			
CO_2	1.00	kg CO_2/kg CO_2	The CO_2 emission factor

Table 5.30: CS 2: CO_2 emissions for production of OPC (input-output category–wise)

Input	**CO_2 emissions**	**Unit**
Electricity		
Electricity	30.47	kg CO_2/ton of clinker
Raw material		
Clinker	823.98	kg CO_2/ton of clinker
Other physical inputs		
LPG	0.03	kg CO_2/ton of clinker
Output		
Emission to air		
CO_2	9.92E-05	kg CO_2/ton of clinker
Total	**854.48**	**kg CO_2/ton of clinker**

Table 5.31: CS 2: CO_2 emissions for production of OPC (process–wise)

Process	**CO_2 emissions**	**Unit**
Grinding of cement till packing of cement		
Input		
Clinker	823.98	kg CO_2/ton of clinker
Electricity	30.47	kg CO_2/ton of clinker
	854.45	**kg CO_2/ton of clinker**
Others		
Input		
LPG	3.14E-02	kg CO_2/ton of clinker
Output		
CO_2	9.92E-05	kg CO_2/ton of clinker
	3.15E-02	**kg CO_2/ton of clinker**
Total	**854.48**	**kg CO_2/ton of clinker**

5.7.4 Interpretation

The results obtained in the CO_2 emission calculation is interpreted here with respect to the goal and scope

1) Identification of the significant issues

The CO_2 emission results are analysed to identify the significant issues.

a) **Structured result**

Table 5.32: CS 2: CO_2 emissions for production of OPC (structured)

Data category \ Unit processes	Grinding to packing of cement	Other processes	Total
Embodied CO_2 from clinker	823.98		823.98
Embodied CO_2 from electricity	30.47		30.47
CO_2 release from LPG		3.14E-02	0.03
CO_2 release from a fire extinguisher		9.92E-05	9.92E-05
Total	854.45	0.03	854.48

Note: All values are in kg CO_2/ton of OPC

The embodied CO_2 of the OPC with respect to the gate to gate system boundary is calculated. The embodied CO_2 from clinker and electricity, and traces of CO_2 from LPG and fire extinguisher are identified and quantified. The embodied CO_2 of clinker is 854.48 kg CO_2/ton of OPC

b) **Analysis**

i) **Contribution**

The major contribution is from clinker with 96% and remaining electricity. The contribution of CO_2 from LPG and fire extinguisher is less than 0.01%. The grinding and packing process alone contribute around 100% of total CO_2.

ii) **Anomaly**

The CO_2 associated with data is calculated using inventory from Ecoinvent database V3 and modified version of the impact assessment method "IPCC 2013 GWP100a", corresponding to five geographical area. The most contributing data are clinker and electricity. The embodied CO_2 of clinker varies from 721-853 kg, where three of them are above 840kg. The corresponding value obtained in the study (824 kg) seems to be low. The embodied CO_2 of electricity is in range of 0.55-34.5 kg, the values are equally distributed across the range. Compared to this the corresponding value obtained in the study is 30.47 kg, which seems to be at the higher end of the expected range. The total embodied CO_2 of electricity and clinker is in range of 725-877 kg, three of them are above 850 kg. The corresponding value in the study (854 kg) seems to be an average value with respect to the expected range**.**

2) **Evaluation**

   a) **Completeness check:** The incompleteness faced in obtaining embodied CO_2 of electricity and CO_2 emission factor of LPG from the cement plant. For electricity, the value from case study 1 is cited and for LPG value from the database is used.

   b) **Consistency check:** The embodied CO_2 calculation seems to be calculated as methodology defined in the goal and scope with consistency.

3) **Conclusions, limitations and recommendation**

   a) **Conclusions:**

      i) The embodied CO_2 of OPC within gate to gate system boundary is 854.48 kg CO_2/ton of OPC. The contribution comes from clinker and electricity

      ii) The major contribution is from clinker with 96% and remaining electricity. The grinding and packing process alone contribute 100% of the total CO_2.

      iii) The embodied CO_2 of clinker is low whereas electricity is high, however, both lies in the expected range. The total embodied CO_2 of clinker and electricity is average or normal value. All these values lie in the expected range.

   b) **Limitations:**

      i) The CO_2 factor of electricity and LPG is not obtained from cement plant data and thus it is cited from other sources.

      ii) Other than the LCI inconsistencies, no inconsistencies are found in embodied CO_2 emission calculation.

   c) **Recommendation:**

   The results can be reported as embodied CO_2 of Indian OPC in the embodied CO_2 databases of building materials. It needs to be mentioned along with the assumptions and limitations faced during calculation. It can be used to estimate the embodied energy value of OPC based concrete. Another data collection can be conducted to find the embodied CO_2 of electricity and carbon emission factors of fuels.

5.8 LCI for PPC production

As defined in the methodology chapter a detailed and structured analysis is carried out. The three sections and the key information from the same is provided as follows.

5.8.1 Goal and scope

The goal and scope are defined initially before the LCA. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is reported here

1) **Goal**

   The goal is same as that of OPC for LCI analysis (section: 4.5.1) except few changes like the change of functional unit from OPC to PPC. The sub-elements of goal not defined in the OPC section will be the same as that of provided in clinker (section: 4.2.1).

2) **Scope**

   The scope of PPC is also similar to that of the scope defined for OPC for LCI analysis (Section: 4.5.1), except for few details. The sub-elements which differs from the scope of clinker is provided as follows.

   a) **System boundary**

      i) **Criteria:** Gate to gate.

      ii) **List of the unit process:**

         (1) **Grinding of cement:** The grinding of clinker, gypsum, fly ash, and grinding aid into the cement of required fineness.

         (2) **Packing of cement:** The packing of cement into plastic/paper bags.

         (3) **Others (services etc.):** All miscellaneous processes excluded in the previous processes or happening simultaneously in a non-continuous way.

   b) **Data required:**

      i) **Grinding of cement:** Clinker, fly ash, gypsum, grinding aid, electricity, oil, water, steel balls, ball mill, cement, dust, and radiation and convection losses.

      ii) **Packing of cement:** Cement, electricity, packing bags, oil, ink, equipment, and packed cement bags.

      iii) **Others (services etc.):** Electricity consumed for other processes like lighting plant area, office and colony, water for colony area, other equipment, and fuels for the canteen.

5.8.2 Life Cycle Inventory

As per methodology, the six methods are conducted to find the LCI analysis.

1) **Preparation of data collection:** Same as that for clinker analysis as data collection is done at same site visits (section: 4.2.2).

2) **Data collection, formatting and compiling:** Same as that for clinker analysis as data collection, formatting and compilation is conducted together (Section: 4.2.2).
3) **Data validation:** Is conducted as per defined methodology. The results are provided in Annexure (Table C. 6).
4) **LCI analysis:** The total clinker used for OPC and PPC produced was not provided. Thus the calculation using miscellaneous data is carried out as the first step. It is found by solving two equations with clinker to cement ratio of OPC and PPC, total clinker and total cement produced. Thus the clinker content for OPC and PPC are obtained. Using the respective clinker to cement ratio, OPC and PPC produced are also calculated. In the first step, the calculation using miscellaneous data is conducted. The data regarding the clinker content was only provided. Based on the assumption gypsum content is the same for OPC and PPC (total cement). The gypsum content is calculated. The remaining percentage apart from clinker and gypsum is assumed to be from the contribution of fly ash (Table C. 10). In the second step, the LCI analysis is conducted using absolute data (Table C. 8). In the third step, the LCI analysis is conducted using reference flow data (Table C. 9). The LCI results are provided as input-output category-wise and process-wise in Table 5.33 and Table 5.34 respectively.
5) **LCI data aggregation:** LCI result aggregated is also calculated. Since every data is a different kind the aggregated result is same as LCI result – Input-output category-wise
6) **Refining the system boundary:** No change in system boundary

Table 5.33: CS 2: LCI result for production of PPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.650	Ton/ton of PPC
Gypsum	0.020	Ton/ton of cement
Fly ash	0.330	Ton/ton of PPC
Electricity		
Electricity	28.03	kWh/Ton of cement
Ancillary materials		
Water	0.0471	Ton/Ton of cement
Other physical inputs		
LPG	1.08E-05	Ton/ton of cement
Output	**Value**	**Unit**
Product		
PPC produced	1	Ton/ton of PPC
Emission to air		
CO_2	9.92E-08	Ton/ton of cement
Freon (R22)	1.18E-07	Ton/ton of cement

Table 5.34: CS 2: LCI result for production of PPC (process–wise)

Process	Value	Unit
Grinding of cement - packing of cement		
Input		
Clinker	0.650	Ton/ton of PPC
Gypsum	0.020	Ton/ton of cement
Fly ash	0.330	Ton/ton of PPC
Electricity	28.03	kWh/Ton of cement
Output		
PPC produced	1	Ton/ton of PPC
Others		
Input		
Water	47.1	kg/Ton of cement
LPG	1.08E-05	Ton/ton of cement
Output		
CO_2	9.92E-08	Ton/ton of cement
Freon (R22)	1.18E-07	Ton/ton of cement

5.8.3 Interpretation

1) Identification of significant issues

a) Structured results

To get a holistic view on results, the LCI results are structured data type and process wise. The structured result is provided in Table 5.35.

Table 5.35: CS 2: LCI result for production of PPC (structured)

Unit processes / Data category-wise	Grinding to packing of cement	Other processes	Total
Clinker (kg/ton of PPC)	650		650.00
Gypsum (kg/ton of cement)	20.42		20.42
Fly ash (kg/ton of PPC)	329.58		329.58
Electricity (kWh/Ton of cement)	28.03		28.03
Water (kg/Ton of cement)		47.1	47.10
LPG (gm/ton of cement)		10.77	10.77
CO_2 (mg/ton of cement)		99.2	99.21
Freon (R22) (mg/ton of cement)		118.11	118.11

b) Analysis

Apart from clinker and fly ash value all the results are the same as that of OPC and thus the contribution and anomaly results look same.

i) Contribution

The data like clinker, gypsum, fly ash and electricity is associated completely (100%) with a group of the process from grinding to the packing of cement. The data like water, LPG, CO_2 and Freon (R22) is associated completely (100%) with "other" processes.

ii) Anomaly

According to Cement, Pozzolana and fly ash LCI from Ecoinvent database V3 corresponding, clinker content reported is 688.75 kg and 731.5 kg for four different geographical area across the globe. The clinker value (650 kg) obtained in the study seems to be a little low than expected range. From the above-mentioned inventory, the gypsum content is reported as 47.5 kg and 50 kg for different geographical region across the globe. The value obtained in the study (20.42 kg) seems to be low than expected range. According to IS 1489 Part 1 (1991), the fly ash should be of 15-35% of the cement. The fly ash consumed (329.58 kg) is within this limit thus the value was as expected. From the Ecoinvent database four electricity consumption value is found in a range of 37.6-55.8 kWh, were two values lies in the lower limit and two values lie around the higher limit. The value obtained in the study (28.03 kWh) seems to be less than the expected range. The water consumption per ton of Portland cement is in a range of 537 - 1605 kg as per values reported in literature (Josa et al. 2004; Li et al. 2014; Marceau et al. 2006). Compared to this the value in the study (47 kg) seems to be too low. Few new values like Freon, CO_2 from a fire extinguisher, LPG for factory and canteen usage were found, which is having negligible value

2) **Evaluation**

   a) **Completeness check:** The data incompleteness is present. The values like clinker for PPC, PPC produced, gypsum, and fly ash are calculated based assumption and miscellaneous data. There is a lack of other data also. Electricity breakup is also not provided.

   b) **Consistency check:** Data accuracy is not consistent. The units are rounded of differently.

3) **Conclusions, limitations and recommendations**

   a) **Conclusions**

      i) The inventory details of the PPC are identified and quantified. The inventory results obtained are clinker (650 kg), fly ash (330 kg), gypsum (20 kg), electricity (28 kWh), water (47.1 kg), LPG (11 gm), CO_2 (99 mg) and Freon R22 (118 mg). One of the applications of water is sprinkling in a ball mill to cool the system. The LPG is consumed in the canteen, CO_2 is from a fire extinguisher and the Freon R22 is consumed as a refrigerant**.**

      ii) The data like clinker, gypsum, fly ash and electricity is associated completely (100%) with a group of the process from grinding to the packing of cement. The data like water, LPG, CO_2 and Freon (R22) is associated completely (100%) with "other" processes.

      iii) The fly ash amount seems to be within the recommendation of Indian standards. The inputs like clinker, gypsum, electricity and water seem to be low with respect to the expected values. The data like LPG, CO_2, and Freon (R22) are unexpected or new data observed.

   b) **Limitations**

      i) The data incompleteness is present. The values like clinker for PPC, PPC produced, gypsum, and fly ash are calculated based assumption and miscellaneous data. There is a lack of other data also. Electricity breakup is also not provided.

ii) Data accuracy is not consistent. The value of data is rounded of differently.

c) Recommendation

The data can be submitted to the LCI database as the inventory for Indian PPC. The Inventory data can be used for impact assessments, estimation of energy and cost. It needs to be stated that the data is valid with the limitations of assumptions made during calculation. Reiteration of data collection can be conducted to collect a more complete set of data, rectify these assumptions. The inventory data on the equipment (e.g. ball mill and cyclone separator) and infrastructure (e.g. buildings for equipment, office buildings and colony) was not obtained. Thus further data collections can improve the completeness of inventory. More analysis can also be conducted on the current LCI results.

5.9 Energy use for PPC production

As defined in the methodology chapter a detailed and structured analysis is carried out. The four sections and the key information from the same is provided as follows.

5.9.1 Goal and scope

The goal and scope are defined initially before the analysis. It will be subjected to alterations as the study progresses and at the end of the study, the goal and scope defined will be of adjusted form. This final goal and scope after the analysis is reported here. Goal and scope defined

1) Goal

The goal and scope are same as that of energy consumption calculation of OPC (section: 5.6.1), except few sub-elements like objective which is provided below

a) Objective

To quantify the energy consumption related to the production of PPC (Portland Pozzolana Cement) in a typically integrated cement factory in India

5.9.2 Life Cycle Inventory

The life cycle inventory result provided in the PPC - LCA for inventory section is used here (Section: 4.8.2)

5.9.3 Energy calculation

The selected inventory results are converted to energy using suitable energy factors,

1) **Energy calculation methodology:** Same as defined in section 5.6.3.

2) **Classification**

The inventory results obtained is classified into selected and rejected data for energy calculation. The selected data is those which contribute towards the embodied energy of the PPC within gate to gate analysis. The LCI selelcted are provided in table 5.36.

Table 5.36: CS 2: LCI selected for calculation of energy for production of PPC (input-output category–wise)

Input	Value	Unit
Raw material		
Clinker	0.650	Ton/ton of PPC
Electricity		
Electricity	28.03	kWh/Ton of cement
Other physical inputs		
LPG	1.08E-05	Ton/ton of cement

As explained before from the LCI results few data are rejected as it is not contributing to the energy consumed within gate to gate system boundary. Such data are provided below

1) **Input** :
   a) **Raw material**: Fly ash, and gypsum
   b) **Ancillary inputs**: Water
2) **Output**
   a) **Emission to air:** CO_2, and Freon (R22)

3) **Energy calculation**

The energy is calculated using the suitable energy factor values

a) **Energy factor**

The energy factor for selected inventory data is provided in Table 5.37.

b) **Energy calculation**

The selected inventory result is multiplied with energy factor to get the total energy use for PPC. The energy results are provided as input-output category-wise and process-wise in Table 5.38 and Table 5.39 respectively.

Table 5.37: CS 2: Energy factors for calculation (OPC)

Input	Value	Unit	Remark
Electricity			
Electricity	13.40	MJ/kWh	Sum of energy consumed from fuels in thermal power plant and fuel for transportation. Source: Case study 1
Fuel			
LPG	51.80	MJ/kg	Formula = Heating value / Density. The unit is converted from MJ/L to MJ/kg by dividing with density. Heating Value, Source: EPA 2014, fuel named: Liquefied Petroleum Gases (LPG). The density used in 0.495kg/litre, Source: http://www.elgas.com.au/blog/453-the-science-a-properties-of-lpg.
Raw material			
Clinker	3625	MJ/ton of clinker	The energy from processes like extraction of raw material, limestone crushing till clinkerization, and transportation, within gate to gate system boundary.

Table 5.38: CS 2: Energy use for the production of PPC (input-output category–wise)

Inventory	Energy	Unit
Raw material		
Clinker	2356.41	MJ/ton of PPC
Electricity		
Electricity	375.57	MJ/ton of cement
Other physical inputs		
LPG	0.56	MJ/ton of cement
Total	**2732.54**	**MJ/ton of PPC**

Table 5.39: CS 2: Energy use for the production of PPC (process–wise)

Process	Energy	Unit
Grinding of cement till packing		
Input		
PPC	2356.41	MJ/ton of PPC
Electricity	375.57	MJ/ton of PPC
	2731.98	**MJ/ton of PPC**
Others		
Inputs		
LPG	0.56	MJ/ton of PPC
	0.56	**MJ/ton of PPC**
Total	**2732.54**	**MJ/ton of PPC**

5.9.4 Interpretation

The results obtained in the energy calculation is interpreted here with respect to the goal and scope

1) Identification of the significant issues

The energy use is structured process-wise in column and data-wise in a row to get a holistic view. It is then analysed to identify the significant issues. The structured results are provided in Table 5.40.

a) Structured result

Table 5.40: CS 2: Energy use for the production of PPC (process–wise)

Unit processes / Data category	Grinding to packing of cement	Other processes	Total
Clinker	2356.41	-	2356.41
Electricity	375.57	-	375.57
LPG	-	0.56	0.56
Total	2731.98	0.56	2732.54

Note: All values are in MJ/ton of PPC

The embodied energy of PPC within gate to gate is calculated. The main input considered are embodied energy of clinker (2356 MJ) and the embodied energy of electricity (376 MJ). The embodied energy of PPC is 2733 MJ/ton of PPC**.** The other input, LPG is of negligible contribution.

b) Analysis

i) Contribution

The main input which contributes to embodied energy is Clinker (`86%) and electricity (`14%). Both belong to set of processes from grinding to the packing of cement.

ii) Anomaly

Clinker and electricity are the primary contributing inputs in embodied energy. The embodied energy contribution for different data is measured using LCI from Ecoinvent database V3 and impact assessment method "Cumulative energy Demand V1.09". The analysis is conducted for four different geographical area. All the comparative statements are made with respect to this analysis. The embodied energy of clinker varies from 2180-2800 MJ, where three of them are above 2600MJ. The value obtained in the study (2356 MJ) seems to be low. The embodied energy of electricity is in range of 334-534 MJ where three of them are below 370 MJ. Compared to this the corresponding value obtained in the study is 376 MJ, which seems to be high. The total embodied energy of electricity and clinker is in range of 2514-3165 MJ, where three of them are above 3100MJ. The corresponding value in the study (2732 MJ) seems to be low among most of the expected values.

2) **Evaluation**

a) **Completeness check:** Apart from the incompleteness in LCI, Incompleteness is found in embodied energy factor of electricity and calorific value of LPG

b) **Consistency check:** Apart from inconsistency in LCI analysis, no inconsistency is met during energy calculation.

3) **Conclusions, limitations and recommendation**

a) **Conclusions:**

i) The embodied energy of the PPC within the gate to gate system boundary is calculated as 2732.54 MJ/ton of PPC. The result is valid within the limitations of data quality. The main energy contributing data is clinker with embodied energy contribution of 2356 MJ and electricity contributes around 376 MJ. The other input, LPG is of negligible contribution.

ii) The main input which contributes to embodied energy is clinker (`86%) and electricity (`14%).

iii) The embodied energy of clinker seems to be low, and electricity seems to be high with literature. Both lie in the expected range. The sum of the embodied energy of clinker and electricity also seems to be low, however, it is within the expected range.

b) **Limitations:**

i) a part from the incompleteness in LCI, Incompleteness is found in embodied energy factor of electricity and calorific value of LPG

ii) Apart from inconsistency in LCI analysis, no inconsistency is met during energy calculation.

c) **Recommendation:** The embodied energy value can be reported in embodied energy database as a value corresponding to Indian PPC. The data can also be used in calculating the embodied energy of PPC. The reiteration of data can be conducted to get more data and also data with break-up value towards different unit processes. The calorific value of the fuels can also be collected from the cement plant.

5.10 CO_2 emissions for PPC production

5.10.1 Goal and Scope

The goal and scope are same as defined in the embodied CO_2 calculation of the OPC (Section: 4.7.1), few sub-elements which are different is provided as follows.

1) Goal

- **a) Objective**: To compute the CO_2 emission related to the PPC production within gate to gate system boundary

5.10.2 Life Cycle Inventory

The life cycle inventory result provided in the section 5.8.2 for inventory is used here

5.10.3 CO_2 emission calculation

CO_2 emissions of PPC is calculated in three steps in this section.

1) CO_2 emission calculation methodology: It is same as provided in section 5.7.3

2) Classification

The LCI data which is associated with CO_2 emissions are selected from LCI results for calculation. The selected LCI data are provided in Table 5.41.

Table 5.41: LCI selected for calculation of CO_2 emissions for production of PPC

Input	Value	Unit
Raw material		
Clinker	0.650	Ton/ton of PPC
Electricity		
Electricity	28.03	kWh/ton of cement
Other physical inputs		
LPG	1.08E-05	Ton/ton of cement
Output	**Value**	**Unit**
Emission to air		
CO_2	9.92E-08	Ton/ton of cement

The data which is assumed to be not associated with the CO_2 emissions are as follows.

1) **Input**

a) **Raw material** – Gypsum and fly ash

b) **Ancillary materials** – Water

2) **Output**

a) **Emission to air**: Freon

3) **CO_2 emission calculation**

The CO_2 emission is calculated using the suitable CO_2 factors.

a) **CO_2 emission and embodied CO_2 factors**

The CO_2 factor of selected inventory data is provided in Table 5.42.

Table 5.42: CO_2 emission factors for calculation (PPC)

Input	Value	Unit	Remarks
Electricity			
Electricity	1.09	kg CO_2/kWh	Sum of CO_2 emission from fuels in a thermal power plant. Source: Case study 1
Raw material			
Clinker	867.35	kg CO_2/ton of clinker	CO_2 release due to decomposition of carbonates in raw material, burning of fuel for clinkerization, Embodied CO_2 of electricity. Source: Case study 2, Dalmia cement plant.
Other physical input			
LPG	2.91	Kg CO_2 /kg	The LPG kg CO_2 factor, Time Period: yearly, Source: File: Co2 emission.xls, Worksheet: co2 emissions, Table 5.1 SCOPE 1 Emissions, Cell address: E9. The unit is not provided checking with the value reported in the "Table 5.2, India: Greenhouse Gas Emissions 2007, INCCA, MoEF" and considering the density of 0.495kg/litre. The possible unit is kg CO_2/kg. Density value, source: http://www.elgas.com.au/blog/453-the-science-a-properties-of-lpg.
Output	**Value**	**Unit**	**Remark**
Emission to air			
CO_2	1.00	Kg CO_2/kg CO_2	The CO_2 emission factor

b) **CO_2 emission calculation**

The selected inventory result is multiplied with CO_2 factors to get the total embodied CO_2 of the PPC. The CO2 emission results are provided in Table 5.43.

Table 5.43: CS 2: CO_2 emissions for production of PPC (input-output category–wise)

Input	CO_2 emissions	Unit
Electricity		
Electricity	30.47	kg CO_2/ton of PPC
Raw material		
Clinker	563.78	kg CO_2/ton of PPC
Other physical inputs		
LPG	3.14E-02	kg CO_2/ton of PPC
Output		
Emission to air		
CO_2	9.92E-05	kg CO_2/ton of PPC
Total	**594.28**	**kg CO_2/ton of PPC**

Table 5.44: CS 2: CO_2 emissions for production of PPC (process–wise)

Process	CO_2 emissions	Unit
Grinding of cement till packing of cement		
Input		
Clinker	563.78	kg CO_2/ton of PPC
Electricity	30.47	kg CO_2/ton of PPC
	594.25	**kg CO_2/ton of PPC**
Others		
Input		
LPG	3.14E-02	kg CO_2/ton of PPC
Output		
CO_2	9.92E-05	kg CO_2/ton of PPC
	3.15E-02	**kg CO_2/ton of PPC**
Total	**594.28**	**kg CO_2/ton of PPC**

5.10.4 Interpretation

The results obtained in the CO_2 emission calculation is interpreted here with respect to the goal and scope

1) Identification of the significant issues

The embodied CO_2 is structured and analysed to identify the significant issues. The structured CO_2 emissions results are provided in Table 5.45.

a) Structured result

The embodied CO_2 of PPC is calculated within gate to gate system boundary. The embodied CO_2 from clinker (566 kg) and electricity (30 kg) contributes the most with negligible contribution from CO_2 from LPG and fire extinguisher. The embodied CO_2 of PPC is calculated as 594 kg CO_2.

Table 5.45: CS 2: CO_2 emissions for production of PPC (structured)

Data category \ Unit processes	Grinding to packing of cement	Other processes	Total
Embodied CO_2 from clinker	563.78		563.78
Embodied CO_2 from electricity	30.47		30.47
CO_2 release from LPG		3.14E-02	0.03
CO_2 release from a fire extinguisher		9.92E-05	0.00
Total	594.25	0.03	594.28

Note: All values are in kg CO_2/ton of PPC

b) Analysis

i) Contribution

The clinker contributes thus 95% of the total embodied CO_2 and 5% of the emission is from electricity. The CO_2 contribution from other inputs are negligible (<0.01%)

ii) Anomaly

The CO_2 associated with data is calculated using inventory from Ecoinvent database V3 and modified version of the impact assessment method "IPCC 2013 GWP100a", for four different geographical area. The embodied CO_2 of clinker varies from 584-690 kg, where three of them are above 640 kg. The value obtained in the study (564 kg) seems to be low than expected range. The embodied CO_2 of electricity is in range of 2.79-29.4 kg where three of the value is above 14 kg. The corresponding value obtained in the study (30.47 kg) seems to be higher than expected values. The total embodied CO_2 of electricity and clinker is in range of 587-712 kg, where three of them are above 670 kg. The corresponding value in the study (594 kg) lies in the lower limit of expected values.

