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GWP IMPACT OF UTILIZING SRF IN CEMENT PLANTS: FINNSEMENTTI CASE STUDY

Examiners: Professor Mika Horttanainen

Doctor (Sc.) Jouni Havukainen

ABSTRACT

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Cement production is of grave concern on account of its high energy consumption and greenhouse gas emission. Global cement production causes 5-10% of total anthropogenic CO_2 emissions. Considering the adverse effect of greenhouse gas on global climate change, it is important to reduce greenhouse gas emission from cement production process. The aim of the study was to identify the reduction of global warming potential through alteration of fossil fuel by solid recovered fuel (SRF) in cement production process. A cradle to gate life cycle assessment according to ISO 14040:2006 standard was conducted to quantify CO_2 eq emission per tonne of ordinary portland cement production (OPC). Four scenarios were established based on 2006 and 2016 production data provided by Finsementti Oy, where different share of SRF in the fuel mixture was used. In scenario 1 and 2, 98% of total fuel energy was sourced by

fossil fuel, when in scenario 3, fossil fuel (energy) share was 47% and in scenario 4, only 20% of total fuel energy was supplied through fossil fuel. The result of the study showed that scenario 2 was responsible for maximum GWP (890 kg CO_2 eq/ tonne cement), followed by scenario 1, which released 797 kg CO_2 eq/ tonne cement. A significant GWP reduction was noticeable in scenario 3 when the emission dropped to 663 kg CO_2 eq/ tonne cement. In scenario 4, GWP reduction was even further to 609 kg CO_2 eq/ tonne cement.

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In Lappeenranta 25 October 2018

Md.Musharof Hussain Khan

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LIST OF ABBREVIATIONS

AFR	Alternative Fuel and Raw Materials
CC	Climate Change
C&DW	Construction and Demolition Waste
C&IW	Commercial and Industrial Waste
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Impact
LCIA	Life Cycle Inventory Analysis
LHV	Lower Heating Value
MBM	Meat and Bone Meal
MSW	Municipal Solid Waste
NCV	Net Calorific Value
OPC	Ordinary Portland Cement
ppm	Parts Per Million
RDF	Refuse Derived Fuel
SCM	Supplementary Cementitious Materials
SRF	Solid Recovered Fuel
TDF	Tire Derived Fuel

LIST OF SYMBOLS

$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
Cd	Cadmium
CH_4	Methane
Cl	Chlorine
CO_2	Carbon Dioxide
Cr^{6+}	Chromium
$FeSO_4.H_2O$	Ferrous Sulfate
Hg	Mercury
$MgCO_3$	Magnesium Carbonate
MgO	Magnesium Oxide
NOx	Nitrogen Oxides
S	Sulfur
SO_2	Sulfur Dioxide
PCB	Polychlorinated Biphenyl

1 INTRODUCTION

Global climate change is responsible for intensifying extreme weather events, notably heat waves (Brian Kahn, 2017) . Extensive discussions are taking place on global warming and climate change throughout in all forms of media in the world. Climate change subjects to the change of weather patterns over decades due to human activities. Since industrial revolution, the emission of carbon dioxide (CO_2) followed by methane (CH_4) has been the largest contributors to climate change (EPA, 2017). The concentrations of CO_2 have increased drastically from preindustrial value of 280 parts per million (ppm) (Mikulčić et al., 2016, p. 120) to 403 ppm in 2016 with an annual growth rate of 2 ppm/year (IEA, 2017).

Climate change causes different types of environmental, social and economic impacts (EDF, 2018). A forthright relation between the intensity of adverse environmental impacts and the rise in the average global temperature shows that the world needs to take appropriate actions to control the uprising global temperature. European Union (EU) has already adapted a target to limit the global temperature at 2°C relative to pre-industrial levels and even further to 1.5°C to avoid any severe irreversible consequences (European Commission, 2018). However, the limitation of average temperature is eminently challenging due to the fact that the emission needs to be reduced from 50% to 80% from the year 2000 to 2050 (IPCC, 2007).

The construction industries are viewed as one of the industries which causes depletion of natural resources and negative environmental impact due to high amount of raw materials and energy consumption (Zabalza Bribián et al., 2011, p. 1134). Cement is one of the most commonly used construction materials. Population rising, urbanization and infrastructure development are predicted to lift global cement production by 12-23% above the 2014 level by 2050 (International Energy Agency, 2018). Cement production is of great concern for adverse environmental impact on account of its high energy consumption and greenhouse gases (GHGs) emission (Mikulčić et al., 2016, p. 119). Global cement production causes 5-10% of total anthropogenic CO_2 emissions (Hossain et al., 2017, p. 199). The source of CO_2 emission during cement production process can be divided into direct emission source and indirect emission source (Gao et al., 2016). Direct emission source includes combustion of fossil fuels and decomposition of calcium carbonate in clinker production, where indirect emission source encompasses raw materials acquisition, transportation of raw materials, and electricity consumption for raw material processing and cement grinding. 90% of total CO_2 emission from cement production process is sourced from direct emission, where indirect source comprises 10% of total CO_2 emission (Gao et al., 2015).

The production of GHGs largely depends on the types of fuels and raw materials which are used in the cement production process. Conventional fossil fuels such as coal and oil are being used as traditional fuels since the beginning of cement production. However, it is possible to use alternative products to replace raw materials and fossil fuels to control the GHGs emission. Since 1970, wastes subjected as alternative fuels and raw materials (AFR) have been used to substitute conventional fuels for the purpose of cost reduction as well as saving natural resources (Boesch et al., 2009). AFR utilization in cement plant can be a viable option for the treatment of hazardous and non-hazardous wastes (Boesch et al., 2009) to reduce negative environmental impact of cement production. Currently in Europe, 5% of raw materials totaling 8 million tonnes (Mt)/ year of clinker production are replaced by recycled materials such as contaminated soil, mineral containing waste, coal fly ash and furnace slag (CEMBUREAU, 2017). As of 2012, in Europe, on average 30-36% of total fuel used in cement industries was replaced by alternative fuel (Ecofys, 2016). However, the alternative fuel utilization rate varies in the EU countries; such as Greece had only 6-7%, while Netherlands substituted more than 80% of fossil fuels by alternative fuels. In Finland the AFR utilization ratio lies between 40-45% (Finnsementti, 2017).

Various waste derived fuels i.e. paper & cardboard, textiles, plastics, sewage sludge, and wood can be utilized as alternative fuel in cement industry. A considerable amount of hazardous waste are also used in cement industries (Thomanetz, 2012). Holcim’s Geocycle and Recyfuel, two waste treatment companies treat 50% of total hazardous waste in Belgium (Jan Theulen, 2015). After passing the advanced treatment system, hazardous wastes are sent to cement kilns, where these are completely burned out and ashes from these hazardous waste are used as raw materials replacement (Jan Theulen, 2015). Utilization of AFR offers numerous environmental and economic benefits. By using waste as alternative fuels, cement industries can contribute to the lowering of GHGs emissions, increase security of energy supply and reduce the amount of waste sent to the landfill (CEMBUREAU, 2017). In countries like Japan, Canada and Western Europe, utilization of waste in cement industries become economically viable because of the high cost of landfilling (Jan Theulen, 2015). Also, AFRs are generally cheaper compare to the fossil fuels as AFRs are generated from waste, which needs a small processing cost (CEMBUREAU, 2017). However, utilization of waste in the cement production process is challenging. Several factors must be considered when selecting AFRs such as chemical composition of cement and physical state of the alternative fuels. (CEMBUREAU, 2017).

Traditionally cement is highly energy consuming and emission intensive material. As a result of this, cement industries are facing enormous challenges for the reduction of GHGs emission and lowering fossil fuels demand. Even though, many initiatives have been taken to reduce environmental impact, there are still some rooms for utilization of waste derived fuel for further exploration. The most significant environmental burden on cement production is the CO_2 emission. For the production of one tonne OPC, about 700-900 kg CO_2 eq of emission is released to the environment (Salas et al., 2016a). To reduce the CO_2 emission, EU launched CO_2 emissions trading system (EU-ETS) in 2005 and cement industries in Finland has been involved from the beginning. Since 2009, Finnsementti the prime cement company of Finland has started utilizing solid recovered fuel (SRF) in Lappeenranta plant to reduce the load on fossil fuel and reduce negative environmental impact. By 2016, ~53% of total fuel energy was substituted by SRF and in the long run the company’s goal is to replace up to 80% from conventional fuels (energy) with SRF (Finnsementti, 2017).

1.1 Research problems and objectives

Finnsementti has initiated SRF in Lappeenranta plant in 2009, which is aimed to reach up to 80% of total fuel share (mass) within couple of years. This study conducted a comparative analysis to present environmental impact associated with cement manufacturing process by combusting SRF and without combusting SRF. Also a sensitivity analysis was practiced to determine the impact of SRF composition on the CO_2 emission. The following questions were being asked during the study:

1. How SRF utilization effect on the overall GWP of cement production system.
2. What is the influence of SRF composition on the CO_2 emission, released from the fuel combustion in the cement plant?
3. What is the GWP impact of treating commercial and industrial waste in the incineration plant and/or in the landfill, instead of producing SRF and utilize the SRF in the cement plant?
4. What is the best treatment method for commercial and industrial waste (C&IW) among thermal treatment of C&IW in the waste incineration plant, landfilling and utilization of SRF in the cement plant on the perspective of CO_2 emission reduction?

The study was focusing only on global warming potential impact (GWP) and all other environmental impacts were excluded from this study for not having enough data from each sectors of cement production.

2 BACKGROUND INFORMATION OF CEMENT

2.1 Cement History

Cement is a fine mineral powdery substance manufactured from a mixture of elements such as limestone, clay, sand or shale. By coming into contact with water, powdery substance of cement transforms into a paste that hardens to adhere constructing units such as stones, bricks, tiles etc. (CEMBUREAU). The history of cement is connected with Roman history. The first material used in the cement was limestone and volcanic ash, which was later called ‘pozzolanic’ cement, named after the village Pozzuoli in Italy (CEMBUREAU). Later in 1824, a British stone mason named Joseph Aspdin invented a new type of cement called Ordinary Portland cement in his kitchen (CEMBUREAU). He heated a mixture of finely grounded limestone with clay in his kitchen stove and ground the combusted mixture into a powdery substance, which he found transforms into hard solid material with the touch of water. The inventor named the product as ‘Portland Cement’ by the name of stone quarried in the Isle of Portland. The Portland cement invention set up the foundation of today’s Portland cement industry (CEMBUREAU).

2.2 Cement Manufacturing Process.

The aim of the study was to analyze GWP impact associated with the utilization of waste derived fuels i.e. SRF in cement manufacturing process. Thus, it was important to understand various raw materials, fuels and different stages of cement production process. Cement is a very fine powdery substance mainly made from limestone, blast furnace slag, diabase, bauxite, gypsum and some mineral waste (Portland Cement Association, 2018). Exposing cement to water causes chemical reaction, which forms paste that consolidate to inlay different structures of building materials. Cement is used to construct concrete, mortar as well as binding building blocks. Figure-1 shows different stages of cement production process.

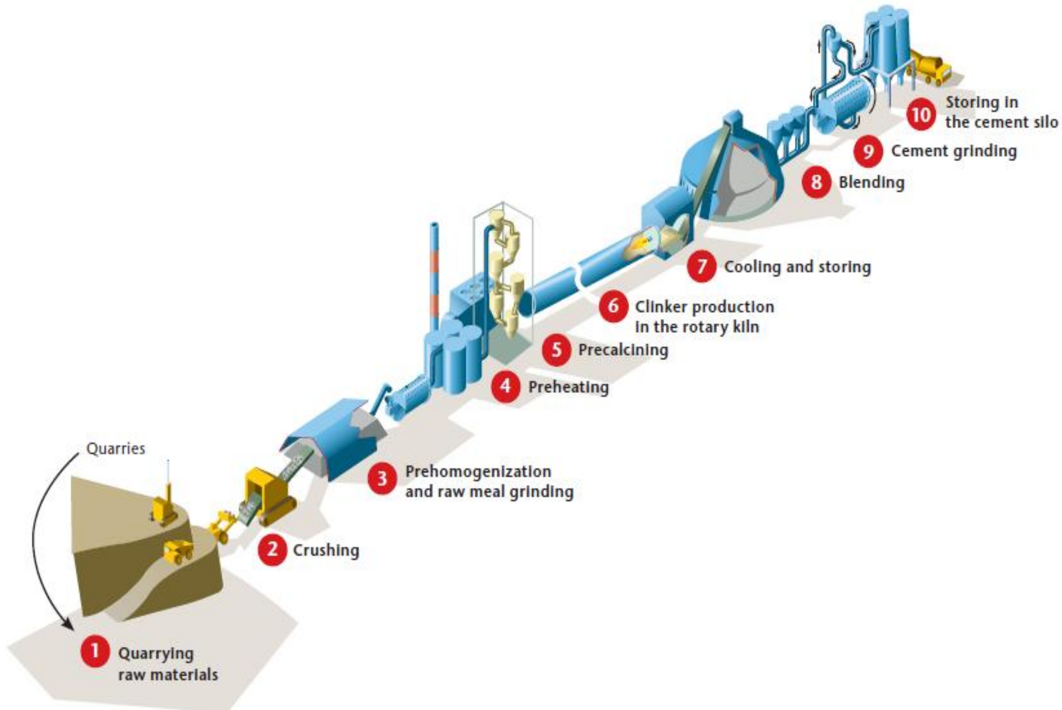

Figure 1. Cement production process.(WBCSD, 2009)

2.2.1 Raw materials extraction

Cement manufacturing process can be divided into three major processes, such as raw material preparation, clinker production and cement preparation (Salas et al., 2016b). Portland cement is generally made from limestone, combined with smaller amount of iron and aluminum containing minerals which are quarried and transported to the manufacturing plant. A list of raw materials for cement manufacturing process is given in table-1.

Table 1. Raw materials for cement production (WBCSD, 2009)

Group	Raw materials
$CaCO_3$	Limestone
SiO_2	Sand
Si-Al	Clay
Fe_2O_3	Iron ore
Al_2O_3	Bauxite

2.2.2 Crushing

The quarried raw materials undergo a drying process followed by a series of screening, crushing and grinding to obtain optimum size for cement production. The optimum size of the raw materials are considered to be 20 mm - 80 mm after crushing. The size of the crushed raw materials can be further reduced to 0.2 mm after grinding process (ASEC Academy).

2.2.3 Pre-homogenization

Chemical composition of the raw materials has major impact on the quality of clinkers. Variations in the raw material composition have negative impact on clinker quality. Due to this reason, it is important to minimize chemical composition variations, by efficiently blending and homogenizing the raw materials in the continuous blending silos (Gao et al., 2016).

2.2.4 Preheating

Preheating is one of the common methods that modern cement industries have embraced to increase the energy efficiency of the cement plant. In preheating system, raw meals are preheated before it enters to the main combustion chamber, which leads to less thermal energy requirement. Hot exhaust gas from rotary kiln preheat the raw meal that is fed from the upper end of the pre-heater tower. A preheater tower consists of several cyclones through which raw meal is passed from the top of the cylinder and hot flue gas is counter currently supplied from the bottom of the cylinder (Gao et al., 2016). Figure 2 shows a flow diagram of cement kiln with preheating system. The thermal heat from hot flue gas is recovered with the ambition to dehydrate the raw meal and increase fuel efficiency by minimizing fuel requirement in the cement production process.

