UNIVERSITY OF GAZIANTEP
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LIFE CYCLE ASSESSMENT AND ANALYSIS OF HEAT AND POWER PRODUCTION ALTERNATIVES FROM DIGESTED SEWAGE SLUDGE

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ABSTRACT

LIFE CYCLE ASSESSMENT AND ANALYSIS OF HEAT AND POWER PRODUCTION ALTERNATIVES FROM DIGESTED SEWAGE SLUDGE

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In this thesis, a comparative Life Cycle Assessment (LCA) method has been conducted on two different technologies for incineration of sewage sludge to produce heat and/or power. For this, Gaziantep GASKI Sewage Sludge Incineration Plant based on a fluidized bed combustor (FBC) and a hypothetical cement kiln (CK) facility using sewage sludge as a secondary fuel, were taken as two different case studies. This study aimed to show the environmental burdens of each option from different impact categories aspects, in order to give a clear perspective to decision makers for drawing an environmentally friendly and sustainable sludge disposal policy. The FBC option showed better performance in the global warming category, while another option preceded in human health category regard. CK option has several limitation conditions to compete FBC option like a limitation of sludge feed and the distance of such facility to the wastewater treatment plants. In this thesis, SimaPro IMPACT2002+ software with 15 different impact categories was used as impact assessment method, and the inventories of the systems were characterized and then normalized at the endpoint.

Keywords: *Life cycle assessment; sewage sludge; incineration; cement kiln, environmental burden.*

ÖZET

İŞLENMİŞ ATIK SU ÇAMURUNDAN ISI VE GÜÇ ÜRETME ALTERNATİFLERİNİN YAŞAM DÖNGÜ DEĞERLENDİRMESİ VE ANALİZİ

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Bu tez çalışmasında, atık su çamurunun ısı ve/veya güç üretimi amacıyla farklı iki teknik kullanılarak yakılması karşılaştırmalı bir Yaşam Döngü Değerlendirmesi (YDD) yöntemi kullanılarak gerçekleştirilmiştir. Bu amaçla, atık su çamurunu ikincil yakıt olarak kullanan akışkan yataklı bir fırın içeren Gaziantep GASKI Atık Su Çamuru Yakma Tesisi (ÇYT) ile kuramsal bir çimento fırınında yakma (ÇFY) iki farklı durum çalışması olarak ele alınmıştır. Bu çalışmada, ele alınan alternatiflerden her birinin, çevre dostu ve sürdürülebilir çamur bertaraf politikalarını belirlemek konusunda ve çevresel etki kategorileri temelinde karar alıcılara açık bir bakış açısı sunması amaçlanmaktadır. Çamur yakma tesisi küresel ısınma etki kategorisinde daha iyi bir performans sergilerken, çamurun çimento fırınında yakılması insan sağlığı bakımından daha etkin ve olumlu bir sonuç göstermektedir. Atık su çamurunun çimento fırınlarında yakılmasının, çamur besleme miktarının sınırlı olması ve atık su arıtma tesislerine uzaklığı gibi sebeplerle çamur yakma tesislerine göre dezavantajları bulunmaktadır. Bu çalışmada, yaşam döngü analizi ve değerlendirmesi yapılırken 15 farklı çevresel etki değerlendirmesi yapabilen lisanslı SimaPro IMPACT2002+ programı ve söz konusu durum çalışmaları verilerini içeren özgün veritabanları kullanılmıştır.

Anahtar Kelimeler: *Yaşam döngü değerlendirmesi; atık su çamuru; yakma; çimento fırını, çevresel yük.*

This thesis is dedicated to my beloved wife, sons and daughters

for their endless love, support and encouragement.

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Bq	Bequerel
CFBC	Circulating Fluidized Bed Combustor
CHF	Swiss Frank
CSTR	Continuous Stirring Tank Reactor
DALY	Disabled Adjusted Life Year
DM	Dry Matter
DS	Dry Solid
EC	European Community
EU	European Union
FBC	Fluidized Bed Combustor
F u	Functional Unit
GHG	Green Gas Gases
GSSIP	Gaziantep Sewage Sludge Incineration Plant
GWP	Global warming Potential
LCA	Life Cycle Assessment
MHF	Multiple Hearth Furnace
MRS	Mixed Raw Sludge
MS	Mild Steel
PDF	Potentially Disappeared Fraction
PE	Population Equivalent
Pers	Persons

SRT	Sludge Retention Time
VM	Volatile Matter
WtCHP	Waste to Co-generation Heat and Power
WtH	Waste to Heat
WWTP	Waste Water Treatment Plant
Yr	Year

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter describes the subject, methodology and tools used to carry out this research and shows the goal and scope of it. Additionally, the main layout of this study has been presented.

1.2 DISPOSAL OF SEWAGE SLUDGE

Of the constituents removed from wastewater treatment, sludge is by far the largest in volume, is a serious environmental pollutant, and its disposal is one of the most difficult issues which faces the large cities' municipality's administration [1]. The old techniques of sludge disposal, focused on some common uses of sludge as a fertilizer in land reclamation, damping in the sea and landfill. Due to the adverse effects of sewage sludge, like aggressive odor, pathogens and heavy metals, and the bad consequences of some of those used disposal methods, a noticeable number of these methods have been banned or restricted by new legislations aiming to protect the global environment. On the other hand, and in contrast with the common consideration of sludge as a mere waste, sludge can be considered as a sustainable resource of energy and can be converted to a renewable energy with the aid of some new technologies and treatments. The main challenge which comes into view is to specify the best disposal route for this environmental pollutant in a manner that ensures the minimum damage to the environmental system and the maximum utilization of the energies and resources embedded within this waste. Thermal disposal treatments showed the best performance in this regard, as it is concluded from the most new and reliable researches and studies, and accordingly, a growing interest is now being directed towards incineration and other thermal sludge disposal processes [2].

In this study, two thermal disposal options for sewage sludge within the Turkish context have been investigated and the most common sludge incineration facilities were described. First disposal option adopted to be studied in this research is Gaziantep sewage sludge incineration plant, which is the first dedicated sludge incineration plant to be installed in Turkey. The second option is a hypothetical cement production plant which uses sewage sludge as a secondary fuel and as a raw material compensator, located in the vicinity of the Gaziantep city.

1.3 LIFE CYCLE ASSESSMENT METHODOLOGY

Nowadays, as an interesting issue for both goods producers and consumers, the environmental consequences of any product or service possess the highest rank of priority. From this standpoint, this study aims to compare two disposal options for municipal sewage sludge from the most common environmental impact categories perspective included within the Life cycle Assessment (LCA) methodology.

The life cycle of a product consists of all the stages from raw material extraction to its waste management [3]. To assess the environmental impacts of any product or service throughout all its life span, several worldwide used methodologies are available. The most common and widely used is the LCA tool. This analytical tool adopts the strategy of analyzing the whole life span stages of a product or service from the early extraction stage to the final disposal stage, compiling all input and output flows to the studied system, assessing them and finally, interpreting the results to determine the most effective life stages of the product from an environmental perspective [4].

For the first time, the concept of the LCA was implemented in a study in 1969 in the USA, but the name of LCA was adopted at a conference in 1991. This tool has been used and developed by several groups of scientists and researchers in different countries, and huge databases for related processes and substances were created. As a consequence, a large number of methods and databases were published. The difference between these methods was based on the number of impact categories, characterization factors and stages of impact assessing progress. The method of IMPACT2002+ was used in this LCA study, which belongs to a scientific group from Switzerland. The software of SIMAPRO7.3.3 and Ecoinvent database were used to carry out this LCA.

1.4 ORGANIZATION OF THE THESIS

This thesis includes six chapters, followed by the referencing of the sources which have been used within the research. Chapter sequence and contents are as bellow:

Chapter two includes a review of the similar studies in the open literature to show the place of this research among other identical studies and researches.

Chapter three describes the theoretical part of this thesis, the working principles and the main components of the systems which have been studied within this research.

Chapter four defines the concept and methodology of LCA, its components and stages.

Chapter five is assigned to show the limitations and assumptions adopted for carrying out this study, followed by the obtained results and the interpretation of these results.

Chapter six constitutes the conclusions arose from the study and its results to assess the value of this research.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter introduces the literature survey related to the main headings of the title of this study regarding the disposal of the sewage sludge in the frame of LCA methodology, showing the results they have obtained and considering the conclusions revealed from those studies.

2.2 DISPOSAL METHODS OF SEWAGE SLUDGE

Recently, the environmental issues became the most vital criterion to evaluate any activity or product. Sewage sludge is one of the byproducts of wastewater treatment that needs to be eliminated in an environmentally safe manner [5]. With the dramatic population and Urbanism growth, and in line with the new strict legislations of sludge disposal methods, the determination of the best disposal method, especially from an environmental viewpoint, became an inevitable issue. Some disposal methods were available and legal for a long time, but they have been gradually banned or restricted due to the adverse consequences resulted from them, like dumping into the sea, land application and landfilling [1].

A (wet) sludge production of 230 million tones was estimated in the European Union in 1993. In Germany, 25% of the production was used in agriculture, 65% was landfilled, and 10% was incinerated. The corresponding figures in Switzerland were 50, 30 and 20, respectively, whereas the figures in France were 55, 25 and 20, thus demonstrating large variations from country to country. However, in the future the use of landfills will have the lowest priority in the waste hierarchy and will only be chosen when no other ways to dispose of the sludge exist. The directions today are towards agricultural use and incineration [6].

2.2.1 Landfilling of Sewage Sludge

Historically, the problem of human waste disposal began when communities first formed. At that time, population densities were low enough that the surrounding land or waterways could handle human wastes. Wastes that were applied to land increased soil fertility. As populations grew, the nearby land could not handle all the wastes, so they were dumped into streams and rivers that carried the problem "away". Landfilling is considered as the most ancient method for disposal of waste in general, and sewage sludge in particular. The landfilling disposal method had no serious burdens on the environment when the city population was low and lifestyle was simple, but nowadays the disposal of sewage sludge in the sanitary landfills takes the bulk of sludges in developed countries, and constitutes a big challenge to be overcome. Till 2000 About 40% of the sludge produced in the European Union is disposed of through land filling [2]. In Swiss context, disposal of sewage sludge in landfills has been banned since 2000 [7]. The Landfill Directive (99/31/EC) which is an interpretation of EU policy in the field of solid waste and sludge disposal implies that it is obligatory to Member States of EU to reduce the amount of biodegradable waste that they send to landfills to 35% of 1995 levels by 2016. This implies that land filling is not considered a sustainable approach to sludge management in the long-term [8]. There are two alternatives for sludge disposal in landfill sites: mono-deposit which uses sludge only, and mixed- deposit which mixes sludge with municipal solid wastes [6].