2) Evaluation

a) Completeness check: The incompleteness faced is in obtaining the embodied energy of electricity and calorific value of the LPG (with proper unit) from the cement plant. For electricity, the value from case study 1 is cited and for LPG, a factor from cement plant is used after unit correction.

b) **Consistency check:** All the consistency issues are faced during the LCI analysis are applicable here also. Apart from that, the embodied CO_2 calculation methodology followed is consistent

3) **Conclusions, limitations and recommendation**

a) **Conclusions:**

i) The embodied CO_2 of PPC within gate to gate system boundary is 594 kg CO_2.

ii) The clinker contributes thus 95% of the total CO_2 emission and 5% of the emission is from electricity.

iii) The embodied CO_2 from clinker is lower than expected values. Electricity is high, however, lies within the expected range. The total embodied CO_2 of clinker is lower, still within the expected values.

b) **Limitations:**

i) The incompleteness faced is in obtaining the embodied energy of electricity and calorific value of the LPG (with proper unit) from the cement plant. For electricity, the value from case study 1 is cited and for LPG value from cement plant is used after unit correction.

ii) Apart from the inconsistencies in LCI result, embodied CO_2 calculation methodology is consistent

c) **Recommendation:** The embodied CO_2 value can be reported in the building materials embodied CO_2 databases, as a value corresponding to Indian PPC in the gate to gate system boundary. It needs to be mentioned along with the assumptions and limitations associated with calculation. Another data collection can be conducted to find the embodied CO_2 of electricity and suitable CO_2 emission factors of fuels.

CHAPTER 6

COMPARISON OF CASE STUDIES WITH CSI DATA

6.1 Introduction

Two case studies are conducted in order to set the baseline LCI, embodied energy and embodied CO_2 related to clinker the within gate to gate system boundary. In this chapter, the results are compiled and compared to form an average LCI, embodied the energy and embodied emission for clinker produced in India. The findings are compared with the CSI data in order to understand the reliability of the results. These values are also expected to be used for further calculations as a typical LCI, embodied energy and embodied CO_2 related to clinker produced in India.

6.2 Life Cycle Assessment for clinker production

The inventory, energy use and CO_2 emissions are reported and the average value of each is found which can represent a typical value for the region of case studies (Reddipalayam district). There are data which are not commonly present in every case study. Thus, the data categories and unit processes presented is a comprehensive list. Thus, provision is provided to report all the type of data present. Sometimes, even data category is subdivided based on the flow of the data towards different processes. In order to find the average LCI data set, the average of the inventory values are calculated and reported, if the data is not available the average of the existing values are reported.

6.2.1 Life Cycle Inventory analysis

The LCI results obtained in the two case studies are reported here input-output category-wise. Certain categories are subdivided based on the processes towards which the data is flowing. The data cannot be represented process wise as the table seems to be lengthy, as the intermediate output and the inputs are reported, and further if the data is consolidated in order to make it compact, it can lead to the loss of clarity on data. Table 6.1 presents the LCI results of two case studies on clinker and the average value for LCI of clinker. The average LCI data set represents the LCI for production of clinker within gate to gate system boundary for the region studied (Reddipalayam district) based on two case studies.

Table 6.1: Average LCI results of clinker

Input	**Case study 1**	**Case study 2**	**Average LCI data set**	**Unit**
Energy - Electricity (Extraction)	-	0.09	0.09	kWh / ton of clinker
Energy - Electricity (Limestone crushing till clinkerization)	59.92	49.80	54.86	kWh / ton of clinker
Energy – Fuel	114.97	111.28	113.12	kg / ton of clinker
Raw material - Limestone and marl	1.45	1.38	1.42	ton / ton of clinker
Raw material - White clay	0.034	0	0.017	ton / ton of clinker
Raw material - Fire clay	0	0.021	0.011	ton / ton of clinker
Raw material – Feldspar	0	0.010	0.005	ton / ton of clinker
Raw material - ETP Sludge	0.021	0	0.011	ton / ton of clinker
Raw material - Fly ash (in kiln feed)	0.008	0	0.004	ton / ton of clinker
Other physical inputs - Transportation - Diesel (Limestone extraction process)	1.723	0.202	1.318	kg / ton of clinker
Other physical inputs - Transportation - Diesel (Limestone transportation process)		0.712		kg/ton of clinker
Other physical inputs - Transportation - Diesel oil (onsite transportation)	0.783	-	0.783	kg / ton of clinker
Others - Refractories and castable	0.426	-	0.426	kg / ton of clinker
Output	**Case study 1**	**Case study 2**	**Average LCI dataset**	**Unit**
Waste - Releases to air - CO_2 from diesel for extraction of limestone	5.45	0.65	4.20	kg / ton of clinker
Waste - Releases to air - CO_2 from diesel for transportation of limestone		2.29		kg / ton of clinker
Waste - Releases to air - CO_2 from diesel oil (onsite transportation)	2.48	-	2.48	kg / ton of clinker
Waste - Releases to air - CO_2 from fuel	260.40	281.51	270.95	kg / ton of clinker
Waste - Releases to air - CO_2 from raw meal	514.86	529.31	522.08	kg / ton of clinker
Waste - Releases to air – SPM	0.156	0.100	0.128	kg / ton of clinker
Waste - Releases to air - SO_2	0.034	-	0.034	kg / ton of clinker
Waste - Releases to air – NO_x	1.878	-	1.878	kg / ton of clinker
Waste - Releases to air - Radiation and Convection losses from cooler	186.19	217.57	201.88	MJ / ton of clinker

Note: If a data is not present in a set of LCI dataset, zero is reported. If a data is present, but not available in the LCI dataset '–' is mentioned.

6.2.2 Energy use

The energy use of clinker in both case studies are compiled and the average value of energy use is calculated. The results are reported and the average value is calculated input-output category-wise and process-wise. The average value of the embodied energy is 3824MJ/ton of clinker. Due to lack of break up, certain values are reported as aggregated values of two or more categories. It needs to be noted that the results are not the average of total energy values of two case studies. It is the sum of the average of the values corresponding to each category. Thus, if data is only present in one LCI dataset that value itself is reported (as it is the average value). Thus, the average total energy calculated will be higher than the normal average of two total energy values.

Table 6.2: Average energy use for clinker – input-output category–wise

Input/output	**Case study 1**	**Case study 2**	**Average value**	**Unit**
Energy – Fuel	3079.56	2916.30	2997.93	MJ/ton
Energy – Electricity	802.85	668.46	735.65	MJ/ton
Other physical inputs - Transportation of limestone	73.51	30.60	57.00	MJ/ton
Other physical inputs - Extraction		9.89		MJ/ton
Other physical inputs - Onsite transportation	33.42	-	33.42	MJ/ton
Total	**3989.35**	**3625.25**	**3824.01**	**MJ/ton**

Table 6.3: Average energy use for clinker – process–wise

Process	**Case study 1**	**Case study 2**	**Average Value**	**Unit**
Limestone extraction	73.51	9.89	57.00	MJ/ton
Limestone transportation		30.60		
Limestone crushing, stacking and reclaiming	13.63	3584.76	3733.59	MJ/ton
Raw meal preparation	310.28			
Fuel preparation	79.72			
Clinkerization, cooling and storing	3478.78			
Others (services etc)	33.42	-	33.42	MJ/ton
Total	**3989.35**	**3625.25**	**3824.01**	**MJ/ton**

6.2.3 CO_2 emissions

CO_2 emissions calculated for two case studies are reported input-output category-wise and process-wise in Table 6.4 and Table 6.5. As mentioned in section 6.2.2, few values are reported in aggregated values due to unavailability of breakup values. Also, the average values of each category are reported and added up. If data is only available in one data set and not in other data set, the value from the first data set is reported as it is the average value. Thus, the average CO_2 emissions are slightly higher than the simple average value of CO_2 emissions reported in each case study. Thus, the CO_2 emissions corresponding to Indian clinker is calculated and reported based on two case studies.

Table 6.4: Average CO_2 emissions results for clinker - input-output category–wise

Input/output	**Case Study 1**	**Case Study 2**	**Average value**	**Unit**
Indirect CO_2 from electricity	65.14	54.24	59.69	kg CO_2/ton of clinker
CO_2 from fuel for clinkerization	260.40	281.51	270.95	kg CO_2/ton of clinker
CO_2 from raw meal	514.86	529.31	522.08	kg CO_2/ton of clinker
CO_2 from diesel for transportation of limestone	5.45	2.29	4.24	kg CO_2/ton of clinker
CO_2 from diesel for extraction		0.75		kg CO_2/ton of clinker
CO_2 from diesel for onsite transportation	2.48	-	2.48	kg CO_2/ton of clinker
Total	**848.32**	**867.35**	**859.45**	**kg CO_2/ton of clinker**

Table 6.5: Average CO_2 emissions results for clinker - process–wise

Process	**Case Study 1**	**Case Study 2**	**Average value**	**Unit**
Limestone extraction	5.45	0.75	4.24	kg CO_2 / ton of clinker
Limestone transportation		2.29		kg CO_2 / ton of clinker
Limestone crushing, stacking and reclaiming	1.11	864.31	852.35	kg CO_2 / ton of clinker
Raw meal preparation	25.18			kg CO_2 / ton of clinker
Fuel preparation	6.47			kg CO_2 / ton of clinker
Clinkerization, cooling and storing	807.65			kg CO_2 / ton of clinker
Others (services etc)	2.48	-	2.48	kg CO_2 / ton of clinker
Total	**848.32**	**867.35**	**859.07**	**kg CO_2 / ton of clinker**

6.2.4 Comparison of results with CSI

In this section, the results are compared with respect to the CO_2 and energy performance indicators of CSI. CSI is a global sustainability program of WBCSD, a global NGO. 4 indicators are considered say, Gross CO_2 emission, Net CO_2 emission, Specific heat consumption and Power consumption up to and including clinkerization. The equation of each indicator is provided in Equation 6.1 (Eq 6.1), Equation 6.2 (Eq 6.2), Equation 6.3 (Eq 6.3) and Equation 6.4 (Eq 6.4) respectively. Using the above formulas, results reported for case studies one and two are converted in terms of the CSI performance indicators. These values along with the values reported in the CSI database corresponding to the Indian average and world average is reported in Table 6.6.

$$\begin{aligned}
&Gross\ CO_2\ emission \\
&= CO_2\ from\ decarbonisation\ of\ raw\ meal, CKD\ and\ bypass\ dust \\
&+ CO_2\ from\ burning\ of\ organic\ carbon\ in\ raw\ meal \\
&+ CO_2 from\ fossil\ fuels\ and\ alternate\ fossil\ fuels\ used\ for\ clinkerization \\
&+ CO_2\ from\ onsite\ transportation + CO_2\ from\ room\ heating\ and\ cooling \\
&+ CO_2 from\ drying\ of\ mineral\ components
\end{aligned} \qquad Eq.\ 6.1$$

$$\begin{aligned}
Net\ CO_2 emission &= Gross\ CO_2 emission \\
&-\ CO_2\ from\ alternate\ fossil\ fuels\ used\ for\ clinkerization
\end{aligned} \qquad Eq.\ 6.2$$

$$\begin{aligned}
&Specific\ heat\ consumption \\
&= Heat\ from\ the\ burning\ of\ fuel, alternative\ fuels, and\ biomass\ fuels\ used\ for\ clinkerization
\end{aligned}$$
$Eq.\ 6.3$

$$Power\ consumption = Electricity\ consumed\ till\ and\ including\ clinkerization$$
$Eq.\ 6.4$

Table 6.6: Comparison with CSI performance indicators

Performance indicators	Unit	Case study 1	Case study 2	Average values	CSI data India (2013-2014)*	CSI data Global (2013-2014)*
Specific heat consumption	MJ / t clinker	3080	2917	2999	3067	3513
Gross CO_2 emissions	kg CO_2/ton of clinker	775	810	784	828	842
Net CO_2 emissions	kg CO_2/ton of clinker	755	801	779	822	814
Power consumption up to and including clinker production	kWh / t clinker	60	50	55	63	70

Note: * - All values are from CSI (2014)

Both the case studies are based on the data during the 2014-2015 fiscal year. The alternative fuels used in the second case study is solid waste fuels and spent wash. Spent wash is neither biomass fuel nor fossil fuel and thus classified as alternative fossil fuels. Solid waste fuels can have both biomass and alternative fossil fuels. But it is assumed that solid waste fuels are completely composed of alternative fossil fuels in this calculation.

The average value of specific heat consumption for clinker production in India is less with respect to the global average. This shows that the energy consumption of clinkerization in the form of fuel is less for the considered Indian cement plants than the global average. The gross CO_2 emissions are less for Indian average, but the net CO_2 emissions are high this clearly shows that the alternate fossil fuels used are less in India compared to global average. The power consumption value is also comparatively less for the Indian cement industry.

All the indicators like specific heat capacity, gross and net CO_2 and power consumption with respect to the average value of the case studies are comparatively lower than the Indian average reported by the CSI. This shows that the plants considered in this study are more conservative in terms of energy consumption and CO_2 emission with respect to sample set of Indian plants considered by CSI, which is 88 plants belonging to 8 cement companies.

CHAPTER 7

LIMESTONE CALCINED CLAY CEMENT (LC^3)

7.1 Introduction

Limestone and calcined clay (kaolinitic clay) combination are one of the potential additives which can replace clinker content up to 60% (Antoni 2013). In this chapter, the objective of assessing the sustainability aspects, like energy use and CO_2 emissions, of cement based on a mixture of limestone and calcined clay are addressed. The cement based on a mixture of limestone and calcined clay is named as Limestone Calcined Clay Cement. It is also abbreviated as LC^3. The objective is met in two steps. First, the estimation of clay calcination energy is conducted for clay samples with different kaolinite content. In the second step, the energy and CO_2 related to LC^3 production is estimated.

In the first step, the clay calcination energy is estimated. There are different factors affecting the clay calcination energy as shown in Figure 7.1.

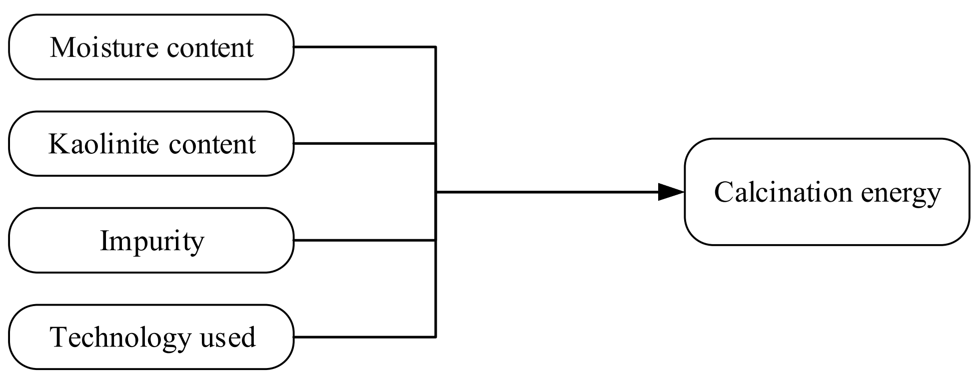

Figure 7.1: Factors affecting calcination energy

The first three factors like moisture content, kaolinite content, and impurity are the material properties and thus depends on the properties of clay considered for the analysis. The last factor is the technology used for the calcination, which reflects the energy contribution due to practical limitations. The details on the contribution of energy from different factors are discussed in the following Table 7.1.

Table 7.1: Factors and different means of energy contribution

Factors	Different means of energy contribution
Moisture	1) The energy consumed for raising the temperature till 100^oC
	2) The latent heat of vaporization at 100^oC during dehydration
Kaolinite content	1) The energy consumed to raise temperature till 700^oC
	2) The energy consumed for the chemical reaction (dehydroxylation) of dissociating kaolinite to metakaolin and water
Impurity	1) The energy consumed to raise temperature till 700^oC
	2) The energy consumed or released related to chemical reaction/s
Technology	1) The additional energy to be supplied beyond the theoretical energy demands depends on the technology used for calcination

The estimation of energy is based on the Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) analysis of clay samples collected. These test results serve as a base for estimation of the theoretical energy required for the calcination of kaolinitic clay. The effect of moisture, kaolinite and impurities will be considered at this estimation. Dry kiln technology is considered in order to scale the energy from the theoretical energy requirement to practical energy demand. Based on literature the energy loss related to technology is estimated. Two cases for the technology is considered. One is a dry kiln with a heat recovery system and other is without heat recovery system. Two scenarios of heat recovery are considered as follows,

1) With heat recovery (WH) – Where clay exits the kiln after calcination with 100^oC
2) Without heat recovery (WoH) – Where clay exits the kiln after calcination with 700^oC

In the second step of estimating the energy and CO_2 emissions for production of LC^3, four cases are considered which are basically two cases corresponding to each heat recovery case. Two cases are as follows,

1) Case one – LC^3 produced with clay having low calcination energy
2) Case two – LC^3 produced with clay having high calcination energy

The low and high calcination energy are chosen from calcination energy calculated for a set of clay samples analyzed (which has a minimum of 40% kaolinite content). In total, a set of four combinations are considered based on heat recovery and calcination energy. The four combinations considered are provided in Table 7.2.

Table 7.2: Four scenarios for clay calcination energy

Calcination energy \ Heat recovery	Without heat recovery	With heat recovery
High	Scenario 1	Scenario 3
Low	Scenario 2	Scenario 4

The energy and CO_2 emissions related to the production of LC^3 with respect to the above mentioned four scenarios are calculated with respect to Case Study 1 and Case Study 2 separately. The results are then compared with the OPC and PPC results of the respective case studies.

7.2 Review of studies on calcination energy

Few studies are present in relation to the estimation of energy required for the chemical reaction of metakaolin formation, similarly few studies are also been reported in estimating the energy required during the industrial production of calcined clay. The energy for the chemical reaction of dissociating the kaolinite to metakaolin and water is called in the literature as activation energy. It is same as the dehydroxylation energy. The activation energy is measured and reported per mole of the kaolinite. This is converted to MJ/ton of kaolinite based on the molar mass. Based on four literature values, it is understood that the values vary between 630-879 MJ/ton of kaolinite. One of the literature has cited a value of 2211 MJ/ton of metakaolin which is equal to 1902 MJ/ton of kaolinite. This value indicates the practical energy consumed for calcination in a flash calciner. Flash calciner in the most efficient technology for calcination. Few values like 4234, 3088, and 2734 MJ/ton of calcined clay are estimated by Cancio Díaz et al. (2017) corresponding to technologies like a repaired old wet kiln, refurbished dry kiln and flash calciner respectively. The literature values are reported in terms of calcined clay and not in terms of kaolinite. The details of the literature are provided in Table 7.3.

Few studies are only available on the quantification of the calcination energy of kaolinite clays from mines as such, with different kaolinite content and impurities. Moreover, a practical energy demand in kiln starting from the clay feed till the calcined clay comes out (including effects of heat recovery) needed to be studied for more understanding. A good estimate on the calcination energy enables to understand the potential of this additive in terms of energy consumption for production. This literature gap of less study on the practical energy requirement for clay calcination process and LC^3 production is addressed in this chapter.

Table 7.3: Calcination energy reported in the literature

Calcination energy and reference	Remarks
630 kJ/kg of kaolinite Cassel et al. 2012	The energy value is a calculated value. The value of energy is 327.154 J/gm of clay for 51.9 % kaolinite content, thus the energy for 100% kaolinite is proportionately calculated as 630.354 J/gm of clay. Lab experiment: The value is based on DSC results and thus corresponds to theoretical energy for the chemical reaction. Heating rate: 10 or 20 ^{o}C/min to a maximum temperature of 1500 ^{o}C. Sample: Porcelain clay, with 50.5 kaolinite content (based on TGA results).
755.36±7.74 kJ/kg of kaolinite Ptáček et al. 2011a	Estimated energy value from the results provided in the literature. The apparent activation energy or calcination energy correspond to 195±2 kJ×mol^{-1}. The apparent activation energy when converted with respect to kaolinite content (by dividing with molar mass 258.156 gm/mol), activation energy will be 755.36±7.74 J/gm. Lab experiment: Differential Thermogravimetry (DTG) technique under non-isothermal conditions. Kissinger method is used to find the activation energy. Heating rate: different rates from 1 to 40 K min^{-1}, to 800 ^{o}C. Sample details: Washed mine clay sample with >90% of kaolinite content; the sample is from the Czech Republic.
879.31±3.87kJ/ kg of kaolinite Ptáček et al. 2010a	The median of overall activation energy (227±1 kJ mol^{-1}) can be converted in terms of mass by dividing with a molar mass of (258.156 gm). The results values are 879.31±3.87 J/gm. Lab experiment: Thermogravimetric Analysis (TGA) experiments under non-isothermal conditions. Heating rate: from 1 to 40 K min^{-1}, to a maximum temperature of 850 ^{o}C. 91.6% of kaolinite content. Sample type: Washed mine clay with 91.6% of kaolinite content, impurities like minerals of mica and quartz are present, and a trace amount of hematite (0.85%) and rutile (0.2%) is also present. Sample details: sourced from the Czech Republic. The previous literature value is also from the same author the value is different as the calculation method is different.
782 kJ/kg of kaolinite Ptáček et al. 2010b	Estimated energy value from the results provided in the document. The dehydroxylation of kaolinite to metakaolin shows overall activation energy of 202 kJ/mol, which when converted in terms of kaolinite (using molar mass - 258.156 gm) will be 782.47 J/gm. Lab experiment: Thermogravimetric Analysis (TGA) experiments under isothermal condition. The activation energy is calculated by solving the Arrhenius equation and a third order kinetic equation. The third order is found

Calcination energy and reference	Remarks
	matching for >400 °C. The activation energy presented here is corresponding to 410-500 °C. Heating rate: The sample was heated to 110 °C with rate of 10 °C/min (underflow of argon with rate of 100 cm^3 min^{-1}). This temperature was kept for 30 min (to remove adsorbed water). Dry sample was then rapidly heated at 100 ◦C min−1 to desired temperature (which is located within the investigated interval from 370 to 500 ˚C). Next, the isothermal conditions were held for a time depending on the applied temperature (from 300 min at 500 °C to 3 days at 370 °C). Sample details: 10gm of washed mine clay with 91.6% of kaolinite content. Impurities like minerals of mica and quartz are present, a trace amount of hematite (0.85%) and rutile (0.2%) is also present. The sample is sourced from the Czech Republic.
1902 kJ/kg of kaolinite Cancio Díaz et al. 2017	The energy value is a cited value from other literature (of a different language). The energy value represents the energy consumed in the field with the presence of heat recovery. The cited value is in the form of energy/ton of metakaolin. This is converted to energy/ton of kaolinite to make value comparaable with other literature values. The conversion is conducted by multiplying the molar mass of metakaolin (222.13 gm) and dividing with a molar mass of kaolinite (258.156 gm). The value corresponds to practical industrial production. The technology used is a flash calciner with several heat recovery cycles.
4234 kJ/kg of calcined clay Cancio Díaz et al. 2017	The energy value is reported as an estimated value based on data obtained from other articles. The value corresponds to practical industrial production. The technology used is a repaired old wet kiln.
3088 kJ/kg of calcined clay Cancio Díaz et al. 2017	The energy value is reported as an estimated value based on data obtained from other articles. The value corresponds to practical industrial production. The technology used is a refurbished dry kiln.
2734 kJ/kg of calcined clay Cancio Díaz et al. 2017	The energy value is reported as an estimated value based on data obtained from other articles. The value corresponds to practical industrial production. The technology used is a flash calciner.

7.3 Clay calcination process: Estimation of theoretical clay calcination energy

7.3.1 Clay calcination

Clay calcination is an endothermic process, in which the kaolinite ($Al_2O_3.2SiO_2.2H_2O$) will be dehydroxylated to form metakaolin ($Al_2O_3.2SiO_2$). In this process, two water molecules will be lost. Calcination usually happens between 300 to 700 ^oC. From the maximum calcination temperature of 700 ^oC, it is understood that the calcination is an energy-intensive process. The flash calcination process even goes up to a temperature of 1200 ^oC. There are studies conducted exclusively on the energy consumed for the dehydroxylation reaction of pure kaolinites (as reported in Table 7.3).

An attempt is made to develop a methodology to quantify the theoretical calcination energy, based on Thermo Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) experiments. The TGA analysis gives the profile of mass change with respect to the temperature. Thus, the mass loss or gain which the material experience during the heating, within the defined temperature, will be reflected in the results. A typical graph of TGA analysis of kaolinitic clay is provided in Figure 7.2. The drop at 100 ^oC corresponds to a loss of moisture and the drop between temperatures 300 ^oC to 700 ^oC corresponds to change in energy due to dehydroxylation.

The DSC analysis results give the profile of the heat flow through the sample. The heat absorption and release can be distinguished by the sign conversion of the value of the curve. The endothermic reaction or the reactions which absorb energy the heat flow will be positive. The exothermic reaction or the reactions where heat is released the heat flow will be negative. This sign conversion is also found reversed in certain results. In either case, both the reactions can cause heat flow measurement but in opposite signs. The value will be steady for most of the temperature, which indicates the amount of energy consumed by the samples to raise the temperature. A typical graph of DSC analysis results on the kaolinitic clay samples is provided in Figure 7.3. The hump at 100 ^oC corresponds to energy absorbed for dehydration and the jump between temperatures 300 ^oC to 700 ^oC corresponds to energy absorbed for dehydroxylation.

The DSC results provided in Figure 7.3 is converted to a cumulative form in Figure 7.4. The cumulative DSC values are plotted against the corresponding temperature. This is to easily understand the total energy consumed till different temperatures, and also the energy consumed between two intervals can also be easily calculated.

The results of TGA/DSC are obtained simultaneously in the form of raw data in a text file. The data primarily contains the temperature ranging between initial temperature till the temperature limit of the experiment and corresponding mass and heat flow through samples. Using the heat flow data the cumulative DSC value is calculated. All the figures are created as explained above. This data is plotted to graphs using a spreadsheet. The TGA, DSC, and cumulative DSC figures in this chapters are plotted as explained.