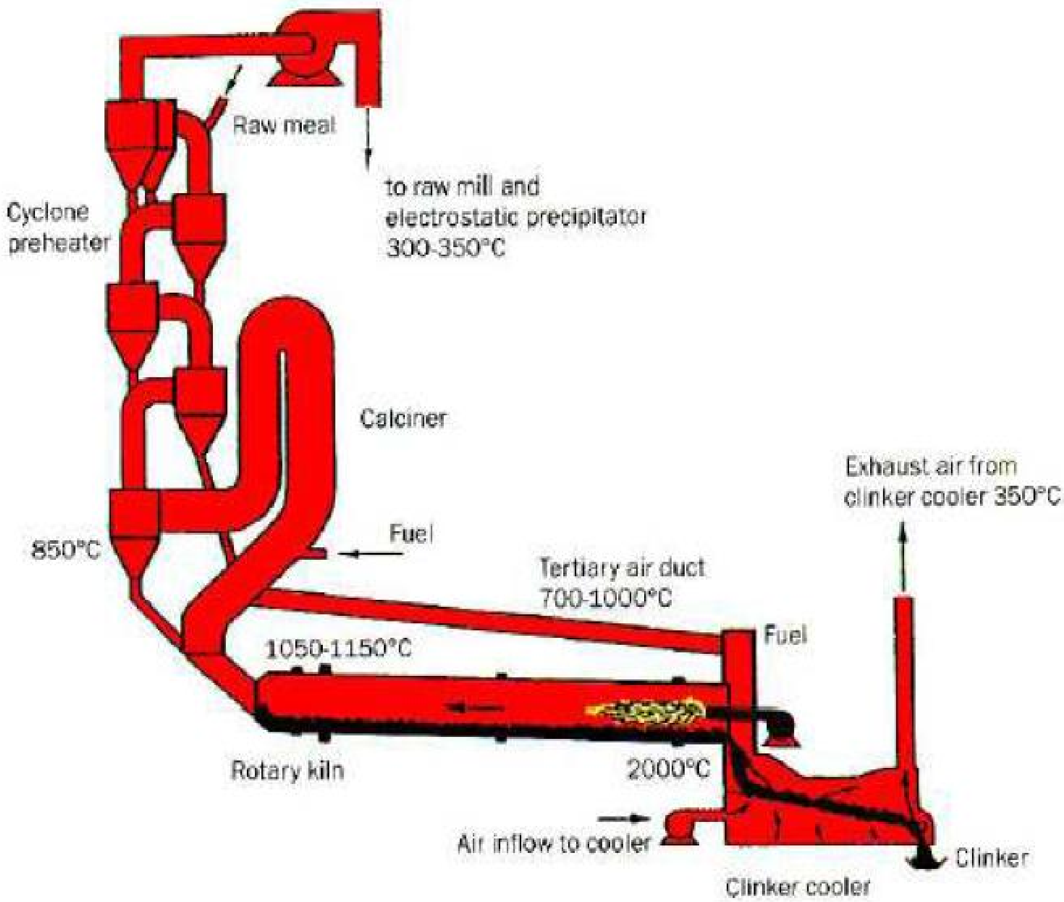

Figure 2. Rotary kiln with cyclone preheater (Radwan, 2012).

2.2.5 Pre-calcining

Modern cement manufacturing process has pre-calcining stage after pre-heating system. Generally 60-65% of total calcination process occurs during pre-calcination process (Gao et al., 2016). Precalciner is placed at the bottom of the preheater and on top of kiln where part of the calcium carbonate ($CaCO_3$) decomposed into calcium oxide (CaO) and CO_2. This process has high impact on greenhouse gas production rate since during this process, carbon bound in minerals transformed into CO_2 (Chen et al., 2010).

2.2.6 Clinker production

After pre-calcination process, pre-calcined meal then enters the kiln, where traditional fossil fuel such as coal, petroleum coke, light fuel oil or natural gas are combusted directly into the kiln to attain the high temperature necessary for the clinker formation. The raw meal can be incinerated in wet process kilns or dry process kilns. An example of specific thermal energy consumption of a kiln process is given in table 2. Wet process kilns are relatively old process compared to dry process (WBCSD, 2005). In wet process, raw meals are supplied at ambient temperature in the form of slurry, which may contain 36% moisture (Madlool et al., 2011). Due to high share of water content, a large amount of thermal energy is consumed to evaporate the moisture from the raw meal. On the contrary, dry process kilns are considered to be more energy efficient compared to wet process kilns because of its low energy consumption rate (Gao et al., 2015). The dry process can be divided into three types, such as, dry process with long rotary kiln, dry process with cyclone system without precalciner, and dry process with cyclone and precalciner (Radwan, 2012).

Table 2. Thermal energy consumption of different kiln processes (Gao et al., 2015)

Types of rotary kiln	Thermal energy requirement (GJ/t clinker)
Wet rotary kiln	5.86-6.28
Dry long rotary kiln	4.60
Dry long rotary kiln with 1-stage cyclone preheater	4.18

Dry long rotary kiln with 2-stage cyclone preheater	3.77
Dry long rotary kiln with 3-stage cyclone preheater	3.55
Dry long rotary kiln with 4-stage cyclone preheater	3.14
Dry long rotary kiln with 4-stage cyclone preheater, calciner and high efficiency cooler	3.01
Dry long rotary kiln with 4-stage cyclone preheater, calciner and high efficiency cooler	<2.93

The rotary kiln is installed horizontally with an inclination of 3-4° (Gao et al., 2016) and rotates about 3-5 times per minute (CEMBUREAU, 2017) to move the raw meal towards the lower end of the kiln. The high temperature facilitates the chemical reactions which converts raw meal into clinker. During clinkering process calcium oxides reacts with oxides of silicon, aluminum and iron at high temperature to form silicates, aluminates and ferrites, which form the clinker (Rahman et al., 2013).

The temperature in the kiln is usually raised to 2000 °C to ensure the raw materials obtain the material temperature of up to 1450 °C (Salas et al., 2016b). Fossil fuel combustion is one of the major CO_2 emission sources during cement manufacturing process. According to WBCSD, (2005), approximately 40% of total CO_2 emission in cement manufacturing process is generated from fossil fuel combustion. The quantification of CO_2 emission of fossil fuel combustion is more difficult and imprecise than decarbonization of limestone. The emission from fossil fuel depends on the type and quantities of combusted fuels. Table 3 depicted that, highest amount of emission comes from coal and petroleum coke followed by recycled tires and fuel oil. The least amount of emission comes from solid recovered fuel (SRF), releasing only 25-38 g non-biogenic CO_2/MJ of energy production. SRF is considered to be a low CO_2 emitting fuel compared to fossil fuels, because in SRF, biogenic carbon content on energy basis is about 50-65% (Iacovidou et al., 2018), and according to IEA Bioenergy, (2003), biogenic carbon can be considered as renewable resource.

Table 3. Heating value and emission from various fossil fuels

Fuel	Heating value, MJ/kg	Emission, g CO_2/MJ
Coal	25-27 (Staffell, 2011)	95-100 (Staffell, 2011)
Petroleum coke	30-34 (Staffell, 2011)	94-97 (Staffell, 2011)
Fuel oil	39-40 (Staffell, 2011)	77-80 (Staffell, 2011)
Recycled tires	28-35 (U.S. Department of Trasportation, 2016)	80-85 (WBCSD, 2014)
SRF	3-25 (ERFO)	25-38 (Chen, 2010)

2.2.7 Cooling and storing

The hot clinker passes through several types of coolers to reach lower temperature and to recover its thermal energy which can later be used in preheating and pre-calcination system of raw meal (Gao et al., 2016). The cooled clinker is then sent to the onsite storage tank or transported to other grinding plants for final grinding process (CEMBUREAU).

2.2.8 Blending

The cooled cement is blended with 4-5% gypsum and other mineral as additives to control the settling time of the final cement product (CEMBUREAU). The types and amounts of inclusive additives depends on the standards of cement and availability of additives (Gao et al., 2016). Clinker and other additives are mixed in required proportions, which are later transferred to the mill for final grinding.

2.2.9 Cement grinding

In this phase the clinker, gypsum and other minerals are grounded into fine product. Generally ball mills are used for grinding. Roller presses, vertical mills or combinations of both are also used in modern cement factories for their more efficient performance (CEMBUREAU). The most common types of cement is Ordinary Portland Cement (OPC), which has about 93-97% of clinker share (Feiz et al., 2015). The European standard EN 197-1 categorizes 27 distinct common cement products that are grouped into five different major types of cement (CEM I-V) (CEMBUREAU, 2012). The list of five major cement types according to clinker share is given in table 4.

Table 4. Clinker share in various types of cement (CEMBUREAU, 2012)

Cement types	Clinker share (%/t cement)
CEM I (Portland cement)	>95%
CEM II (Portland composite cement)	65%-94 %
CEM III (Blast furnace cement)	5%-64%
CEM IV (Pozzolanic cement)	45%-89%
CEM V (Composite cement)	20%-64%

The type of the cement is determined according to materials content. For example, CEM-I which is also known as Portland cement has highest content of clinker, where other types of cement have lower content of clinker and rather higher content of alternative material. The alternative materials are known as Supplementary Cementitious Materials (SCM). In SCM, fly ash from coal fired plant and ground granulated blast furnace slag are used to replace clinker in cement production (Feiz et al., 2015). In addition, Ferrous Sulfate ($FeSO_4.H_2O$) from titanium dioxide manufacturing process is used to reduce harmful hexavalent chromium [Cr^{6+}] in cement manufacturing process (PRECHEZA, 2017). Chromium content of cement should be <2 ppm to control the allergic hand dermatitis by chromium among the construction workers (Roto et al., 1996). In the cement production process, 900 ppm of Ferrous Sulfate ($FeSO_4.H_2O$) can reduce hexavalent chromium [Cr^{6+}] to less than 2 ppm (CHEMICAL, 2017). The final cement product is then stored in the cement silos which is later packed or transported by silo truck (WBCSD, 2009).

2.3 Role of SRF in cement industry

Cement production process is highly energy intensive. Nearly 30-40% of cement production cost is accounted from energy resources (Dondur et al., 2015). Also, ~40% of total CO_2 emission is addressed from the combustion of fossil fuels in cement manufacturing process. Due to environmental awareness, legislation and economic perspective, cement manufacturers are moving rapidly towards on utilizing SRF in cement industries.

SRF should not be confused with refused derived fuel (RDF), because RDF is a non-standardized fuel, which typically contains unprocessed combustible contents of municipal solid waste (MSW) (Iacovidou et al., 2018). On the contrary, SRF is produced from non-hazardous (MSW), commercial and industrial waste (C&IW), and construction and demolition waste (C&DW) (Nasrullah et al., 2015). The production process of SRF takes place in mechanical only or mechanical and biological treatment plant (Iacovidou et al., 2018). SRF production according to European Committee for standardization must meet the classification and specifications standards developed by CEN/TC 343 and EN 15359 is amongst the most crucial (Nasrullah et al., 2015). According to EN 15359, the classification of SRF is based on three parameters which is given in table 5.

Table 5. SRF classification based on three key parameters (Nasrullah et al., 2015)

Classificati-on parameter	Classificat-ion property	Statistical measures	Unit	Classes				
				1	2	3	4	5
Economic	Net calorific value (NCV)	Mean	MJ/kg	≥ 25	≥20	≥15	≥10	≥3
Technical	Chlorine (Cl)	Mean	% dry	≤0.2	≤0.6	≤1.0	≤1.5	≤3.0
Environmental	Mercury (Hg)	Median	Mg/MJ (as received)	≤0.02	≤0.03	≤0.08	≤0.15	≤0.50
		80th percentile	Mg/MJ (as received)	≤0.04	≤0.06	≤0.16	≤0.30	≤1.00

Biogenic components such as paper, cardboard, textiles, and wood consist 40-80 wt.-% of SRF mixture (Hilber et al., 2007). However, a considerable amount of plastics such as polyethylene, polypropylene, or polystyrene are also present in the SRF mixture. SRF utilization requires modernization of the combustion process, because the burning characteristics of SRF varies significantly than fossil fuels due to the differences in particle sizes, heating values and material densities (Schneider et al., 2011). Also, the cement production process can be affected by the feeding point of SRF into the rotary kiln (Aranda Usón et al., 2013). SRF can be introduced in the main burner and in the pre-calciner burner. In the pre-calciner burner, fossil fuels alteration have less impact on kiln performance. On the contrary, fossil fuel substitution in the main burner has significant effect on kiln operation (Schneider et al., 2011).

SRF has different physical and chemical properties due to the differences in water, chlorine, ash, and Sulphur (Gao et al., 2015). The combustion of various types of SRFs require technological adaptation and detailed control of the process. The utilization of SRF must follow some criteria to fulfill the certain legislative and technical requirements. The summary of most important issues that should be taken into account for the utilization of SRF are given below:

- Alternative fuels Composition such as chlorine (Cl) (<0,2%), S (<2,5%), polychlorinated biphenyl (PCB) (<50 ppm), titanium (Tl) (<2500 ppm), mercury (Hg) (<10 ppm), cadmium (Cd)+Tl (<90 ppm) is important to control technical and environmental problems (Aranda Usón et al., 2013).
- The lower heating value of the SRF should be over 14 MJ/kg (Aranda Usón et al., 2013) .
- Humidity content of SRF generally lower than 20% of moisture content is required (Mokrzycki and Uliasz- Bocheńczyk, 2003) to reduce the requirement of energy consumption as well as the reduction of the material to the kiln (Smith).
- The cement quality must not be compromised (Aranda Usón et al., 2013)
- SRF price must be lower than traditional fuels (Aranda Usón et al., 2013)

2.3.1 Benefits of the utilization of SRF in the cement manufacturing process

The cement industries are working hard to reduce the CO_2 emission from the cement production process. As stated earlier, 5-10% of total anthropogenic CO_2 emission produced from cement manufacturing processes (Hossain et al., 2017). Therefore, it is indisputably important to search the solutions for the minimization of the CO_2 production from cement industries. Approximately 50% emission produced from calcination process, 40% from fossil fuel combustion and rest of the 10% from electricity consumption and transportation of raw materials and fuels (WBCSD, 2005).

Fuel cost is one of the major costs for cement manufacturing process (Dondur et al., 2015). SRF might reduce cement manufacturing cost. However, utilization of SRF may require further treatment to homogenize the chemical composition of the fuels, which might increase the cost for cement manufacturing companies. Fossil fuels such as coal, and petroleum coke used in the cement production are quarried or mined. Extraction, transportation and processing of quarried materials produce huge amount of CO_2 emission (WBCSD, 2005). Using SRF may reduce exploitation of natural resources and environmental footprint associated with the extraction process.