2.2.2 Agricultural use and land application of Sewage sludge

The purpose of using sludge in agriculture is partly to utilize nutrients such as phosphorus and nitrogen and partly to utilize organic substances for soil improvement. In principle, all types of sludge can be spread on farmland if they fulfill the quality requirements (heavy metals, pathogens, pretreatment) laid down by the legislation of the relevant country [6]. Care should always be taken when applying sewage sludge to land to prevent any form of adverse environmental impact. The sludge must not contain non-degradable materials, such as plastics, which would make land disposal unsightly [9]. Odor control is the most important environmental dimension of sludge application to land. Untreated sludge should be injected under the soil surface using special vehicles or tankers fitted with injection equipment [9].

By comparing several treated sewage sludge samples from different WWTPs, the most appropriate digested sludge for agricultural use was the lime stabilized sample from pathogen destruction point of view. The above conclusion was obtained by Gulcin Ozsoy [10]. Gulcin Ozsoy, presented the agricultural potential use of sewage sludge based on various samples from four different wastewater treatment plants in Turkey. The researcher conducted heavy metal analysis with the aid of a microwave assisted digestion procedure and pathogen level according to reliable standards due to their adverse health effects. This study does not include any thermal treatment method, but it focused on the agricultural use of sewage sludge and how to avoid adverse effects of any disease causing organisms and heavy metals. The results showed that the ranges of heavy metals and pathogens in most of the samples are below the permissible limits given by Soil Pollution Control Regulation (SPCR) of Turkey, except for some samples which contained a type of pathogens (Salmonella and Giardia) exceeding the given limits.

There are four chief options for land utilization of municipal sludge, namely; applying sludge directly to croplands, to forests, to disturbed lands as a means of land reclamation, and providing composted sludge for landscaping and gardening. The benefits of sludge are similar in all these uses. Sludge can provide all nitrogen (N) and/or phosphorus (P) for plant growth; potassium (K) supplements may be needed [11]. In the UK context, approximately 3-4 million tones of sewage sludge is applied to land each year. Sewage sludge has been used as a fertilizer on farmland for many years and is not waste when tested, supplied and used in accordance with the Sludge (Use in Agriculture) Regulations [12]. The land application and agricultural usage of sewage sludge witnessed a great withdrawal as a reliable sludge disposal method due to its negative environmental burdens. In this regard, the spreading of sewage sludge on agricultural fields has been completely prohibited in Switzerland by the October 2006 [13].

2.2.3. Incineration of Sewage Sludge

There are several thermal processing technologies aiming to dispose sewage sludge by controlling different parameters that affect the final products of the process; mainly temperature, pressure and insulation condition (i.e. the absence of oxygen). The more familiar thermal technologies for sludge disposal are mono or co-incineration, pyrolysis, wet oxidization and gasification [14]. Nowadays, the incineration of sewage sludge is considered the best promising method used for disposal of waste sludges, either alone or in combination with other wastes. Treatment by incineration represents 15% of the total mass of sludges treated in Europe. The agricultural use of sludges, by direct application, as well as landfilling of sludges is subject to more and more regulatory control (agricultural usage and landfilling of sewage sludge have been prohibited in Switzerland by 2000 and 2006 respectively) [13]. For this reason, incineration of sludges is expected to increase, even though it can be a capital intensive investment and it is also subject to strict regulation pertaining to combustion criteria, management of the off-gas treatment residues and treatment of fly and bottom ashes. Incineration of sludges can be performed in designated incinerators or in municipal solid waste incinerators under the particular constraints for each type, where the process results in combustion of the organic matter of the sludges [6].

After pre-drying, sludges can also be incinerated in cement kilns because they have a high calorific value. Pollutants are stabilized in the clinker which is an interesting way of treating polluted sludges. From an economic point of view, these methods of sludge treatment are mainly justified for sludges not allowed to be used in agriculture or incinerated in municipal solid waste incinerators, or when the local authorities give the priority to these disposal methods more than conventional ones [6]. Sludge incineration enjoys a combination of several advantages that are not found in other treatment alternatives, including a large reduction of sludge volume to a small stabilized ash, which accounts for only 10% of the volume of mechanically dewatered sludge, and thermal destruction of toxic organic constituents. Further, the calorific value of dry sludge corresponds to that of brown coal, and therefore through the incineration method, the recovery of this energy is an available option [2]. Thermal treatment for disposal of sludge in spite of that it is less used method, it is a promising disposal way for sludge, especially if we considered that it affords a significant amount of sustainable energy recovery. On the other hand, the new regulations and legislations tends to limit, restrict or ban the most common disposal methods like dumping into the sea, landfilling and land application due to complex environmental burdens of each method. Figure 1.2 shows the above mentioned facts regarding European Union states up to 2005.

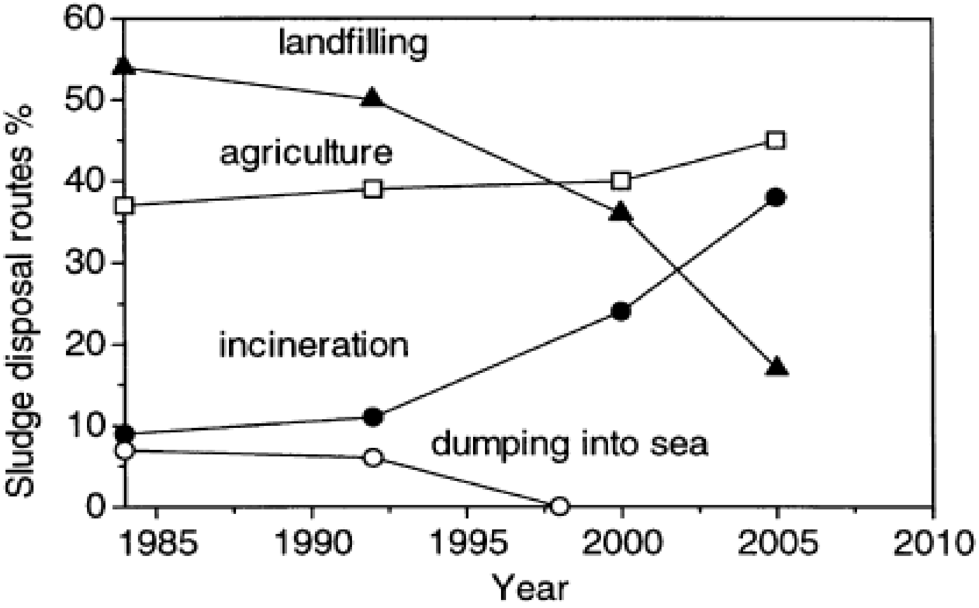


Figure 2.1. Sludge disposal routes in the European Community up to 2005 [2]

Incineration is a promising method for the disposal of municipal sewage sludge as mentioned previously, and it is more preferable if the heat of the flue gases of incineration plant were recovered in its heat form or converted to another form of energy or power (i.e. electricity power). In a sludge incineration process, the water in the sludge is completely evaporated and the organic matter in the sludge is effectively oxidized at high temperatures to CO2 and H2O, as shown in the reaction formula below [15]:

Oxidation and combustion: sludge solids/organics + $O_2 \longrightarrow CO_2 + H_2O$ + ash + heat

Since the water evaporation reaction is highly endothermic, in order to sustain the combustion for sludge with a low total solid (TS) content, dewatering of the original sludge must be conducted or additional fuels (bark, wood waste and oil, etc.) shall be added [15].

Mika Horttanainen et al [16] conducted a performance analysis for power and heat generation from sewage sludge, focusing on both technical and economical viewpoints. They compared two co-generation plants by burning sludge-only and sludge+ biofuel respectively (WtCHP) with a control plant which generates heat only. The researcher concluded that the usage of waste to heat (WtH) is more profitable due to lower cost of heat production if it compared with electricity. The plants which have been analyzed in this study are equipped with steam power plant which is more complicated and expensive than gas power plants. The economic respective is not the only criterion which could by rely on in such critical decisions.

Pavel Stasta et al [17] studied several options for sewage sludge treatment from both economical and thermal balance perspectives, concentrating on the usage of sludge as a secondary fuel and raw material substitution in a cement factory. In spite of the scarceness of information about other thermal treatments in this study, the results show that incineration of sewage sludge in cement kiln with utilization of flue gases for sludge drying is the best option from both mentioned points of view.

J. Werther, T. Ogada [2] described in detail various issues related to sewage sludge combustion and four common disposal methods, i.e. land application, landfilling, dumping into the sea and incineration were investigated, focusing on the increasing role of sludge incineration and also used technologies and methods for sludge combustion were presented in different classification ways. The issues of drying, emissions and heavy metal transactions were analyzed. This study states that combustion of sewage sludge will play an important role in sewage sludge disposal, especially because of its matching with the strictest emission limits and the fact that the resulted ash can be smelted and reused in different construction fields.

Sebastian Werle et al [18] showed the Polish perspective regarding utilization of sewage sludge and predicted the predominant method for the disposal of sewage sludge within next coming couple decades. Accordingly, thermal utilization, e.g. combination between mono-combustion and gasification or pyrolysis and gasification would be the best solution for sludge disposal from both economic and environmental points of view, especially when heat and energy recovery are taken in consideration.

A. Zabaniotou, C. Theofilou [19] studied the utilization of sewage sludge as an alternative fuel in cement kilns, examining both positive and negative effects related to energy balance, health, safety and environment aspects. Wet sludge of moisture content 65-70% was used and the consequences of this usage were analyzed to determine the rate of emissions and heavy metal concentrations, focusing on mercury (Hg) existence. Since high temperature is used in cement factories, combusted sludge does not emit dioxin harmful to human health. Researchers conclude that usage of sewage sludge in cement kilns is the best way to solve the problem of large quantities of sludge production besides, reducing fuel usage in cement factories, consequently lowering cement production costs.

2.3 LIFE CYCLE ASSESSMENT OF SEWAGE SLUDGE DISPOSAL

LCA is an effective tool to evaluate the environmental burdens associated with a product, process, or activity by identifying, quantifying and assessing the impact of the utilized energy, materials and the wastes released to the environment [20]. LCA can be used anywhere in different fields of sciences to play a detective role in showing existing and future environmental consequences of different products and services. LCA has been used in a large number of studies and researches dealing with sewage sludge, from different aspects i.e. its disposal methods and energy recovery.

Houillon G. & Jolliet O. [21] had performed an LCA on six different options for sludge treatment to find out in comparison manner the energies and emissions participation in global warming phenomenon for each option. Researchers in this study didn't take into consideration any other environmental potential categories. The scenarios of sludge treatment which were taken by the researchers were; agricultural spreading, fluidized bed incineration, wet oxidization, pyrolysis, incineration in cement kiln and land-fill. The results of the study showed that incineration is the best scenario from the energy balance point of view, while incineration in cement kiln is the best from an environmental perspective (only for global warming impact category). Mixed sludge was used in this study and too shallow data were reported regarding replacing mixed by digested sludge in this paper.