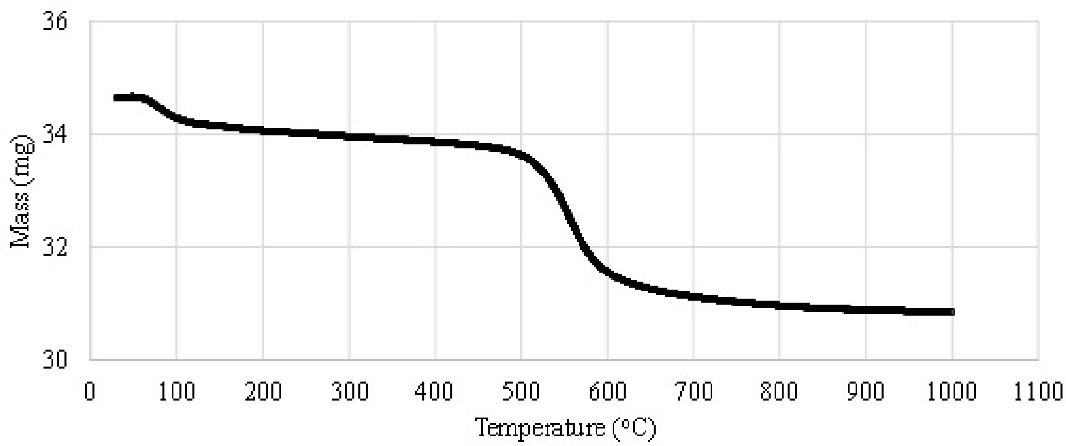

Figure 7.2: Typical TGA result of kaolinite clay

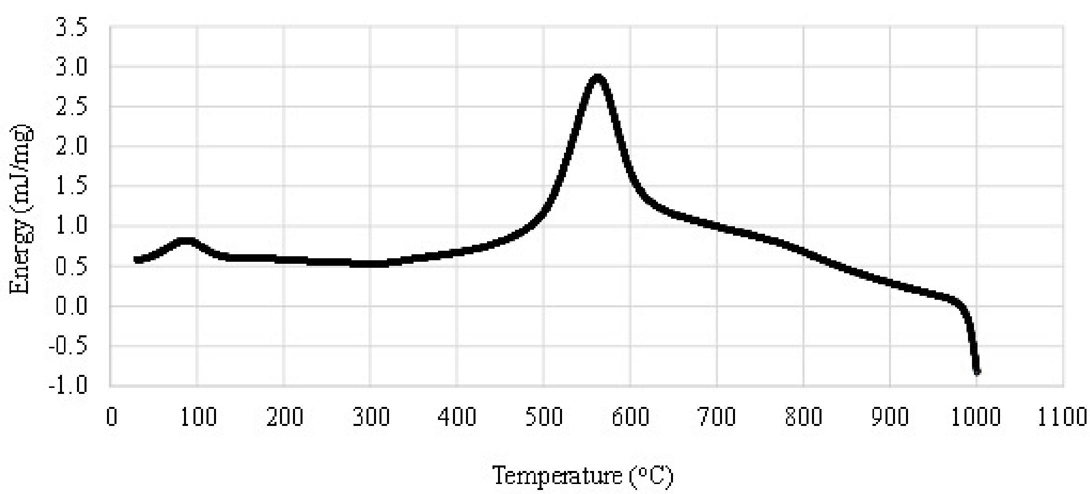

Figure 7.3: Typical DSC curve of kaolinite clay

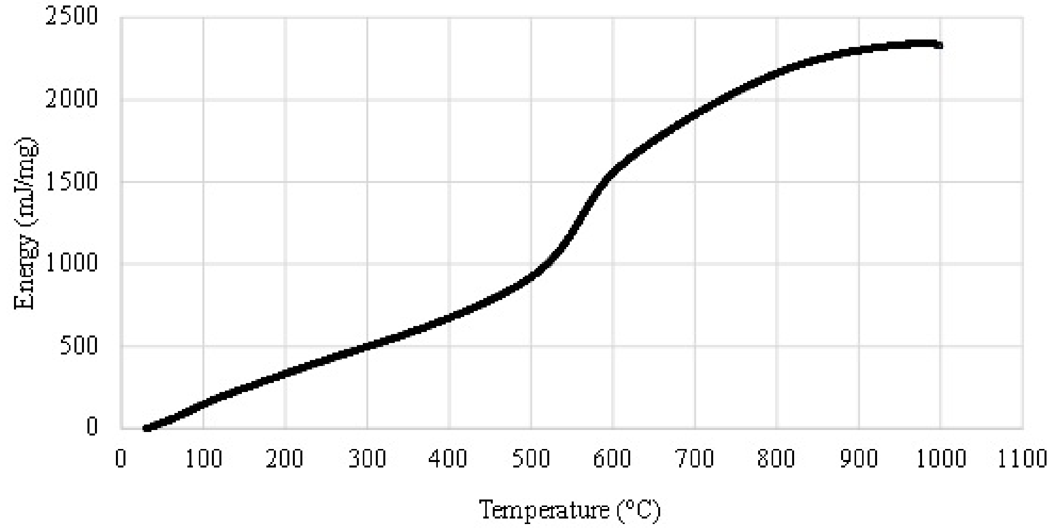

Figure 7.4: Cumulative DSC curve of kaolinite clay

7.3.2 Methodology and Assumptions

Quantification of the area in the DSC plot of clay samples gives the heat flow through the material corresponding to a temperature range considered. In order to quantify the heat consumed for the dehydroxylation reaction a few assumptions are made,

1) It is assumed that the jump in the curve around temperature 300 °C to 700 °C corresponds completely towards the energy consumed for dehydroxylation. Thus the presence of impurities and the mass loss caused due to the same is considered to be due to kaolinite clay.

2) It is assumed that the fall in the TGA curve in this range corresponds completely to mass loss due to dehydroxylation. Thus, the energy consumed during this temperature range by any impurities (like illite and montmorillonite) is considered to be part of calcination. Any mineral other than kaolinite is considered to be an impurity. Thus, the result need not be consistent as that of pure samples.

3) And it is also assumed that the estimated value of specific heat capacity remains constant during heating and cooling of clay.

As mentioned in the introduction section, two cases of heat recovery are considered in order to scale the results to a practical level. The heat recovery cases are as follows:

- Without heat recovery: No heat is recovered and calcined clay comes out at 700 °C.

- With heat recovery: The heat provided (>100 ^{o}C) other than for calcination is recovered back. Thus, the temperature of calcined clay comes out will be 100 ^{o}C

The total heat supplied is calculated based on the following four components

1) **Component 1 (C_1): Heat for evaporation of moisture –** Heat absorbed by water for dehydration
2) **Component 2 (C_2): Heat of dehydroxylation reaction –** The energy consumed by the dehydroxylation reaction alone
3) **Component 3 (C_3): Heat energy of clay to raise temperature –** The energy supplied to raise temperature till 700 ^{o}C
4) **Component 4 (C_4): Heat energy of clay recovered till final solid temperature –** The heat energy of clay recovered when it is cooled from 700 ^{o}C to exit temperature or final solid temperature

For the case of heat recovery, the sum of the first three components minus the fourth component will be the energy consumed. Whereas for the case of without heat recovery the sum of first three components will be the energy consumed. Equation 7.1 (Eq. 7.1) is a case of Equation 7.2 (Eq. 7.2) where the component C_4 is zero.

$$Calcination\ energy\ (with\ heat\ recovery) = C_1 + C_2 + C_3 \quad \dots\dots\dots Eq. 7.1$$

$$Calcination\ energy\ (without\ heat\ recovery) = C_1 + C_2 + C_3 - C_4 \quad \dots\dots\dots Eq. 7.2$$

7.3.3 Defining required parameter

The total energy is calculated based on a few parameters selected from TGA/DSC results and material properties, the parameters are provided in Table 7.4. The parameters are then marked in the TGA graph provided in Figure 7.5 and DSC graph provided in Figure 7.6.

The parameters mentioned in Table 7.4 are basically a set of cumulative heat values and mass values corresponding to a few defined temperatures. The critical temperatures and the corresponding mass values are mentioned in Figure7.5. The mass values mentioned here are used to calculate the moisture amount and the kaolinite content. The calculations formula is mentioned in the later sections.

The critical temperatures and the corresponding heat flow values are mentioned in Figure 7.6. The heat flow values mentioned are later used to calculate the calcination energy per kaolinite content and specific heat capacity. The formulas used for the same are discussed in the later sections. All the numerical values of parameters mentioned in Table 7.4 are used for estimations of calculations.

Table 7.4: Basic parameters from the TGA/DSC graph for energy calculation

Basic parameters		
Parameter	**Symbol**	**Unit**
Initial temperature	T_o	^oC
Water evaporation temperature	T_e	^oC
Final solid temperature	T_f	^oC
150 ^oC Temperature	T_1	^oC
Calcination initiation temperature [300 ^oC]	T_2	^oC
Calcination completion temperature [700 ^oC]	T_3	^oC
Cumulative energy consumed at 150 ^oC	h_1	mJ/mg
Cumulative energy consumed at 300 ^oC	h_2	mJ/mg
Cumulative energy consumed at 700 ^oC	h_3	mJ/mg
Mass of sample at ambient temperature	W_o	Mg
Mass of sample at 150 ^oC	W_1	Mg
Mass of sample at calcination initiation temperature	W_2	Mg
Mass of sample at calcination completion temperature	W_3	Mg
Specific heat capacity of water (Energy/unit mass and temperature)	C_w	mJ/mg ^oC
Latent heat of vaporization of water (Energy/unit mass)	L_w	mJ/mg

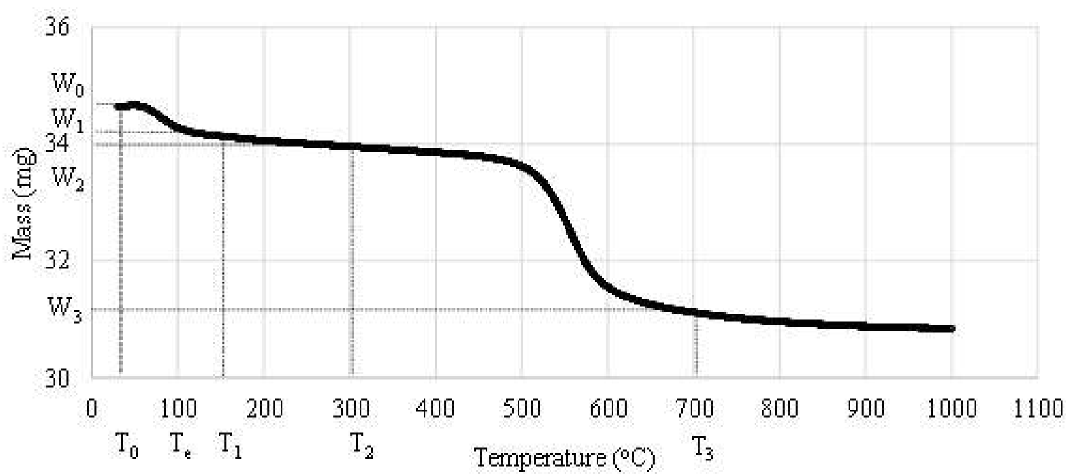

Figure 7.5: TGA graph with parameters

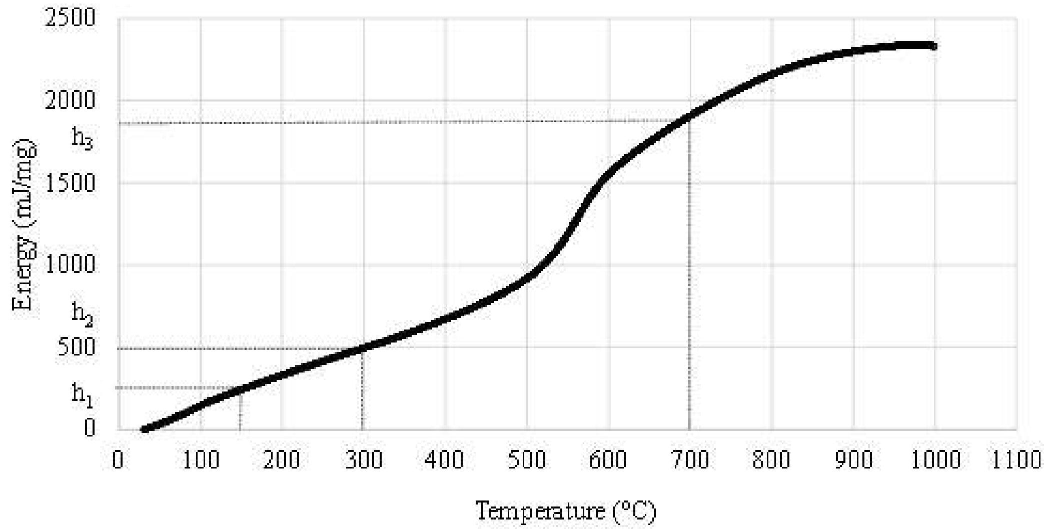

Figure 7.6: Cumulative DSC graph with parameters

7.3.4 Development of Energy equation

Few more parameters for the equation are calculated based on the basic parameters, the derived parameters are provided in Table 7.5.

Table 7.5: Derived parameters from the TGA/DSC graph for energy calculation

Derived parameters			
Parameter	**Symbol**	**Formula**	**Equation label**
Percentage of moisture (%)	m	$m = \frac{(W_0 - W_1)}{W_1}$	Equation 7.1: Moisture content
Percentage of Kaolinite (%)	k	$k = \frac{(W_2 - W_3)}{W_1} \times \frac{100}{14} \times \frac{100}{1}$	**Equation 7.4: Kaolinite Content**
Specific heat capacity (mJ/mg °C)	C_c	$C_c = \frac{h_2 - h_1}{T_2 - T_1}$	**Equation 7.5: Specific heat capacity**
Calcination energy (per Kaolinite content) (mJ/mg)	E_c	$E_c = \frac{(h_3 - h_2) - C_c \times (T_3 - T_2)}{(k/100)}$	Equation 7.2: Calcination energy per kaolinite content

The dry mass of clay is considered as base mass for calculating the moisture and kaolinite content. The Equation 7.3 calculates the moisture content of sample using the mass loss at 100 ^{o}C and the dry mass. The kaolinite content is estimated using a molar mass ratio of water lost and metakaolin formed during calcination or dehydroxylation of clay. The chemical reaction of kaolinite dehydroxylation is provided in following Equation 7.7 (Eq. 7.7).

$$Al_2O_3.2SiO_2.2H_2O \rightarrow Al_2O_3.2SiO_2 + 2H_2O \quad Eq.7.7$$

Kaolinite (258 gm) Metakaolin (222gm) Water (36 gm)

The mass of water is (36 gm) is around 14% of the mass of kaolinite (258gm) thus the mass loss is multiplied with a factor of (100/14) to calculate the corresponding amount of kaolinite clay in the raw clay sample. This mass is converted into percentage with respect to the dry raw clay sample mass. Thus it is to be noted that after 100 ^{o}C the reduction in mass should be equal or less than 14%. The specific heat capacity is found by finding the cumulative energy per unit dry weight consumed between 150 ^{o}C to 300 ^{o}C and dividing the same with temperature difference. A temperature range between 150 ^{o}C and 300 ^{o}C are considered as the DSC value between the same look steady. Constant value also indicates absence of any chemical reaction during this period and thus the heat flow value corresponds to raise the temperature. This specific heat capacity value can be found in the equation by finding the slope of cumulative DSC curve between 150 ^{o}C to 300 ^{o}C. This value represents the average heat flow value between 150 ^{o}C and 300 ^{o}C. The dehydroxylation reaction results in absorption of energy. The hump present in the DSC curve between the temperatures 300 ^{o}C to 700 ^{o}C indicate the energy absorbed for calcination. This energy changes depending on the amount of kaolinite content. A clay sample with zero kaolinite content can have no change in the DSC value at this temperature range. Thus the resulted change of graph is normalized with content of kaolinite to understand the energy consumed per kaolinite content. In order to find the area of the hump in the graph a baseline should be considered. The average value of DSC between 150 ^{o}C and 300 ^{o}C is considered as a baseline. The area of DSC results between 300 ^{o}C and 700 ^{o}C and the baseline value is estimated. This physically indicates the reduction of heat absorbed for raising the temperature, from the total energy supplied during the temperature range. Thus the remaining energy value will be the energy absorbed for chemical reaction. This energy for chemical reaction is divided by the kaolinite content to normalize with kaolinite content.

Using the above-defined parameters an equation is developed as provided in Equation 7.8 (Eq. 7.8). The total energy is measured in mJ/mg.

$$Total\ energy = \left((T_e - T_o) \times C_w + L_w\right)\left(\frac{m}{100}\right) + \left(E_c \times \frac{k}{100} + C_c(T_f - T_o)\right) \times \frac{(100-m)}{100} \quad Eq.7.8$$

This equation physically means the sum of heat energy for moisture evaporation, dehydroxylation, and heat to raise the temperature till 700 ^{o}C, minus the heat retained through heat recovery system as mentioned in Equation 7.2 (Eq. 7.2).

7.3.5 Experimental details

The clay samples are collected from mines and TGA/DSC experiments are conducted on the same. The raw data output from the equipment is analyzed and suitable values corresponding to the basic parameters defined in the Table 7.4 is selected. Using these parameters the derived parameters provided in Table 7.5 is calculated. Using the previously obtained parameters the clay calcination energy is calculated based on Equation 7.8. A sample calculation of the clay calcination energy is provided in following section.

The basic parameters and derived parameters of a clay sample tested is provided in Table 7.6 and Table 7.7. Using the parameter values in Equation 7.8 the total energy is calculated. The total energy is calculated for two scenarios of clay calcination, which is ‘with and without heat recovery system’. In with heat recovery system an exit temperature of 100 ^{o}C is assumed and the heat released by hot clay till it cooldowns to 100 ^{o}C is recovered. For without heat recovery system the exit temperature considered is 700 ^{o}C. In Table 7.6 the exit temperature is given as 100 ^{o}C but for case of without heat recovery 700 ^{o}C is used for calculation. The calculation for the total heat for clay calcination energy with heat recovery is given below.

$$Total\ energy = \left((100-30)\times 4.19 + 2257\right)\left(\frac{1.46}{100}\right) + \left(1255\times 59.75 + 1.72\,(100-30)\right)\times\frac{(100-1.46)}{100}$$

$$Total\ energy = 894\ mJ/mg$$

Similarly the calculation of energy consumed for calcination without heat recovery is as follows

$$Total\ energy = \left((100-30)\times 4.19 + 2257\right)\left(\frac{1.46}{100}\right) + \left(1255\times 59.75 + 1.72\,(700-30)\right)\times\frac{(100-1.46)}{100}$$

$$Total\ energy = 1909\ mJ/mg$$

Table 7.6: Basic parameters of sample calculation

Basic parameters			
Parameter	**Symbol**	**Value**	**Unit**
Initial temperature	T_o	30	^oC
Water evaporation temperature	T_e	100	^oC
Final solid temperature	T_f	100	^oC
150 ^oC Temperature	T_1	150	^oC
Calcination initiation temperature [300 ^oC]	T_2	300	^oC
Calcination completion temperature [700 ^oC]	T_3	700	^oC
Cumulative energy consumed at 150 ^oC	h_1	248.99	mJ/mg
Cumulative energy consumed at 300 ^oC	h_2	506.32	mJ/mg
Cumulative energy consumed at 700 ^oC	h_3	1942.20	mJ/mg
Mass of sample at ambient temperature	W_o	34.65	Mg
Mass of sample at 150 ^oC	W_1	34.14	Mg
Mass of sample at calcination initiation temperature	W_2	33.96	Mg
Mass of sample at calcination completion temperature	W_3	31.12	Mg
Specific heat capacity of water (Energy/unit mass and temperature)	C_w	4.19	mJ/mg ^oC
Latent heat of vaporization of water (Energy/unit mass)	L_w	2257	mJ/mg

Table 7.7: Derived parameters of sample calculation

Derived parameters				
Parameter	**Symbol**	**Calculation**	**Result value**	**Unit**
Percentage of moisture (%)	m	$m = \frac{(34.65 - 34.14)}{34.14} \times 100$	1.46	%
Percentage of kaolinite (%)	k	$k = \frac{(34.14 - 31.12)}{34.14} \times \frac{100}{0.14}$	59.75	%
Specific heat capacity (mJ/mg ^oC)	C_c	$C_c = \frac{(506.32 - 248.99)}{(300 - 150)}$	1.72	mJ/ mg ^oC
Calcination energy (per Kaolinite content) (mJ/mg)	E_c	$E_c = \frac{(1942.20 - 506.32) - 1.72 \times (700 - 300)}{59.75/100}$	1254.65	mJ/ mg ^oC

The sample collection from mines and TGA/DSC testing of all samples were conducted by an organization 'Technology and Action for Rural Advancement' (TARA). The equipment used for TGA/DSC analysis is STA 8000 by PerkinElmer. The heating rate followed is 20 ^{o}C/min and the sample size used was around 25mg.

A total of 74 clay samples (in few cases two or more samples are from same mine) were collected from different mines and one clay samples each were collected from two cement plant from case studies 1 and 2 respectively. TGA/DSC were conducted on the samples collected. Out of 76 samples tested, 23 samples were discarded due to following reasons.

- kaolinite content less than 40
- Unnatural trend in the results

7.3.6 Result and observation

Analysis of selected 53 TGA/DSC results are conducted as explained in the sample calculation provided in section 7.3.5. The results of specific heat capacity, calcination energy per kaolinite content, and total calcination energy with heat recovery and without heat recovery are obtained and compiled. The results are discussed in the following section.

The specific heat capacity results are shown in Figure 7.7. The average value of specific heat capacity (C_c) of clay sample is 2.5 kJ/kg ^{o}C with coefficient of variation of ± 31%. The minimum and maximum value is coming about 1.1 – 4.1 kJ/kg ^{o}C. In literature specific heat capacity of kaolinite is ranging between (0.7-1.3) J/g K for a temperature range of 0 to 1000 ^{o}C (Michot et al. 2008). Thus, the values obtained in the study are higher. The scatter is assumed to be due to the presence of impurities. This specific heat capacity will be used to calculate the energy supplied to clay for raising the temperature till 700 ^{o}C and the energy recovered from hot clay.

The result of calcination energy per kaolinite content is shown in Figure 7.8. The average value of E_c = 1515 kJ/kg of kaolinite, with a coefficient of variation of ± 26%. The minimum and maximum value is coming about 626-2655 kJ/kg of kaolinite. The values reported in literature ranges from 140-300 kJ/mol (Horvath 1985). Considering the molar mass of 258 gm for the kaolinite the range comes to 0.54-1.16 kJ/kg of kaolinite. Thus, the value obtained in the study seems to be high. It is assumed that the impurities present in the clay sample can be one of the reasons for this variation. This value is used to estimate the energy for dehydroxylation reaction. According to literature values provided in Table 7.3, the result values ranges from 630-883 kJ/kg of kaolinite. Compared to this literature value the results obtained is having high variation, the lower limit is comparable where the upper limit is 3 times the value reported in literature.

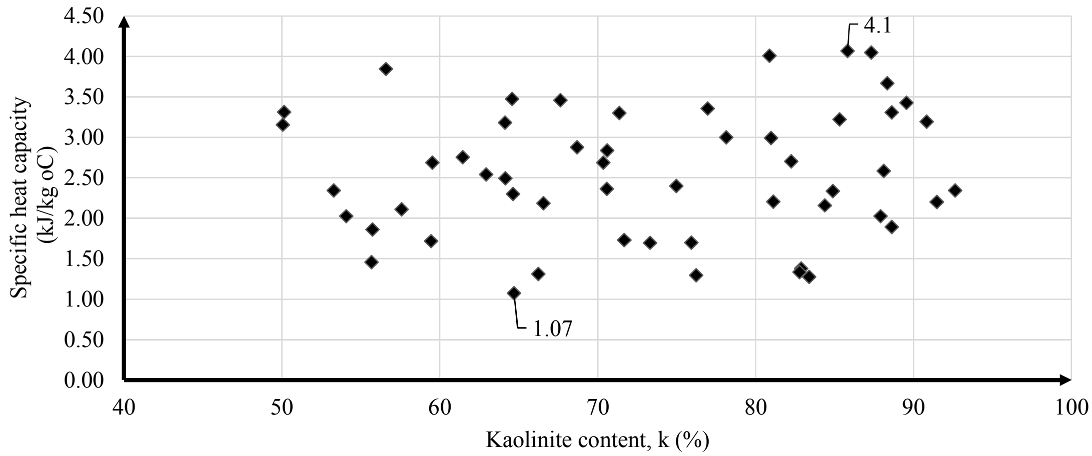

Figure 7.7: Specific heat capacity (C_c) of 53 clay samples

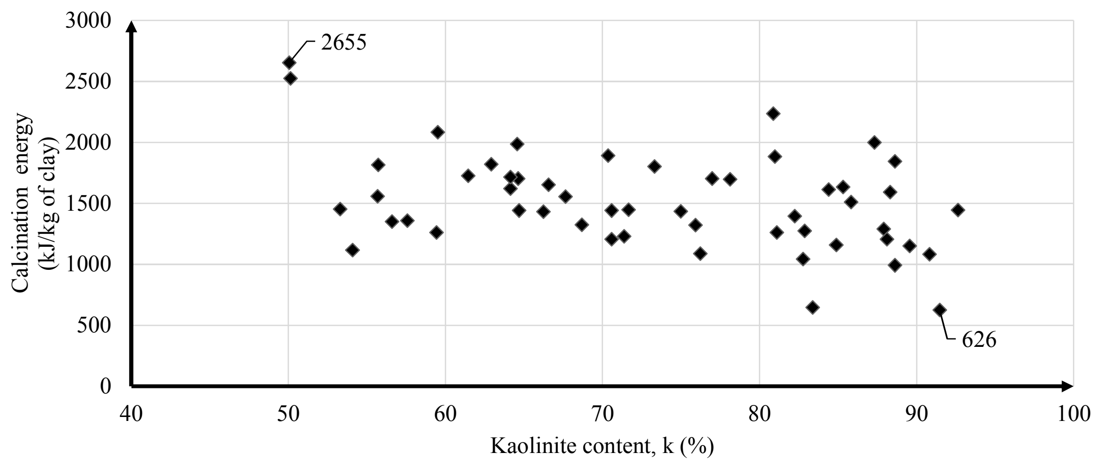

Figure 7.8: Calcination energy per kaolinite content (E_c)

The results for theoretical calcination energy with the presence of heat recovery is shown in Figure 7.9. Average of total calcination energy with heat recovery is 1287 kJ/kg of clay with a coefficient of variation of ± 23%. The minimum and maximum value is coming about 689 - 2091 kJ/kg of clay. Here it is assumed that the specific heat capacity, when clay was getting heated (during 150 ^{o}C to 300 ^{o}C) is followed when the clay was getting cooled down also. And the energy till the hot clay cools down to 100 ^{o}C is been recovered

The results for theoretical calcination energy with the presence of heat recovery is shown in Figure 7.10. Average value of total calcination energy with heat recovery system is 2794 kJ/kg of clay with a coefficient of variation of ±25%. The minimum and maximum value is coming about 1428 - 4488 kJ/kg of clay. Here it is assumed that no heat is been recovered back and clay is coming out with an exit temperature of 700 ^{o}C.