SRF utilization enables a society to utilize its resources more effectively. SRF is produced after recovery and recycling of waste. Only the waste that cannot be recycled or recovered are used as SRF (ERFO). Having a good share of biogenic carbon in the mixture, SRF utilization allows a cement company to save emission allowances every year. Also, SRF incineration produces ash that can be used in the cement complex as raw material. Overall, SRF utilization reduces the industries demand of virgin materials, minimize CO_2 emission as well as maximize the effectiveness of a society's resource utilization.

However, there are some limitations of SRF that restrict high share of SRF in the fuel mixture. As mentioned in table 5, class 1 SRF has NCV of ≥25 MJ/kg, but it is not possible get class 1 SRF when the biogenic carbon share of SRF is 50-65%. Calorific value of SRF depends on the composition of SRF. SRF with higher biogenic carbon share has lower calorific value than SRF with lower biogenic share of carbon which has higher calorific value. For example, paper and cardboard has NCV of 16 MJ/kg (Nasrullah et al., 2015) with 99% of biogenic carbon (Angeles et al), when plastic (soft) has NCV of 37 MJ/kg (Nasrullah et al., 2015) with 13% of biogenic carbon (Angeles et al). Utilization of SRF with high share of non-biogenic carbon does not eventually help to achieve desired CO_2 emission reduction from cement production process. Also from table 3, it can be seen that fossil fuels have higher heating value than SRF. Due to lower LHV than fossil fuels, more quantity of SRF is required to achieve optimum energy in the kiln. As a result, more space is needed to store SRF which may lead to higher investment cost for a cement company. Also more quantity of transportation is needed to supply SRF to the cement plant, which may increase GWP as well as cost of cement production process.

3 REVIEW ON ENVIRONMENTAL IMPACTS OF CEMENT PRODUCTION

Cement is one of the most consumed materials on earth (Stafford et al., 2016). According to CEMBUREAU, (2013), global cement production reached to 4.2 billion tonnes in 2016, and it is projected to reach 4.4 billion tonnes by 2020 (MS Reeta Sharma, 2017). About 2.6 gigatonnes of CO_2 was released in 2011 due to the cement production process (Stafford et al., 2016). Calcination and fossil fuel combustion are the main sources of CO_2 emission in cement manufacturing process (Gao et al., 2016). In addition, cement production also requires huge amount of electricity consumption for crushing and milling the raw materials, pyro processing, clinker cooling and cement mixture, which accounts about 75 kWh/tonne of cement (Madlool et al., 2011). As cement is one of the highly energy consumptive and GHG intensive materials, it is important to assess its environmental impact and search for solutions that the cement industries should adapt to minimize its negative environmental impact. Life Cycle Assessment (LCA) is one of the environmental tools that has frequently been used all around the world to deduce the impact of cement production have on the environment. Many studies have been conducted to evaluate environmental impacts of practicing waste derived fuels in cement industries. However, the results can vary due to the methodological differences and processing variables such as raw materials composition, system boundaries, fuel mixture etc. A summary of the previous studies regarding LCA analysis on cement production is given in table 6.

Table 6. Summary of previous LCA studies on cement production

Reference	Key findings
Chen et al., 2015	GWP for large rotary kiln was 734kg CO_2 eq / tonne Portland cement, moderate rotary kiln 801 kg CO_2 eq / tonne Portland cement, small rotary kiln 693kg CO_2 eq / tonne Portland cement, and shaft kiln 1000 kg CO_2 eq / tonne Portland cement.
Song et al., 2016	GWP for baseline scenario (new suspension preheater (NSP) plant) was 678 kg CO_2 –eq/ tonne portland cement, while in the scenario where 100% of Cao in limestone was substituted with carbide slag produced 667 kg CO_2- eq/ tonne Portland cement. Also, 50% of total fuel substituted by corn straw produce 605 kg CO_2 eq/ tonne portland cement.
García-Gusano et al., 2015	Climate change (CC) value for baseline scenario was 799 kg CO_2 eq / tonne cement, followed by thermal efficiency scenario 783 kg CO_2 eq / tonne cement, electrical efficiency scenario 791 kg CO_2 eq / tonne cement, material substitution scenario 711 kg CO_2 eq / tonne cement, and fossil fuel substitution scenario 743 kg CO_2 eq / tonne cement, and ideal scenario was 628 kg CO_2 eq / tonne cement.
Georgiopoulou and Lyberatos, 2018	GWP for the scenarios such as coal- petcoke was 498 kg CO_2 eq / tonne clinker, coal 491 kg CO_2 eq / tonne clinker, petcoke 502 kg CO_2 eq / tonne clinker, coal-petcoke-tire derived fuel (TDF) 490 kg CO_2 eq / tonne clinker, coal-petcoke-BS 490 kg CO_2 eq / tonne clinker, cola-petcoke-refused derived fuel (RDF) 483 kg CO_2 eq / tonne clinker, and coal-petcoke-TDF-RDF-biological sludge (BS) 488 kg CO_2 eq / tonne clinker.

Stafford et al., 2016	GWP value was 632 kg CO_2-Eq/ tonne Portland cement.
Boesch et al., 2009	GWP for baseline scenario was 944 kg CO_2 eq/ tonne clinker, scenario CD was 526 kg CO_2 eq/ tonne clinker, scenario AS was 827.6 kg CO_2 eq/ tonne clinker, scenario RT was 669.4 kg CO_2 eq/ tonne clinker, and scenario PL was 856 kg CO_2 eq/ tonne clinker.

Limestone share and non-renewable energy inputs have large impact on GWP of cement production process as it can be seen from the result of a study conducted by Chen et al., (2015). According to that study, shaft kiln followed by moderate dry kiln had maximum GWP than large and small dry rotary kiln, due to higher amount of limestone and non-renewable energy consumption. According to Song et al., (2015), environmental benefits of carbide slag and the mixture of carbide slag and limestone slag as raw material is not prominent as it includes extra environmental burden due to extra electricity consumption in the raw material preparation. Coal substitution by corn straw and heat recovery showed a prominent reduction of emission from cement production process. From the study by García-Gusano et al., (2015), it was found that a significant amount of CO_2 emission reduction can be achieved by improving thermal and electrical efficiency, reducing clinker to cement ratio from 08 to 0.7 and substituting 50% of total fuel by alternative fuels.

Georgiopoulou and Lyberatos, (2018) showed that selection of alternative fuels can effect on GWP. The study presented that fuel with 30% share of BS had higher GWP compared to 30% share of RDF. It was worth noting from that study that BS has lower calorific value compared to RDF, resulting in higher quantities of BS combustion in the kiln operation. Stafford et al., (2016), included raw materials extraction, fuel production, transportation of raw materials and fuels, electricity and atmospheric emissions from the kiln inside system boundary. The study found that 632 kg CO_2 eq/ tonne of cement produced when 43% of fuels were replaced by end of life tires and

RDF. Boesch et al., (2009), compared baseline scenario (1% coal and 99% petroleum coke) with four different alternative fuels such as construction and demolition wood waste, railway ties, asphalt shingles, and plastics. It was found from that study that alternative fuels utilization reduce total CO_2 emission significantly. Also it was found that the higher the biogenic share of carbon in the alternative fuel, the more GWP decreases.

4 MATERIALS and METHODOLOGY

LCA is a tool for addressing the environmental burdens associated with a product's life cycle, i.e., raw material acquisition, logistics, production, utilization, and disposal (cradle to grave) (Song et al., 2015). Environmental burden includes all types of environmental impacts such as emissions to air, water and land, energy consumption, and natural resources depletion. (Georgiopoulou and Lyberatos, 2018). LCA can assist in identifying the pollution that shifts from one stage to another and search the opportunities to improve the environmental performance of the product. By conducting LCA analysis, decision makers can prepare proper strategic plan, which helps them to design or re-design more environmental friendly products. This study was performed according to ISO 14040:2006 standard to show the environmental performance of Finnsementti's cement production in Lappeenranta plant. The framework of the LCA was according to ISO 14040:2006 standard, which is given in figure 3.

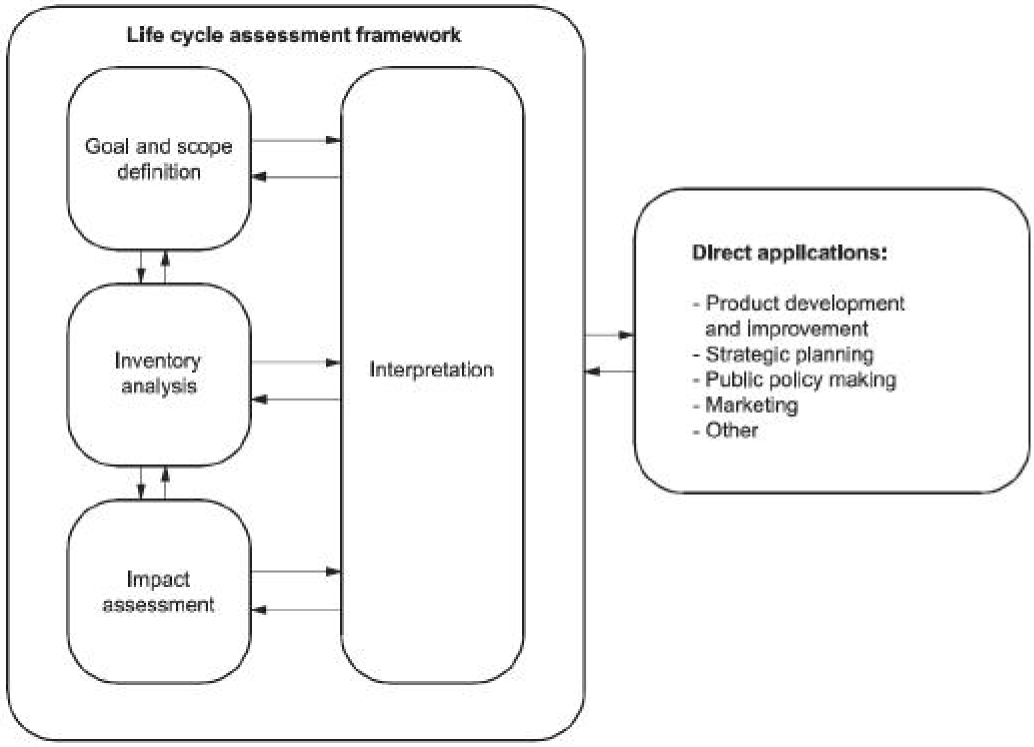

Figure 3. The framework of LCA (ISO, 2006)

In order to obtain accurate and detailed information on environmental impacts caused by a product or service, a specialized tool is required. In this study, GaBi 6.0 with the version of 8.6.2 software was used. It has most accurate industrial and commercial database (Spatari et al., 2001). This tool is used for system modelling, inventory analysis, energy balances of the input and output materials, and calculating impact assessment of the cement production. The overall result was obtained by CML-2015 weighing methodology.

4.1 Goal and Scope Definition

The cement production requires a large amount of raw materials, energy, and heat. Also a huge amount of gaseous emission released to the environment during the cement manufacturing process. In this study, a LCA was conducted to evaluate the global warming potential (GWP) of cement production. Cradle to gate methodology was followed in this assessment, which was started from raw material extraction, fuel production through transportation, electricity consumption to kiln operation. It was assumed that GWP impact caused by cement transportation, utilization and disposal was same for all the scenarios. Thus GWP related to cement transportation, utilization and disposal was excluded from the study. The goal of the study was to compare GWP of Finsementti's cement production process in Lappeenranta plant between 2006 and 2016. In 2006, no SRF was utilized, when in 2016, 53% of total fuel (energy) was replaced by SRF. Also this study tried to find the GWP of cement production for substituting 80% fuel energy by SRF. Nevertheless, the objective of the study was also to pursue the impact on GWP for not utilizing C&IW (SRF produced form C&IW) in the cement plant.

The cement production process data was provided by Finnsementti Oy, but due to confidentiality issues, some data were not directly disclosed. As for environmental impact, only GWP for 100 years excluding biogenic carbon was considered and other environmental impacts were excluded as the required emission data from SRF combustion were unavailable. For SRF production, no emission related to commercial and industrial waste (C&IW) production was considered for this study. Because, C&IW was considered as waste material of secondary production process. That is why, all of the emission related to C&IW production were excluded. Only the collection of C&IW, production of SRF and transport them to the cement plant was considered. GWP impact from raw material acquisition, transportation of the raw materials and fuels and electricity consumption were collected from GaBi thinkstep database.

4.2 System boundary and Functional Unit

As stated previously, a cradle to gate LCA analysis was employed for this study. Figure 4 shows the summary of the input, output of the system boundary as well as corresponding CO_2 emission of the process. The system boundary included all the input and output of the cement production; from raw material and fuel extraction, fuel combustion, clinker and cement production as well as energy consumption for each of the process steps. The boundary also included energy, fuels, and emissions caused with the transportation of raw materials and fuels to the cement plant. SRF utilization was one of the prime research areas of this study. The utilized SRF in this study was derived from commercial and industrial solid waste (C&IW). To get a clear view of the GWP associated with the utilization of SRF in the cement plant, this LCA analysis also included C&IW collection, and transport to the SRF production plant, and SRF production and transportation to the cement plant. By following allocation principle, C&IW production process was considered as secondary process, where waste was treated to produce a by-product suitable for its further use (Chen et al., 2010). Thus GWP regarding to C&IW production was excluded from this study. Also as stated before, this study was conducted by following cradle to gate methodology. That is why, packaging, transporting, utilization and disposal of the cement were excluded from system boundary. A more elaborated system boundary is presented in the Life Cycle Inventory (LCIA) chapter.

To ensure all the inputs and outputs are related to each other, it is important set up a reference unit. In LCI results, different critical systems are being analyzed that, it should be compared on a common ground. In that case it is also necessary to set up a common reference unit, which is called functional unit. The functional unit of this research was established as 1 tonne of Ordinary Portland Cement (OPC). All raw materials, fuels, energy consumption and transportation were analyzed based on this functional unit.