Suh & Rousseaux [22] conducted an LCA on five treatment options including incineration, agricultural spreading, compositing, anaerobic digestion and landfill. Incinerator type used in this study was not identified while a mixed sludge was used in France context. By using reference contribution of a single person in Western Europe over one year, the indicator results of environmental impacts for scenarios were normalized. Normalized results of the study have been weighed in order to show a unified result which can be used by decision makers to use the best option for each specified case. Most of impact categories were taken into consideration to show the effect of each scenario from different environmental aspects. The researchers focused mostly on old treatments like landfill, agricultural spreading and compositing while most scientists and researchers tend to prefer novel treatment options represented in thermal handling of sludge due to the significant amount of energy recovery and sludge volume decreasing (90%) in case of using a strict flue gas treatment facility.

Hospido et al [23] presented an LCA of different sewage sludge treatment processes represented in anaerobic digestion versus pyrolysis and incineration. For the first scenario, a supplementary fuel was used beside a different type of waste to obtain a complete combustion of the sludge. Mixed sludge was used in this study and drying systems were powered by an external source (not by the heat of flue gas). Several impact category indicators were used and normalization of these indicators has been carried out to compare the chosen scenarios from different environmental perspectives. System boundaries of the studied cases were too narrow by neglecting the effect of machineries and equipment which declares implicitly that life cycle stages effect of those machineries and equipment were not considered.

Ngelah akwo [4] made a life cycle study to evaluate the environmental performance of four selective sludge treatment options; incineration in cement kiln, land application of pasty sludge, compositing and fluidized bed incineration. Many impact category indicators and normalization of these indicators were used in this study. Digested sludge was used to be incinerated in both cement kiln and fluid bed incinerators. Infrastructure, machineries and equipment (mechanical and electrical) and their life cycle stages (except operation) were considered to be out of system boundary of selected options.

Olivier Jolliet et al [24] studied different sludge management options with the aid of the LCA tool. The study comprised six alternative scenarios followed by three end-of-life treatments; dewatering, compositing, drying, incineration, melting of incinerated ash and dewatered sludge melting, in addition, the used sludge being digested or not digested was taken in consideration for each option.

Four potential impact categories were included to show the environmental burden of each treatment. Later, the obtained indicators were normalized to enable easier comparison between the environmental effects of these treatments. Incineration of sludge in cement kiln was not involved in this study and the results showed that the incineration of sludge lies in the middle intersection point of both environmental and economical position.

2.4 SEWAGE SLUDGE DISPOSAL IN THE TURKEY CONTEXT

On the road of Turkey's accession to the European Union, great structural improvements were made to Turkey's administration of environmental legislation for pollution prevention, covering many environmental fields, such as water and wastewater treatment, air pollution control, and waste management. By the 2004, Turkey, with a population about 70.5 million people, has 16 greater metropolitan cities, 3200 municipalities [25]. The main common disposal methods for sewage sludge in Turkey were; land application (agricultural usage as fertilizer) and landfilling but, such disposal routes were limited by new legislations and new sludge treatment options become an inevitable issue. Accordingly, thermal treatment methods for sludge disposal are relatively a new issue, so few researches and studies can be found in the open literature.

Murat dogru et al [18] conducted an experimental study on gasifying of sewage sludge by using a 5 kWe-throated downdraft gasifier. The researcher suggested a set of operating conditions to achieve good quality gas and to avoid clinker formation at the throat of the gasifier because of high ash content of sludge and thermal efficiency was calculated to be about 40% at above mentioned circumstances. This study declares that the obtained gas from this process has a calorific value about 4 MJ/m3 which can be used as an alternative fuel in internal combustion engines, and recommended for decision makers and investors in several countries, including Turkey to adopt gasification method to fractionally replace fossil fuel and solve partially sewage sludge accumulation problem.

Nezih Kamil Salihoglu et al [26] studied in a pilot scale the effects of solar drying of sewage sludge in Bursa city in Turkey. The researcher made prototype of an opened and covered solar drying facilities and measured different parameters and conditions.

The study focused on partial liming of dewatered sludge followed by solar drying instead of the process of liming of dewatered sludge prior to its landfilling which is the most common widely used treatment for disposal of sewage sludge in Turkey. The study resulted that covered solar drying is the most beneficial process which led to a more efficient reduction of faecal caliform, pathogen reduction and total sludge volume reduction of 40% with a 35% dry solid content in 10 days during the summer and 20 days during the winter. This dryness percentage cops with the limits imposed by authorities' legislations to sludge to be landfilled. This study recommended to apply covered solar drying systems in cities receiving high solar radiation and the design of such systems can be improved by applying new technologies.

M. Ozcan et al. [27] conducted a research about the electrical energy potential from the treatment of both municipal solid waste and urban wastewater sludge in Turkey. In this attempt, the electrical energy potential of these resources has been obtained by assuming the usage of the recent available waste to energy technologies. The electrical energy potential of Biogas (Landfill gas included) based on these resources is an amount of 6.73 billion kWh/year. Municipal solid waste (MSW) and dried municipal wastewater treatment sludge electrical energy potential is an amount of 23.81 billion kWh/year. These results are based on 100% dry matter for both of waste and sludge, while the energy needed to be consumed to obtain this dryness ratio has not been considered.

2.7 CONCLUSIONS

Thermal treatment of sewage sludge gained a good area of attention, especially when it is combined with energy recovery processes. As a candidate to join European Union, Turkey had stepped several vital steps towards complying with EU standards and legislations related to wastewater and wastewater sludge treatment. One of the most sensitive issues that needs a great carefulness is treatment and disposal of sewage sludge due to its double sided feature; while it's considered as an environment pollutant, it is from the other side, a source of sustainable energy. New studies and researches showed that a thermal treatment accompanied with energy recovery is the best solution for both sides of this issue (a significant amount of energy can be recovered within the disposal of sewage sludge).

In Turkish context, few studies can be reached regarding treatment and disposal of sewage sludge in general and incineration of sewage sludge in particular. Moreover, the use of LCA in this regard can be said it is virtually not exist, while the need of such studies for this transitional stage in the life of the republic of Turkey is vital and indispensable.

The extended overview provided in this chapter indicates that there are a few number studies on a comparative LCA of different sewage sludge elimination methods to provide heat and power in the open literature. This study aims to analyze and assess the most environmental burdens related to the incineration of sewage sludge in two different facilities to give a guidance key for the future policy regarding the disposal of sewage sludge. The first option is to study the incineration of sewage sludge in an incineration plant, and the second option is to use sewage sludge in a cement factory as a secondary fuel. This thesis differs from the previously conducted studies as follows:

a) The thesis is original in scope and content and there is no such study in the open literature, to the best of the author’s knowledge and it is the main motivation behind this study.

b) In literature, a small number of studies consider all impact categories regarding to LCA and the assessments in these studies are mostly limited to the very familiar impact categories such as global warming, human health, etc.

c) The thesis provides a wide range of evaluation of environmental burden including all impact categories served by a very effective LCA software, SimaPro Impact 2002+ based on its original and updated database.

CHAPTER 3

SLUDGE THERMAL DISPOSAL TECHNOLOGIES

3.1 INTRODUCTION

This chapter presents the definitions and main concepts related to the sewage sludge disposal, mostly focusing on the incineration, main common types of sludge incinerators and description of the facilities of the case study, which uses sewage sludge as a source of power and/or heat productions in the first system and raw material in the second one.

3.2 SEWAGE SLUDGE

The constitutes removed in wastewater treatment units contains screenings, grit, scum, and sludge. The sewage sludge resulting from wastewater treatment processes is typically in a liquid or semisolid liquid forms, that generally includes from 0.25 to 12 percent dry matter by weight, depending on the used processes [1]. As a consequence, this sludge often contains a large percentage of liquid as shown in Figure 3.1.

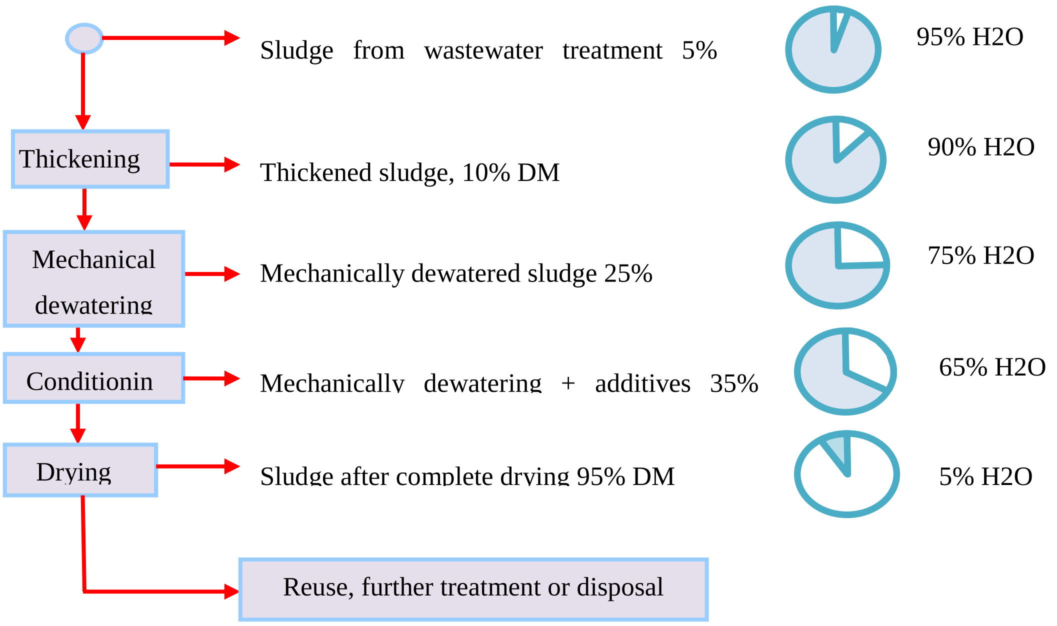


Figure 3.1 Moisture and dry matter percentages for most common treatment [2].

Initially, the wet sludge contains a percentage of moisture about 92-96 % and the rest are solid matter, which in turn normally contains approximately 60-70 % volatile matter. Implicitly, the sludge contains uncertain rates of hazardous materials like pathogens, heavy metals and different organic materials.

Sludge is formed within the wastewater treatment processes. Two main types of wastewater are exist; municipal (domestic) and industrial wastewaters. Municipal wastewater is the combination of water carried wastes from residential, commercial and institutional establishments mixed with groundwater, surface water and precipitation water [2].