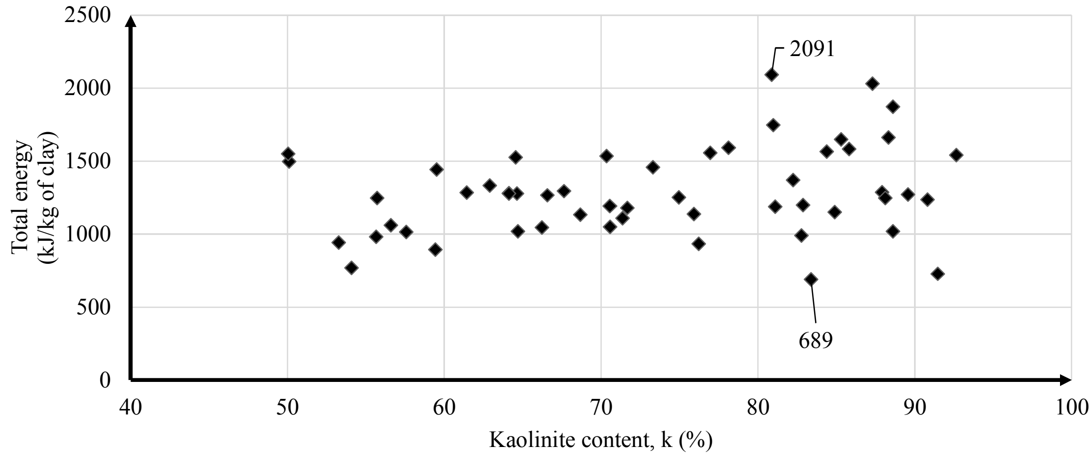

Figure 7.9: Total energy for clay calcination with heat recovery (exit temperature 100 ^{o}C)

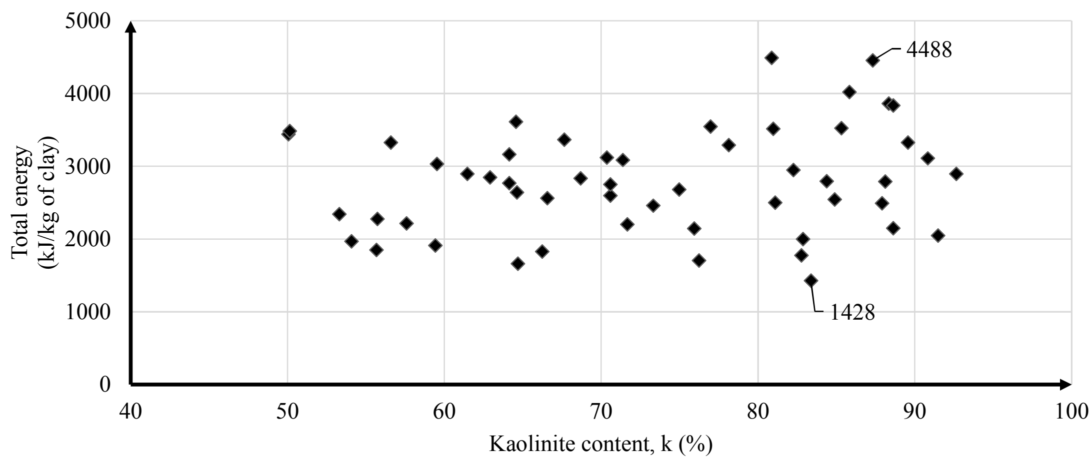

Figure 7.10: Total energy for clay calcination without heat recovery (exit temperature 700 ^{o}C)

7.3.7 Conclusions, limitations, and recommendations

1) Conclusions

a) TGA/DSC analysis was conducted on 53 clay samples. Based on an equation developed, few attributes like specific heat capacity, calcination energy, and total heat of calcination (with and without heat recovery) are estimated.

b) As the clay samples with similar kaolinite content have highly variable calcination energy, it can be concluded that the contribution from impurities are very high.

c) Specific heat capacity (per clay)

i) Range: 1.1 – 4.1 kJ/kg ^{o}C

ii) Average specific heat capacity (C_c) of clay sample: 2.5 kJ/kg ^{o}C (± 31%)

iii) Value seems to be higher than the literature values

d) Calcination energy (theoretically)

i) Range: 626 - 2655 kJ/kg of kaolinite

ii) Average E_c = 1515 kJ/kg of kaolinite (± 26%)

iii) Value seems to be very higher than literature values

e) Total energy (with heat recovery)

i) Range: 689 - 2091 kJ/kg of clay

ii) Average total energy: 1287 kJ/kg of clay (± 23%)

f) Total energy (without heat recovery)

i) Range: 1428 - 4488 kJ/kg of kaolinite

ii) Average total energy: 2794 kJ/kg of clay (±25%)

2) Discussion on clay calcination process

The clay calcination can be conducted using different technologies say retrofitting old wet kiln, refurbished dry kiln and flash calciner (Cancio Díaz et al. 2017; Vizcaíno-Andrés et al. 2015). Cancio Díaz et al. (2017) stated that the flash calciner is the best option considering the CO_2 cut-down and return of investment. The calcination using refurbished dry kiln is also having comparable benefits. Considering the time period of installation of technology, the refurbished dry kiln has an advantage over the flash calciner.

Four extreme cases of clay calcination energy are identified corresponding to the scenarios mentioned in Table 7.2 out of different clay calcination values obtained. The calcination energy corresponding to each scenario along with kaolinite content and exit clay temperatures are provided in the Table 7.8.

3) Limitations

The results are valid within the assumptions and limitations made during the calculations. Few assumptions and limitations considered in the study are provided as follows,

a) The mass loss between 300 ^{o}C to 700 ^{o}C corresponds completely to the dehydroxylation of kaolinitic clay. Thus the effect of impurities are ignored.

b) The energy consumed in this phase corresponds completely for dehydroxylation. Thus the effect of impurities are ignored.

c) The specific heat capacity estimated remains constant at any temperature between 300 ^{o}C to 700 ^{o}C, despite the heating or cooling process.

d) The loss percentage considered is same for with and without heat recovery. The loss percentage will vary when the heat recovery system is introduced and thus doesn't remain the same. This is not considered in the study.

Table 7.8: Clay calcination energy for four scenarios

SL. No	Scenario	Clay calcination energy
1	**Scenario 1 (S 1):** Without heat recovery or case with exit temperature of clay = 700 °C. The kaolinite content of clay with high calcination energy is 80.87%	4488 kJ/kg of raw clay
2	**Scenario 2 (S 2):** Without heat recovery or case with exit temperature of clay = 700 °C. The kaolinite content of clay with low calcination energy is 83.88%	1428 kJ/kg of raw clay
3	**Scenario 3 (S 3):** Without heat recovery or case with exit temperature of clay = 100 °C. The kaolinite content of clay with high calcination energy is 80.87%	2091 kJ/kg of raw clay
4	**Scenario 4 (S 4):** Without heat recovery or case with exit temperature of clay = 100 °C. The kaolinite content of clay with low calcination energy is 83.88%	689 kJ/kg of raw clay

4) Recommendations

a) The results obtained in the study can be used to estimate the energy of products based on the same, for example LC^3.

b) All the limitations need to be rectified and the assumptions need to be optimized to actual conditions.

c) Since the results of C_c and E_c are not matching with literature, the reason for the same need to be found and addressed.

7.4 Production systems for Limestone Calcined Clay Cement (LC^3)

Multiple industrial trial production of LC^3 was conducted in Cuba (Berriel et al. 2016; Cancio Díaz et al. 2017; Vizcaíno-Andrés et al. 2015) and India (Bishnoi et al. 2014; Emmanuel et al. 2016). The production trials were conducted as a part of the research project named "LC^3" under the university EPFL (École polytechnique fédérale de Lausanne), at Switzerland. The clay was transported to the cement plant and calcined at the Cuban industrial production. In India, the clay is calcined at one place and then transported to a grinding unit in first trial, and to an integrated unit in second trial. In both cases the ingredients were then ground to produce cements. As mentioned in Table 7.3, few energy values on LC^3 production were reported in literature. Since there were only few studies conducted on energy and CO_2 emission, an attempt was made to calculate energy and CO_2 related to cement production.

In terms of cement production, there are different possibilities of LC^3 production scenarios which can result in different process systems. The two main processes after the clinker production are calcination and grinding. And these processes can be conducted in the cement plant premises or other locations. Various possible process systems for LC^3 production are discussed here.

The calcination process can be conducted in (i) cement plant or clinkerization unit with calcination facility, (ii) clay mine with calcination facility, (iii) grinding unit with calcination facility, and (iv) at an optimal location exclusively for calcination. Similarly the grinding process can be conducted at (i) an integrated cement plant, (ii) grinding unit, and (iii) clay mine with grinding facility. The four sources of calcination and three sources of grinding makes a set of twelve LC^3 production process systems. The process systems obtained are provided in following sections. The source of calcination process is abbreviated as SoCP and source of grinding process is abbreviated as SoGP in the following sections. The source of a process is marked using a box with dashed lines. In every process system considered, it is assumed that the gypsum will be transported to the source where grinding process are conducted. Thus the flow of the gypsum is not mentioned in the process flow charts. Similarly it is assumed that the cement plants and the clinkerization units are located next to the limestone mines and thus the limestone to be added along with the calcined clay is available at these locations. The circles in the flow chart represent location, the rectangles represent process and the parallelograms represent the material. The material undergo internal transport when the same moves within a source, and external transportation if the material moves from one source to other. In the flow chart, if the material move from one circle to other circle, it can be considered as external transportation.

7.4.1 Process system - 1

Figure 7.11 shows the process system with clay mine as the source of calcination process and integrated cement plant acting as the source for grinding process. This process system physically indicates, a case of setting up a calcination facility in a clay mine, and the transportation of calcined clay to a conventional integrated cement plant. Conventional integrated cement plant, is the plant where clinker is produced and ground to cement with required additives. Thus in this case the cement plant which have the clinker produced, limestone extracted, and gypsum bought, will be ground together with calcined clay transported from clay mine to make LC^3. The calcined clay will be having less mass with respect to the raw clay. The mass reduction can go up to 14% for a clay with complete kaolinite content (100% kaolinite content). Depending on the content of kaolinite it can vary proportionally. There can be additional loss in mass due to loss of moisture. In this system the advantage of reduction in mass of calcined clay to be transported is utilized. Emmanuel et al. (2016) has reported an industrial pilot production of LC^3 following this process system. The clay is calcined near clay mine (Gujarat, India) and transported to integrated cement plant (Haryana, India).

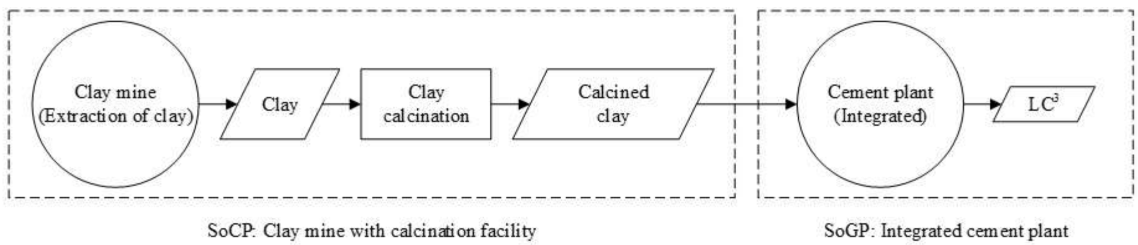

Figure 7.11: Process system 1 for LC^3 production

7.4.2 Process system - 2

Figure 7.12 shows the process system with integrated cement plant as the source for calcination and grinding process. In practice, this is a case where a calcination technology is provided within the integrated cement plant. Since the plant is integrated, the grinding facility is present. The clay is transported from clay mine and calcined at the cement plant. The clinker produced in the plant, limestone extracted from mine within cement plant premises, clay calcined at the cement plant, and gypsum bought to cement plant are ground to produce LC^3. This is a highly feasible process system with respect to current Indian integrated cement plant. It is because, all the supply chain of materials and the equipments related to this process system except the calciner are already available in a conventional integrated cement plant. Cancio Díaz et al. (2017) has discussed about the process system of clay extracted and transported to the cement plant. The retrofitted old wet kiln or refurbished dry kilns at cement plant can be used as clay calciner. And even the refurbished kilns have benefit in economic and environmental aspects (CO_2 emission) with respect to latest clay calcining technologies like flash calcination. Since there is more probability for the availability of old kilns in cement plants and it is reported in literature that it is par with latest technologies, this process system has high probability of field application. Vizcaíno-Andrés et al. (2015) has also reported the case of process system where raw clay is transported to cement plant and calcined, to make LC^3.

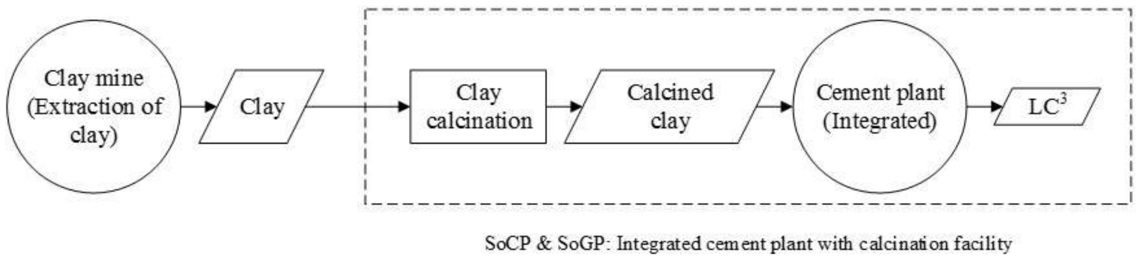

Figure 7.12: Process system 2 for LC^3 production

7.4.3 Process system - 3

Figure 7.13 shows a case where the source of calcination is an optimal location which is neither clay mine, nor cement plant. This can be physically related to a case where the clay is been transported from mine to a clay factory (optimal location) with calcining facility. The calcining can be conducted on requirement based on mutual agreement, and the calcined clay can be transported to integrated cement plant. There are also possibilities like hiring a calcining unit from an existing clay factory for the calcination process. This can increase the transportation process as the clay need to be transported not directly to cement plant but to calcination location first and to cement plant location. Some more optimal locations are old clinkerization unit converted to a calcination unit and hired clay calcination facility from a clay factory.

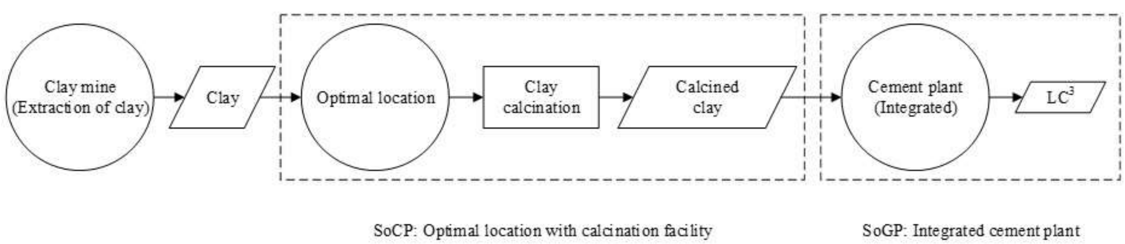

Figure 7.13: Process system 3 for LC^3 production

7.4.4 Process system - 4

The process system four is same as that of process system three, with an additional facility of grinding in the source of calcination process. Figure 7.14 shows a case where the source of clay calcination is a grinding unit with calcination facility and the source of grinding process is cement plant. This process flowchart represents a case of hiring clay factory with calcination and grinding facility or setting up of clay calcination unit in a cement grinding unit (instead of at cement plant due to some reasons). In this case the clay is transported from clay mine to the grinding unit where it is calcined. The calcined clay is then transferred to the cement plant, where it is ground with clinker (produced), limestone (extracted) and gypsum (bought). The transportation is same as that of the process system three.

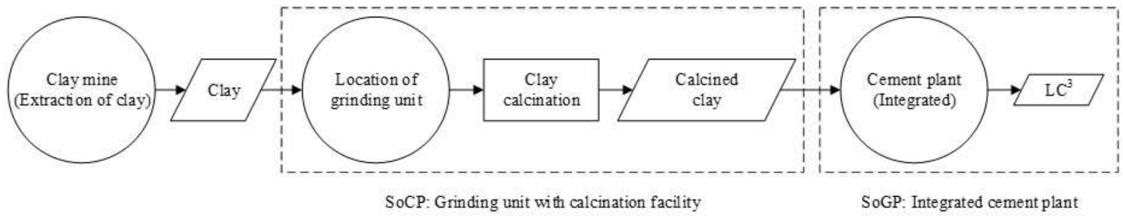

Figure 7.14: Process system 4 for LC^3 production

7.4.5 Process system - 5

Figure 7.15 depicts a case of calcination happening in the clay mine and the grinding happening in grinding unit. This process system depicts a combination of clinkerization unit, clay mine and grinding unit. In field, this process system represents the case where the clinker and limestone produced in clinkerization unit, and clay calcined at a calcination unit at clay mine are transported to the grinding unit. The calcination unit can also be a clay plant with calcination facility located at clay mine. In grinding unit the clinker, limestone, and calcined clay, are ground along with the gypsum to produce LC^3 cement. The mass loss of clay after calcination can provide a slight advantage in transportation, whereas the transportation of the clinker and limestone which forms ~65% of cement by mass can cause high transportation burden. Since all the materials, are transported from the sources to grinding unit, there is more process of transportation. Even though there is high amount of transportation, these process systems can be viable in location where cement grinding units are present and successfully functioning.

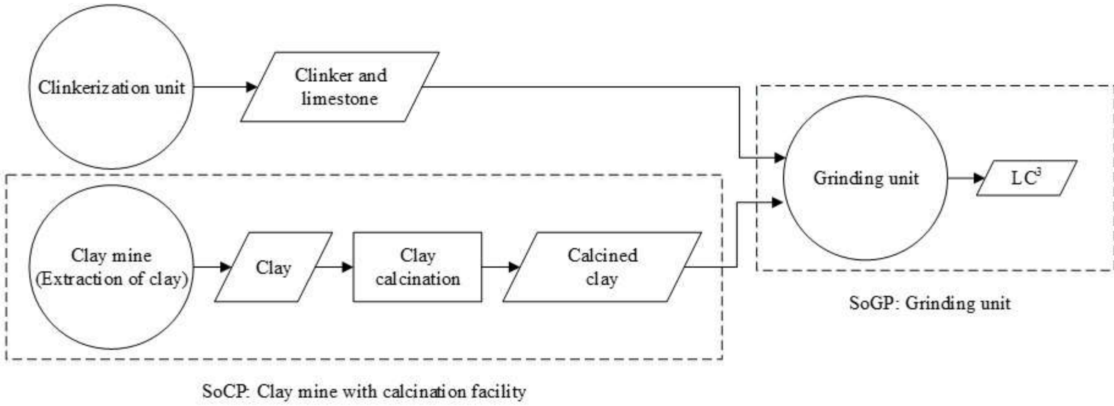

Figure 7.15: Process system 5 for LC^3 production

7.4.6 Process system - 6

Figure 7.16 depicts the case of calcination conducted in clinkerization unit and grinding happening in the grinding unit. In practice this process system depicts a case of calcination facility set up in a clinkerization unit. The clay from the mines are transported from mine to clinkerization unit, where it is calcined. The clinker, limestone and calcined clay from the clinkerization unit is then transported to the grinding unit, where it is ground along with gypsum to produce LC^3. It is a feasible technique as the clinkerization units can have old kilns, or back up kilns to meet the seasonal demands of clinker. Cancio Díaz et al. (2017) and Vizcaíno-Andrés et al. (2015) has reported the cases of old clinkerization kiln converted for calcination. Here also the disadvantage will be regarding the transportation of every ingredient from different sources to grinding unit. This increases the related transportation process and consequentially the associated environmental and economic burdens also increases. Even though there is high amount of transportation, these process systems can be viable in location where cement grinding units are present and successfully functioning.

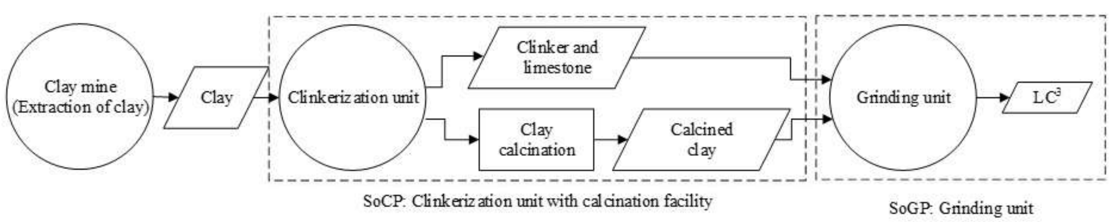

Figure 7.16: Process system 6 for LC^3 production

7.4.7 Process system - 7

Figure 7.17 depicts a case of calcination conducted in an optimal location and the grinding conducted in a grinding unit. This process system depicts a situation of clay transported to an optimal location other than clay mine, clinkerization unit and grinding unit for calcination. This optimal location can be clay factory, where calcination can be conducted based on mutual agreement. The clay is first transported to optimal location, where it is calcined, and then transported to grinding unit. The clinker and limestone from the clinkerization unit are also transported to grinding unit. At grinding unit clinker, calcined clay and limestone along with the gypsum is ground to LC^3. Even though there is high amount of transportation, these process systems can be viable in location where cement grinding units are present and successfully functioning. Bishnoi et al. (2014) has reported a pilot LC^3 production where the clay is calcined at an optimal location and grinding is conducted in a grinding unit where all the ingredients are transported.

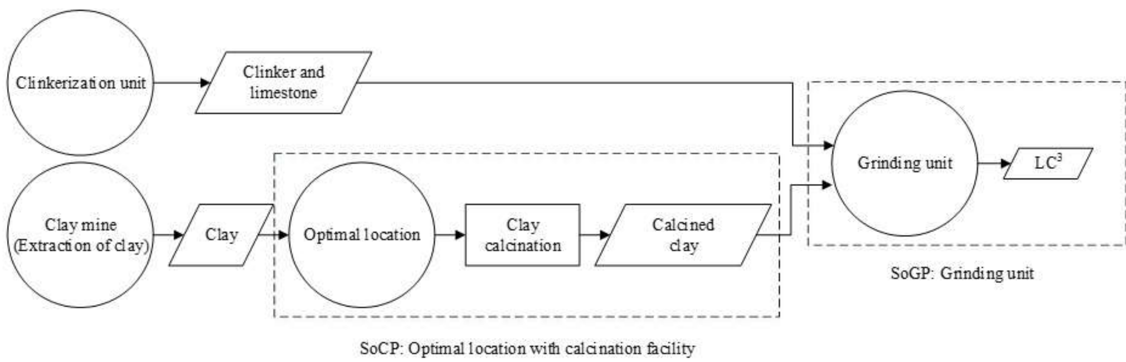

Figure 7.17: Process system 7 for LC^3 production

7.4.8 Process system - 8

Figure 7.18 depicts the case of calcination and grinding conducted in grinding unit. This case practically represents a scenario of setting up a calcination facility at cement grinding unit. Here the clay is transported to grinding unit and calcined. The clinker and limestone transported from clinkerization unit along with calcined clay and the gypsum bought are ground together to produce LC^3. In this case also, all the materials are transported from its sources to grinding unit. Thus there is abundant process of transportation. Even though there is high amount of transportation these process systems can be viable in locations where cement grinding units are present and successfully functioning.

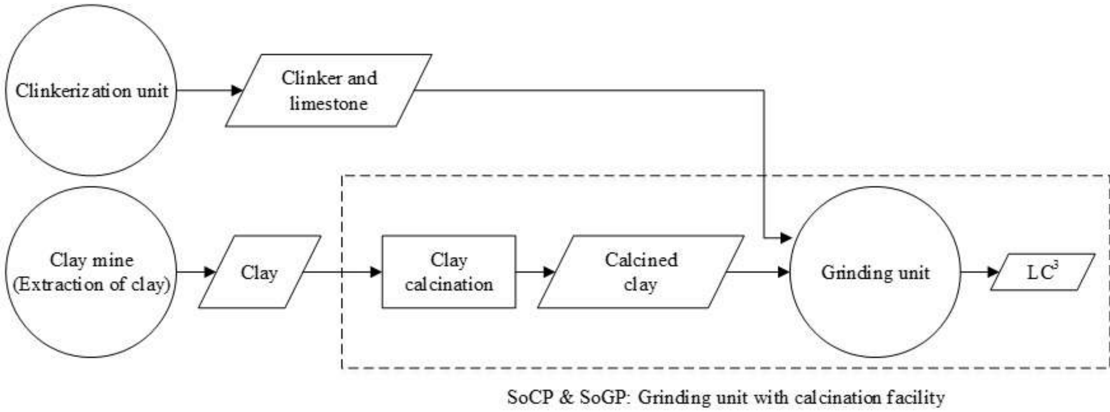

Figure 7.18: Process system 8 for LC^3 production

7.4.9 Process system - 9

Figure 7.19 illustrates a case of calcination and grinding facilities provided within the clay mine. This process in practice reflects a case of setting up a calcination set up and grinding mill within the clay mine premises. It can also simulate, case like setting up a grinding facility in clay factories with calcination facility next to clay mines. The clay is extracted and calcined in the clay mine. Clinker and limestone from the clinkerization unit are transported to clay mine. Clinker, calcined clay, and limestone, along with gypsum bought to the clay mines are ground together to produce LC^3.