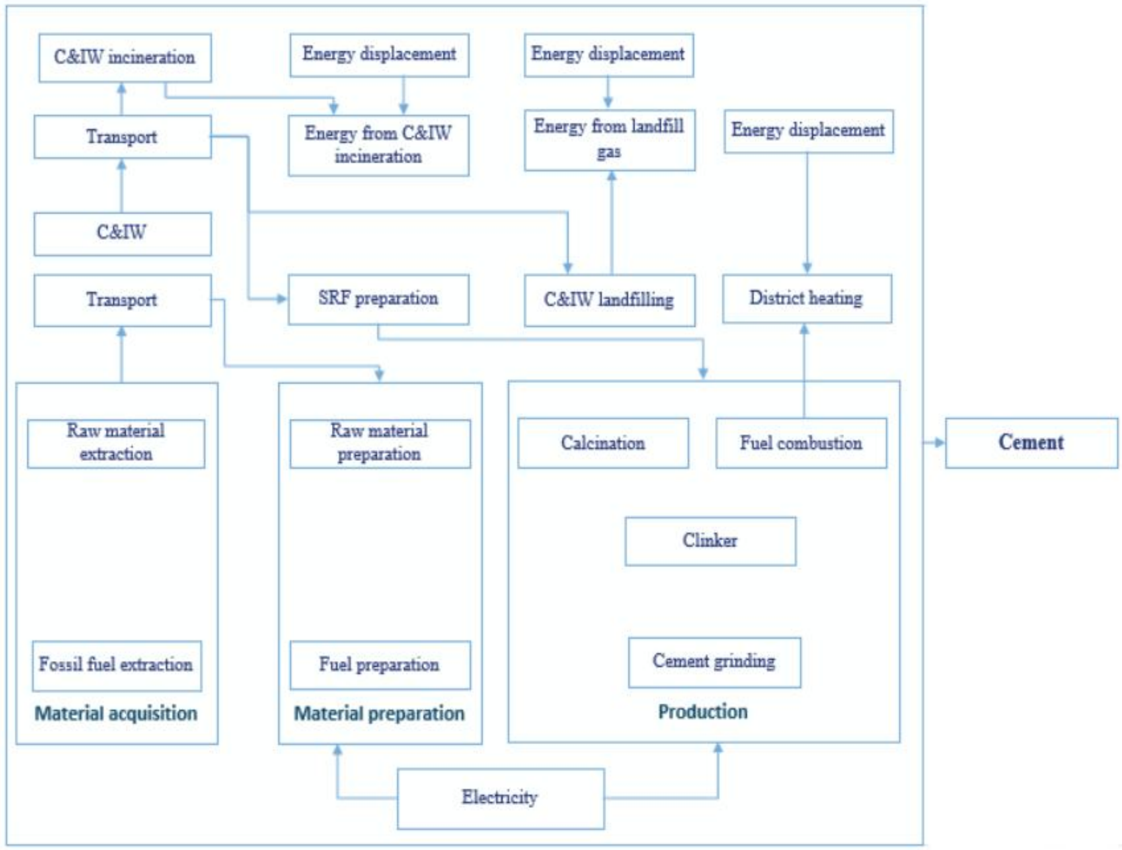

Figure 4. System boundary of the cement production.

4.3 Cement Production Scenarios

In order to identify the GWP of SRF utilization as alternative fuel in cement production, four scenarios were developed and compared. As mentioned earlier, scenario 1 and 2 were based on 2006 cement production data and scenario 3, and 4 were based on 2016 production data. After 2006, Finnsementti brought considerable changes in cement production process to increase energy efficiency of the plant and reduce emissions. To brought changes in the emissions, the company adapted new technologies i.e., SNCR as well as it changes raw material and fuel composition of the cement. By comparing the two data set, this study tried to find out how GWP production was affected by altering 53% share of total fuel energy with SRF in 2016, and what happens to the GWP production when SRF share in the fuel mass is increased even further. Table 7 presents the description of the four scenarios.

Table 7. Description of the scenarios.

Scenario	Description
Scenario 1	Based on 2006 production data where fossil fuels had dominant energy share in the fuel mixture. The energy share of fuel was 60% from coal, 27% from petroleum coke, 12% from waste fuel oil, and 2% from meat and bone meal (MBM). To identify the necessity of treating C&IW inside cement production plant, GWP from C&IW treatment in waste incineration plant was included in this scenario.
Scenario 2	Like to scenario 1, this scenario was also based on 2006 production data. The energy share of fuel as well as raw materials quantity were same as scenario 1. In scenario 2, landfilling for C&IW was included to analyze how much GWP can be reduced by avoiding landfilling of C&IW.
Scenario 3	Scenario 3 was based on 2016 cement production data. In this scenario, different raw material composition as well as fuel composition were used than scenario 1 and 2. As alternative fuels, SRF had 53%, and waste fuel oil had 6% of total energy share.
Scenario 4	This scenario was also based on 2016 data with same raw material composition and energy requirement as scenario 3. However, in this scenario, 80% of the total fuel energy was supplied by SRF and 20% of total fuel energy was supplied by petroleum coke.

4.4 Assumptions

The production of cement involves large quantities of materials, which come from different sources. The cement manufacturing process is a complex system which involves raw materials and fuels input, combustion of raw materials and fuels and treatment of gaseous and solid substances. Therefore, accurate data collection for inventory analysis is always a tough nut to crack. On virtue of the complexity of the data sources, some assumptions have been made for this study.

The energy consumption of SRF production can be divided into in-plant operations and out-plant operations (Nasrullah et al., 2015). In both cases, the amount of energy consumption largely depends on the composition and physical properties of the C&IW. According to Nasrullah, (2015), 60 kWh of energy is consumed for per tonne of C&IW input material. On the basis of this figure, this study considered the energy consumption as 60kWh/tonne of input C&IW material. Annual waste incineration plant efficiency for themal treatment of C&IW was considered 69%, where 64% from thermal energy production and 5% from electrical energy productoin (Anttila, 2011).

Finnsementti supplies around 30 GWh of district heat annually, which helps to reduce GHG emission from thermal energy production in power plant. For this research work, it was assumed that the supplied thermal energy from fuel combustion system in cement plant, and C&IW incineration in waste incineration plant replaced the thermal energy production from natural gas combustion system.

4.5 Life cycle inventory

The life cycle inventory (LCI) data includes the input of energy and materials and release of emission air, water and soil, associated with the production of a product, operation of a process and conduct a service throughout its life cycle. When LCI data are available, it can be summed up for every phase of the products life cycle to form a complete picture of that product's environmental performance. LCI data allows to form meaningful decision regarding the design and manufacture of the product. It helps to focus on improvement efforts, identify opportunities to innovate, reduce risk and cost, and improve brand preference and sales.

LCI data that are used in this research work can be divided into three sections, such as:

a) Primary data: The primary data included raw materials, fuels utilization, and electricity consumptions. The primary inventory data for the foreground system were delivered by Finnsementti Oy for the year 2006 and 2016. As aforementioned earlier, due to confidentiality issues, not all of the data are directly disclosed.

b) Secondary data: The secondary inventory data regarding to raw materials extraction, fuels acquisition, electricity and heat production and supply, transportation, landfilling and thermal treatment of C&IW were obtained from thinkstep data in the form of GaBi database. GaBi LCI datasets are one of the best sources of datasets, because it represents real industrial processes and materials which is purposed for professional use not for the academic concepts (Spatari et al., 2001). This country wise database are annually refreshed by the professional to provide information about latest technologies, materials and science (Spatari et al., 2001).

c) Tertiary data: Biological and non-biological carbon share of SRF components as well as SRF production process data were collected from different literatures, which were considered as tertiary data.

4.5.1 Raw material preparation

The principal raw materials of Finnsemetti's cement production are limestone, fly ash, blast furnace slag, bauxite and diabase in all of the scenarios. Limestone is used to produce clinker by calcination process, which is also one of the largest emitters of GHG in the cement production. A certain amount of fly ash is used to replace clinker, which can be generated from coal fired power plants or waste incineration plants. Slag is recovered as waste materials from iron blast furnace. In cement industry, slag is used as cementitious agent which is less permeable, and increase ultimate compressive strength (World Cement, 2018).

Table 8 shows the amount of raw materials that were used in 2006 and 2016 to produce a tonne of cement. As stated before, limestone is the main raw materials of the cement production. Together with limestone, quartz sand, diabase, iron, and bauxite are grinded, mixed together and finally produce raw meal. The rest of the raw materials such as gypsum, ferrous sulfate, and all mineral waste are mixed with clinker, grinded properly and produce cement.

Table 8. Amount of raw materials used to produce raw meal (unit, tonne / tonne cement).

Raw materials	2006	2016
Limestone	1.27	1.18
Quartz-sand	0.00	0.00
Slag	0.06	0.08
Nickel slag	0.00	0.01
Diabase	0.02	0.00
Gypsum	0.05	0.05
Fly Ash	0.03	0.06
Iron (roll shale)	0.01	0.01
Bauxite	0.02	0.00
Ferrous sulfate	0.01	0.01
All mineral waste	0.00	0.02

During the preparation of raw meal, a certain amount of electricity was consumed depending on the raw materials mixture. For example in scenario 1 and 2, ~102 MJ/ tonne cement equivalent of electricity was consumed, when in scenario 3 and 4, it was ~101 MJ/tonne cement equivalent. The GWP impact caused by electricity consumption was collected from GaBi thinkstep database. In this study the following electricity production mix was followed.

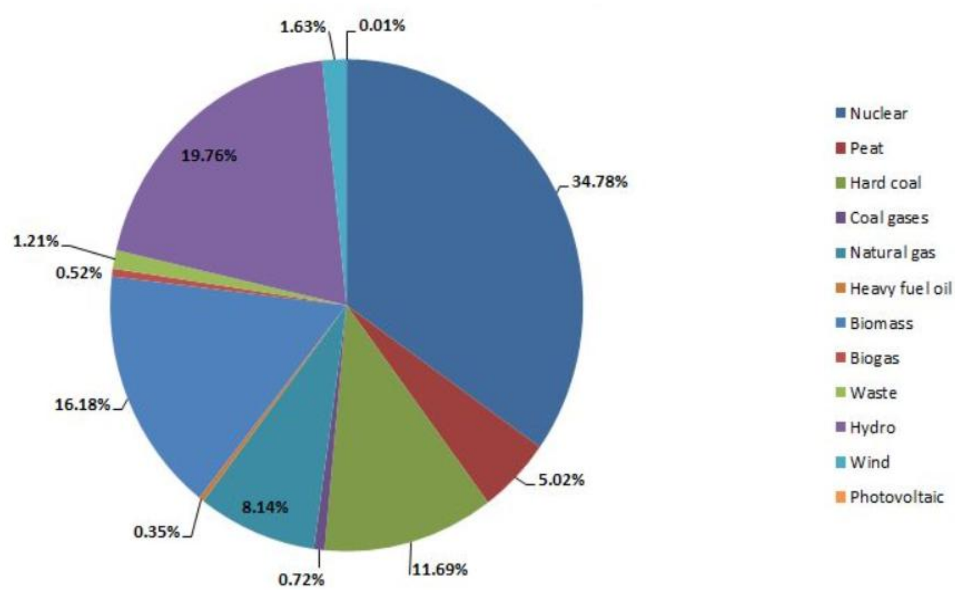

Figure 5. Electricity production mix in Finland, 2014 (GaBi thinkstep).

The GaBi modelling for raw meal production is presented in figure 6. Out of these materials, limestone, diabase, bauxite, and quartz sand were recognized as valuable materials and environmental impacts related to the acquisition were included in this research work. As for blast furnace slag, fly ash, and iron (roll scale), these were considered as waste materials; due to this, no environmental impacts related to the acquisition of these materials were included in this study.

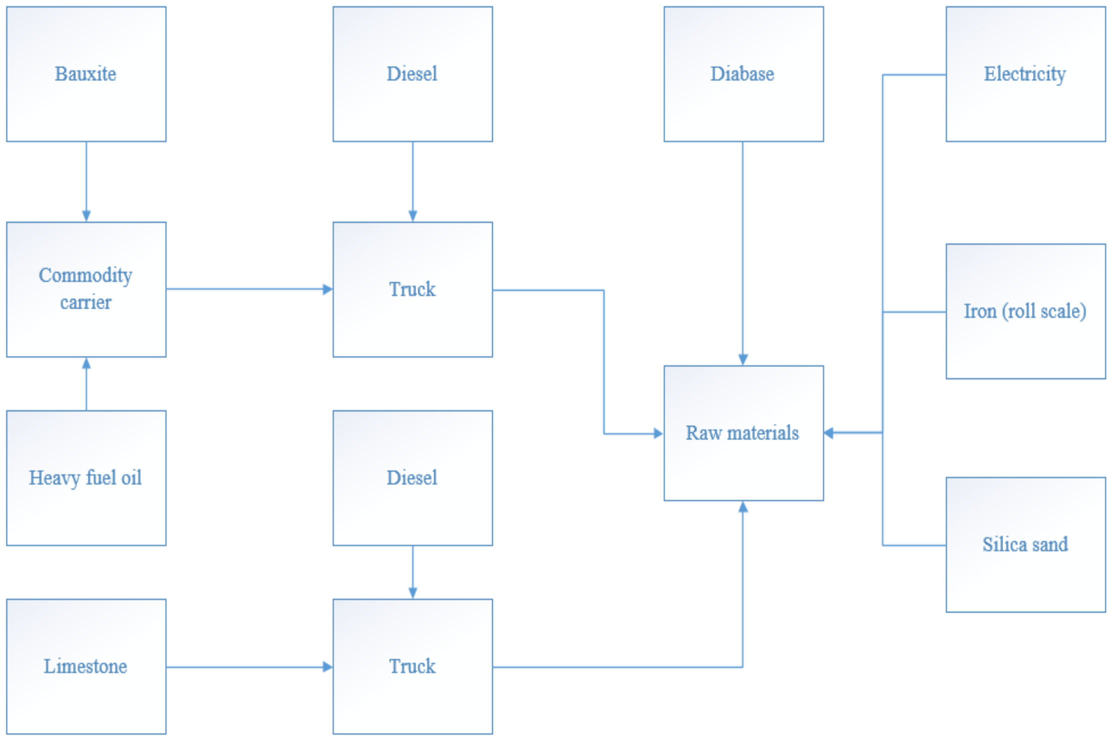

Figure 6. GaBi modelling for raw meal production.

4.5.2 SRF production

The system boundary for SRF production is given in figure 7. C&IW collection and energy production in waste incineration plant was included inside the system boundary to examine the environmental burden that would have caused for not utilizing SRF in the cement plant. Not all of the countries in the world have strict rules about landfill of C&IW. In some countries C&IW are still sent to the landfill without any recovery. Therefore, thermal treatment of C&IW and landfilling was included in the system boundary to analyze the effect on environment could have done by those treatment process.

As can be seen from figure 7, collected C&IW transported to either SRF production plant, waste incineration plant or landfill based on scenarios. In scenario 1, C&IW was sent to the municipal waste incineration plant to produce electricity and thermal energy.

The recovered electricity was displaced and offset CO_2 emission that would have released to produce same amount of electricity from production mix. Following the electricity displacement, thermal energy was also displaced which offset CO_2 emission generated from same amount of thermal energy by natural gas combustion.