Wastewater facilities collect and treat wastewater in order to return the huge amount of water to its natural cycle without causing any undesired effects to both human being and the surrounding environment. Usually, untreated wastewater is not valid to be returned to its natural cycle for several reasons; first, the biological decomposition of the organic materials in wastewater consumes oxygen and thus reduces the quantity available in the receiving waters for the aquatic life and this decomposition leads to production of undesired malodorous gases. Secondly, the great health hazards potential related with the numerous amount of pathogens or disease- causing micro-organisms included in the untreated wastewater. Third, the presence of various types and quantities of toxic compounds represented mainly in heavy metals is a dangerous health issue for both plants and animals. Finally, the existence of both phosphate and nitrogen in the untreated wastewater may cause an uncontrolled growth of aquatic plant, reducing the quality of aquatic areas.

The composition of sewage sludge varies depending on the source of this sludge. Municipal sludges anywhere have approximately the same composition with respect to other types of sludges such as industrial sludges. The reuse and disposal treatment of wastewater (sewage) sludge had been considered as a secondary subject compared to the main wastewater treatment processes, but since a few years ago, it became a significant challenge which faced municipal waste treatment management all over the world, due to the strong growth of sludge output and the reinforcement of the regulations [5, 22, 54]. The unavoidable continuous dramatic increment of sewage sludge is a fact beyond dispute and requires more and more studies and researches to determine the most appropriate disposal treatment options from different environmental, economic and thermodynamic perspectives. The old techniques of sludge disposal, focused on some common uses of sludge as a fertilizer in land reclamation, damping in the sea and landfill. Nowadays, most of these treatments have been banned or restricted by new legislations aiming to protect the whole global environment. On the other hand, sludge can be converted to a sustainable resource of energy (renewable energy) with the aid of some new thermal technologies and treatments, these advantages created a tendency to adopt these technologies by researchers and decision makers.

3.3 INCINERATION OF SEWAGE SLUDGE

It is expected that the role of the incineration as a disposal method will increase in the future. This expectation resulted from the limitations facing landfilling and recycling, and the ban of sea disposal of sludge. The combination of several advantages in the incineration process, granted this method a priority against other disposal route, namely; large volume reduction to a small amount of a stabilized ash (about 10% of the mechanically dewatered sludge), thermal destruction of pathogens and degradable organic materials. Furthermore, the heating value of the dry sludge is almost identical to that of the brown coal, and thus through the incineration process this energy content could be recovered [2]. For large cities where a huge amount of sewage sludge are generated, the need to minimize the aggressive odor generation from landfills, the scarcity of readily available landfills and the aesthetic objections of the nearby inhabitants, makes incineration an attractive sludge disposal route.

A great improvement has been applied to the incineration technology. Nowadays, various techniques are available to control gaseous emissions and incineration costs tends to be much more competitive with other disposal methods, to the extent that incineration is seen by a large group of scientists and researchers as the only solution to the increasing problems of other sludge disposal options [2].

3.4 SEWAGE SLUDGE INCINERATION TECHNOLOGIES

In the field of sewage sludge incineration, many novel technologies and systems are applied with different designs and features. The main common types of sewage sludge incinerators available in the markets can be summarized as follows:

a. Fluidized Bed Combustor (FBC)
b. Multiple Hearth Furnace (MHF)
c. Grate Incinerator
d. Electric Incinerator
e. Rotary Kiln

Historically, Fluidized bed and Multiple Hearth incinerators were more frequently used technologies for incineration of sewage sludge in the United States and Europe last century. FBC got more preference rather than other technologies due to its simplicities and less maintenance required, besides its more acceptable performance from both economic and environmental viewpoints. Next item describes some of these technologies in more details. Figure 3.2 shows a general flow diagram of an incineration process.

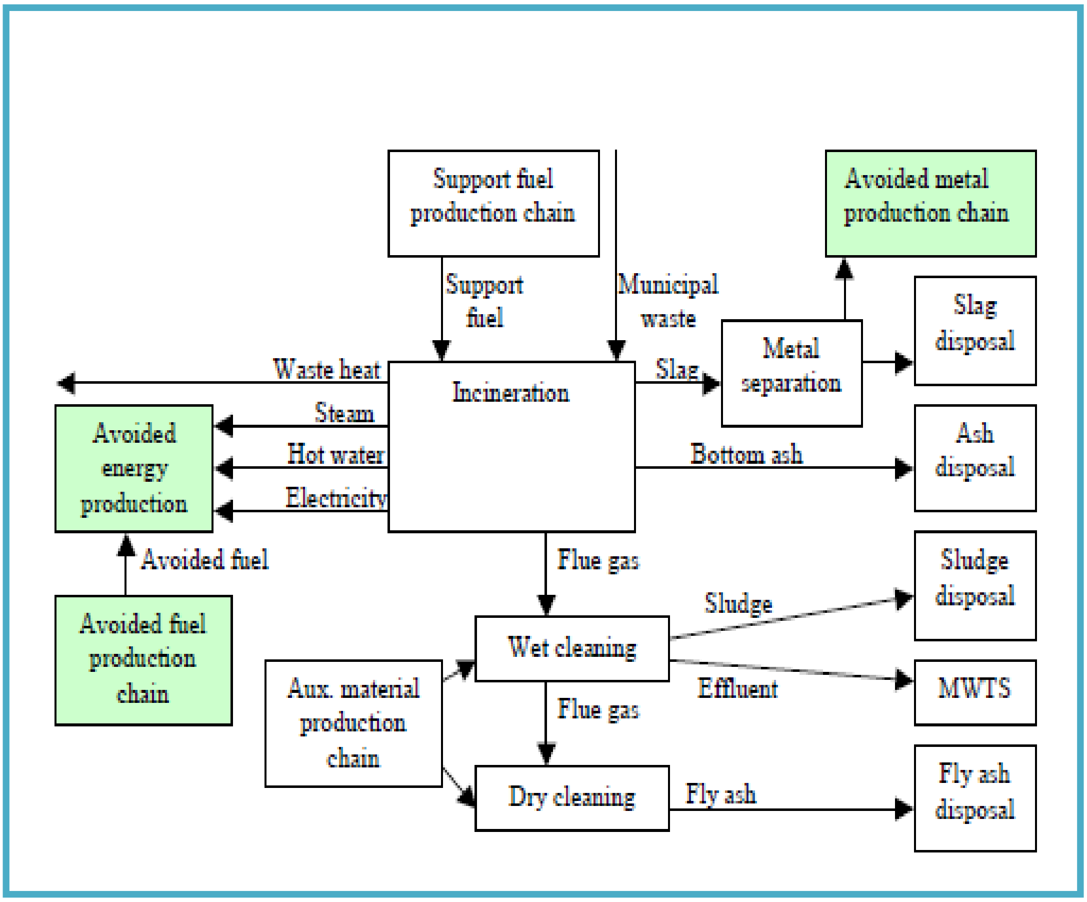


Figure 3.2 The general flowchart of Municipal Waste Incineration System [28]

3.4.1 Fluidized Bed Combustor

Historically, Fluidized bed technology was first developed by the petroleum industry to be used for catalyst regeneration, later it has been used for combustion of various types of wastes, including sewage sludge. Fluidized bed combustors (FBCs) constitutes a vertically oriented outer shell constructed of steel and lined with refractory. Tuyeres (nozzles designed to deliver blasts of air) are located at the base of the furnace vessel within a refractory-lined grid. A bed of fine particles (typically sand), approximately 0.75 meters (2.5 feet) thick, rests upon the base grid.

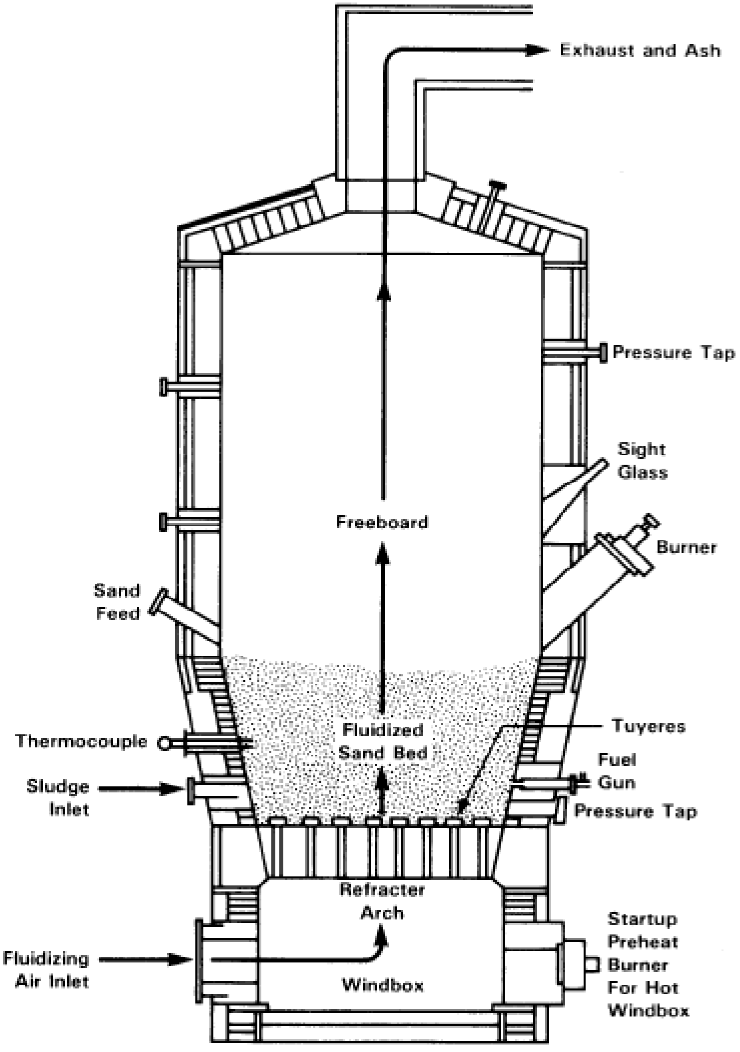


Figure 3.3 Cross Section of a Fluidized Bed Furnace [29]

Generally, there are two distinguished configurations of FBC, on the basis of how the fluidizing air is injected into the furnace chamber. Hot windbox design is the first configuration type in which the fluidizing air is first preheated by a heat exchanger where heat is recovered from the hot flue gases of the furnace. Alternatively, in the cold windbox configuration design (second configuration), directly the ambient air is injected into the furnace. The sludge is fed into the lower part of the furnace. Air injected through the tuyeres, at pressures of from 20 to 35 kilopascals (3 to 5 pounds per square inch gauge), simultaneously fluidizes the bed of hot particles and the fed sludge. Temperatures of 750 to 925 ºC are maintained in the fluidized bed. Residence times are typically 2 to 5 seconds. As the sludge burns, lighter ash particles are carried out the top of the furnace chamber. In addition to the fine ash, a little amount of sand is removed in the air stream; sand substitution requirements are about 5 percent of the bed for every 300 hours of operation [29].