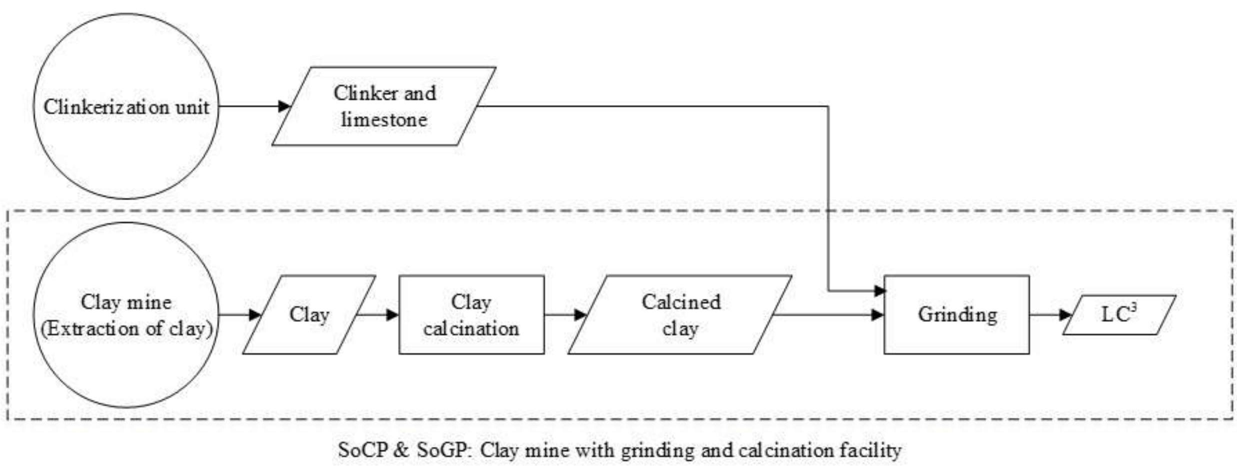

Figure 7.19: Process system 9 for LC^3 production

7.4.10 Process system - 10

Figure 7.20 provided here shows a case of calcination conducted in a clinkerization unit and grinding conducted in clay mine itself. This process system in practice simulates a condition of setting up a calcining equipment in clinkerization plant, and adopting a clay plant with grinding facility next to a clay mine for grinding process. The setting up of calcination facility in clinkerization unit is easy as the modified old kiln can serve the purpose. The clay is transported to clinkerization unit where it is calcined. The clinker, calcined clay and limestone are then transported to clay mine for grinding. Here the clay is transported back and forth between the clay mine and clinkerization unit, and clinker and limestone is transported from clinkerization unit to clay mine. Thus there is more transportation process conducted. But these can be viable where there exists a clay plant with grinding facility in clay mine premises and clinkerization units

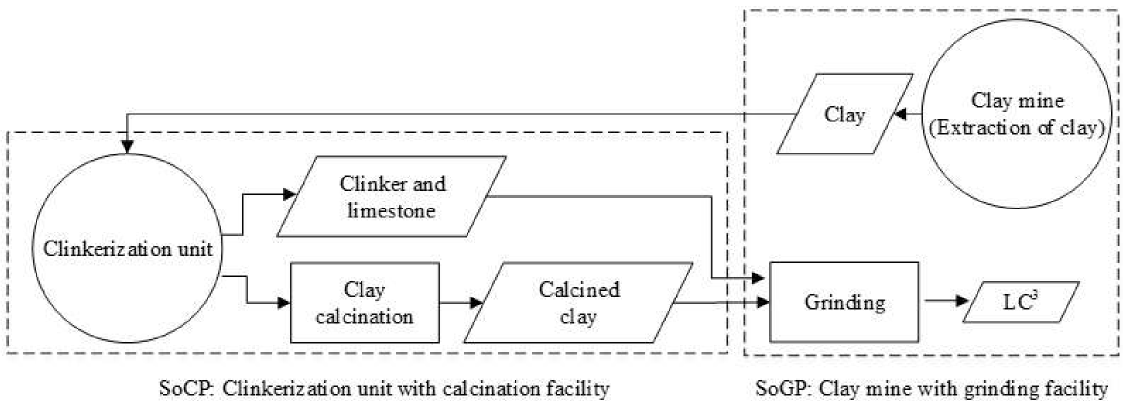

Figure 7.20: Process system 10 for LC^3 production

7.4.11 Process system - 11

Figure 7.21 shows a case of calcination conducted in an optimal source and grinding conducted in the clay mine. This process system practically corresponds to a case where the clay from clay mine is transported to an optimal source, say a clay plant with calcination facility and calcined. This calcined clay is transported back to clay mine. The grinding location can physically be represented by a clay plant with grinding facility located next to clay mine. The clinker and limestone are also transported to clay mine. Clinker, calcined clay and limestone along with the gypsum bought to clay mine are ground to produce LC^3. This is a viable solution if a clay plant with grinding facility is present near to clay mine and clay plant with calcining facility is available nearby. There can be also more physical combinations for this process system. These kind of process systems are viable where numerous clay plants are present next to clay mine.

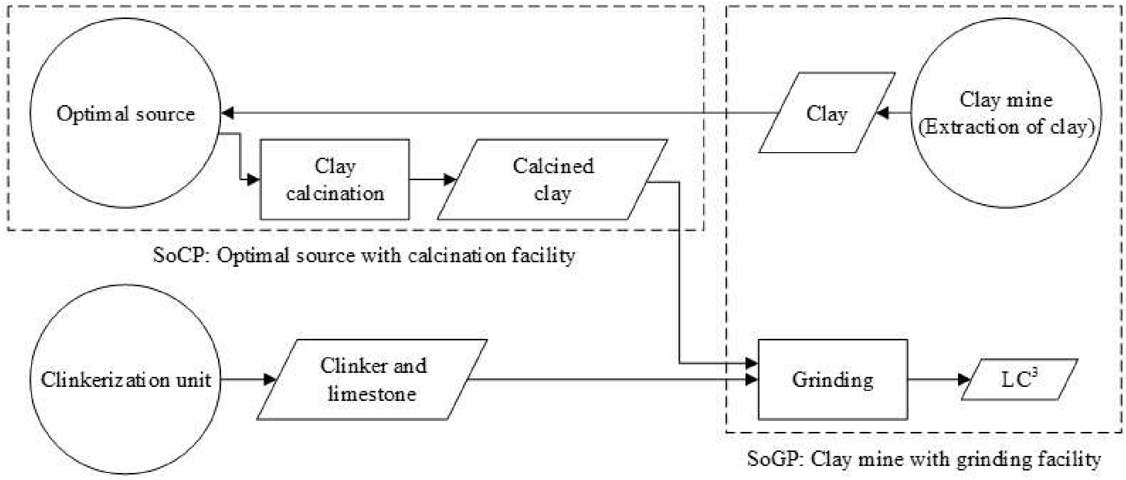

Figure 7.21: Process system 11 for LC^3 production

7.4.12 Process system - 12

Figure 7.22 shows the case of calcination happening in the grinding unit and grinding conducted in the clay mine. This physically indicates a case of clay plant with calcining facility conducting the calcination of clay transported from clay mine to the clay plant, and another clay plant with grinding facility near to clay mine conducting grinding. The clay is transported from clay mine to the clay plant with calcining facility. The clay get calcined at clay plant and the calcined clay will be transported back to clay mine. From clinkerization unit the clinker and limestone are also transported to clay mine. The clinker, calcined clay and limestone along with the gypsum bought is ground in the clay plant with grinding facility. This scenario is same as that of process system eleven, except an additional grinding facility in the calcination source

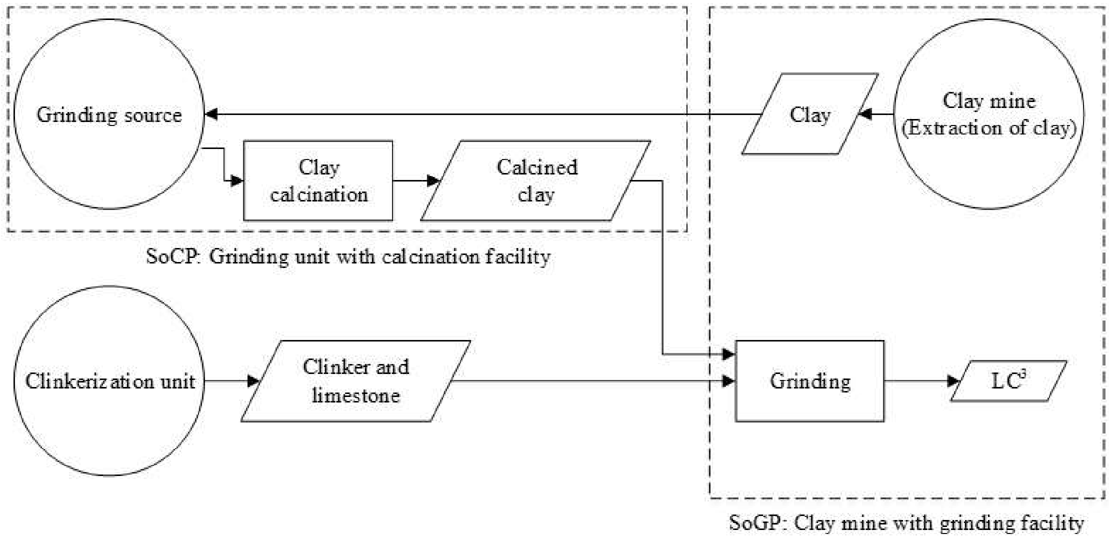

Figure 7.22: Process system 12 for LC^3 production

7.5 Estimation of energy and CO_2 of LC^3 production

A hypothetical case of LC^3 production is considered based on the results obtained corresponding to case studies 1 and 2 respectively and clay calcination process studied (Section: 7.3). From a set of process systems discussed in section:7.4, a highly probable (according to literature) LC^3 production process system is selected for analysis. Within the selected process system four calcination scenarios mentioned in the Table 7.2 are considered for clay calcination process. This results in total of four cases of LC^3 production corresponding case study 1 and 2 respectively. Thus a total of eight energy and CO_2 emission results are obtained corresponding to LC^3 production corresponding to four scenario each in two cement plants. These results are compared with the OPC and PPC results obtained from each case studies.

7.5.1 Goal and scope

Goal:

a) Objective

To estimate the inventory, energy and CO_2 emission related to LC^3 production

b) Application

i) To assess the sustainability aspects of LC^3 in terms of energy consumed and CO_2 emitted

ii) The preliminary results on energy use and CO_2 emission can be used to educate the industrialist or governmental bodies on the advantages or disadvantages of using cements based on calcined clay and limestone additives.

c) Intended audience

Academicians, industries and government bodies

d) Whether the results will be shared with public

Yes, it is intended to share the results through means like journal articles, conference papers, and stakeholders meetings.

Scope:

a) Product/process system to be considered:

Out of different process systems discussed in section 7.4.1, the process system - 2 is selected. This process system sounds logical and practical, as stated in literature (Cancio Díaz et al. 2017; Vizcaíno-Andrés et al. 2015) on the evidence of applying this process system in field. Since process system - 2 is a simple and proven process system for LC^3 production, the same is considered in this study. This system considers a calcination facility provided at the cement plant. Thus the clay is transported from clay mine to cement plant, where it is calcined and ground along with other ingredients to produce LC^3.

The process system - 2 is considered in case study 1 and 2 (CS 1 and CS 2). Within the process system considered the clay calcination process is considered in four different scenarios (S 1, S 2, S 3, and S 4) as mentioned in Table 7.8.

The system boundary considered is shown in the Figure 7.23. In figure the box with solid line indicates the gate to gate system boundary, whereas the box with dashed lines indicates the process considered in the analysis. The effect of all the processes outside the dashed box but within the solid box are considered in terms of intermediate product. For example the effect of clinkerization, raw meal preparation etc are accounted to clinker which is entering to grinding process. Thus energy and CO_2 contribution from the processes like extraction and transportation of limestone, preparation of raw meal, and clinkerization are considered as embodied energy and CO_2 associated with clinker. Thus even though the processes like grinding, calcination (of clay), and packing are only considered for analysis, the energy and CO_2 associated with other processes are considered in terms of embodied energy and CO_2 of clinker. Thus the final result reflects the energy and CO_2 emission in association with gate to gate system boundary of integrated cement plant. All the conventional processes involved in cement production after clinkerization along with clay calcination is considered.

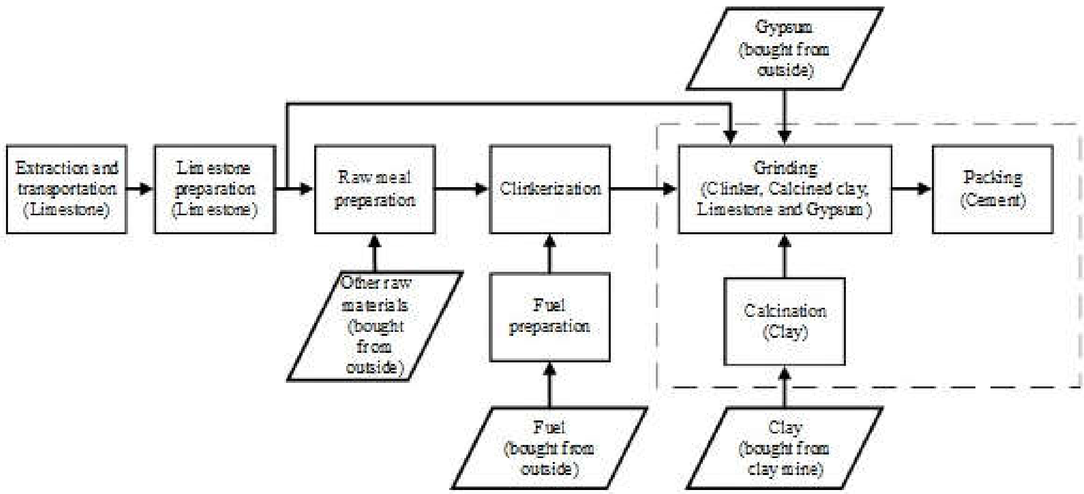

Figure 7.23: Schematic diagram of the gate to gate system boundary

b) **Functions of the product system/systems:** Production of cement

c) **Functional unit:** 1 ton of LC^3 is considered as the functional unit.

d) **System boundary**

- **Criteria:** Gate to gate
- **List of unit processes:**
  - **Calcination of clay:** The raw clay is thermally treated in a dry rotary kiln (same kind used for clinkerization) to a temperature around 700 ^oC. The clay gets dehydroxylated during the same and becomes calcined clay. During calcination, the kaolinite content is converted to metakaolin.
  - **Grinding of cement:** The grinding of clinker, calcined clay, limestone, gypsum, and grinding aid into cement of required fineness. The clinker, calcined clay, limestone, and gypsum are ground in the ratio of 0.5:0.3:0.15:0.05.
  - **Packing of cement:** The packing of cement into plastic/paper bags.
  - **Others (services etc):** All miscellaneous processes excluded in the previous processes or happening simultaneously in a non-continuous way.
- **Cut off value:** No cut off value any inventory value above zero is acceptable.

- **Deleted process:** No deleted process.

e) **Data required:**

- **Calcination of clay:** Electricity, fuel, raw clay, lubricant, rotary kiln, factory, castable, calcined clay, water vapour, CO_2, NO_x, and dust.
- **Grinding of cement:** Electricity, clinker, calcined clay, limestone, gypsum, grinding aid, oil, water, steel balls, ball mill, cement, dust, and radiation and convection losses.
- **Packing of cement:** Cement, electricity, packing bags, oil, ink, equipment, infrastructure and packed cement bags.
- **Others (services etc):** Electricity consumed for other processes like lighting plant area, office and colony, water for colony area, other equipment, and fuels for canteen.

f) **Data quality requirement:**

An expected list of data quality parameters are provided below.

- **Time period coverage:** Time period - 1 year; Age of data - <5 years. A year is a cyclic period where all the activities take place in cement plant. Say, repair of the equipment used to take place at the end of a year.
- **Geographical representation:** According to report by PSCC (2011) most of the cement plant is situated in the raw material prone area. The major raw material for clinker and cement is limestone. Thus, a cement plant which is situated next to limestone quarry be representative. Thus, a cement plant which is situated next to limestone mine need to be studied.
- **Technological coverage:**
    - About 93% of the Indian cements are made based on the dry processing technology (Kumar 2015) for clinkerization. And thus, a cement plant with dry processing technology is required to be studied.
    - Calcination is reported to be carried out in refurbished dry kiln (previously used for clinkerization) successfully (Cancio Díaz et al. 2017; Vizcaíno-Andrés et al. 2015). Thus the data related to calcination conducted in a refurbished dry kiln is required to be studied.
- **Precision:** Raw material mass in kg, fuel in kg, electricity in kWh, CO_2, and NOx in kg, SO_2, dust in grams, and radiation in MJ. Other data are required in a unit

such that the numerical value is greater than the numerical value of product in functional unit. This units are reported based on values reported in literature.

- **Completeness:** All the data described in the data requirement with respect to the processes should be met.
- **Consistency:** The data, methods and assumptions used in the study should be consistent throughout the study.
- **Reproducibility:** The data should be extrapolated to region level data
- **Sources of data:** From case studies 1 and 2 presented in chapter 4 and 5, clay calcination study mentioned in this chapter (Section: 7.3.6), and literature are considered as the sources of the data required for calculation.
- **Uncertainty of the information:**The energy and emission value should have no uncertainty or there should not be any ambiguity for the factors used. Uncertainty can be experienced if two or more data are reported regarding same input/output.

g) Allocation: The input specific for a product is completely assigned to that product, rest of the inputs or output are allocated using mass allocation.

h) Energy and CO_2 calculation methodology

The energy and CO_2 emission associated with the production of LC^3 within the gate to gate system boundary is calculated. The energy is calculated in MJ and CO_2 is calculated in kg CO_2 units respectively. The suitable energy and CO_2 factors are used to convert the inventory to related energy and CO_2 emission. The sources of energy and CO_2 emission factor of fuels are presented as follows:

The energy factor sources are provided in the decreasing order of priority: (i) Calorific value collected from cement plant, (ii) Energy factors derived based on experiments (Bomb calorimetry), (iii) Emission factors for greenhouse gas inventories 2014 (US EPA 2014) and (iv) 2006IPCC guidelines for national greenhouse gas inventories (IPCC 2006).

The CO_2 emission factor sources as provided in the decreasing order of priority are as follows: (i) Emission factor collected from cement plant, (ii) CHNS results of samples collected, (iii) Emission factors for greenhouse gas inventories 2014 (US EPA 2014), (iv) CSI protocol 2013 (CSI 2013), and (v) 2006IPCC guidelines for national greenhouse gas inventories (IPCC 2006).

For data other than fuels, suitable factors corresponding to each case study is used. Say for clinker, electricity, and limestone the associated energy use and CO_2 emission of each case study is used as conversion factors.

For clay calcination, the inventory value of fuel is back calculated. The fuel consumed is calculated by dividing the energy of each scenario by the weighted average energy factor of each case study. And for this fuel inventory value the weighted average energy factor is used to find the energy consumed and weighted average CO_2 factor is used to estimate the CO_2 emitted.

i) **Value choices:** Not used as the study is not considering any characterization factor corresponding to impact category.

j) **Interpretation methodology:** Comparison of results (energy and CO_2 emission) among LC^3 with PPC, and OPC for case study 1 and 2.

k) **Limitations:**

- All the limitations of case study 1 are applicable to, energy and CO_2 estimated with respect to LC^3 produced in cement plant of case study 1. Similarly, all the limitations of case study 2 are applicable to energy and CO_2 estimated with respect to LC^3 produced in cement plant of case study 2. For example in case study two the grinding and packing electricity is given as a total value and not separated. Thus along with electricity for grinding LC^3 (cited from the literature), the packing electricity value was not considered.
- All the limitations related to the clay calcination energy estimation is also applicable here as they are used to estimate the inventory results.
- The inventory values are cited from literature. Thus the underlying limitations during calculation of the inventory results are reflected in this study also.
- Since the system boundary is gate to gate the mining and transportation of the clay is not considered. Thus the results may have different trend if the transportation is considered.

l) **Assumptions:**

- All the assumptions of case study 1 are applicable to, energy and CO_2 estimated with respect to LC^3 produced in cement plant of case study 1. And similarly all the assumptions of case study 2 are applicable to, energy and CO_2 estimated with respect to LC^3 produced in cement plant of case study 2.

- It is assumed that the calcination of clay is conducted in a rotary kiln within the cement plant. The rotary kiln is also assumed to possess a loss of 37% in terms of energy Scrivener et al. (2016). Or it can also be interpreted that considering the loss, the actual calcination energy required is 59% more than the theoretical calcination energy determined based on laboratory studies.
- It is assumed that the fuel mix used for clinkerization is used for calcination of clay.
- All the energy for thermal treatment of calcination is from the fuel mix considered.
- All the assumptions related to the clay calcination energy estimated is applicable here also as those values are used to estimate fuel used for calcination. The assumptions are provided in section 7.3.2.
- Electricity for packing is same for LC^3 with OPC and PPC in cement plants

m) **Type of reporting**: For research purpose

n) **Critical review**: Not conducted

7.5.2 Life Cycle Inventory

Steps of LCI analysis described in the methodology chapter is followed. The data collection is as planned to conduct on previous case studies, and clay calcination study provided in this chapter and from literature. The required data is collected, formatted, and compiled. The results are then validated, followed by LCI analysis. In the LCI analysis the inventory is estimated for LC^3 corresponding to four scenarios of clay calcination in case study 1. The same exercise is repeated for case study 2. The LCI results obtained are provided in Table 7.9..

Table 7.9: LCI results for four scenarios of LC^3 production

Input	Case Study 1				Case Study 2				Unit
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Electricity									
Electricity - clay calcination	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	kWh/ ton of LC^3
Electricity - cement mill section	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	kWh/ ton of LC^3
Electricity - packing plant section	0.65	0.65	0.65	0.65	-	-	-	-	kWh/ton of Cement
Electricity - services	3.15	3.15	3.15	3.15	-	-	-	-	kWh/ton of cement
Fuel									
Fuel mix	89.98	28.74	41.92	13.88	91.65	29.28	42.70	14.13	kg/ton of LC^3
Raw material									
Clinker	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	ton/ton of LC^3
Clay (raw)	0.338	0.340	0.338	0.340	0.338	0.340	0.338	0.340	ton/ton of LC^3
Limestone	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	ton/ton of LC^3
Gypsum	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	ton/ton of Cement
Ancillary inputs									
Water - Cement plant and mines	60.194	60.194	60.194	60.194					litre/ton of cement
Water					47.10	47.10	47.10	47.10	kg/ton of cement
Water - Colony	21.146	21.146	21.146	21.146					litre/ ton of cement
Oil (Lubricant)	0.13	0.13	0.13	0.13	-	-	-	-	kg/ton of cement
Grease	6.92	6.92	6.92	6.92					gm/ton of cement
Bags PP	1.05	1.05	1.05	1.05					kg/ton of cement
Bags (Paper)	0.80	0.80	0.80	0.80					kg/ton of cement

Input	Case Study 1				Case Study 2				Unit
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Others									
Grinding media	12.95	12.95	12.95	12.95	-	-	-	-	gm/ton of cement
LPG					10.77	10.77	10.77	10.77	gm/ton of cement
Output	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Unit**
Product									
LC^3	1	1	1	1	1	1	1	1	ton/ton of LC^3
CO_2 from fuel (for calcination)	203.80	65.10	94.95	31.43	231.33	73.89	107.78	35.68	kg CO_2/ton of LC^3
CO_2 from LPG					31.39	31.39	31.39	31.39	gm CO_2/ton of cement
CO_2 from extinguisher					99.21	99.21	99.21	99.21	mg CO_2/ton of cement
SPM - Cement Mill Stacks	3.21	3.21	3.21	3.21	-	-	-	-	gm/ton of cement
R-134A	0.49	0.49	0.49	0.49					gm/ton of cement
Freon (R22)					0.12	0.12	0.12	0.12	mg/ton of cement
Recycled water	45.73	45.73	45.73	45.73					litre/ton of cement
Solid waste	1.04	1.04	1.04	1.04					ton/ton of cement

Note: The cell is left blank if the presence of data is unknown. A hyphen ('-') mark is provided, if the data is present but the value was not obtained or unable to collect. The unit is provided per ton of LC^3 if the data is specific for LC^3. The unit is provided per ton of cement, if the data is generic to all cements like OPC, PPC, and LC^3.

Most of the inventory are same as that of generic cement, except few inventories like, electricity for calcination, electricity for grinding, fuel for calcination, amount of clinker, raw clay, limestone, gypsum and CO_2 from calcination. Within which the electricity for calcination, electricity for grinding, amount of clinker, amount of limestone, and amount of gypsum are cited from literature and thus remain same in all cases. The electricity considered for operating rotary kiln during calcination of clay considered is 16 kWh, and grinding of cement is 24 kWh. Both values are cited from the work of Sánchez Berriel et al. (2016). The work was based on a trial LC^3 production conducted in Cuba. The mass proportion of raw materials (clinker, calcined clay, limestone and gypsum) considered are cited from one of the trial LC^3 production described in the work of Bishnoi et al. (2014). The amount of raw clay is back calculated from the amount of calcined clay and the kaolinite content. Pure kaolinitic clay losses mass by 14% during calcination (Equation 7.7). Thus based on the kaolinite content of the raw clay, the mass of raw clay is calculated. The Equation 7.9 (Eq. 7.9) illustrate the procedure used for estimating the fuel.

$$Raw\ clay = calcined\ clay \times \left(\frac{100}{100 - 0.14 \times k}\right) \ldots\ldots\ldots. Eq. 7.9$$

The raw clay mass considered is scenario 1 and 3 are having the kaolinite content of 80.87% and scenario 2 and 4 are having 83.88%. The raw clay mass is 338.3 kg for high calcination scenario (S 1 and S 3) and 339.6 kg for low calcination energy scenario (S 2 and S 4). The fuel for calcination is calculated based on the estimated total thermal energy for calcination and the calorific value of fuel mix used for clinkerization. The Equation 7.10 (Eq. 7.10) illustrates the procedure used for estimating the fuel.

$$Fuel = \frac{Raw\ clay \times Calcination\ energy \times \left(\frac{100}{100 - loss\ percentage}\right)}{weighted\ average\ calorific\ value\ of\ fuel\ mix\ used\ for\ clinkerization}\ Eq. 7.10$$

The numerator in Eq. 7.10 indicates the practical energy consumed for calcining a certain amount of clay. The raw clay value is calculated using Eq.7.9. The clay calcination energy is selected from Table 7.8 based on the scenario of calcination considered. The value in the bracket indicates factor which considers the additional energy to be supplied to accommodate kiln efficiency. The loss percentage is cited from a report authored by Scrivener et al. (2016). Weighted average calorific value is calculated from the fuel mix used for clinkerization in case studies. The CO_2 from calcination is calculated by multiplying the amount of fuel with the weighted average CO_2 emission factor of the fuel mix used for clinkerization.