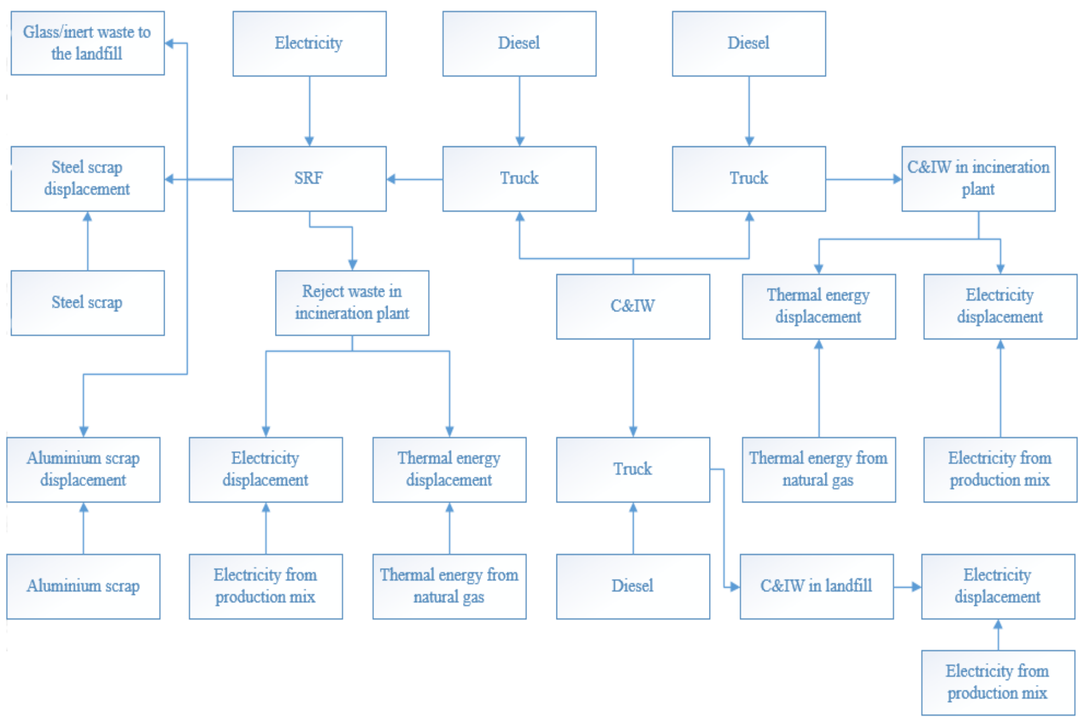

Figure 7. System boundary for SRF production.

In scenario 2, C&IW was transported to landfill site where the distribution of landfill gas was assumed 22 % flare, 28 % used, and 49 % emissions. Also net calorific value of landfill gas was assumed 10.4 MJ/kg. The landfill gas was utilized to produce electricity and electricity displacement was done same as scenario 1. Lower heating value depends on the composition, physical and chemical properties of the waste. The heating value for SRF was considered as 20 MJ/kg, which was taken from Finnsementti's annual environmental report. The energy content for reject materials was considered 11.6 MJ/kg, and C&IW was considered 13 MJ/kg (Nasrullah et al., 2015). There is an uncertainty to achieve 20 MJ/kg energy content of SRF from the

C&IW, which energy content is 13 MJ/kg. However, it might be possible if the plastic share in the SRF composition could be increased. In this study annual energy efficiency for C&IW and reject materials are considered as 69% (electricity 5%, thermal 64%) (Anttila, 2011). For SRF, C&IW, and reject materials, the following formula was used to calculate the CO_2 production.

$$m(CO_2) = m\ (SRF\ /\ C\&IW\ /reject\ materials) * CO_2\ factor * LHV$$

m (CO_2)	*mass of carbon dioxide* [kg]
m (SRF/C&IW/ Reject materials)	*mass of SRF/C&IW/Reject materials* [kg]
LHV	*lower heating value of fuel* [MJ/kg]
CO_2 *factor*	*carbon dioxide emission factor of fuel* [g/MJ]

The collected C&IW was transported to the SRF production center. After passing all of the mechanical treatment processes, SRF was produced together with reject materials, heavy fraction, fine fraction and ferrous and non-ferrous metals. During the production process, in scenario 3, ~28 MJ / tonne cement equivalent of electricity was consumed and in scenario 4, it was ~43 MJ / tonne cement equivalent. The mass flow balance of C&IW treatment process are given in table 9.

Table 9. Mass flow balance in process streams of SRF from C&IW (wet basis) (Nasrullah et al., 2015).

Component	Share
SRF	62%
Reject material	21%
Fine fraction	11.6%
Heavy fraction	0.4%

Ferrous metal	4%
Non-ferrous metal	1%
Total (C&IW)	100%

The SRF composition from Nasrullah et al., (2015), is presented in table 10. The net calorific value as received material of SRF was considered 18 MJ/kg. The carbon content of the materials can be divided into biogenic carbon and non-biogenic carbon. The biogenic and non-biogenic share of carbon was taken from Angeles et al., (2015). In this study only non-biogenic carbon was considered as biogenic carbon is considered as neutral.

Table 10. SRF composition (Nasrullah et al., (2015), Angeles et al., (2015), Kunioka et al., (2014)).

SRF	**Share**	**Moisture content**	**C %**	**Mass, kg, C**	**Biogenic C share**	**Non-biogenic C share**	**Biogenic carbon**	**Non-biogenic carbon**
Paper & cardboard	35,60 %	15,00 %	43,00 %	0,13	99,40 %	0,60 %	0,13	0
Plastic (soft)	24,00 %	14,00 %	74,40 %	0,15	13,20 %	86,80 %	0,02	0,13
Plastic (hard)	16,50 %	14,00 %	74,60 %	0,11	13,20 %	86,80 %	0,01	0,09
Textile	8,50 %	10,00 %	57,40 %	0,04	75,00 %	25,00 %	0,03	0,01
Wood	6,40 %	20,00 %	49,00 %	0,03	99 %	1 %	0,02	0
Rubber	1,00 %	2,00 %	48,00 %	0	97 % (Kunioka et al., 2014)	3 % (Kunioka et al., 2014)	0	0
Foam	1,20 %		62,50 %	0,01	0 %	100,00 %	0	0,01
Metal	0,80 %	10,00 %	0,20 %	0	50,00 %	50,00 %	0	0
Glass	0,00 %	8,00 %	0,70 %	0	50,00 %	50,00 %	0	0

Stones	0,00 %			0	0 %	100,00 %	0	0
Fines	6,00 %	8,00 %	26,80 %	0,01	66,70 %	33,30 %	0,01	0
Total	100,00 %						0,23	0,25

The chemical reaction for CO_2 production is simple as one mole of carbon reacts with one mole of oxygen to produce one mole of carbon dioxide. The CO_2 emission factor for the SRF was calculated by using the following formula.

$$C + O_2 = CO_2$$

$$\frac{m_{CO_2}}{m_C} = \frac{n_{CO_2} * M_{CO_2}}{n_C * M_C}$$

m_{CO_2} *mass of carbon dioxide* [kg]

m_C *mass of carbon* [kg]

n_{CO_2} *mole of carbon dioxide* [mol]

M_{CO_2} *molar mass of carbon dioxide* [g/mol]

n_C *mole of carbon* [mol]

M_C *molar mass of carbon* [g/mole]

In scenario 3 and 4, reject materials were sent to the waste incineration plant for energy production and heavy and fine fraction were sent to the landfill without any energy recovery purpose and energy displacement from thermal treatment of reject materials was done as scenario 1. The composition of C&IW and reject materials are presented in table 11. In this model, ferrous metal was sent to steel recovery center and non-ferrous metal was sent to the aluminum recovery center.

Table 11. Composition of various process streams (Nasrullah et al., 2015).

Component	C&IW	Reject
Paper & cardboard	31.00 %	12.40 %
Plastic (soft)	17 %	14 %
Plastic (hard)	15 %	5 %
Textile	9.00 %	9.20 %
Wood	7 %	4 %
Rubber	2.60 %	6.80 %
Foam	1.00 %	0.20 %
Metal	6.40 %	3.20 %
Glass	4 %	10 %
Stones	3.00 %	18.50 %
Fines	5 %	17 %

4.5.3 Fuel combustion

The system boundary for thermal energy production is given in figure 8. In this model, system boundary included fuel acquisition, transportation and treatment of the fuels to obtain clearer picture of environmental burden caused by cement production. All of the fuels except waste fuel oil were considered as valuable materials in this GaBi model. Even though, C&IW was assumed as waste, GWP impact for preparation of SRF was included in the study for considering SRF as valuable material. Fuels like coal and petroleum coke were transported from different parts of the world. In coal crushing process, ~2 MJ / tonne cement equivalent of electricity was consumed in scenario 1 and 2, as same amount of coal was utilized in those scenarios. The electricity consumption for coal crushing dropped to ~0.003 MJ/ tonne cement equivalent in scenario 3, because in that scenario, only a small amount of coal was consumed. Also in scenario 4, no coal was consumed, resulted no electricity consumption for coal crushing. Emission caused by each types of fuel combustion was calculated by the following formula.

$$m(CO_2) = m\,(fuel) * LHV * CO_2\,factor$$

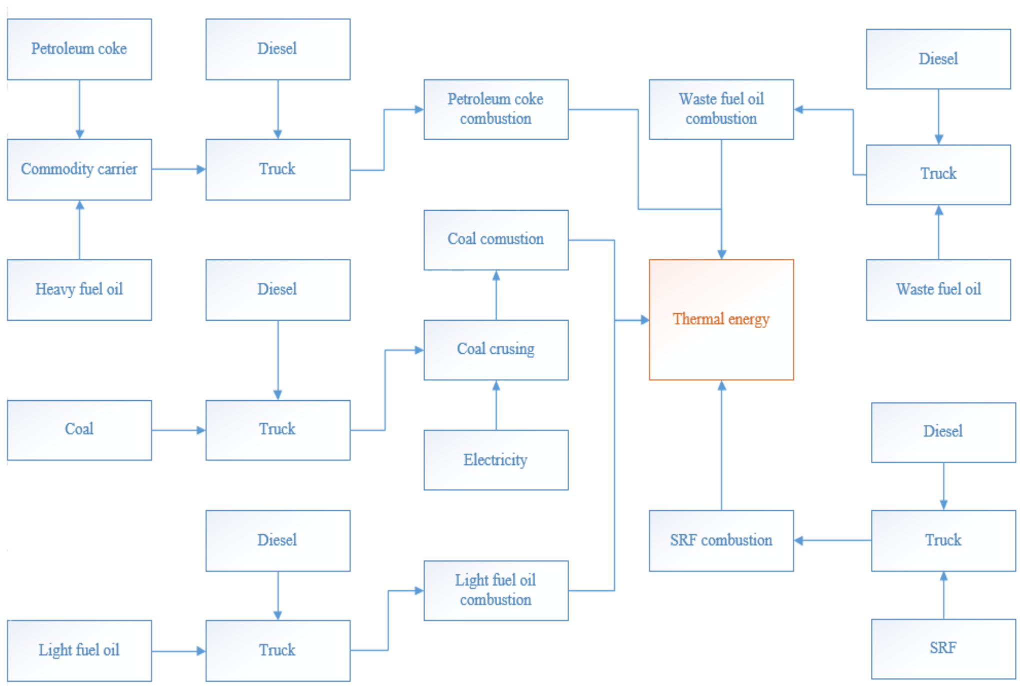

Figure 8. GaBi modelling for thermal energy production.

Generally Finnsementti uses six different types of fuel for thermal energy consumption. These are coal, petroleum coke, waste fuel oil, tires, PPAF (it's kind of industrial waste generated by the manufacture of liquid board, containing paperboard, aluminum and plastic), and SRF. The types of fuel utilization were changed by years to minimize CO_2 emission of fuel combustion in cement plant. The demand of emission trading system in cement industry ensures that information about CO_2 emission from cement production system is accurate. Due to the pressure from EU-ETS system, fuels are continuously analyzed in the laboratory and mapped new recycled fuels for use. Table 12 presents fuel consumption for cement production in Finnsementti Oy.

Table 12. Fuel composition (unit, tonne / tonne cement).

Fuel	2006	2016
Coal	0,07	0,01
Petroleum coke	0,03	0,05
Recycled fuel	0,01	0,06

The heating value as well as CO_2 emission factor of the fuels are given in table 13. As can be seen from this table that fossil fuels have higher LHV, when SRF got bit lower LHV. However, CO_2 emission factor of SRF is much lower compared to fossil fuels as 60% of SRF was considered from biogenic sources.

Table 13. Lower heating value and CO2 emission factors of the fuels.

Fuel	LHV (MJ/kg)	CO_2 emission factor (g/MJ)	Thermal energy consumption (GJ/ ton cement)
Coal	25	95	2,94
Petroleum coke	32	94	
Tires	28	68	
PPAF	24	44	
Waste oil	30	77	
SRF	20	32	

4.5.4 Cement production

The summary of GaBi model for cement production is presented in figure 9. In this model, prepared raw materials were supplied to the rotary kiln where fuels were introduced for the thermal treatment of raw materials and as a result of the thermal treatment, clinker was produced. Meanwhile for operating the kiln, electricity was supplied. After clinker production, it is mixed with gypsum, fly ash, blast furnace slag, and mineral waste. All of these materials are grinded together and cement was produced as an output. For grinding and mixing of clinker, gypsum, ferrous sulfate, fly ash, all mineral waste, and blast furnace slag, ~265 MJ / tonne cement equivalent of electricity was consumed in scenario 1 and 2, and in scenario 3 and 4, ~263 MJ / tonne cement equivalent of electricity was consumed.

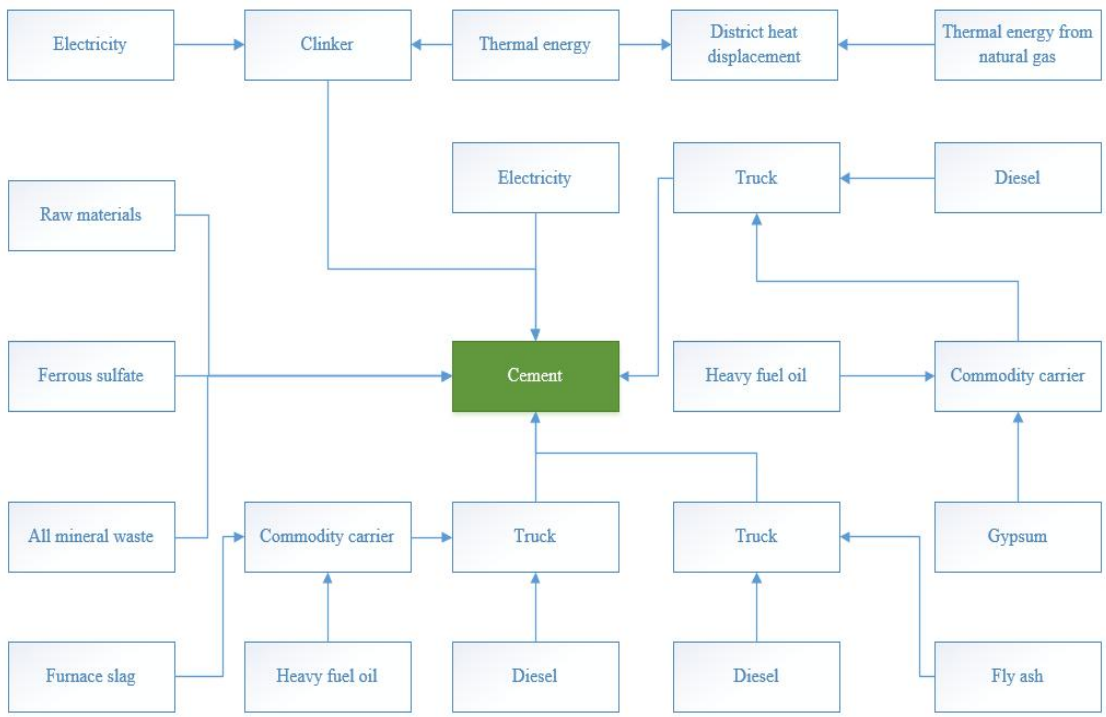

Figure 9. GaBi model summary for cement production.