Simultaneously, as the temperature of the sludge is rapidly raised, the evaporation of water and the pyrolysis of the organic materials included in the sludge combustion occur in the bed zone, and a final combustion of the left free carbon and combustible gases occurs in the second zone (freeboard area). The freeboard zone acts basically like an afterburner. Fluidization grants an ideal mixing between the sludge and the combustion air and the turbulence caused by the air jet enables the transfer of heat from the hot sand to the sludge. The most significant characteristic of the fluidized bed incinerator is represented in the minimal excess air required to maintain better burning conditions for obtaining a complete combustion of the fed sludge.

Generally, the complete combustion in FBCs can be achieved with 20 to 50 percent excess air, which accounts for 50 percent of the excess air required by multiple hearth furnaces. Consequently, FBC incinerators consume typically less fuel compared to MHF incinerators. When the evenly distributed combusted air or gas is passed upward through a homogeneous divided bed of solid particles such as sand supported on a fine mesh, the particles are undisturbed at low velocity. As air velocity is gradually increased, the individual particles suspend in the air stream – then the bed is called “fluidized”. With further increasing of air velocity, the bubble formation, vigorous turbulence, rapid mixing and the formation of dense defined bed surface are experienced. The bed of sand exhibits the properties of a boiling liquid and assumes the appearance of a fluid – “bubbling fluidized bed”.

At considerably higher velocities, the bubbles vanish, and particles are driven out of the bed. Therefore, the replacement of removed particles is done by a recirculation device to maintain a stable system – “Circulating Fluidized Bed”. The main differences between FBC and CFBC are illustrated in Figure 3.4.

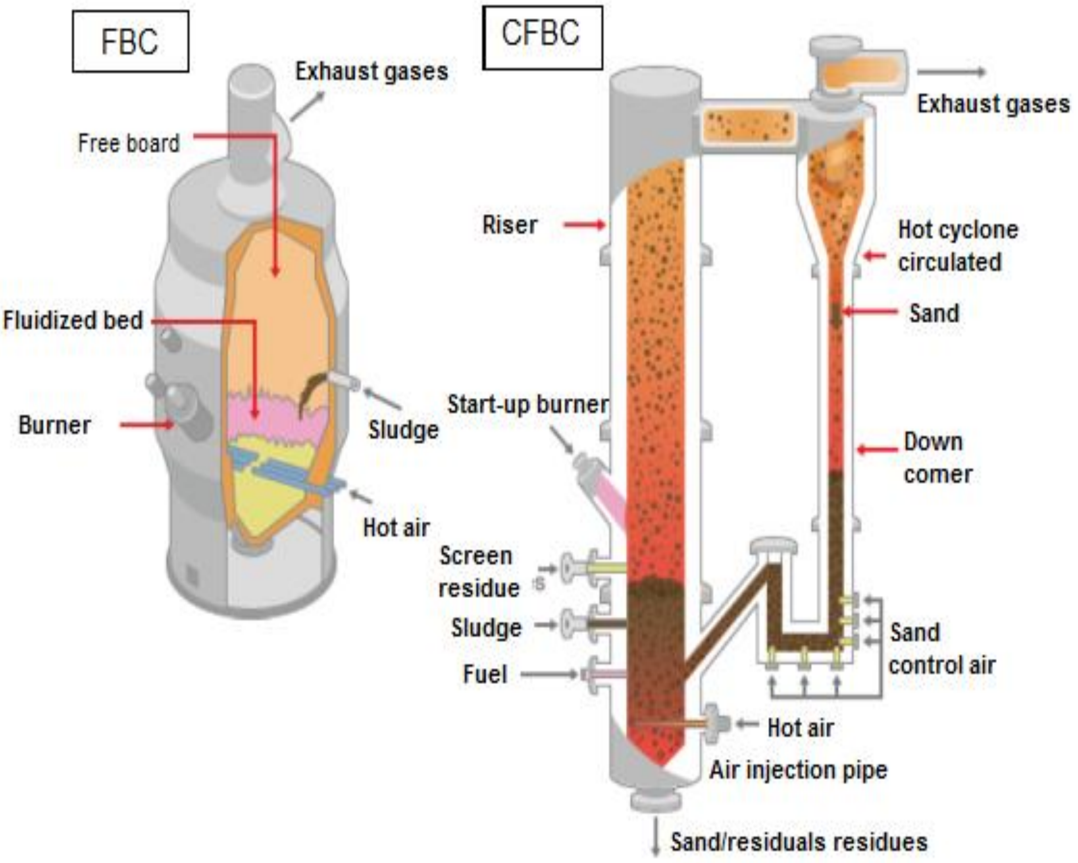


Figure 3.4 Shows the general feature of both FBC and CFBC [30]

3.4.2 Multiple Hearth Furnace

Approximately a century ago, the multiple hearth furnace was specifically developed for roasting of mineral ores. Since the 1930s, the air-cooled configuration type of this furnace has been used in the incineration of sewage sludge. Figure 3.5 represents a cross sectional view of a typical multiple hearth furnace. The common multiple hearth furnace (MHF) is a vertically oriented cylinder.

The external shell is constructed of steel, lined with refractory, and surrounds a series of horizontal refractory hearths. A rotating hollow cast iron shaft passes through the center of the hearths. Cooling air is rushed through the shaft which protrudes above the top cover. At each hearth zone a number of rabble arms are fixed to hollow shaft, and in turn, each arm constitutes a number of teeth, about 6 inches in length, and pitched by about 10 inches apart. The teeth are shaped to rake the fed sludge in a spiral motion, alternating in direction of sludge dropping from the outside in, to the inside out, between hearths.

In general, the upper and lower hearths are equipped with four rabble arms, and the middle ones are equipped with two. Auxiliary heat burners are mounted on the side walls of the furnace. In most common multiple hearth furnaces, the sludge is fed from the side wall onto the perimeter of the top hearth. The rabble arms move the sludge through the incinerator by raking the sludge toward the center shaft where it drops through holes located at the center of the hearth. In the next hearth the sludge is raked in the opposite direction. This operation is repeated in all of the remained hearths. The importance of the rabble motion is to shred the solid material to gain better surface contact with heat and oxygen inside the hearths. At the designed sludge flow rate of the furnace, a sludge thickness of about 1 inch is maintained in each single hearth [29].

Scum may also be supplied to one or more hearths of the furnace. Scum can be defined as the material that floats on wastewater surface. It typically contains vegetable and mineral oils, grease, waxes, fats, and other materials. Scum may be collected from various treatment chambers, including preparation, skimming, and sedimentation tanks. Scum volume is generally smaller than those of other wastewater solids. Ambient air is injected through the central hollow shaft and its corresponding rabble arms, a portion, or all, of this air is later taken back from the top of the shaft and re-pumped into the lowermost hearth as preheated combustion air. The excessive cooling air which is not fed back into the hearths is passed into the stack downstream of the air pollution control unit. The combustion air blows through the drop holes in the rabbile arms, countercurrent to the flow of the sewage sludge, before being rejected from the top of the furnace.

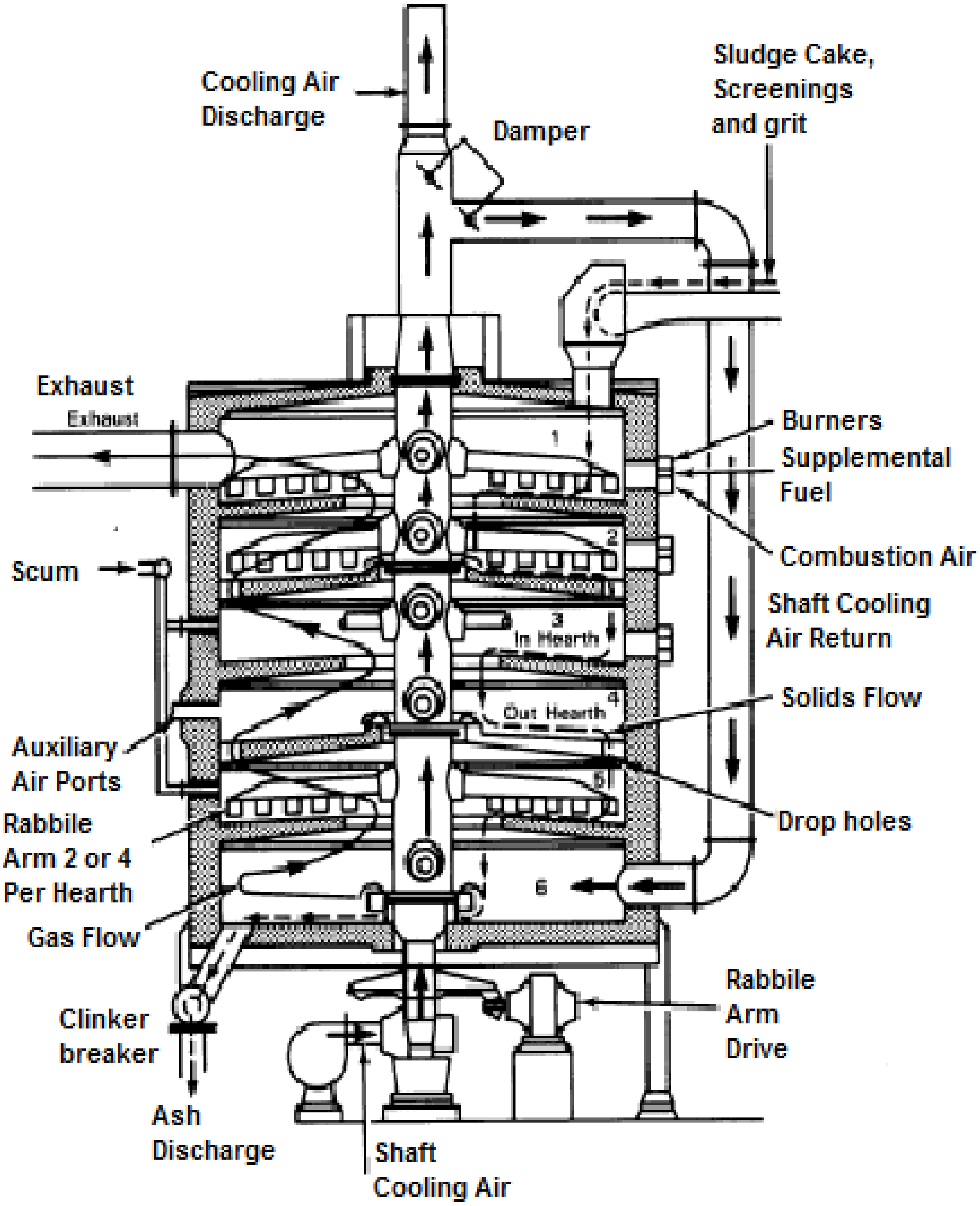


Figure 3.5 Cross Section of a Multiple Hearth Furnace [29]

From the standpoint of the overall combustion process, multiple hearth furnaces are typically divided into three zones. The upper hearths include the drying zone where most of the water content in the sludge is removed by evaporation. In drying zone, the temperature is typically varies between 425 and 760 ºC. Almost, all sludge combustion occurs in the middle hearths (second zone) as the temperature rises to about 925 ºC (1700 ºF).