7.5.3 Energy consumption and CO_2 emission estimation

1) Energy use estimation

The energy use is calculated based on the same methodology followed in case study one and two.

a) In the first step, the methodology is defined. Here the energy consumption related to the LC^3 production is estimated. The energy is calculated in MJ. Energy is estimated by multiplying the inventory data which is associated with energy consumption, with suitable energy factor.

b) In the second step, the inventory data associated with the energy use within gate to gate system boundary is selected from LCI results. The Table 7.10 presents the inventory data used for the energy calculation.

Table 7.10: Inventory selected for energy calculation

Input	Value	Unit
Energy - Electricity		
Electricity for clay calcination	16	kWh/ ton of LC^3
Electricity - cement mill section	24	kWh/ ton of LC^3
Electricity - packing plant section	0.65	kWh/ ton of cement
Electricity - services	3.15	kWh/ton of cement
Fuel		
Fuel mix	89.98	kg/ton of LC^3
Raw material		
Clinker	0.500	ton/ton of LC^3
Limestone	0.150	ton/ton of LC^3

c) In third step the suitable energy factor for these selected inventory is chosen. The energy factor is then used to multiply with inventory value to convert the inventory to corresponding energy. The sum of the energy associated with each data is added together to obtain the energy associated with production of LC^3. The energy factor used corresponding to the inventory related to Case study 1 are provided in Table 7.11.

Table 7.11: Energy factor for case study 1

Input	Value	Unit	Remark
Raw material			
Clinker	3.99	MJ/kg	Energy consumed for the Production of clinker. Energy consumed is considered for the process like limestone extraction, limestone crushing, fuel preparation, raw meal preparation, and clinkerization. Source: The value calculated using case study 1 (Chapter 4).
Limestone	0.06	MJ / kg of limestone	Annexure D
Fuel			
Fuel mix	26.79	MJ/kg of fuel	Weighted average of fuel mix for clinkerization. Source : Case study 1 (Chapter 4)
Energy - Electricity			
Electricity	13.40	MJ/kWh	Sum of energy consumed from fuels in thermal power plant. Source: Case Study 1 (Chapter 4)

Similar value of energy factors for case study 2 are cited from values provided in chapter 5 and from Annexure E. A sample calculation of the energy consumption for the scenario one of case study one is provided in Table 7.12.

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Table 7.12: Illustration of energy consumption for LC^3 production (CS 1 - S 1) process-wise

Process and selected inputs	Input value	Energy factor	Energy
Calcination of clay			
Input			
Fuel mix	89.98 kg/ton of LC^3	26.79 MJ/kg of fuel	2410.18 MJ/ton
Electricity for clay calcination	16.00 kWh/ ton of LC^3	13.40 MJ/kWh	214.38 MJ/ton
			2624.56 MJ/ton
Grinding of cement			
Input			
Clinker	0.500 ton/ton of LC^3	3.99 MJ/kg	1994.67 MJ/ton
Limestone	0.150 ton/ton of LC^3	0.06 MJ / kg of limestone	8.92 MJ/ton
Electricity - cement mill section	24.00 kWh/ ton of LC^3	13.40 MJ/kWh	321.57 MJ/ton
			2325.17 MJ/ton
Packing of cement			
Input			
Electricity - packing plant section	0.65 kWh/ ton of Cement	13.40 MJ/kWh	8.73 MJ/ton
			8.73 MJ/ton
Others			
Input			
Electricity - services	3.15 kWh/ ton of Cement	13.40 MJ/kWh	42.24 MJ/ton
			42.24 MJ/ton
Total energy consumed			**5000.70 MJ/ton**

Similar exercises are conducted for remaining three scenarios of case study one and all four scenarios of case study two. Table 7.13 presents the energy for LC^3 production for case studies 1 and 2 for 4 scenarios each.

Table 7.13: Energy consumption for LC^3 production

Case study	Scenario 1 (S 1)	Scenario 2 (S 2)	Scenario 3 (S 3)	Scenario 4 (S 4)
Case study 1 (MJ/ton of LC^3)	5000.70	3360.42	3713.43	2962.23
Case study 2 (MJ/ton of LC^3)	4763.71	3123.42	3476.44	2725.23

Thus a set of energy values for LC^3 production are obtained. This set of results shows the energy consumption for the production of LC^3 in the cement plants corresponding to case studies 1 and 2, in relation to the four scenarios of clay calcination process.

2) CO_2 emission estimation

CO_2 emission is calculated based on the methodology followed in case studies one and two.

a) In the first step, methodology is defined: Here CO_2 emission related to the LC^3 production is estimated. The CO_2 emission is calculated in kg CO_2. CO_2 emissions is estimated by multiplying the inventory data which is associated with energy consumption with suitable energy factor.

b) In the second step, the inventory data associated with the CO_2 emissions within gate to gate system boundary is selected from LCI results. The inventory selected for CO_2 estimation are provided in the Table 7.14.

Table 7.14: Inventory data selected for CO_2 emissions calculation

Input	Value	Unit
Raw material		
Clinker	0.500	ton/ton of LC^3
Limestone	0.150	ton/ton of LC^3
Energy - Electricity		
Electricity for clay calcination section	16	kWh/ ton of LC^3
Electricity - cement mill section	24	kWh/ ton of LC^3
Electricity - packing plant section	0.65	kWh/ ton of Cement
Electricity - services	3.15	kWh/ton of cement
Output	**Value**	**Unit**
Emission to air		
CO_2 - from fuel mix	203.80	kg CO_2/ton of LC^3

c) In third step, the suitable CO_2 emission factor for these selected inventory is chosen. The selected CO_2 emission factors are provided in Table 7.15. The CO_2 emission factor is then used to multiply with inventory value to convert the inventory to corresponding energy. The sum of the CO_2 associated with each data is added together to obtain the CO_2 associated with production of LC^3.

Table 7.15: CO_2 emission factor for case study 1

Input	Value	Unit	Remark
Raw material			
Clinker	0.85	kg CO_2 / kg	The CO_2 emission during the production of the clinker. The value is calculated considering processes limestone extraction, limestone crushing, fuel preparation, raw meal preparation, and clinkerization. Source: Case study 1 (Chapter 4)
Limestone	4.47	kg CO_2 / ton	Source: Annexure D
Electricity			
Electricity	1.09	kg CO_2 / kWh	Sum of CO_2 emission from fuels in thermal power plant and diesel for transportation. Source: Case study 1
Output	**Value**	**Unit**	**Remark**
CO_2	1.00	kg CO_2 / kg	Same input

Similar CO_2 emission factor for case study 2 is cited from chapter 5 and annexure E. A sample calculation of the CO_2 emission for the scenario one of case study one is provided in Table 7.16.

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Table 7.16: Illustration of CO_2 emissions for LC^3 (CS 1, S 1) process-wise

Process and selected inputs	Input / Output	CO_2 emission factor	CO_2 emissions
Calcination of clay			
Input			
Electricity - calcination of clay	16 kWh/ ton of LC^3	1.09 kg CO_2/kWh	17.39 kg CO_2/ton of LC^3
Output			
CO_2 - from fuel mix	203.80 kg CO_2/ton of LC^3	1.00 kg CO_2/kWh	203.80 kg CO_2/ton of LC^3
			221.19 kg CO_2/ton of LC^3
Grinding of cement			
Input			
Clinker	500 kg/ton of LC^3	0.85 kg CO_2 / kg	424.16 kg CO_2/ton of LC^3
Limestone	150 kg/ton of LC^3	0.00 kg CO_2 / kg	0.67 kg CO_2/ton of LC^3
Electricity			
Electricity - cement mill section	24 kWh/ ton of LC^3	1.09 kg CO_2/kWh	26.09 kg CO_2/ton of LC^3
			450.92 kg CO_2/ton of LC^3
Packing of cement			
Input			
Electricity - packing plant section	0.651 kWh/ ton of Cement	1.09 kg CO_2/kWh	0.71 kg CO_2/ton of LC^3
			0.71 kg CO_2/ton of LC^3
Other			
Input			
Electricity - for services	3.15 kWh/ ton of Cement	1.09 kg CO_2/kWh	3.43 kg CO_2/ton of LC^3
			3.43 kg CO_2/ton of LC^3
Total CO_2 emission			**676.25 kg CO_2/ton of LC^3**

Similar exercises are conducted for remaining three scenarios of case study one and all four scenarios of case study two. Table 7.17 presents the results of CO_2 emissions due to production of LC^3 in case studies 1 and 2 corresponding to 4 scenarios of clay calcination process.

Table 7.17: CO_2 emission for LC^3 production

Case study	Scenario 1 (S 1)	Scenario 2 (S 2)	Scenario 3 (S 3)	Scenario 4 (S 4)
Case study 1 (kg CO_2/ton of LC^3)	676.25	537.55	567.40	503.88
Case study 2 (kg CO_2/ton of LC^3)	708.85	551.41	585.30	513.20

Thus a set of energy values for the production of LC^3 is obtained. This set of results shows the CO_2 emissions for the production of LC^3 in the cement plant corresponding to case study 1 and 2, in relation to four scenarios of clay calcination process.

7.5.4 Interpretation

1) Conclusions

The conclusions related to the energy and CO_2 emission of LC^3 in 4 scenarios, OPC and PPC in case study 1 and 2 are provided as follows. The case study 1 and 2 are abbreviated as CS 1, and CS 2 respectively. The clay calcination scenario 1, 2, 3, and 4 are abbreviated as S 1, S 2, S 3, and S 4.

a) Energy consumption

An energy consumption result provided in Table 7.12 can also be represented in comprehensive structured manner. The columns in the table represents the unit processes and rows represent the data type, which are as suggested in ISO 14040/44. The structured result of energy consumption is provide in Table 7.18.

Within a Case Study, the only energy contributing factor which varies with clay calcination scenario is energy from fuel. The energy value from rest of the input data in case study one is 2591 MJ/ton of LC^3. This value along with different clay calcination energy can make the total energy result for LC^3 production. The energy consumption of PPC and OPC is 3077 and 4014 MJ. If the energy from fuel for calcination is 486 MJ, the LC^3 becomes equal to PPC, and if it is 1423 MJ the LC^3 becomes equal to OPC in terms of energy. Similarly in Case Study 2 the energy contribution from input data other than fuel for calcination is 2354 MJ. Thus adding energy from fuel for calcination will provide the total energy for LC^3. The energy for PPC and OPC are 2733 and 3820 MJ respectively. Thus if the calcination energy is 379 MJ, the LC^3 becomes equal to PPC and if calcination energy is 1466 MJ, the LC^3 becomes equal to OPC. Thus depending on the calcination energy considered in the clay calcination scenarios the energy for LC^3 with respect to OPC and PPC can be more or less. Figure 7.24 shows the total energy of LC^3 related to four scenarios of clay calcination are compared with the PPC and OPC produced, in case studies.

Table 7.18: Structured table of energy use for LC^3 (CS 1, S 1)

Unit process / Data type	Calcination of clay	Grinding of cement	Packing of cement	Others	Total
Fuel	2410.18	-	-	-	**2410.18**
Electricity	214.38	321.57	8.73	42.24	**586.93**
Clinker	-	1994.67	-	-	**1994.67**
Limestone	-	8.92	-	-	**8.92**
Total	**2624.56**	**2316.25**	**8.73**	**42.24**	**5000.70**

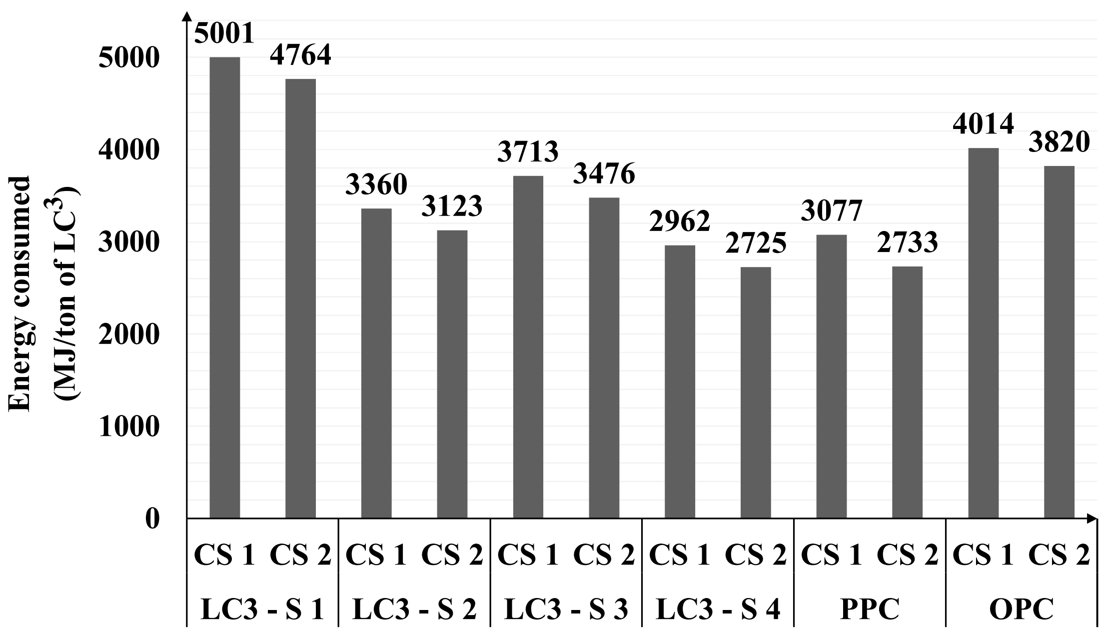

Figure 7.24: Comparison of energy LC^3, OPC, and PPC

In case study 1, the energy for LC^3 is less than OPC in scenario 2, scenario 3 and scenario 4, whereas LC^3 has higher energy than OPC in scenario 1. The same trend is found in case study 2 also.

The energy of PPC is compared with LC^3. In case study 1, the energy of LC^3 is found to be low for scenario 4, whereas the LC^3 is found to be high for scenario 1, scenario 2, and scenario 3. The same trend is found in case study 2 also.

The percentage change in the energy use for 4 scenarios of LC^3 production with respect to OPC and PPC are provided in Table 7.19. The percentage change values are calculated with respect to the PPC and OPC values of corresponding case study.

Table 7.19: Percentage change in the energy results of LC^3

Reference cement	Percentage difference							
	Case Study 1				Case Study 2			
	LC^3 - S 1	LC^3 - S 2	LC^3 - S 3	LC^3 - S 4	LC^3 - S 1	LC^3 - S 2	LC^3 - S 3	LC^3 - S 4
OPC (in %)	+24.6	-16.3	-7.5	-26.2	+24.7	-18.2	-9.0	-28.7
PPC (in %)	+62.5	+9.2	+20.7%	-3.7	+74.3	+14.3	+27.2	-0.3

All the percentage differences are calculated based on the reference cement (OPC or PPC). It is observed that OPC is lower that LC^3 - S 1 in both case studies at least by 24%. In case of LC^3 produced in scenarios S 2, S 3, and S 4, there is a reduction of at least by 16.3, 7.5, and 26.4 % respectively for both case studies with respect to OPC. It is observed that the PPC is lower than LC^3 produced in scenarios S 1, S 2, and S 3 by at least 62, 9, and 20 % respectively considering both cases. The LC^3 - S 4 is less than PPC by 0.3% and 3.7 % respectively for case study 1 and 2.

b) CO_2 emission

The CO_2 emission results can also be represented in a consolidated table with unit processes as columns and data as rows. ISO 14044 recommends the same for the wholistic overview of results and to have easy analysis. The consolidated table of CO_2 emission result of the case study 1 - scenario 1 is provided in the Table 7.20.

Within a case study the only CO_2 contributing factor which varies with clay calcination scenario is CO_2 from fuel. The CO_2 value from rest of the input data in case study 1 is 472 kg CO_2/ton of LC^3. This value along with CO_2 from fuel used for clay calcination makes the total energy result for LC^3 production. The energy consumption of PPC and OPC is 606 and 801 kg CO_2 respectively. If the energy from fuel for calcination is 134 kg CO_2, the LC^3 becomes equal to PPC, and if it is 329 kg CO_2 the LC^3 becomes equal to OPC in terms of CO_2 emissions. Similarly in case study 2 the CO_2 associated with inputs other than fuel for calcination is 478 kg CO_2/ton of LC^3. Thus, adding CO_2 from fuel for calcination will provide the total energy for LC^3. The CO_2 emission for PPC and OPC are 594 and 854 kg CO_2 respectively. Thus, if the calcination energy is 116 kg CO_2, the LC^3 becomes equal to PPC and if calcination energy is 376 kg CO_2 the LC^3 becomes equal to OPC. Thus, depending on the calcination energy considered in the clay calcination scenarios the energy for LC^3 can be more or less with respect to OPC and PPC. The CO_2 emissions due to LC^3 production related to four scenario of clay calcination are compared with the PPC and OPC, produced in case study one and two. Figure 7.25 shows the CO_2 emission results of LC^3 (All scenarios), OPC and PPC.

Out of the CO_2 emission calculated for four scenarios for both case studies, the CO_2 emission for LC^3 is less than OPC in all LC^3 production possibilities. When comparing the results with PPC in case study 1, the LC^3 has less CO_2 emissions in scenario 2, 3 and 4, whereas the LC^3 has high CO_2 emissions in scenario 1. All these trends are observed in case study 2 also.

Table 7.20: Structured table of CO_2 emissions for LC^3 (CS 1, S 1)

Unit process / Data type	Calcination of clay	Grinding of cement	Packing of cement	Others	Total
Electricity	17.39	26.09	0.71	3.43	**47.62**
Clinker		424.16			**424.16**
Limestone		0.67			**0.67**
CO_2 from fuel	203.80				**203.80**
Total	**221.19**	**450.92**	**0.71**	**3.43**	**676.25**

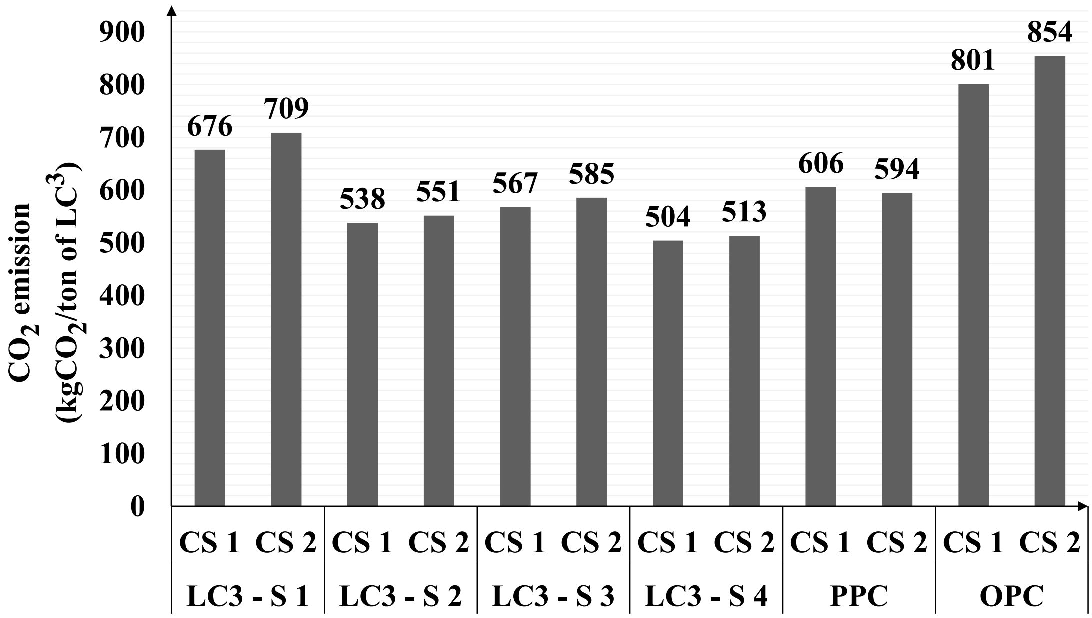

Figure 7.25: Comparison of CO_2 emission for LC^3, OPC, and PPC

The percentage change of the CO_2 emissions for 4 scenarios of LC^3 production with respect to OPC and PPC are provided in Table 7.21. The percentage change values are calculated with respect to the PPC and OPC values of corresponding case study.

Table 7.21: Percentage change in the CO_2 emissions of LC^3

Reference cement	Percentage difference							
	Case Study 1				Case Study 2			
	LC^3 - S 1	LC^3 - S 2	LC^3 - S 3	LC^3 - S 4	LC^3 - S 1	LC^3 - S 2	LC^3 - S 3	LC^3 - S 4
OPC (in %)	-15.6	-32.9	-29.2	-37.1	-17.0	-35.5	-31.5	-39.9
PPC (in %)	+11.7	-11.3	-6.3	-16.8	+19.3	-7.2	-1.5	-13.6

It is observed that LC^3 Scenarios like S 1, S 2, S 3, and S 4 are lower that OPC by at least 15, 32, 29, and 37 % respectively. LC^3 - S 1 is higher than PPC by a minimum of 11 % in both case studies. Whereas the LC^3 of scenarios S 2, S 3, and S 4 are lower than PPC by a value no less than 7, 1.5 and 13 % respectively.

2) Limitations

a) The results are valid under the limitation of the study as mentioned in section: 7.5.1.

b) It is to be noted that the transportation and mining of the truck is not considered in the study. If the transportation process is considered, the result can alter and may result in change in trend.

3) Recommendations

From the results, it is observed that the LC3 produced with scenario 4 (with clay having low calcination energy under a heat recovery system) is better than PPC and OPC in terms of energy and CO_2 emissions. These estimated results can be circulated among the interested industrialists and government officials in order to improve their understanding and to perform field execution.

7.6 Scope for future work

There is potential future scope associated with the research work provided in this chapter. The future works mainly include the removal of errors in current results and the optimization of the calculation steps. As mentioned before, C_c, and E_c values are comparatively high with respect to literature. It is hypothesized that the variation can be due to equipment error. In order to validate the same, DSC tests are conducted on 3 samples at Polymer Engineering and Colloidal Sciences (PECS) Lab, in Chemical engineering department of IIT Madras. The raw data seems to be lower than the result of the same samples obtained previously. The specific heat capacity of three samples was observed to be 15%, 20% and 29% of the previously obtained result. These results support the possibility of equipment error. Since the variation in the results is high, it can even change the trend of results and conclusions. This need to be further studied. Since the values obtained previously were high, further rectification of these errors can result in less energy and emission of LC^3. This indicates the current conclusions which are favourable to LC^3 will be valid even after rectification of the error noticed. Few of the future works associated with this research are provided as below.

1) The mass of raw clay corresponding to 300 kg of calcined clay can be calculated for set of clay samples collected. This along with the inventory data of OPC and PPC can be used to estimate hypothetical inventory results for LC^3.

2) A theoretical energy model can be made using literature values, like theoretical calcination energy, heat flow distribution in kiln, and different clay samples (variation in kaolinite content and impurities).

3) The DSC results need to be normalized using calibration factor, which can further reduce the energy and CO_2 estimation.

4) The loss percentage considered is higher due to kiln inefficiency. This can be optimized further.

5) The clay with most probable calcination energy value can be identified from the sample clay set obtained. The energy and CO_2 associated with clay sample with most probable calcination energy can be calculated with and without heat recovery.

6) The electricity consumed for the operation of rotary kiln for calcination and grinding of LC^3, was cited from a trial case study on LC^3 production in Cuba. A thorough literature survey or more field visits can be conducted to find the most possible electricity consumption values.

7) The different LC^3 production scenarios discussed can be further developed. Few possibilities are mentioned as follows,

   a) The associated transportation process for each process system (discussed in section 7.4) can be estimated based on the amount of freight to be transported and assumed distance between sources. An example of sample calculation is provided in Annexure F.

   b) There are also possibilities like producing an admixture of limestone and calcined clay in the required proportion. Incorporation of LC^2 plant in the process system can results in more combinations of process systems.

CHAPTER 8

CONCLUSION

8.1 General conclusions – Overview of important contributions

The general conclusions of this research work are summarised as follows:

- The sustainability parameters like inventory, energy use, and CO_2 emissions associated with the production of clinker, OPC and PPC are studied based on two case studies.
- The sustainability aspects of Limestone Calcined Clay Cements is studied in terms of energy use and CO_2 emissions.

8.2 Specific conclusions – Overview of important contributions

The specific contributions of this research work are summarised as follows:

8.2.1 LCA methodology

- A practice oriented, form of explanation on LCA is provided, based on the guidelines of ISO 14040 and ISO 14044. The explanation are provided in a detailed manner which even enable a practitioner without background knowledge to perform the same.
- A spread sheet template is made using the above explanation, which can be used by LCA practitioners to perform LCA on a product or a process.

8.2.2 Assessment of conventional cements

- Inventory, energy use, and CO_2 emissions associated with clinker, OPC and PPC within Gate to Gate system boundary are studied and reported for two typical cement plants. The energy use and CO_2 emissions results are provided in Table 8.1.