Clinker is produced from the decomposition of carbonates to calcium oxide and magnesium oxide. Meanwhile, CO_2 is also produced which is one of the major sources of CO_2 emission in cement production system. The total CO_2 emission from cement production system largely depends on the share of clinker in cement. Lower share of clinker produces less amount of CO_2. Clinker can be replaced by fly ash, blast furnace slag, and limestone powder. However, reducing clinker share and maintaining cement quality is always a challenging task for cement manufacturing companies. The chemical reaction for decomposition of carbonates are given below:

$$CaCO_3 = CaO + CO_2$$

$$MgCO_3 = MgO + CO_2$$

$CaCO_3$	*calcium carbonate*
$MgCO_3$	*magnesium carbonate*
CaO	*calcium oxide*
MgO	*magnesium oxide*

The CO_2 emission from clinker production was calculated by using the following formula.

$$m(CO2) = carbonate\,\% * (\frac{CaO\,\%}{M_{CaO}M_{CO_2}} + \frac{MgO\,\%}{M_{MgO}M_{CO_2}})$$

5 RESULTS ANALYSIS

5.1 Life Cycle Impact Assessment

Since cement production is highly emission intensive, the use of SRF complying with the local regulation can reduce the environmental impact by lowering the use of fossil fuel in cement production. In fact, utilization of SRF is proven from this study to be a better choice to recover optimal energy from waste and reduce further environmental impact. The overall result presented in figure 10 proves the argument that utilization of SRF can lower environmental burden associated with cement production process.

As mentioned earlier, scenario 1 was based on 2006 production data when no SRF produced from C&IW was utilized in cement plant and instead the environmental impact that could happen for utilizing C&IW in the incineration plant was included in scenario 1. Resembling to the scenario 1, scenario 2 was also based on 2006 data but in this scenario the environmental impact was checked when C&IW was sent to the landfill. In scenario 3, 53% of total fuel (energy) was from SRF and in scenario 4, SRF contribution was 80% of total fuel (energy).

Among all of the scenarios, scenario 2 released highest of emission followed by scenario 1. A significant change can be noticed when SRF was utilized in scenario 3. Near about 17% of total GWP compared to scenario 1, and ~26% of total GWP compared to scenario 2 was decreased in scenario 3. In addition, a further reduction of GWP (~24% based on scenario 1 and ~32% based on scenario 2) was observed in scenario 4, when 80% total energy share of fuel was replaced by SRF.

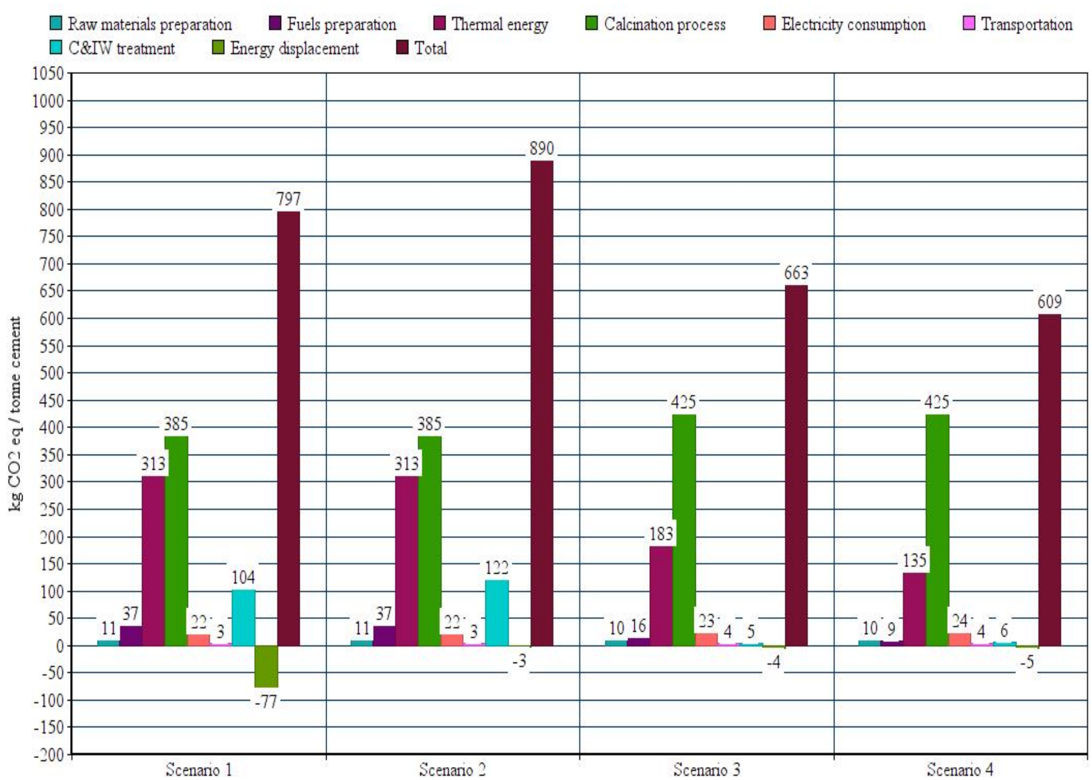

Figure 10. Contribution of scenarios to the GWP.

In all of the scenarios, highest amount of emission released from clinker production. In scenario 1, calcination process constituted 48% of total emission, where in scenario 2, the share was 43%. For scenario 3 and 4, total GWP share for calcination process was 64% and 70% respectively. The second highest GWP for scenario 1 to 4, came from thermal energy production. In scenario 1, the GWP share of thermal energy production was 39%, while in scenario 2, it was 35%, scenario 3, 28% and in scenario 4, the share was 22%. In scenario 1, the third highest GWP (13% of total share) came from the thermal treatment of C&IW in waste incineration plant. However, ~ 10% total share of GWP was offset when energy from thermal treatment process was recovered from C&IW. In scenario 2, landfilling of C&IW comprised ~14% of total GWP share. Unlikely to scenario 1, only ~3% of total GWP was offset for producing energy from landfill gas.

Figure 11 presents GWP of raw material preparation for all of the scenarios. Raw materials preparation had total GWP share of 1% in scenario 1 and 2, and 2% in scenario 3 and 4. In this stage of the cement production, maximum amount of GWP came from limestone extraction followed by gypsum preparation. GWP impact for silica sand, diabase and bauxite extraction ranged between 0.01-0.3 kg CO_2 eq / tonne cement in all of the scenarios.

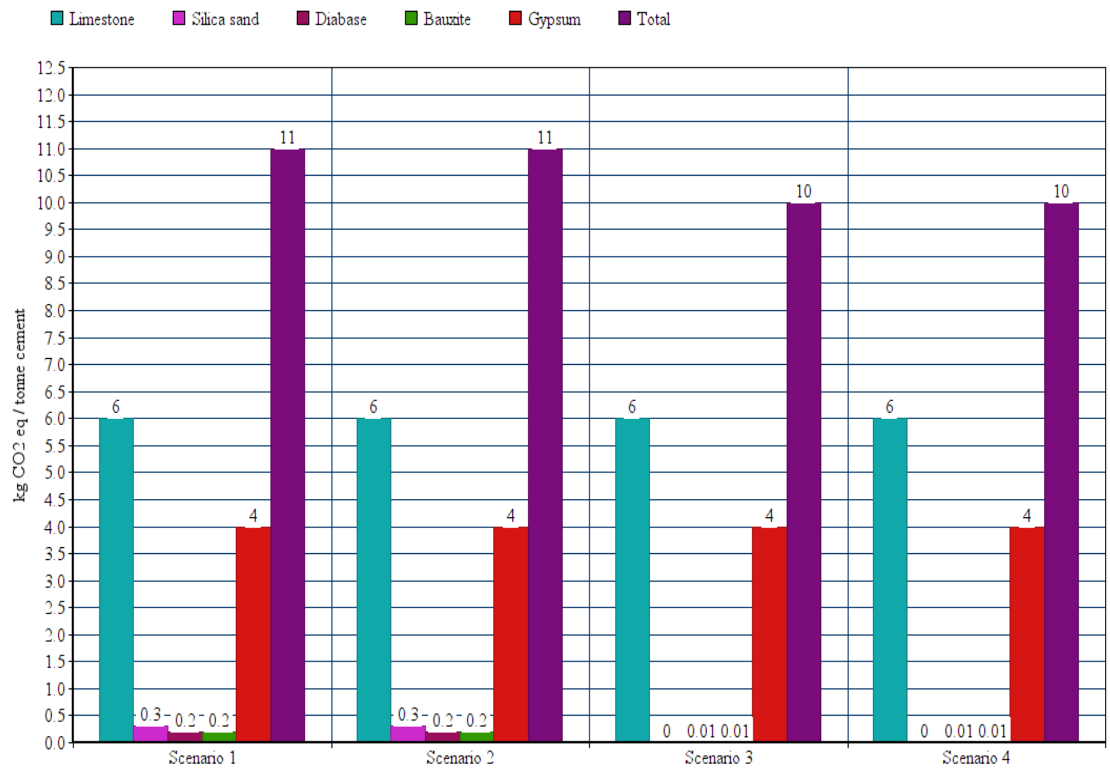

Figure 11. GWP in the raw material preparation.

The result of the GWP in fuel preparation can be found from figure 12. The share of fuel preparation in total GWP depends of the types of fuels consumed in the process. For example, in scenario 1, coal and petroleum coke were the main fuel, which resulted 5% of total GWP in cement production process. Similarly as scenario 2, 4% of total GWP share was from fuel preparation. However, in scenario 3 and 4, the GWP share dropped to 2 % and 1% respectively, because in those scenarios SRF was the main fuel. In fuel preparation, GWP depended on the types of fuel that were used in fuel consumption. Fuels like coal, petroleum coke, light fuel oil and SRF were considered as valuable resources. On the other hand, waste oil and C&IW were considered as waste product, due to that reason, emission related to waste oil and C&IW production were not included in this study. SRF was produced by consuming electricity in SRF production center. That is why, GWP concerning SRF production is not presented in figure 12 but included in figure 14.

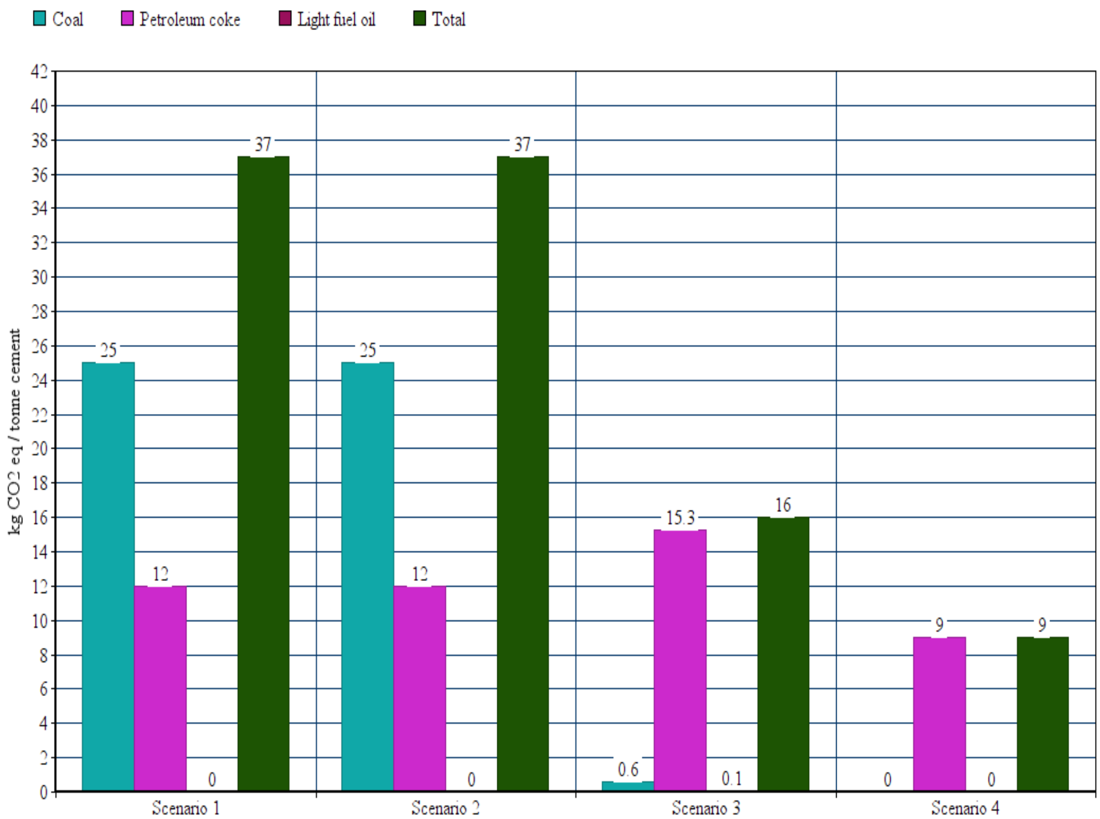

Figure 12. GWP in fuel preparation.

In scenario 1 and 2, thermal energy production contributed 35%-39% of total GWP impact of cement production process, while in scenario 3 and 4, total GWP share from thermal energy production ranged from 22%-27%. The result of GWP in thermal energy production presented in figure 13 showed that scenario 1 and 2 produced much higher CO_2 emission compared to scenario 3 and 4. Nearly 88% of total fuel energy was from coal and petroleum coke in both of the scenarios 1 and 2. As a result, the highest amount of GWP for energy production came from coal and petroleum coke combustion. Even though 53% of total fuel energy was supplied from SRF, maximum amount of GWP came from petroleum coke combustion in scenario 3. The lowest GWP for thermal energy production was obtained from scenario 4, where, highest amount of emission came from SRF combustion, followed by petroleum coke combustion.