Additionally, the combustion zone (second zone) may be further subdivided into the upper-middle hearths where the combustible gases and organic solids are burned, and the lower-middle hearths where the largest amount of the fixed carbon is incinerated. The third zone, which stands for the lowermost hearth(s), is the cooling zone. In this zone the ash is cooled by transferring its heat to the combustion air. In order to ensure continuous complete combustion of the sludge, and under normal operating condition, 50%- 100% excess air should be supplied to an MHF. In addition of the improving contact between the fuel and oxygen, the supplied excess air maintains a smooth continuous operation of the MHF in spite of the variation of sludge characteristics and feed rate. When insufficient excess air is injected to the furnace, a partial combustion of the carbon will be obtained, leading to increase emissions of carbon monoxide, soot, and hydrocarbons. In contrary, too much excess air, can cause increased emissions of particulate and unacceptable high supplementary fuel consumption [29].

3.4.3 Rotary Kiln

Rotary kiln is a type of furnace that consists of a metallic cylinder with conical sides on both ends. Mild steel plate is used for construction of this shell and its thickness varies depending upon the capacity of the equipment. This shell rotates on its own axis at 1-2 RPM. For this purposes tires (also called riding rings) are fitted on the shell. These are fabricated from mild steel (MS) squares or flats, machined for a smooth finish. These tires ride on steel rollers which are again machined finely. These rollers are fitted on a robust MS structural frame and driven by a gear & motor arrangement. The shell is lined inside with insulation and fire bricks of suitable Alumina content. Conical ends of the furnace are open on both sides.

The furnace is charged with Raw or Waste materials along with additives from the front end. This side is provided with a movable door on which a burner is mounted.

The burner can be a conventional one or a fully automatic one depending upon the fuel used. At the other end, an exhaust block lined with refractory bricks is provided. A tapping hole is provided in the center of the shell from where molten metal & slag are discharged. Flue gases generated are sucked from the exhaust block side of the furnace [31].

Usually, Rotary Furnaces are used in cement factories and different types of fuels are used including natural gas, Gasoline, crude oil and etc. Normal operating temperature used in this kind of furnace lies between (800 – 1650 ºC). The usage of sewage sludge in Rotary kiln as an additional fuel for cement manufacturing was adopted by scientists and researchers, aiming to find the best options for these novel technologies from different economic and environmental perspectives. Figure 3.6 Shows a Rotary Kiln.

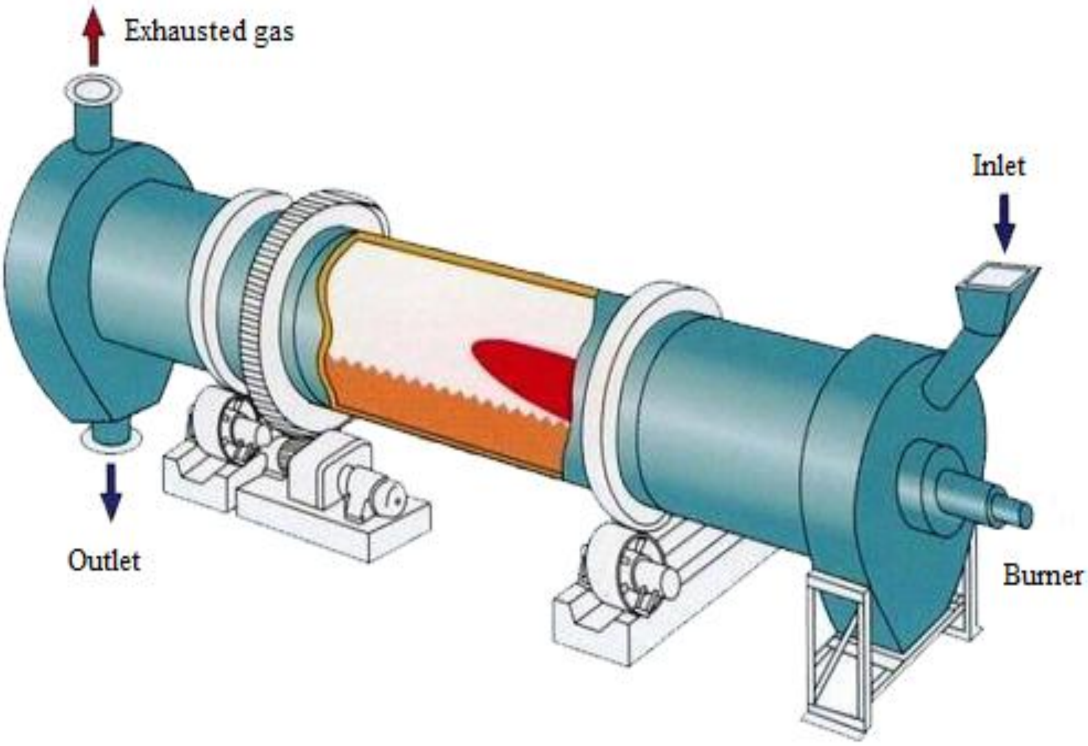


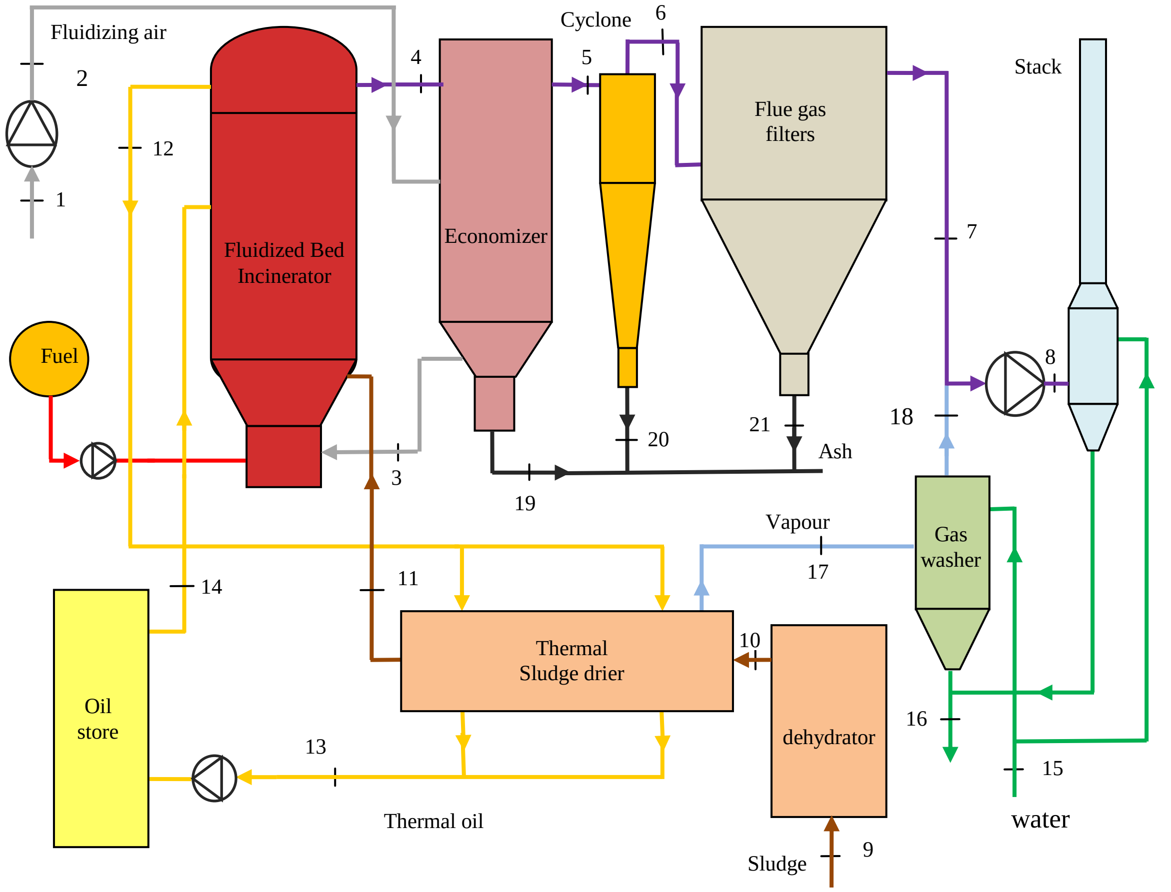
Figure 3.6 General feature of a Rotary Kiln [32].

3.5 STUDIED SYSTEMS

In this thesis, two systems were chosen to be analyzed by the LCA methodology. The first system is an incineration plant of sewage sludge in which sewage sludge is incinerated by using a fluidized bed furnace. This system lies in the wastewater treatment plant's field (the source of the sludge), which means that no transportation for the sewage sludge is needed. The second system is a cement factory which uses sewage sludge as a secondary fuel for the production of Portland cement and it is about 20 km far away from the wastewater treatment plant.

3.5.1 Sewage Sludge Incineration Plant (First System)

The first system in this study (case study) is Gaziantep Sewage Sludge Incineration plant (GSSIP). This plant lies nearby GASKI wastewater treatment plant and it has been recently installed, therefore, some components of the system are still under construction. This system includes an Oil-Air Rotary thermal Sludge Dryer, Fluidized Bed Furnace, Heat Exchanger, Economizer, Cyclone and a flue gas purification system, including the flue gas Stack. It is planned to apply an energy recovery system to generate electricity power from the hot flue gases [55]. The general schematic diagram of the mentioned system is shown in Figure 3.7.



Flow legend	▬	1-3	Fluidizing air
	🟪	4-8	Flue gases
	🟫	9-11	Sludge
	🟨	12-14	Thermal oil
	🟩	15-16	Water
	🟦	17-18	Sludge vapor
	⬛	19-21	Bottom ash

Figure 3.7 General Components of GASKI Sewage Sludge Incineration Plant.

The Fluidized Bed Incinerator in this plant is of vertical type works at temperatures about 850 ºC and the combustion air supplied from the bottom of the furnace with a pressure about 800 kPa is heated by exhaust gases from the furnace. The excess air supplied by the hot windbox to the furnace is normally about 25-50 %. Generally, the fluidized bed is made of sand with a height of 0.75 m, acts as a perfect medium to achieve complete combustion of the fed sludge. The thermal sludge drier is of a rotary type (Thin film drier) which dries the fed sludge from 27% to 40% dry matter, by a combined hot oil and hot air cycles [33].