Table 8.1: Energy use and CO_2 emissions

Product	Data related to energy	Energy use (MJ/ton)		Data related to CO_2 emissions	CO_2 emissions (kg CO_2/ton)	
		Cement Plant - 1	Cement Plant - 2		Cement Plant - 1	Cement Plant - 2
Clinker	Fuel for thermal treatment	3079.56	2916.30	Direct emissions from fuel and raw material	775.25	810.82
	Electricity	802.85	668.46	Electricity	65.14	54.24
	Others	106.94	40.49	Others	7.92	3.04
	Total	**3989.35**	**3625.25**	**Total**	**848.32**	**867.35**
OPC	Clinker	3614.73	3443.99	Clinker	768.66	823.98
	Electricity	399.30	375.57	Electricity	32.40	30.47
	Others	-	0.56	Others	-	0.03
	Total	**4014.03**	**3820.12**	**Total**	**801.06**	**854.48**
PPC	Clinker	2707.47	2356.41	Clinker	575.73	563.78
	Electricity	369.06	375.57	Electricity	29.94	30.47
	Others	-	0.56	Others	-	0.03
	Total	**3076.53**	**2732.54**	**Total**	**605.68**	**594.28**

- Energy use: Case Study - 1 and Case Study - 2
  a) The sum of major components of energy use for clinker production seems to be higher than similar values reported in different geographical regions across the world.
  b) The sum of major components of energy use for OPC production is around the higher end of values reported in databases corresponding to different geographical regions across the world.
  c) The sum of major components of energy use for PPC production is around the lower limit of values reported, corresponding to several other regions across the world.
- CO_2 emissions: Case Study - 1 and Case Study - 2
  a) The sum of major contributors of CO_2 emissions for the production of, clinker in Case Study - 1 is around the lower limit of similar values reported for many

geographical regions across the world. In case of Case Study - 2, the value is around the average of similar values reported for many geographical regions.

b) The sum of major contributors of CO_2 emissions for the production of OPC in Case Study - 1 is around the lower limit compared to similar values reported for many geographical regions across the world. In case of Case Study - 2, the value is around the average of similar values reported for many geographical regions.

c) The sum of major contributors of CO_2 emissions for the production of PPC is around the lower range in comparison with similar values reported for different geographical regions across the world.

All calculation details are provided in Chapter 4 and Chapter 5. The values provided earlier is rounded off to next integer to make the result conservative. All conclusive statements are compared with values reported for a higher system boundary 'Cradle to gate'. Thus the comparative statements made in this section are safe.

8.2.3 Assessment of clay calcination process and LC^3

- TGA/DSC results of 76 clay samples are shared by TARA. The raw data of results are analysed. Based on 53 samples selected, the attributes like specific heat capacity, calcination energy per kaolinite content, and total calcination energy for two scenarios are calculated for the sample set.

  a) The average value of specific heat capacity (C_c) is 2.5 kJ/kg ^oC with the coefficient of variation of ± 31%. The minimum and the maximum values are 1.1 and 4.1 kJ/kg ^oC respectively. These values seem to be higher than in literature.

  b) The average value of calcination energy per kaolinite content (E_c) is 1515 kJ/kg of kaolinite, with a coefficient of variation of ± 26%. The calcination energy per kaolinite content ranges from 626-2655 kJ/kg of kaolinite. These values seem to be higher than in literature.

  c) The average total energy for calcination with heat recovery is 1287 kJ/kg of clay with a coefficient of variation of ± 23%. The calcination energy with heat recovery ranges from 689-2091 kJ/kg of kaolinite.

  d) The average total energy for calcination without heat recovery is 2794 kJ/kg of clay with a coefficient of variation of ±25%. The minimum and maximum value is coming about 1428-4488 kJ/kg of kaolinite.

The results presented earlier are rounded off to nearest integer. The calculation details are provided in the Chapter 7.

- Twelve process systems for the production of LC^3 are discussed.
- The energy use and CO_2 emissions related to the production of LC^3 in four clay calcination scenarios are estimated in Case Study - 1 and 2. The trend in the magnitude of energy and emission for four scenarios of LC^3 production is same. The energy use and CO_2 emissions of four LC^3 scenarios, PPC and OPC are provided in Table 8.2. The conclusive statements of LC^3 results with OPC and PPC for both case studies are also found to be same.

Table 8.2: Energy use and CO_2 emissions of LC^3 scenarios with OPC and PPC

Case Study	Type of result	Type of cement					
		LC3 - S 1	LC3 - S 2	LC3 - S 3	LC3 - S 4	PPC	OPC
Case study 1	Energy use (MJ/ton)	5001	3360	3713	2962	3077	4014
	CO_2 emissions (kg CO_2/ton)	676	538	567	504	606	801
Case study 2	Energy use (MJ/ton)	4764	3123	3476	2725	2733	3820
	CO_2 emissions (kg CO_2/ton)	709	551	585	513	594	854

Few conclusive statements are presented as follows:

a) LC^3 in comparison with OPC: Case Study 1 and Case Study 2

i) Energy use of LC^3 is less than OPC in all scenarios except the scenario - 'without heat recovery and high calcination energy'.

ii) CO_2 emissions for LC^3 production are less than OPC in all four scenarios: (i) 'Without heat recovery and high calcination energy'; (ii) 'Without heat recovery and low calcination energy'; (iii) 'With heat recovery and high calcination energy'; and (iv) 'With heat recovery and low calcination energy'.

b) LC^3 in comparison with PPC: Case Study 1 and Case Study 2

i) The energy use for LC^3 seems to be less than PPC in one scenario -'with heat recovery and low calcination energy'. And in rest of the three scenarios PPC is has less energy use than LC^3.

ii) CO_2 emissions of LC^3 are less than PPC in three scenarios as follows; (i) 'Without heat recovery and low calcination energy', (ii) 'Heat recovery and high calcination energy', and (iii) 'Heat recovery and low calcination energy'. PPC is better than LC^3 in case -'without heat recovery and high calcination energy'.

All results provided on clay calcination are found to be over-estimated due to equipment error, and thus the comparative conclusive statements made are conservative. The calculation details are provided in Chapter 7.

8.3 Recommendations

- The LCA spreadsheet developed can be used to practice LCA on any product or process.
- Lack of inventory is the main hindrance for sustainability development in India compared to other countries. Proper monitoring and development of LCI can help to identify hotspots related to environmental impacts. Identification of hotspots can lead to application of suitable measures to make the sector more sustainable. This study presents a comprehensive life cycle inventory related to cement production and compares the performance of OPC, PPC and LC_3. The use of mixture of limestone and calcined clay as an additive to the cement can reduce the CO_2 emissions related to cement production.
- The inventory, energy use, and CO_2 emissions associated with clinker can be reported in inventory databases. This can be used to estimate the inventory, energy and CO_2 emission associated with different cements made of clinker
- The inventory, energy use, and CO_2 emissions associated with OPC and PPC can be reported in inventory databases. This can be used to estimate the inventory, energy and CO_2 emission associated with different products made of the same (e.g. concrete)
- The energy use and CO_2 emissions related to the production of LC^3 can be spread among industrialists, academicians, and policy makers. This can create awareness on the potential of LC^3 as a sustainable cement.

8.4 Future Scope

The scope of future work are listed below.

With respect to LCA template

- The template developed need to be operated completely manual. Thus the template can be further developed to a more automated and easier user interface.
- Current compilation of energy and CO_2 emission factors can be further increased by studying more fuel samples.

On assessment of conventional cement

- The data can be extended to a system boundary of "Ground to gate" or "Cradle to gate" for completeness of life cycle approach.
- In India, 93% of the plants are using dry processing technology (Kumar 2015). Thus a hypothesis of 'less energy and CO_2 on cement production, in comparison with respect to the other countries' is made. Despite the case study considered are of dry technology with 5 stage preheater precalciner, the results seems to be contradictory with respect to the hypothesis. Thus, more analysis should be conducted in order to understand the reason.

On assessment of clay calcination energy and LC^3

- A theoretical energy model can be developed using literature values like, theoretical calcination energy, heat flow distribution in kiln, and different clay samples (variation in kaolinite content and impurities).
- The DSC results need to be normalized using calibration factor, which can further reduce the energy use and CO_2 emissions.
- The energy use and CO_2 emissions associated with clay sample of average calcination energy can be calculated for cases - with and without heat recovery.
- The electricity consumed for the operation of rotary kiln for calcination and ball mill for grinding of LC^3, was cited from trial case studies on LC^3 production in Cuba. A thorough literature survey or more field visits can be conducted to find the variability in electricity consumption values.
- The loss percentage considered to account kiln inefficiency is higher. This can be determined accurately.

Improving the scope of inventory parameters and Impact assessment

- The methods employed to scrub and screen atmospheric dust particles and particulate emissions may be included in the life cycle inventory estimation.
- In addition to CO_2, other emissions such as NO_x, SO_2, and PM related to cement production may be studied. Further, the global warming potential of these emissions may be studied.

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ANNEXURE A

Table A. 1: CS 1: Validated result of absolute data

Input	Value	Unit
Energy – Fuel		
Petcoke (imported)	31634	tons
Petcoke (indigenous)	22631	tons
Coal	989	tons
Lignite	32841	tons
Diesel	45	tons
RDF (Refuse derived fuel) including plastics	7606	tons
Tyres	1433	tons
Solvents (Paint Sludge)	2376	tons
Foot wear scrap	1099	tons
Hard rubber	338	tons
Mixed industrial waste (Carbon powder, Coal ash)	643	tons
Other fossil-based wastes and mixed fuels (oily cotton waste)	43	tons
Others (UNL waste, Fibre waste)	111	tons
Agro based	303	tons
Coir pith	49	tons
Cashew nut	321	tons
Coffee husk	2	tons
De oiled Rice Bran	715	tons
Other biomass fuel (wooden dust)	18	tons
Raw material		
Limestone and marl	1303749	tons
White clay	30315	tons
ETP Sludge	19158	tons
Fly ash (in kiln feed)	7382	tons
Other physical inputs - Transportation		
Diesel oil	703	tons
Others - (Consumables)		
Refractories and castable	382	tons
Output	**Value**	**Unit**
Product		
Clinker	8,97,587	tons
Waste - Emission to air		
SPM - Kiln main stacks	91.83	tons
SPM - Coal mill stacks	20.35	tons
SPM - Cooler stacks	28.04	tons
SO2 - Kiln Main stacks	23.29	Tons
SO2 - Coal Mill Stacks	6.94	Tons
NOx - Kiln Main stacks	1654.65	Tons
NOx - Coal Mill Stacks	31.45	Tons

Table A. 2: CS 1: Validated results of reference flow value

Input	Value	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section	0.70	kWh/ton of limestone
Electricity consumed by raw mill section	15.36	kWh/ton of raw meal
Electricity consumed by coal mill section	51.75	kWh/ton of fuel
Electricity consumed by kiln section	28.46	kWh/ton of Clinker
Electricity consumed by kiln section for kiln shut down	1.34	kWh/ton of Clinker
Output	**Value**	**Unit**
Waste - Emission to air		
Radiation and Convection losses from cooler	6.0	kcal/kg of clinker
Radiation and Convection losses from kiln	19.6	kcal/kg of clinker
Radiation and Convection losses from preheater	16.8	kcal/kg of clinker
Radiation and convection losses from tertiary air duct	2.1	kcal/kg of clinker

Table A. 3: CS 1: Validated result of miscellaneous data

Input	Value	Unit
Energy - Fuel		
Diesel	0.84	kg/litre
Other physical inputs - Transportation		
Diesel	1840618	Litre

Table A. 4: CS 1: LCI result using absolute data

Input	Value	Unit
Energy - Fuel		
Petcoke (imported)	35.243	kg / ton of clinker
Petcoke (indigenous)	25.213	kg / ton of clinker
Coal	1.102	kg / ton of clinker
Lignite	36.588	kg / ton of clinker
Diesel	0.050	kg / ton of clinker
RDF (Refuse derived fuel) including plastics	8.474	kg / ton of clinker
Tyres	1.596	kg / ton of clinker
Solvents (Paint Sludge)	2.648	kg / ton of clinker
Foot wear scrap	1.224	kg / ton of clinker
Hard rubber	0.377	kg / ton of clinker
Mixed industrial waste (Carbon powder, Coal ash)	0.716	kg / ton of clinker
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.048	kg / ton of clinker
Others (UNL waste, Fibre waste)	0.124	kg / ton of clinker
Agro based	0.338	kg / ton of clinker
Coir pith	0.055	kg / ton of clinker
Cashew nut	0.358	kg / ton of clinker
Coffee husk	0.002	kg / ton of clinker
De oiled Rice Bran	0.797	kg / ton of clinker
Other biomass fuel (wooden dust)	0.020	kg / ton of clinker
Raw material		
Limestone and marl	1.453	ton / ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton / ton of clinker
Other physical input - Transportation		
Diesel oil	0.783	kg / ton of clinker
Others		
Refractories and castable	0.426	kg / ton of clinker
Output		
Product		
Clinker	1	ton / ton of clinker
Waste - Emission to air		
SPM - Kiln main stacks	0.102	kg / ton of clinker
SPM - Coal mill stacks	0.023	kg / ton of clinker
SPM - Cooler stacks	0.031	kg / ton of clinker
SO2 - Kiln Main stacks	0.026	kg / ton of clinker
SO2 - Coal Mill Stacks	0.008	kg / ton of clinker
NOx - Kiln Main stacks	1.843	kg / ton of clinker
NOx - Coal Mill Stacks	0.035	kg / ton of clinker

Table A. 5: CS 1: LCI result using reference flow

Input	Value	Unit
Energy - Electricity		
Electricity consumed by limestone crushing section per ton of clinker	1.02	kWh/ton of clinker
Electricity consumed by raw mill section per ton of clinker	23.16	kWh/ton of clinker
Electricity consumed by coal mill section per ton of clinker	5.95	kWh/ton of clinker
Electricity consumed by kiln section per ton of clinker produced	28.46	kWh/ton of Clinker
Electricity consumed by kiln section for kiln shut down per ton of clinker produced	1.34	kWh/ton of Clinker
Output	**Value**	**Unit**
Waste - Emission to air		
Radiation and Convection losses from cooler	25.1	MJ/ton of clinker
Radiation and Convection losses from kiln	82.0	MJ/ton of clinker
Radiation and Convection losses from preheater	70.3	MJ/ton of clinker
Radiation and Convection losses from tertiary air duct	8.8	MJ/ton of clinker

Table A. 6: CS 1: LCI result using miscellaneous data

Input	Value	unit	Remark
Other physical inputs - Transportation			
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker	(Diesel consumed for extraction and transportation/ clinker produced) * Density of diesel. Diesel consumed for extraction and transportation, Time period: 2014-2015, Source: File "EN 14-15.xlsx", worksheet "EN -3". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700". Density of diesel, Time period: 2014-2015, Source: "EN-14-15.xls", worksheet "EN -3"

Table A. 7: CS 1: Aggregated LCI result

Input	Value	Unit
Energy - Electricity		
Electricity	59.92	kWh / ton of clinker
Energy - Fuel		
Fuel	114.973	kg / ton of clinker
Raw material		
Limestone and marl	1.453	ton / ton of clinker
White clay	0.034	ton / ton of clinker
ETP Sludge	0.021	ton / ton of clinker
Fly ash (in kiln feed)	0.008	ton / ton of clinker
Ancillary inputs		
Other physical inputs - Transportation		
Diesel	2.506	kg / ton of clinker
Others		
Refractories and castable	0.426	kg / ton of clinker
Output	**Value collected**	**Unit**
Product		
Clinker	1	ton / ton of clinker
Waste - Releases to air		
SPM	0.156	kg / ton of clinker
SO2	0.034	kg / ton of clinker
NOx	1.843	kg / ton of clinker
Radiation and convection	186.2	MJ / ton of clinker

Table A. 8: CS 1: CO_2 emission factor with suitable unit

Inputs	Value	Unit	Remark
Energy - Fuel			
Petcoke	3.06	kg CO_2 / kg	The value obtained by testing the sample collected from plant. CHNS analyser is been used for analysis. It was not mentioned the petcoke provided was indigenous or imported, nevertheless the value is used for calculation related to both the petcoke.
Lignite	1.36	kg CO_2 / kg	The value obtained by testing the sample collected from plant. CHNS analyser is been used for analysis.
Raw material			
Raw meal	0.34	kg CO_2 / kg	Sum of CO2 release per ton of raw meal, due to decomposition of CaCO3 and MgCO3. Calculated using the formula: (CO2 released/amount of CaO * amount of CaO (from CaCO3) / amount of raw meal) + (CO2 released/amount of MgO * amount of MgO (from MgCO3)

Inputs	Value	Unit	Remark
			/ amount of raw meal). Amount of CaO, Source: The 2014-2015 yearly consumption value reported in the file CSI, worksheet, Calc B2. Amount of MgO, Source: The 2014-2015 yearly consumption value reported in the file CSI, worksheet, Calc B2.

Table A. 9: CS 1: CO_2 emission factor in another unit

Inputs	Value	Unit	Remark
Energy - Fuel			
Coal	0.09	kg CO_2 / MJ	Source: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, name of the fuel: Bituminous coal
Diesel	0.07	kg CO_2 / MJ	Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors", Name of fuel: solvents
RDF (Refuse derived fuel) including plastics	0.07	kg CO_2 / MJ	Source: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, Name of the fuel: Plastic
Tyres	0.08	kg CO_2 / MJ	Source: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, Name of the fuel: Plastic
Solvents (Paint Sludge)	0.07	kg CO_2 / MJ	Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors", Name of fuel: solvents
Mixed industrial waste (Carbon powder, Coal ash)	0.08	kg CO_2 / MJ	Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors", Name of fuel: Mixed industrial waste
Other fossil-based wastes and mixed fuels (oily cotton waste)	0.08	kg CO_2 / MJ	Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors", Name of fuel: Other fossil-based wastes
Agro based	0.11	kg CO_2 / MJ	Source: https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf, Name of the fuel: Plastic
Other biomass fuel (wooden dust)	0.09	kg CO_2 / MJ	Source: http://www.wbcsdcement.org/index.php/en/key-issues/climate-protection/co-accounting-and-reporting-standard-for-the-cement-industry, Excel File: CSI_ProtocolV3_1_09December2013, Worksheet: "Fuel CO2 Factors", Name of fuel: another biomass

Table A. 10: CS 1: Assumed CO_2 emission factors

Inputs	Value	Unit	Remark
Energy - Fuel			
Foot wear scrap	0.083	kg CO_2/MJ	Since footwear scrap is not found, Mixed industrial waste value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Mixed industrial waste
Hard rubber	0.083	kg CO_2/MJ	Since hard rubber is not found, mixed industrial waste value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Mixed industrial waste
Others (UNL waste, Fibre waste)	0.083	kg CO_2/MJ	Since others (UNL waste, Fibre waste) is not found, mixed industrial waste value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Mixed industrial waste
Coir pith	0.110	kg CO_2/MJ	Since the coir pith is not found another biomass value is been used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Other biomass
Cashew nut	0.110	kg CO_2/MJ	Since the cashew nut is not found other biomass value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Other biomass
Coffee husk	0.110	kg CO_2/MJ	Since the coffee husk is not found other biomass value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Other biomass
De oiled Rice Bran	0.110	kg CO_2/MJ	Since the de-oiled rice bran is not found other biomass value is being used. Source: File "CSI_ProtocolV3_1_09 Mar-2015.xls" worksheet "Fuel CO2 factors", name of input: Other biomass

Table A. 11: CS 1: The calorific value for unit conversion

Inputs	Value	Unit
Energy - Fuel		
Coal	25.62	MJ/kg
Diesel	42.68	MJ/kg
RDF (Refuse derived fuel) including plastics	16.96	MJ/kg
Tyres	27.49	MJ/kg
Solvents (Paint Sludge)	13.26	MJ/kg
Foot wear scrap	21.75	MJ/kg
Hard rubber	27.04	MJ/kg
Mixed industrial waste (Carbon powder, Coal ash)	15.98	MJ/kg
Other fossil-based wastes and mixed fuels (oily cotton waste)	18.85	MJ/kg
Others (UNL waste, Fibre waste)	15.42	MJ/kg
Agro based	12.18	MJ/kg
Coir pith	10.34	MJ/kg
Cashew nut	18.98	MJ/kg
Coffee husk	13.56	MJ/kg
De oiled Rice Bran	12.62	MJ/kg
Other biomass fuel (wooden dust)	9.18	MJ/kg

Table A. 12: CS 1: CO_2 emission factor with corrected unit

Inputs	Value	Unit
Energy - Fuel		
Coal	2.27	kg CO_2/kg
Diesel	3.16	kg CO_2/kg
RDF (Refuse derived fuel) including plastics	1.21	kg CO_2/kg
Tyres	2.24	kg CO_2/kg
Solvents (Paint Sludge)	0.98	kg CO_2/kg
Foot wear scrap	1.80	kg CO_2/kg
Hard rubber	2.24	kg CO_2/kg
Mixed industrial waste (Carbon powder, Coal ash)	1.33	kg CO_2/kg
Other fossil-based wastes and mixed fuels (oily cotton waste)	1.51	kg CO_2/kg
Others (UNL waste, Fibre waste)	1.28	kg CO_2/kg
Agro based	1.34	kg CO_2/kg
Coir pith	1.14	kg CO_2/kg
Cashew nut	2.09	kg CO_2/kg
Coffee husk	1.49	kg CO_2/kg
De oiled Rice Bran	1.39	kg CO_2/kg
Other biomass fuel (wooden dust)	1.01	kg CO_2/kg

Table A. 13: CS 1: Updated LCI results – Aggregated

Input	Value	Unit	Remarks
Energy - Electricity			
Electricity	59.92	kWh / ton of clinker	Electricity for limestone preparation, raw meal preparation, fuel preparation, clinkerization and shut down of clinker.
Energy - Fuel			
Fuel	114.97	kg / ton of clinker	Fuel consumed for clinkerization. Fuel contain 4 fossil fuel, 8 non-biomass fuel and 6 biomass fuels. Major fuels consumed are petcoke and lignite which comprises of 84.41%.
Raw material			
Limestone and marl	1.45	ton / ton of clinker	(Limestone and marl yearly consumption value/yearly clinker produced). The limestone and marl consumed, Time period: 2014-2015, Source: file "EN-14-15.xlsx", worksheet "EN - 1". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
White clay	0.034	ton / ton of clinker	(White clay yearly consumption value/yearly clinker produced). White clay consumed, Time period: 2014-2015, Source: file "EN-14-15.xlsx", worksheet "EN - 2". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
ETP Sludge	0.021	ton / ton of clinker	(ETP sludge yearly consumption value/yearly clinker produced). ETP sludge consumed, Time period: 2014-2015, Source: file "EN-14-15.xlsx", worksheet "EN - 1". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
Fly ash (in kiln feed)	0.008	ton / ton of clinker	(Fly ash yearly consumption value/yearly clinker produced). Fly ash consumed, Time period: 2014-2015, Source: file "EN-14-15.xlsx", worksheet "EN - 2". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
Other physical inputs - Transportation			
Diesel oil	0.783	kg / ton of clinker	(Diesel consumption for onsite transportation / clinker production). Diesel for onsite transportation, Time duration: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", Sheet "Plant", line 301a. Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
Diesel (Limestone extraction and transportation process)	1.723	kg / ton of clinker	(Diesel consumed for extraction and transportation/ clinker produced) * Density of diesel. Diesel consumed for extraction and transportation, Time period: 2014-2015, Source: File "EN 14-15.xlsx", worksheet "EN -3". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700". Density of diesel, Time period: 2014-2015, Source: "EN-14-15.xls", worksheet "EN -3"

Input	Value	Unit	Remarks
Others			
Refractories and castable	0.426	kg / ton of clinker	(Refractory and castable/clinker produced). Refractory and castable value, Time period: 2014-2015, Source: File "EN-14-15.xls", worksheet "EN -1". Clinker produced, Time period: 2014-2015, Source: "CSI_ProtocolV3_1_09 Mar-2015.xlsx", sheet "CalcB2 (2)", line "700"
Output	**Value collected**	**Unit**	**Remarks**
Product			
Clinker	1	ton / ton of clinker	Functional unit
Waste - Releases to air			
CO_2 from diesel	5.45	kg CO_2 / ton of clinker	Estimated CO_2 emission from extraction and transportation of limestone
CO_2 from diesel oil (onsite transportation)	2.48	kg CO_2 / ton of clinker	Estimated CO_2 emission from onsite transportation
CO_2 from fuel	260.40	kg CO_2 / ton of clinker	Estimated CO_2 from burning of fuel for clinkerization. Fuel contain 4 fossil fuels, 8 non-biomass fuels and 6 biomass fuels. Major fuels consumed are petcoke and lignite which comprises of 84.41%. The CO2 from fuel are estimated using suitable CO2 emission factors.
CO_2 from raw meal	514.86	kg CO_2 / ton of clinker	Estimated CO_2 emission from decarbonation of raw meal in clinkerization
SPM	0.156	kg / ton of clinker	The SPM from kiln mill stack, coal mill stack and cooler stack.
SO_2	0.034	kg / ton of clinker	SO_2 from Kiln mill stack and coal mill stack
NO_x	1.878	kg / ton of clinker	NO_x from coal mill stack and kiln main stack.
Radiation and Convection losses from cooler	186.19	MJ / ton of clinker	Heat lost in the form of radiation and convection from tertiary air duct, preheater, kiln and cooler.