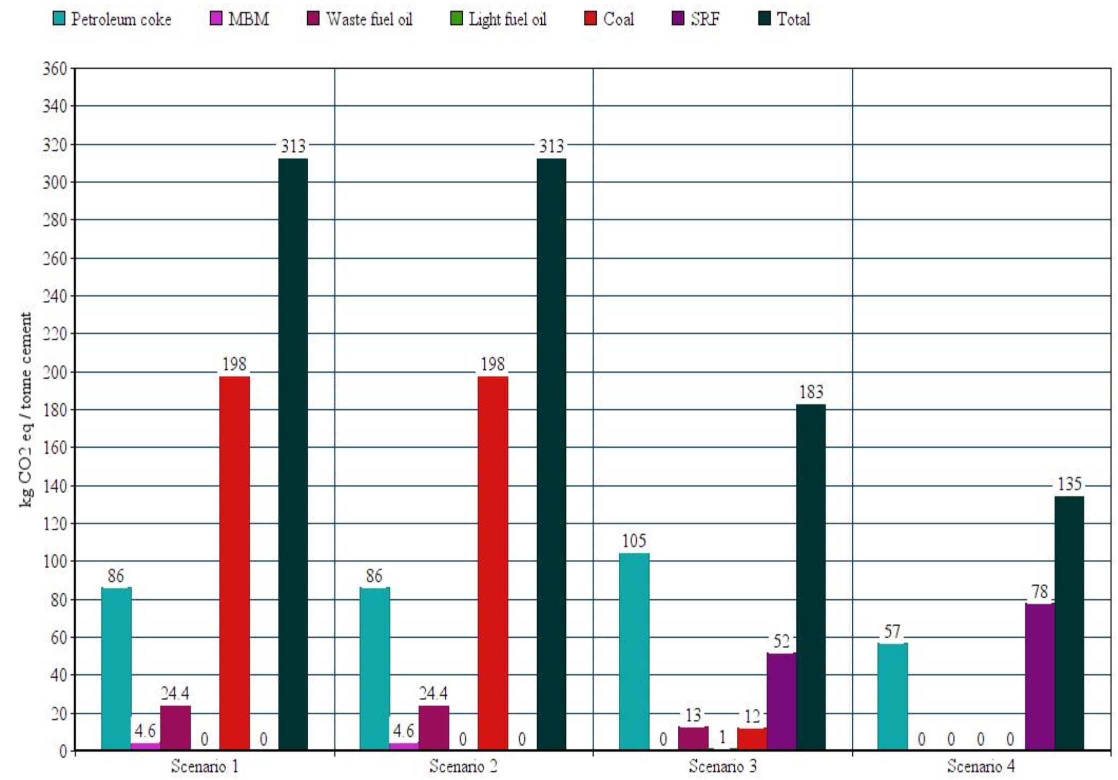

Figure 13. GWP in thermal energy production process.

Electricity consumption did not have much impact in total GWP share of cement production system. In scenarios 1 to 4, the GWP share for electricity consumption was about 2%-4%. In these scenarios, nearly 50% of total GWP came from grinding and mixing of clinker with gypsum, all mineral waste and other supplementary materials. Raw materials preparation was responsible for ~27% and kiln operation for clinker production was liable for ~18% of total GWP in electricity consumption process. SRF was utilized only in scenario 3 and 4, which consisted near about 13% of total GWP for electricity consumption process. GWP impact for electricity consumption in different scenarios are presented in figure 14.

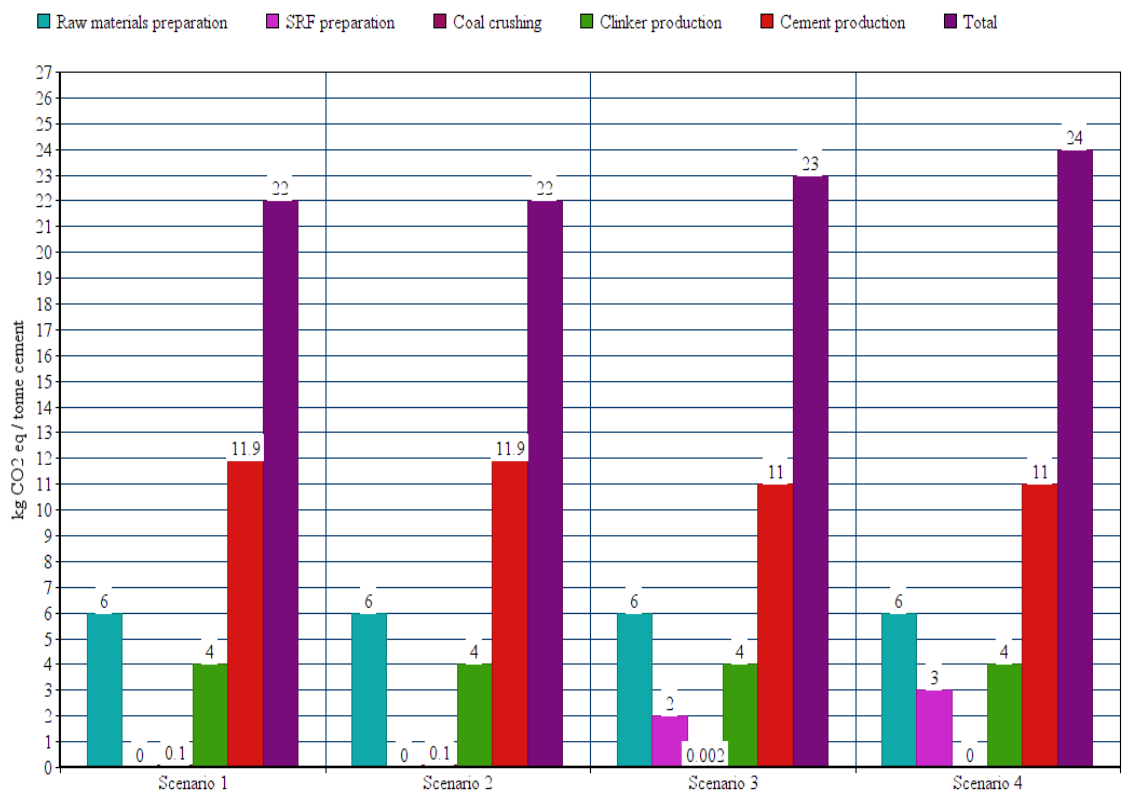

Figure 14. GWP in electricity consumption.

Emission related to transportation of raw materials and fuels are presented in table 14 and 15. The overall GWP impact of transportation in the cement production had a tiny impact (~0.3% - 1%) in all of the scenarios. In scenario 1 and 2, most of the emission came from transporting Gypsum, while in scenario 3 and 4, fly ash transportation showed maximum GWP impact. For fuel transportation, maximum GWP impact was for coal and petroleum coke transportation in scenario 1 and 2. In scenario 3 and 4, maximum GWP impact was for SRF transportation.

Table 14. GWP in transportation of raw materials (unit, tonne/tonne cement).

Raw materials	SC1 (2006+waste incineration)	SC2 (2006+landfill)	SC3 (2016+53% SRF)	SC4 (2016+80%SRF)
Limestone	0,05	0,05	0,05	0,05
Bauxite	0,70	0,70	0,04	0,04
Fly ash	0,74	0,74	1,82	1,82
Furnace slag	0,73	0,73	0,75	0,75
Gypsum	1,46	1,46	1,33	1,33
Total	3,68	3,68	4,00	4,00

Table 15. GWP in transportation of fuels (unit, tonne/tonne cement).

Fuels	SC1 (2006+waste incineration)	SC2 (2006+landfill)	SC3 (2016+53% SRF)	SC4 (2016+80%SRF)
Coal	0,05	0,05	0,00	0,00
Petroleum coke	0,05	0,05	0,06	0,03
LFO	0,00	0,00	0,01	0,00
Waste oil	0,01	0,01	0,01	0,00
SRF	0,00	0,00	1,69	2,49
Total	0,12	0,12	1,77	2,52

The aim of including C&IW treatment in the incineration plant as well as landfill was to find out how much it was possible to save the environment when the same of waste was treated in the cement plant. Figure 15, presents emission related to C&IW treatment for different scenarios. In scenario 1, it was assumed that C&IW waste was sent to the waste incineration plant without any mechanical or biological treatment. Through this treatment process, waste incineration plant produced ~85 MJ of electrical energy and ~1080 MJ of thermal energy. Similarly as scenario 1, in scenario 2, no mechanical or biological treatment was conducted prior to landfilling process. In this scenario, ~45 MJ of electricity was produced by utilizing landfill gas. In scenario 3 and 4, rejected materials from SRF production process were sent to the municipal waste incineration plant to recover thermal and electrical energy. As a result of the thermal treatment of reject materials, a small amount of GHG was released to the environment.

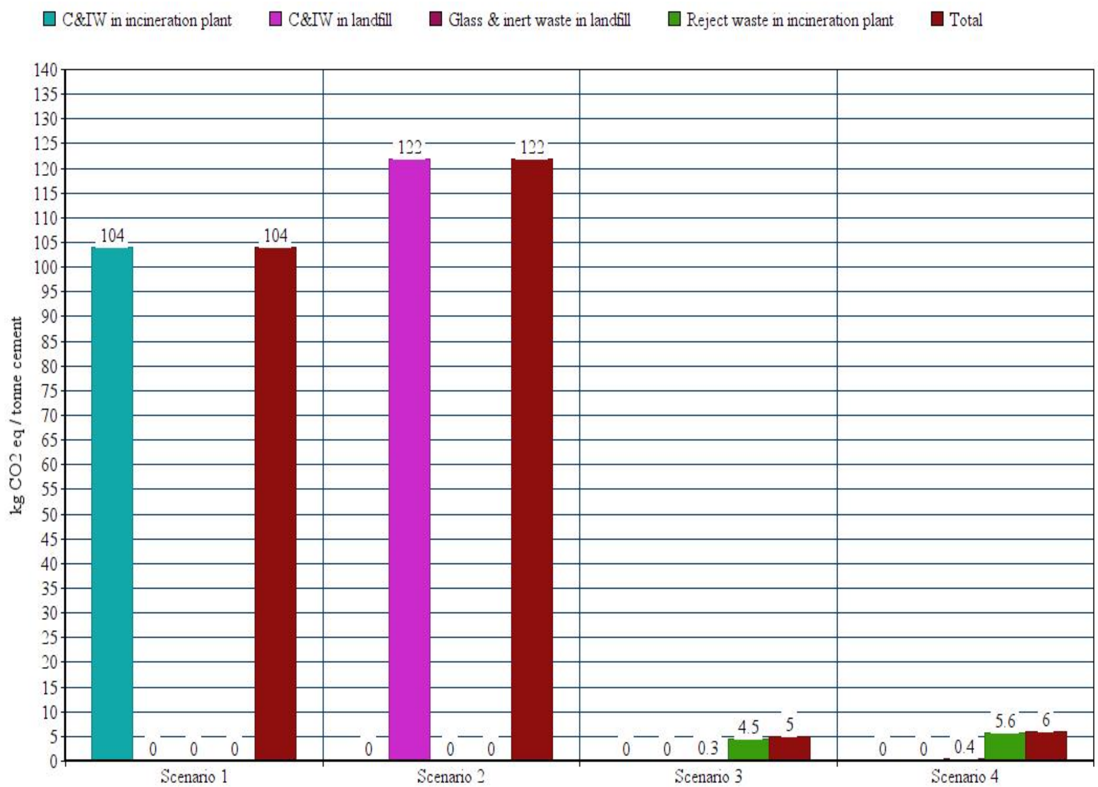

Figure 15. GWP on C&IW treatment.

An energy displacement method was applied to determine the amount of CO_2 that could be offset due the generation of the same amount of energy from conventional sources i.e. electricity from Finnish production mix, 2014 and thermal energy production from natural gas. Finnsementti supplies on average 30 GWh of district heat to the local district heating network every year. In the same way, the recovered electricity and thermal energy from thermal treatment of C&IW or C&IW landfilling, and thermal treatment of reject materials were supplied to the local area. As can be seen from figure 16, the highest amount of CO_2 was offset due to the displacement of electrical energy and thermal energy in scenario 1. The lowest amount of CO_2 was offset in scenario 2, as less than one third of landfill gas was utilized for electricity production. In addition, the total amount of offset CO_2 was quite low in scenario 3 and 4.

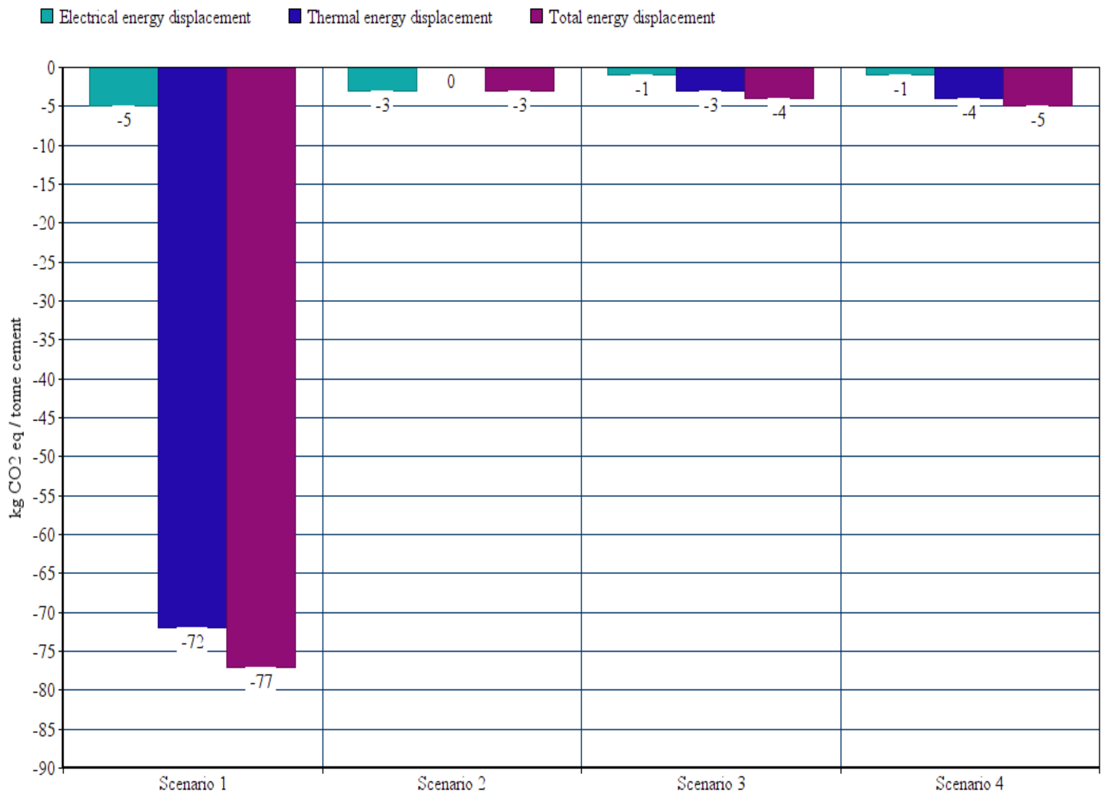

Figure 16. GWP for energy displacement.

5.2 Sensitivity Analysis

From the result part, it was obvious that SRF utilization brought positive impact to the environment. However, there are still some rooms for improvement which may lead even further CO_2 reduction from cement production process. Among all of the scenarios, scenario 4 showed best environmental friendly cement production process. From scenario 4, it was found that maximum share of CO_2 (70%) released from calcination process, followed by 22% from fuel combustion and 4% from electricity consumption. Clinker share in the cement was ~80% in scenario 4, which may be reduced without compromising the quality of the cement and on the virtue of the less clinker in the cement, further CO_2 emission reduction might be possible. According to Harald Justnes,2007, clinker share in the cement could be 65%, while CEMBUREAU, 2013b, claimed that the ratio could be 75%.

One of the major drawbacks of SRF utilization is, it requires large amount of storage spaces. Thus increasing share of SRF in fuel mixture is always challenging. However, SRF with lower CO_2 emission factor or higher LHV might decrease emission from SRF combustion in cement production system. The third highest share of CO_2 emission was from electricity consumptions. In the modelling, electricity was supplied through electricity grid mix. The emission could be lowered by using renewable sources of energy.