3.5.2 Incineration of Sewage Sludge in Cement Kiln.

In the second system of the study, a Cement factory investigated which uses sewage sludge as a secondary fuel source. The type of the incinerator used in this system to incinerate the sewage sludge is a rotary type (Rotary Kiln). To get the best results from incineration of sewage sludge, prior to the incineration process, it is essential to dry the digested sewage sludge. The location of the nearest cement factory to the wastewater treatment plant (WWTP) is about 20-25 km away, which means that a transportation process of a 20-25 km distance is mandatory for the sewage sludge in this system. Figure 3.8 shows the flow diagram of hypothetical cement factory uses sewage sludge as a secondary fuel source and raw material. The sewage sludge should be first dried to maximum permissible water content about 10%, and the feed rate of sludge in clinker production is limited to 5% to avoid any unexpected bad effect of existence of sludge ash and moisture on the clinker quality [34].

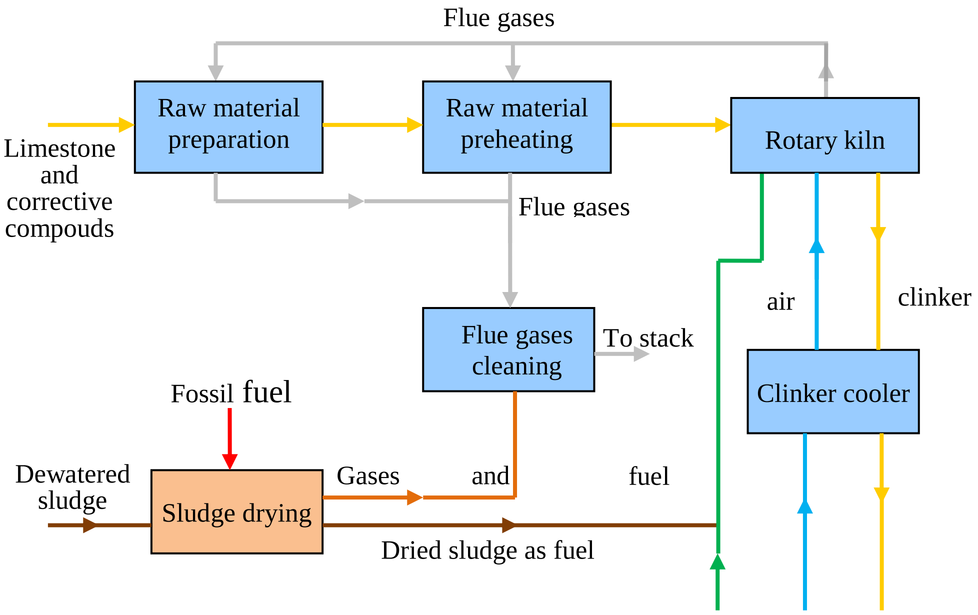


Figure 3.8 Flow diagram of a cement factory uses sludge as a secondary fuel

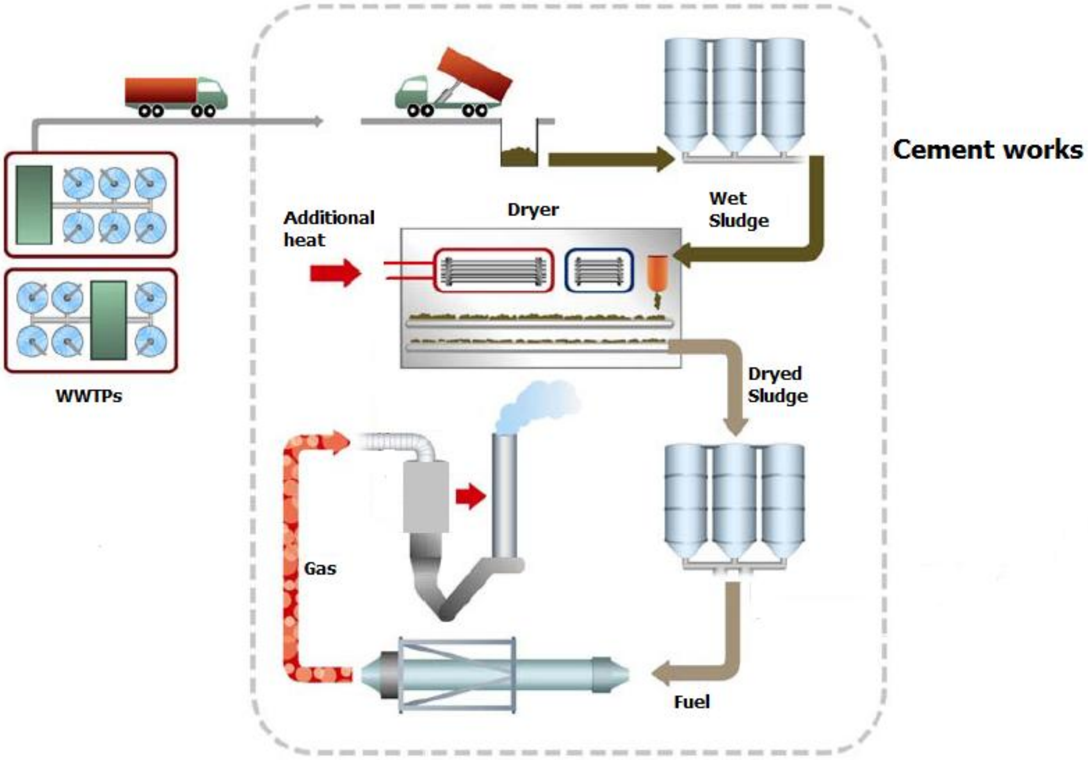


Figure 3.9 Schematic diagram of Sludge usage in a Cement Production plant [35]

3.6 CONCLUSIONS

Nowadays, many sewage sludge incineration technologies are available. Each one has its own characteristics and can be used for some special required purposes. The MHF can deal with wet sludge due to its capability to achieve drying function in the upper hearths of the furnace. The FBC works with semi dried sludge, but its beneficial characteristic is the simplicity of the furnace, which leads to less maintenance work. Rotary Kiln often needs to be supplied with additional fuel source and, it is used typically in cement factories. Many thermal treatment options can be tried to recover as much heat, power and resources as possible from sewage sludge within its disposal processes. The most promising and acceptance acquired among scientists and researchers, is the one-step incineration process method like mono-incineration and incineration in a cement factory as a secondary fuel source and raw material.

CHAPTER 4

LIFE CYCLE ASSESSMENT

4.1 INTRODUCTION

This chapter gives an overview of the methodological framework and concepts of the analytical tool used for the implementation of this study which is referred to as LCA. LCA is a tool used to show the environmental burdens of a product or service throughout its whole life cycle period.

4.2 LIFE CYCLE ASSESSMENT

The continuous increasing awareness about environmental issues regarding global warming, Ozone layer depletion, Acidification and more and more effects of the bad use of products and services led to find and create several methodological frameworks and tools and publication of a series of international standards aim to limit and eliminate the negative burdens of bad use of such products and services. LCA is an analytical tool that is used to achieve sustainable development in different fields of applications by quantifying and comparing products or services from many environmental aspects to reduce or limit its burden on surrounding or even on the whole globe. A life cycle refers to the life span of a product or service, from resource extraction (the early beginning of its lifetime), to manufacture, to use and to final disposal. LCA refers to the analysis and assessment of product life cycles (cradle-to-grave) in an environmental perspective only.

When an LCA study is carried out, one of the most valuable parameters which requires a very intensive effort is the compiling and tabulation of life cycle inventory data. This inventory should contain almost all relevant data that may be defined as inputs and outputs crossing the boundaries of the system at all product's life span like raw materials, energies and emissions [4, 21]. LCA has some important applications like:

- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim of prioritizing improvements on products or processes.
- Comparison between products for internal or external communications.

LCA is a relatively young method that became popular in the early nineties. Initially many people thought that LCA would be a good tool to support environmental claims that could directly be used in marketing. Over the years, it has become clear that this is not the best application for LCA, although it is clearly important to communicate LCA results in a careful and well-balanced way [36]. There are two ISO standards specifically designed for LCA application; ISO 14040 for Principles and Framework and ISO 14044 for Requirements and Guidelines.

The new ISO 14044 standard replaced the 14041, 14042 and 14043, but there have been no major changes in the contents. The ISO standards are defined in a quite vague language, which makes it difficult to see if an LCA has been made according to the standard. The general structure of LCA according to this international reliable standard is:

1. Goal and scope definitions.
2. Compiling a Life Cycle Inventory (LCI).
3. Life Cycle Impact Assessment (LCIA).
4. Interpretation.

4.2.1 Goal and Scope Definition

The goal and scope of an LCA must be clearly defined and be consistent with the intended application. Since LCA is an iterative process, this phase may be revisited and modified during the study whenever it was required. Any study conducted in the framework of LCA should have clear definitions of the purpose of the study and the function it fulfills, the product itself and its life cycle, system boundaries and functional unit. Definition of functional unit is a part of the LCA methodology, and it provides a mathematical reference to which the input and output data are normalized. When the functional unit is defined, the amount of product which fulfills the function unit should be quantified, which is referred to as the reference flow [28].