Table A. 14: CS 1: Validated data for OPC and PPC

Input	**Value collected**	**Unit**
Raw material		
Clinker	897587	tons
Clinker to OPC (overall)	0.91	kg/kg
Clinker to PPC	0.68	kg/kg
Limestone (as performance improver)	13167	tons
Grinding media	16	tons
Fly ash (in cement plant)	271524	tons
Chemical gypsum	44896	tons
Marine gypsum	6381	tons
Cal gypsum	82	tons
Gypsum to PPC	0.04	kg/kg
Gypsum to OPC	0.04	kg/kg
Electricity		
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Electricity consumed by cement mill section	23.74	kWh/ ton of PPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Ancillary inputs		
Water - Cement plant (including mines)	74364	m^3
Water - Colony	26124	m^3
Others		
Oil (Lubricant)	161	tons
Grease	8.55	tons
Bags PP	1293	tons
Bags (Paper)	990	tons
Output	**Value**	**Unit**
Product		
PPC	975294	ton
OPC	260105	ton
Waste - Release to air		
SPM - Cement Mill Stacks	3.97	Tons
R-134A	0.6	Tons
Waste - Release to water		
Recycled water	56492	m^3
Waste - Release to soil		
Solid waste	1280711	Ton

Table A. 15: CS 1: LCI results of OPC using absolute data

Input	Value	Unit
Raw material		
Clinker	0.906	ton/ton of OPC
Limestone (as performance improver)	0.051	ton/ton of OPC
Gypsum	0.042	ton/ton of Cement
Electricity		
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Electricity consumed for services	3.15	kWh/ton of cement
Ancillary inputs		
Water - Cement plant (including mines)	0.060	m^3/ton of cement
Water - Colony	0.021	m^3/ ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Others		
Grinding media	1.30E-05	ton/ton of Cement
Output	**Value**	**Unit**
Product		
OPC	1.00	ton/ton of OPC
Waste - Release to air		
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
R-134A	4.86E-07	ton/ton of Cement
Waste - Release to water		
Recycled water	4.57E-02	m^3/ton of Cement
Waste - Release to soil		
Solid waste	1.04	ton/ton of Cement

Table A. 16: CS 1: LCI results of OPC using reference flow

Input	Value	Unit
Raw material		
Clinker for OPC	0.906	ton/ton of OPC
Energy – Electricity		
Electricity consumed by cement mill section	26.00	kWh/ ton of OPC
Electricity consumed by packing plant section	0.65	kWh/ ton of Cement
Electricity consumed for services	3.15	kWh/ton of cement

Table A. 17: CS 1: Aggregated LCI results of OPC

Input	Value	Unit
Raw material		
Clinker	0.906	ton/ton of OPC
Limestone (as performance improver)	0.051	ton/ton of OPC
Gypsum	0.042	ton/ton of Cement
Electricity		
Electricity	29.80	kWh/ ton of OPC
Ancillary inputs		
Water	0.081	m^3/ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Others		
Grinding media	1.30E-05	ton/ton of Cement
Output	**Value**	**Unit**
Product		
OPC	1	ton/ton of OPC
Waste - Release to air		
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
R-134A	4.86E-07	ton/ton of Cement
Waste - Release to water		
Recycled water	0.046	m^3/ton of Cement
Waste - Release to soil		
Solid waste	1.037	ton/ton of Cement

Table A. 18: CS 1: Aggregated LCI result for PPC

Input	Value	Unit
Raw material		
Clinker for PPC	0.679	ton/ton of PPC
Fly ash (in cement plant)	0.278	ton/ton of PPC
Gypsum	0.042	ton/ton of Cement
Electricity		
Electricity	27.54	kWh/ ton of PPC
Ancillary inputs		
Water	0.081	m^3/ton of cement
Oil (Lubricant)	1.30E-04	ton/ton of Cement
Grease	6.92E-06	ton/ton of Cement
Bags PP	1.05E-03	ton/ton of Cement
Bags (Paper)	8.01E-04	ton/ton of Cement
Others		
Grinding media	1.30E-05	ton/ton of Cement
Output	**Value**	**Unit**
Product		
PPC	1	ton/ton of PPC
Waste - Release to air		
SPM - Cement Mill Stacks	3.21E-06	ton/ton of Cement
R-134A	4.86E-07	ton/ton of Cement
Waste - Release to water		
Recycled water	0.046	m^3/ton of Cement
Waste - Release to soil		
Solid waste	1.037	ton/ton of Cement

ANNEXURE B

The inventory of captive power plant is analysed to find the embodied energy and CO_2 emission of electricity produced. The details of analysis are provided as follows

1) Objective: To find the Energy consumption and CO2 emission for electricity production.
2) Application: This value can be used as characterisation factor for electricity consumed.
3) Process system: Lignite based thermal power plant
4) Function: Production of electricity
5) Functional unit: 1 kWh electricity produced
6) System boundary:
    a) Criteria: Gate to gate
    b) Processes considered: Fuel burning inside thermal power plant
    c) Data required: Fuel consumed, electricity, water consumed, oil consumed, machines, infrastructure, electricity produced, CO_2, NO_x, SO_2, and PM.
7) Allocation:The data is completely allocated to electricity.
8) Energy and CO_2 calculation methodology: Energy consumption (in MJ) and CO_2 emission (in kg) are calculated using inventory and suitable conversion factors. Energy factors are obtained from cement plant data. CO_2 emission factor are from sources like experimental value of fuel samples from cement plant, Emission factor for greenhouse gas inventories (2014) by USEPA, CSI Protocol 2013, and 2006IPCC Guidelines for greenhouse gas inventories depending on the suitability with respect to the inventory.
9) Limitation:The electricity consumed by the TPP not considered.

The inventory collected is normalised with the total electricity produced. The inventory results are as follows

Table B. 1: Inventory result for electricity

Input	Value	Unit
Raw material		
Coal (for Captive power plant)	4.63	gm/kWh
Petcoke (Imported)	43.54	gm/kWh
Lignite	693.14	gm/kWh
LDO	5.22E-03	gm/kWh
Furnace oil	0.66	gm/kWh
Electricity		
TG Auxiliary	9.95E-02	kWh/kWh
Ancillary input		
Water - Power plant	1.73E-03	m^3/kWh
Transportation		
Truck	3.71E-03	tkm/kWh
Output	**Value**	**Unit**
Product		
TG Generation	1	kWh/kWh
Emission to air		
SPM – TPP	0.47	gm/kWh
SO2 – TPP	9.29	gm/kWh
NOx – TPP	4.06	gm/kWh

The input which contributes to energy is selected and converted in terms of energy using suitable conversion factors from thermal power plant related data. The results are as follows

Table B. 2: The embodied energy calculation

Input	Inventory result	Unit		Calorific value	Unit		Energy consumed	Unit
Coal	4.63 E-03	kg/kWh	×	22.62	MJ/kg	=	0.10	MJ/kWh
Petcoke (Imported)	4.35 E-02	kg/kWh	×	32.56	MJ/kg	=	1.42	MJ/kWh
Lignite	6.93 E-01	kg/kWh	×	17.09	MJ/kg	=	11.85	MJ/kWh
LDO	5.22 E-06	kg/kWh	×	44.03	MJ/kg	=	0.00	MJ/kWh
Furnace oil	6.64 E-04	kg/kWh	×	42.48	MJ/kg	=	0.03	MJ/kWh
Total							**13.40**	**MJ/kWh**

Thus 13.40MJ/kWh is embodied energy of the electricity produced

The input which contributes to CO_2 emission is selected and converted in terms of emission using suitable conversion factors from sources initially mentioned. The results are as follows

Table B. 3: The embodied CO_2 of electricity

Input	Inventory result	Unit		CO_2 emission factor	Unit		CO_2 emitted	Unit
Coal	4.63E-03	kg/kWh	×	2.00	kg CO_2 / kg	=	0.01	kg CO_2/kWh
Petcoke (Imported)	4.35E-02	kg/kWh	×	3.06	kg CO_2 / kg	=	0.13	kg CO_2/kWh
Lignite	6.93E-01	kg/kWh	×	1.36	kg CO_2 / kg	=	0.94	kg CO_2/kWh
LDO	5.22E-06	kg/kWh	×	3.26	kg CO_2 / kg	=	0.00	kg CO_2/kWh
Furnace oil	6.64E-04	kg/kWh	×	3.02	kg CO_2 / kg	=	0.00	kg CO_2/kWh
Total							**1.09**	**kg CO_2/kWh**

The embodied CO_2 of the electricity is found 1.09 kCO_2/kWh.

ANNEXURE C

Table C. 1: CS 2: Validated result of clinker

Input	Value	Unit
Raw material		
Limestone	1628106	Ton
Fire clay	25000	Ton
Feldspar	12000	Ton
Fuel		
Diesel (HSD)	237890.432	Kg
SA Coal	2000	Ton
Pet coke	66000	Ton
Lignite	51000	Ton
Alternate fuel	12000	Ton
Electricity		
Electricity	105130	kWh
Electricity	49.8	kWh/Ton
Transportation		
Diesel (HSD)	837869.76	kg
Output	**Value collected**	**Unit**
Product		
Clinker	1,177,261	ton
Emission to air		
CO_2 (from raw material)	623137	Ton
Radiation loss	125.94	MJ/kg of clinker
Radiation loss	75.73	MJ/kg of clinker
Radiation loss	15.90	MJ/kg of clinker
Heat of PH Exit gases	127	kcal/kg of clinker
Heat of PH Exit dust	7.8	kcal/kg of clinker
Heat through Cooler Vent	99	kcal/kg of clinker

Table C. 2: CS 2: LCI results of clinker using absolute data

Input	Value	Unit
Raw material		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
Fuel		
Diesel (HSD)	0.202	kg/ton of clinker
SA Coal	0.002	Ton/ton of clinker
Pet coke	0.056	Ton/ton of clinker
Lignite	0.043	Ton/ton of clinker
Alternate fuel	0.010	Ton/ton of clinker
Electricity		
Electricity	0.089	kWh/ton of clinker
Transportation		
Diesel (HSD)	0.712	kg/ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1.00	Ton/ton of clinker
Emission to air		
CO_2 (from raw material)	0.53	Ton/ton of clinker

Table C. 3: CS 2: LCI results of clinker using reference flow data

Input	Value	Unit
Electricity		
Electricity	49.8	kWh/Ton
Output	**Value**	**Unit**
Emission to air		
Radiation loss	125.94	MJ/ton of clinker
Radiation loss	75.73	MJ/ton of clinker
Radiation loss	15.90	MJ/ton of clinker
Other		
Heat of PH Exit gases	531.37	MJ/Ton of clinker
Heat of PH Exit dust	32.64	MJ/Ton of clinker
Heat through Cooler Vent	414.22	MJ/Ton of clinker

Table C. 4: CS 2: LCI result of clinker aggregated

Input	Value	Unit
Raw material		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
Fuel		
Diesel (for extraction)	0.202	kg/ton of clinker
Fuel (for clinkerization)	0.111	Ton/ton of clinker
Electricity		
Electricity	49.89	kWh/ton of clinker
Transportation		
Diesel (for limestone)	0.712	kg/ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1.00	Ton/ton of clinker
Emission to air		
CO_2 (from raw material)	0.53	Ton/ton of clinker
Radiation loss	217.57	MJ/ton of clinker
Other		
Heat	978.22	MJ/Ton of clinker

Table C. 5: CS 2: Updated LCI result of clinker aggregated

Input	Value	Unit
Raw material		
Limestone	1.383	Ton/ton of clinker
Fire clay	0.021	Ton/ton of clinker
Feldspar	0.010	Ton/ton of clinker
Fuel		
Fuel	111.48	kg/ton of clinker
Electricity		
Electricity	49.89	kWh/ton of clinker
Transportation		
Diesel (for limestone)	0.712	kg/ton of clinker
Output	**Value**	**Unit**
Product		
Clinker	1.00	ton/ton of clinker
Emission to air		
CO_2	813.11	kg CO_2/ton of clinker
Radiation loss	217.57	MJ/ton of clinker
Other		
Heat (through gas and dust)	978.22	MJ/Ton of clinker

Table C. 6: CS 2: Validated LCI data for OPC and PPC

Input	Value	Unit
Raw material		
Clinker	1,177,261	ton
Gypsum	31000	Ton
Clinker to OPC ratio	0.95	
Clinker to PPC ratio	0.65	
Electricity related		
Electricity	28.03	kWh/Ton
Ancillary materials related data		
Water	0.0471	ton/Ton
Others		
LPG	6.84	Ton
Output	**Value**	**Unit**
Products		
Cement equivalent	1518094	Ton
Emission to air		
CO_2	0.063	Ton
Freon (R22)	0.075	Ton

Table C. 7: CS 2: LCI analysis result of OPC using miscellaneous data

Input	Value	Unit
Raw material		
Clinker	0.950	Ton/ton of OPC
Gypsum	0.020	Ton/ton of cement
Filler	0.030	Ton/ton of OPC
Output	**Value**	**Unit**
Product		
OPC produced	1	Ton/ton of OPC

Table C. 8: CS 2: LCI analysis result of OPC and PPC using absolute data

Input	Value	Unit
Others		
LPG	1.08E-05	Ton/ton of cement
Output	**Value**	**Unit**
Emission to air		
CO_2	9.92E-08	Ton/ton of cement
Freon (R22)	1.18E-07	Ton/ton of cement

Table C. 9: CS 2: LCI analysis result of OPC and PPC using reference flow data

Input	Value	Unit
Electricity		
Electricity	28.03	kWh/Ton of cement
Ancillary materials		
Water	47.1	kg/Ton of cement

Table C. 10: CS 2: LCI analysis result of PPC using miscellaneous data

Input	Value	Unit
Raw material		
Clinker	0.650	Ton/ton of PPC
Gypsum	0.020	Ton/ton of cement
Fly ash	0.330	Ton/ton of PPC
Output	**Value**	**Unit**
Product		
PPC produced	1	Ton/ton of PPC

ANNEXURE D

The energy consumed and CO_2 emitted related to production of one ton of limestone for case study 1 is calculated here. The details of calculation is provided as follows,

<u>Goal and Scope</u>

Goal

1) Objective: To find the energy consumption and CO_2 emissions for crushed limestone production.
2) Application: This value can be used as energy and CO_2 factor for produced.

Scope

1) Process system: Open mining of limestone followed by crushing
2) Function: Production of crushed limestone
3) Functional unit: 1 ton of limestone produced
4) System boundary:
   a) Criteria: Gate to gate
   b) Processes considered:
      i) Extraction of limestone: The limestone is extracted from the open mine using excavators, and scrapers. The excavated limestone is loaded in to truck. Which is then transported into the site
      ii) Crushing of limestone. The boulders of limestone which is dumped in the reserve area is transferred using a loader to the crushing unit. The limestone gets crushed in the crusher and the crushed limestone comes out.
   c) Data required
      i) Extraction of limestone: Diesel, electricity, raw limestone, oil, spare parts, equipment, infrastructure, limestone extracted, CO_2, CO, NOx, and PM
      ii) Crushing of limestone: Electricity, limestone chunks, oil, equipment, infrastructure, crushed limestone and PM.
5) Data required:
   a) Extraction of limestone: Diesel, raw limestone, oil, spare parts, equipment, infrastructure, limestone extracted, CO_2, CO, NOx, and PM
   b) Crushing of limestone: Electricity, limestone chunks, oil, equipment, infrastructure, crushed limestone and PM.

6) Data quality requirement: Temporal requirement - recent data with 1 year time period; Geographical coverage - open mine of soft limestone; Technological coverage - equipment like push dozer, scrapper, excavator to extract limestone: Precision - Electricity in kWh, diesel in litre, oil in kg, limestone in tons, and CO_2 in kg; Consistency - the data, assumptions and method of calculation need to be complete consistent; Completeness - all the data are expected to be collected; Reproducibility - to the level of the individual mine: Source of data : collected from site visit to a limestone mine of a cement plant: Uncertainty: No uncertainty.
7) Allocation:The data is completely allocated to limestone
8) Energy and CO_2 calculation methodology: Energy consumption (in MJ) and CO_2 emissions (in kg) are calculated using inventory and suitable conversion factors. Energy factors are obtained from cement plant data. CO_2 emission factor are from a combination of sources like cement plant data and database.
9) Assumption: Diesel used for thermal treatment in kiln is used for extraction of limestone. And thus same factors are used for calculation.

The inventory analysis is conducted followed by calculation of energy and CO_2. The result of inventory analysis are provided in Table D. 1. The energy factors of diesel and electricity are sourced from cement plant data and the energy calculation is provided in Table D. 2. The CO_2 emission factor of electricity is calculated from cement plant data, and diesel is calculated using CSI Protocol 2013 and cement plant data. The CO_2 emission factor of electricity is from cement plant data. The CO_2 emissions calculation are provided in and Table D. 3.

Table D. 1: LCI result for limestone preparation in Case Study 1

Process	Value	Unit
Limestone extraction and transportation		
Input		
Diesel	1.174	kg/ton of limestone
Limestone crushing, stacking and reclaiming		
Input		
Electricity - limestone crushing	0.70	kWh/ton of limestone

Table D. 2: Energy use for limestone preparation in Case Study 1

Process and inputs	Value	Unit		Factor	Unit		Result	Unit
Limestone extraction and transportation								
Input								
Diesel	1.17	kg / ton of clinker	×	42.68	MJ / kg	=	50.10	MJ / ton of limestone
						Total	**50.10**	**MJ / ton of limestone**
Limestone crushing, stacking and reclaiming								
Input								
Electricity - crushing section	0.70	kWh / ton of clinker	×	13.40	MJ / kWh	=	9.38	MJ / ton of limestone
						Total	**9.38**	**MJ / ton of limestone**
Total energy consumed							**59.49**	**MJ / ton of limestone**

Table D. 3: CO_2 emissions for limestone preparation in Case Study 1

Process	Value	Unit		Factor	Unit		Result	Unit
Limestone extraction and transportation								
Input								
Diesel	1.174	kg/ton of limestone	×	3.16	kg CO_2/ kg	=	3.71	kg CO_2 / ton of clinker
							3.71	**kg CO_2 / ton of clinker**
Limestone crushing, stacking and reclaiming								
Input								
Electricity - limestone crushing section	0.70	kWh/ton of limestone	×	1.09	kg CO_2/ kWh	=	0.76	kg CO_2 / ton of clinker
							0.76	**kg CO_2 / ton of clinker**
Total CO_2 emissions							**4.47**	**kg CO_2 / ton of clinker**

ANNEXURE E

The energy consumed and CO_2 emitted related to production of one ton of limestone for case study 2 is calculated here. The details of calculation is provided as follows,

Goal and Scope

Goal

1) Objective: To find the energy consumption and CO_2 emissions for crushed limestone production.
2) Application: This value can be used as energy and CO_2 factor for crushed limestone.

Scope

1) Process system: open mining of limestone followed by crushing
2) Function: Production of crushed limestone
3) Functional unit: 1 ton of limestone produced
4) System boundary:
    a) Criteria: Gate to gate
    b) Processes considered:
        i) Extraction of limestone: The limestone is extracted from the open mine using excavators, and scrapers. The excavated limestone is loaded in to truck. Which is then transported into the site
        ii) Crushing of limestone. The boulders of limestone which is dumped in the reserve area is transferred using a loader to the crushing unit. The limestone gets crushed in the crusher and the crushed limestone comes out.
    c) Data required
        i) Extraction of limestone: Diesel, electricity, blasting materials, raw limestone, oil, spare parts, equipment, infrastructure, limestone extracted, CO_2, CO, NOx, and PM
        ii) Crushing of limestone: Electricity, limestone chunks, oil, equipment, infrastructure, crushed limestone and PM.
5) Data required:
    a) Extraction of limestone: Diesel, raw limestone, oil, spare parts, equipment, infrastructure, limestone extracted, CO_2, CO, NO_x, and PM

b) Crushing of limestone: Electricity, limestone chunks, oil, equipment, infrastructure, crushed limestone and PM.

6) Data quality requirement: Temporal requirement - recent data with 1 year time period; Geographical coverage - open mine of soft limestone; Technological coverage - equipment like push dozer, scrapper, excavator to extract limestone and blasting: Precision - Electricity in kWh, diesel in litre, oil in kg, limestone in tons, CO_2 in kg, dust in gm; Consistency - the data, assumptions and method of calculation need to be complete consistent; Completeness - all the data are expected to be collected; Reproducibility - to the level of the individual mine: Source of data : collected from site visit to a limestone mine of a cement plant: Uncertainty: No uncertainty.
7) Allocation:The data is completely allocated to limestone
8) Energy and CO_2 calculation methodology: Energy consumption (in MJ) and CO_2 emissions (in kg) are calculated using inventory and suitable conversion factors. The value for are obtained from cement plant data. CO_2 emission factor are from sources like cement plant data and website.

The inventory analysis is conducted followed by calculation of energy and CO_2. The result of inventory analysis are provided in Table E. 1. Energy factors of electricity is cited from case study 1 as the value for case study 2 was not available. The energy factor for diesel is cited from (IPCC 2006). The energy calculation are provided in Table E. 2. The CO_2 factor of electricity is cited from case study 1 and factor for diesel is calculated from data collected during cement plant data and density data from website. The CO_2 emissions calculation are provided in Table E. 3.

Table E. 1: LCI result for limestone preparation in Case Study 2

Process	**Value**	**Unit**
Limestone extraction		
Input		
Fuel		
Diesel (HSD)	0.146	kg/ton of limestone
Electricity		
Electricity	0.065	kWh/ton of limestone
Limestone transportation		
Inputs		
Diesel (HSD)	0.515	kg/ton of limestone

Table E. 2: Energy use for limestone preparation in Case Study 2

Process	Value	Unit		Factor	Unit		Energy	Unit
Limestone extraction								
Input								
Diesel (Limestone)	0.146	kg/ton of clinker	×	43.00	MJ/kg	=	6.28	MJ/ton of clinker
Electricity	0.065	kWh/ton of clinker	×	13.40	MJ/kWh	=	0.87	MJ/ton of clinker
							7.15	**MJ/ton of clinker**
Limestone transportation								
Inputs								
Diesel (for limestone)	0.515	kg/ton of clinker	×	43.00	MJ/kg	=	22.13	MJ/ton of clinker
							22.13	**MJ/ton of clinker**
Total							**29.28**	**MJ/ton of clinker**

Table E. 3: CO_2 emissions for limestone preparation in Case Study 2

Process and inputs	Value	Unit		Factor	Unit		Energy	Unit
Limestone extraction								
Input								
Diesel	0.146	kg/ton of limestone	×	3.22	kg CO_2 / kg of fuel	=	0.471	kg CO_2/ton of limestone
Electricity	0.065	kWh/ton of clinker	×	1.09	kg CO_2/kWh	=	0.070	kg CO_2/ton of clinker
							0.54	**kg CO_2/ton of clinker**
Limestone transportation								
Output								
CO_2 from Diesel (for limestone)	0.51	kg CO_2/ton of clinker	×	3.22	kg CO_2 / kg of fuel	=	1.66	kg CO_2/ton of clinker
							1.66	**kg CO_2/ton of clinker**
Total							**2.20**	**kg CO_2/ton of clinker**

ANNEXURE F

The associated transportation process for each process system can be estimated based on amount of freight to be transported and assumed distance between sources. A sample calculation related to the transportation of calcined clay, from clay mine to cement plant (process system 1), is provided as follows.

The transportation of calcined clay from source of calcination process to the grinding unit can have considerable effect, a sample calculation of the energy consumption of transportation process is provided as below.

1) Case 1 : Calcination and grinding source located within state: ≤ 500 km
2) Case 2 : Calcination and grinding source located interstate:
    a) Between 500 and 1000 km
    b) Between 1000 and 1500 km

The calcined clay transported is of mass 0.3 ton. Thus the measurement of freight transportation is

1) Case 1 : Calcination and grinding source located within state: ≤ 150 tkm
2) Case 2 : Calcination and grinding source located interstate:
    a) Between 150 and 300 tkm
    b) Between 300 and 450 tkm

The measurement of transportation can be converted in to corresponding energy consumed using suitable energy factors.

Few energy factors obtained are

1) Energy factor 1: 0.84 MJ/tkm. The factor is calculated from data on freight capacity, mileage and diesel calorific value collected from Case study 1 and a field visit to a grinding unit at Arakkonam under UltraTech.

    The derivation of the equation to calculate the factor is provided as below,

$$Diesel\ consumed\ (in\ kg) = (number\ of\ trip\ or\ truck) \times \frac{Distance\ (km)}{millecge\ (km/litre)} \times density\ (kg/litre)$$

$$Diesel\ consumed\ (in\ kg) = \frac{Total\ mass\ (ton)}{Freight\ capacity\ (ton)} \times \frac{Distance\ (km)}{milleage\ (km/litre)} \times density\ (kg/litre)$$

$$Diesel\ consumed\ (in\ kg/tkm) = \frac{1}{Freight\ capacity\ (ton)} \times \frac{1}{milleage\ (km/litre)} \times density\ (kg/litre) .. Eq.7.11.$$

The freight capacity is estimated from the total mass transported and number of trips for limestone transportation in case study one. The total mass divided by total trip gives the freight capacity. The freight capacity is found to be 25 ton. The mileage of truck of similar capacity is obtained from field visit to Arakkonam grinding unit under UltraTech cements company. The mileage value of the full loaded truck is 3 km/litre and empty truck is 4 km/litre. Density of the diesel is 0.84 kg/Litre as obtained from case study 1. Substituting this values for empty truck transportation, and full truck transportation, the corresponding diesel consumption values will be obtained. Adding up the same provided the diesel required for round trip transportation of a material. The diesel for round trip is obtained as 0.0196 kg/tkm. Using the calorific value of diesel (42.68 MJ/kg from case study one) the diesel consumed is converted to energy as 0.84 MJ/tkm.

2) Energy factor 2: 1.62 MJ/tkm. The factor calculated by multiplying the diesel consumption per tkm from Li et al. 2014 (3.763 kg/100tkm) with diesel calorific value (43 MJ/kg) from IPCC (2006)
3) Energy factor 3: 1.14 MJ/tkm. The factor calculated from SimaPro 8.4.0.0 using ecoinvent V3.2 as inventory database and method of Cumulative Energy Demand (V 1.09). A truck with gross vehicle weight greater than 32 ton is assumed to simulate the trucks used in Case study 1. The vehicle geographically represents Rest of the World (RoW) except United States, Canada, and Europe. The vehicle is selected, and the energy use of this truck with full inventory and with inventory devoid of diesel is calculated. The difference between the two will be the energy consumption in relation to diesel consumed.

There are different conversion factors obtained from data collected and literature. The inventory of transportation is multiplied with energy factor to obtain the possible energy contribution from transportation process. The results are provided in Table F. 1.

Table F. 1: Sample calculation on transportation energy

Energy factor (MJ/tkm) / Transportation distance (km)	Energy Factor 1	Energy factor 2	Energy factor 3
500	125	243	171
1000	251	485	341
1500	376	728	512

Depending upon the factor used the results for,

1) Energy factor 1 are ranging from 125-376 MJ
2) Energy factor 2 are ranging from 243-728 MJ
3) Energy factor 3 are ranging from 171-512 MJ

Since the results are varying depending upon the factor used. Thus a thorough study should be conducted in order to find the suitable energy factors related to the freight transportation and the possible contribution from transportation process.