The sensitivity analysis of this study was divided into two parts. In the first part, 65% and 75% clinker ratio were considered. The rest of the clinker was substituted by fly ash and blast furnace slag depending on share of mass in the raw materials composition. Simultaneously, four different types of renewable energy sources were compared to obtain best environmental friendly path for cement production. In the second part, different composition of SRF was used and compared with scenario 4 data. The new SRF composition was taken from Nasrullah et al., (2015).

The following table shows the relation between different share of clinker and impact of utilizing renewable energy sources in the cement production process. From the result of the analysis, it can be seen that ~17% less CO_2 emission can be possible compared to scenario 4, in clinker production process, by using clinker to cement ratio 0.65, while, 8% less CO_2 produced for clinker to cement ratio 0.75. None the less, a further CO_2 emission reduction was possible when different sources of renewable energy were utilized in the system. Among all of the renewable energy sources, it was found that wind power produces less amount of CO_2 emission. From table 16, it was found that 65% clinker share with the electricity from wind power gave more environmental friendly cement production process than other comparative variables.

Table 16. Comparison of CO_2 emission for different clinker share and renewable energy sources with scenario 4.

	SC4	65% clinker in cement				75% clinker in cement			
Cement production process		Photovoltaic	Wind power	Biomass	Hydropower	Photovoltaic	Wind power	Biomass	Hydropower
Raw materials preparation	10	10	10	10	10	10	10	10	10
Fuel preparation	9	9	9	9	9	9	9	9	9
Thermal energy	135	135	135	135	135	135	135	135	135
Calcination process	**425**	**344**	**344**	**344**	**344**	**397**	**397**	**397**	**397**
Electricity consumption	**24**	**9**	**1**	**2**	**2**	**9**	**1**	**2**	**2**
Transportation	4	6	6	6	6	5	5	5	5
Energy displacement	-5	-5	-5	-5	-5	-5	-5	-5	-5
Commercial & industrial waste treatment	6	6	6	6	6	6	6	6	6
Total (kg CO_2 eq / tonne cement)	609	514	506	507	507	566	558	559	559

The calculated CO_2 emission factor for SRF was 51.42 g/MJ from the SRF composition, which was collected from Nasrullah et al., (2016), while in scenario 4, the CO_2 emission factor for SRF was used as 32 g/MJ. Low LHV and higher emission factor has huge impact on the overall CO_2 emission as it can be found from figure 17. Lower heating value of SRF increased the amount of SRF consumption of the system, which also affected on the transportation, and electricity consumption for SRF preparation. By comparing scenario 4 with new composition of SRF based on Nasrullah et al., (2016), it was found that total CO_2 emission/ tonne cement production increased due the increase in CO_2 emission from SRF combustion system. In scenario 4, the CO_2 emission excluding biogenic C was ~111 kg / tonne SRF, while it increased to ~161 kg / tonne SRF in the compared scenario, because of low LHV and higher CO_2 emission factor of SRF. As a result, the total CO_2 emission of cement production system raised at about 9% in the new scenario compared to scenario 4.

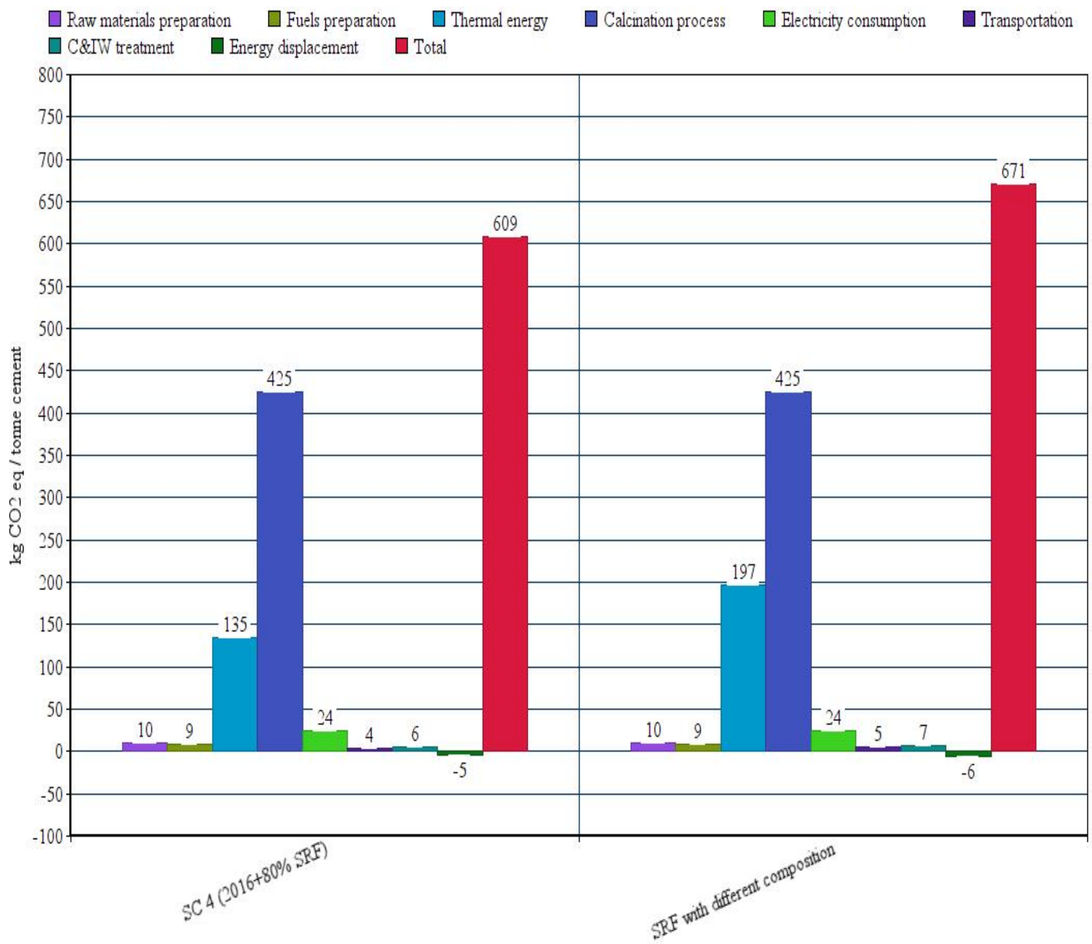

Figure 17. Comparative result between scenario 4 and different lower LHV and higher CO_2 emission factor SRF.

6 DISCUSSIONS

Several LCA studies (Song et al., 2016; García-Gusano et al., 2015; Chen et al., 2015) on cement production process showed that GWP for cement production ranges from 650-800 kg CO_2 eq / tonne of cement. In this case, it can be concluded that Finnsementti is producing more environmental friendly cement than many other companies in the global market. In all of the scenarios of this study, CO_2 released from two major processes in cement production system; (1) calcination process, and (2) fuel combustion process. The share of emission from fuel combustion process depended on fuel types. In addition, C&IW treatment in waste incineration plant or landfill also had impact on total GWP. In scenario 1, 98% of total fuels were from coal, petroleum coke, and waste fuel oil. Also, C&IW was treated in the incineration plant. As a result, the total GWP was 797 kg CO_2 eq/tonne of cement in scenario 1. Even though the same amount of raw materials and fossil fuels were used in scenario 2, due to the landfilling process, the total GWP was 890 kg CO_2 eq/tonne of cement. A significant change in the total GWP impact was observed, when SRF was utilized in scenario 3. On the virtue of utilizing SRF, total GWP from cement production process dropped down to 663 kg CO_2 eq/tonne of cement in scenario 3. A further decrease in the GWP from cement production process was observed when SRF share in the fuel mixture (energy) increased to 80% in scenario 4. The total GWP in scenario 4 was ~28% lower than scenario 1, ~32% compared to scenario 2, and ~8% lower than scenario 3.

As discussed earlier that calcination process and fuel combustion process are the main sources of CO_2 emission in the cement production process, to reduce the overall emission, it is important to reduce clinker share in the cement or increase the utilization of alternative fuel in the fuel mixture. Altering limestone share or clinker share in the cement is always challenging for any cement manufacturing companies when it is subjected to quality control.

However, fuel can be changed from fossil fuel to alternative fuel such as MBM, SRF, TDF or other recycled fuel. Utilization of alternative fuel is not always a good practice to reduce CO_2 emission, when non-biogenic share of carbon in the alternative fuel is high. CO_2 emission reduction by using alternative fuel depends on the biogenic and non-biogenic share of C in the alternative fuel. Higher share of non-biogenic C in the alternative fuel does not reduce overall CO_2 emission of the system. In scenario 1 and 2, waste fuel oil was used as an alternative fuel with the share of 9% of the total fuel (mass) but with no impact on the reduction of total CO_2 emission from thermal energy production was observed because of its high share of non-biogenic carbon. On the contrary, SRF utilization had huge impact on total CO_2 emission from thermal energy production in scenario 3 and 4, due to its high share of biogenic carbon.

The amount of CO_2 emission reduction from SRF utilization depends on the heating value and CO_2 emission factor of the SRF. Sensitivity analysis of this study showed that heating value and CO_2 emission factor largely depended on the composition of the SRF. SRF with higher share of plastic increases the LHV but at the same time it also increases CO_2 emission factor, as plastic has ~87% non-biogenic share of carbon. On the contrary, higher amount of bio-waste such as paper & cardboard, and wood decreases CO_2 emission as well as reduces the LHV of SRF. As a result, it is not possible to get higher LHV and lower CO_2 emission factor from SRF simultaneously.

The aim of including thermal treatment of C&IW in scenario 1 and landfilling in scenario 2 were to understand the impact of treating C&IW in incineration plant and landfill on the environment and later compare the environmental impact when SRF was combusted in the cement production process. CO_2 emission from thermal treatment of C&IW largely depends on the composition of the waste. High share of plastic in the waste mixture increases the overall CO_2 emission from thermal treatment of C&IW. An energy displacement system was established in the model to find out the amount of CO_2 that could be saved when recovered electricity was supplied to the grid and thermal energy was supplied to the local district heating network. In scenario 1, ~104 kg CO_2 eq/ tonne cement was released to the environment, while saving ~77 kg CO_2 eq/ tonne cement for supplying thermal and electrical energy. The amount CO_2 that was offset for supplying energy from waste incineration plant, depended on the annual efficiency of incineration plant. In this study, annual efficiency for thermal energy production was considered 64% and electrical energy production was considered 5%. High annual efficiency of energy production may increase the CO_2 offset amount and lower the environmental burden of the thermal treatment of C&IW. Negative impact on the environment was high in scenario 2, because, only a small amount of CO_2 saved from generated electricity. ~122 kg CO_2 eq/ tonne cement released to the environment, when only ~3 kg CO_2/ tonne cement was saved for supplying recovered electrical energy. The GWP impact of utilizing SRF in the cement plant was considerably low in scenario 3 and 4. Only 4 kg CO_2 eq/ tonne cement released for producing ~81 kg SRF from 130 kg of C&IW and ~52 kg CO_2 eq / tonne cement was emitted for combusting SRF in the cement production process. Also in scenario 4, ~5 kg CO_2 eq/ tonne cement was released for the production of SRF from ~197 kg C&IW and ~78 kg CO_2/tonne cement released for the combustion of SRF in the cement manufacturing plant. By analyzing the results, it was found that SRF combustion in the cement production plant brought positive impact on the environment rather than treating C&IW in waste incineration plant and landfill.

Sustainable development of a city should be based on national and international policies and local conditions (Vinokurov et al., 2015). The EU has set up a target to reduce GHG emission to 20% by 2020 and even further to 40% by 2030, compared to 1990 (Ministry of the Environment). Finland wants to become pioneer in the field of sustainable development. The sustainable development of Finland is carried out according to United Nations (UN), EU, Arctic Council, and Nordic Council of Ministers. Finland has its own GHG emission reduction target, which is to cut GHG emission of 80% by 2050 based on 1990 level (Ministry of the Environment). The city of Lappeenranta wants to provide the cleanest environment to its citizens. Being a member of HINKU network of Finnish carbon neutral municipalities, it has set up an emission reduction target of 80% from 2007 level by 2030 (Greenreality). To reach the emission reduction target, the city is promoting carbon neutral businesses. During the time period of ten years (2006 to 2016), Finnsementti was able to reduce near about 312,000 tonnes of CO_2 emission from Lappeenranta plant and carbon dioxide equivalent emission per ton of produced cement was reduced by 15% from 2006 to

2016. The largest contributor for the reduction of CO_2 was SRF, when SRF share reached up to 53% of total fuel energy in 2016. SRF utilization in Finnsementti not only reduce CO_2 emission from cement production process but also cut emission from the thermal treatment of C&IW. In addition, SRF in the cement plant helps Finnsementti to achieve credit from EU-ETS system as well as support Lappeenranta city to reach its emission reduction goal.

In this study, the system boundary included cradle to gate analysis of cement production as well as thermal treatment and landfill for C&IW was added to find out the impact of utilizing SRF in the cement plant. This study was limited to only GWP impact assessment due to the lacking of data about the relation between SRF combustion and NOx, SO_2, and particulate matter (pm) emission. A further analysis could be done based on NOx, SO_2 and pm emission data from SRF combustion in the cement production plant.

7 CONCLUSION

Concrete is the second largest consumed material in the world after water. Cement is the most essential part of the concrete. The cement production process is not only highly energy intensive but also produces a lot of GHG emissions, partly due to the high energy consumption. Even though many initiatives have been taken so far to reduce CO_2 emission from fuel consumption in cement manufacturing process, there is a high potential of reducing fossil fuel utilization by substituting with alternative fuels such as SRF. Cement industry offers great opportunity to recover energy from waste by following technical and environmental conditions. It also helps to reduce CO_2 emission from waste treatment process by providing alternative to thermal treatment of C&IW and landfilling. By merging waste management industries and cement industries together, it is possible to mitigate anthropogenic carbon emission and reduce the depletion of natural resources significantly. Replacement of fossil fuels with SRF is not only an environmental friendly practice but also a suitable way to conserve natural resources.

The result of the LCA of cement production showed that GWP can be lowered by utilizing SRF in the cement production process. In scenario 1 and 2, no SRF was used, while in scenario 3 and 4, 53% and 80% of total fuel energy was replaced by SRF respectively. In addition, thermal treatment of C&IW in municipal waste incineration plant was included in scenario 1 and landfilling of C&IW was added in scenario 2 to perceive the impact on GWP for not utilizing SRF in cement plant (SRF is produced from C&IW). As a result of the utilization of SRF in scenario 3, the GWP was reduced by~17% compared scenario 1 and ~26% compared to scenario 2. A further decrease in GWP was achieved in scenario 4, when 80% of fuel energy was substituted by SRF. In scenario 4, the total GWP for cement production process was nearly 24% lower compared to scenario 1, ~32% from scenario 2, and ~8% lower than scenario 3. The study also showed that SRF utilization in cement plant can reduce CO_2 emission compared to directing C&IW to energy recovery or landfill. Nevertheless, it was found that CO_2 emission from SRF utilization in the cement plant largely depends on the composition of SRF. SRF with higher content of LHV and higher CO_2 emission factor may not bring the best positive result for cement production process. The study also showed that, CO_2 emission reduced by ~17% compared to scenario 4, when electricity was supplied from wind energy and part of the clinker was replaced by fly ash to adjust the clinker to cement ration to 65%.

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