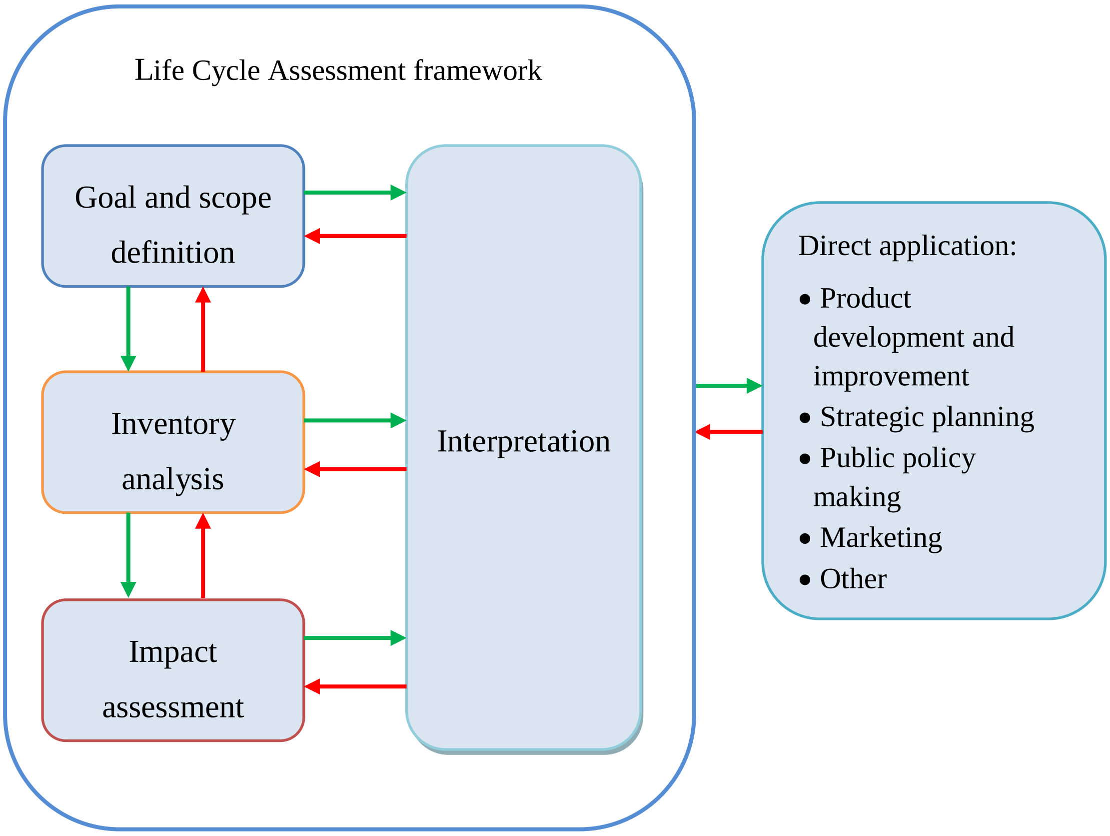


Figure 4.1 The phases of an LCA according to ISO 14040 [37].

The multidisciplinary character represents one of the complexities that faces LCA practitioner. The following three spheres, are the dimensional frame of any LCA, Each sphere has different characteristics [36]:

- **Technosphere**: Includes the modelling of most technical systems and processes, like production, transport and etc. Usually, uncertainties in technosphere modelling are not greater than a factor 2, while almost all values are verifiable and repeatable.
- **Ecosphere**: The modelling of environmental mechanisms, which determines the destination of the emissions and other outputs. Uncertainties are often one to three orders of magnitude, and often verification is difficult or impossible.
- **Valuesphere**: Dealing with subjective choices. This includes weighting of impact categories, which identifies the power of each category, based on political, economical and social preferences.

Product systems when modeled tend to be interrelated in a sophisticated way. For example, in an LCA on a specific product, trucks are commonly used for transportation processes. However, trucks are also products having their own life cycles. To produce a truck steel is needed, to produce steel, fuel is needed, to produce fuel, trucks are needed etc. It is clear that it is not practical to trace all inputs and outputs to a product system, and thus the boundaries around the system should be defined. It is also obvious that by excluding certain components, i.e. leaving them outside the system boundaries, the results can be seriously affected. It is helpful to draw a flowchart of the system and to define the boundaries in this diagram. Important choices in this area are:

- Will the production and disposal of capital goods (trucks, injection molding machines etc.) be included? As in energy analysis, one can distinguish three orders:
    1. First order: only the production of materials and transport are included (this is rarely used in LCA).
    2. Second order: All processes during the life cycle are included, but the capital goods are left out.
    3. Third order: Now the capital goods are included. Usually the capital goods are only modeled in a first order mode, so only the production of the materials needed to produce the capital goods are included.
- What is the boundary with nature? The boundary with the nature should be specified and decided whether the agricultural area to be involved in the system or kept outside the boundaries of the system. The consequences of such decision reflects in including or excluding CO_2 emissions absorbed by plants in the green area and the effects of pesticides applied to the area. In addition, the effect of land use impact should be included. All these relevant issues depends on the decision of LCA practitioner in drawing clear and exact system boundaries.

4.2.2 Life Cycle Inventory (LCI)

The most effort demanding task in performing LCAs is the data collection and tabulation which is referred to as life cycle inventory. Although a lot of data sets are available in different regional databases, it is usually found that at least a few processes or materials are not covered, or the available data is not representative. Depending on the time and budget that are available for the LCA practitioner, there are a number of strategies to collect such inventory [36]. It is useful to distinguish two types of data:

1. **Foreground data**,represents the specific data you need to achieve modelling of your system. Generally it is data that describes a specified product system.

2. **Background data**, which is data for common materials, energy, transport and waste management systems. This kind of data can be found in databases and literature.

There are several comprehensive databases include thousands items for both background and foreground datasets. Ecoinvent is the most largely used database, which is published by the Swiss Centre for life cycle inventories. This database includes the most common industrial processes, system modelling and waste treatment scenarios.

Allocation and Substitution Concepts

Few industrial processes yield a single output or product. According to this fact, the total inventory data (flows and emissions) of the main process need to be allocated over the different functions and outputs. Most database publishers submit their datasets allocated on a common widely known value basis. Several procedures applied to deal with allocation problem:

- Avoiding allocation; whenever possible, allocation should be avoided by dividing the unit to process two or more sub-processes and attach specified inventory to each sub-process or by expanding the system boundary of the process to include the sub-process as an avoided product which is commonly referred to as substitution concept.
- When allocation cannot be avoided, a physical relationship between different products should be found to partition the unit process on the basis e. g. mass basis.
- When a physical basis cannot be found, another acceptable basis for partitioning should be found to fulfill this task e.g. economical key value.

The concept of substitution includes defining the product or function that is replaced (substituted) by the co-product or co-function of the main product in concern, and then quantifying the environmental burdens which would have occurred if this product had been produced. The burdens which would have occurred are then accounted to the main product which is being studied.

4.2.3 Life Cycle Impact Assessment (LCIA)

To determine the environmental impact of a product or a service, a large number of impact assessment methodologies is available. These methods are distributed both spatially and temporally. Some of these methods are updated versions of previously used ones and others are geographically associated with a specified region. Like with the inventory stage, the Goal and Scope phase remains the most important source of guidance for the selection of the method and the impact categories in the life cycle impact assessment phase. The most important choice you make is the desired aggregation level of the results. This usually depends on the way you would like to address your audience, and the ability of your audience to understand detailed results. If an LCA study involves specific waste treatment processes, attempts should be made to collect and apply data that are as specific as possible for the processes in question [51].

Most of LCA software programs come with a large number of standard impact assessment methods like; CML 2001, Eco-indicator 99, ReCiPe endpoint, ReCiPe midpoint, TRACI 2 and IMPACT2002+.

Each impact category assessment method does normally assign a factor to single elementary flows of the submitted inventory. There are different types of factors, namely; characterization factors, normalized factors, weighted factors and damaged factors [38]. Methods typically apply these factors on various flows (input or output) to determine the score of each flow in the frame of the specified impact categories either in its early stage or ahead [38].

According to its structure, LCIA method, generally comprise either midpoint impact category level which its number varies from a method to another or, besides the midpoint, the endpoint level is included with less number of categories. Figure 4.2 shows the sequence and divisions of impact categories.

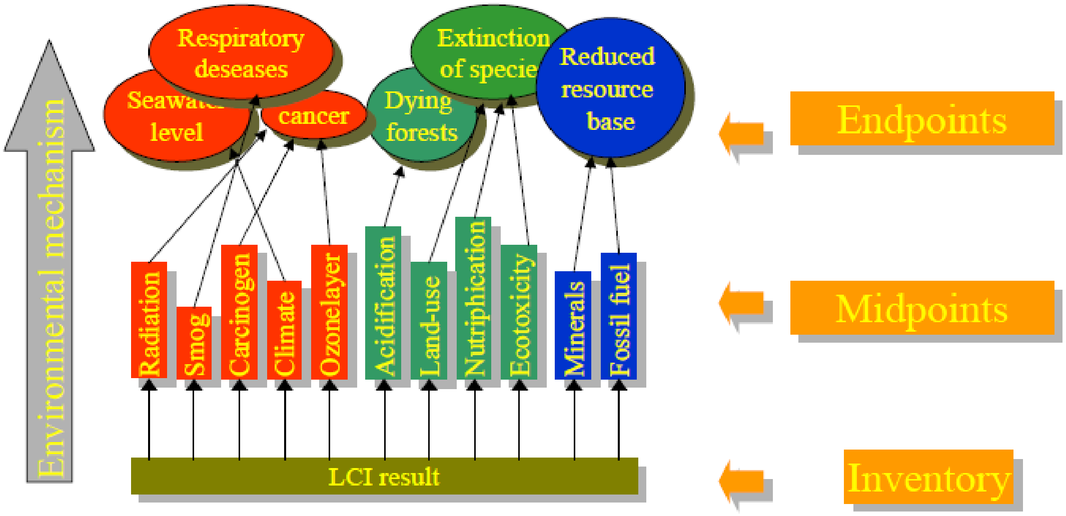


Figure 4.2 General structure of an Impact Assessment Method [36].

According to ISO 14042 (ISO 2000a) which was later replaced by ISO 14044 (ISO 2006), life cycle impact assessment phase includes several steps:

- Assignment of LCI-results (“classification”), hence the impact categories should be pre-defined and the inventory will be assigned to the impact categories according to their ability to contribute to different problem areas.
- Calculation of category indicator results (“characterization”), hence the LCI results are calculated and converted to common units by multiplying them by the characterization factors and finally aggregated within each impact category.
- Normalization or calculating the magnitude of the category indicator results with respect to reference values where the different impact potentials and consumption of resources are expressed on a common scale through relating them to a common reference, in order to obtain comparisons across adopted impact categories.
- Weighting where weights are assigned to the different impact categories and resources reflecting the relative power of effect they are assigned in the study in accordance with the goal of the study.
- Interpretation where sensitivity analysis and uncertainty analysis assist interpreting the results of the LCA according to the goal and scope of the study to reach conclusions and recommendations [39].

In any Life Cycle Impact Assessment, the first three steps; assignment of inventory results to impact categories, the classification, and the characterization are mandatory, while normalization, grouping and weighting are optional elements.

4.2.3.1 Impact Categories

A long list of Impact Categories has been described by several scientific groups working in the field of the LCA in different global region, especially in Europe and the United States. The most well-known and reliable groups and list can be summarized as follows:

- The “Leiden list” (SETAC-Europe 1992)
- The “Nordic list” (Lindfors *et al*. 1995)
- The SETAC “default list” (Udo de Haes 1996)
- The “EDIP list” (Wenzel *et al*. 1996)
- The ISO 14047 list (preliminary) (ISO 1999)

The list of impact categories varies from a group to another, but the most effective categories which have the biggest burdens on the environment and living species had been included by the above mentioned groups [39].

1. Global Warming: it is also called "Greenhouse effect" is the effect of increasing temperature in the lower atmosphere. Generally, global warming is caused by CO_2 and CH_4 emissions and the consumption of some types of chlorofluorocarbons. Figure 4.3 shows the temperature difference measured during 1940-1980 compared with which had been measured during 1999-2008.

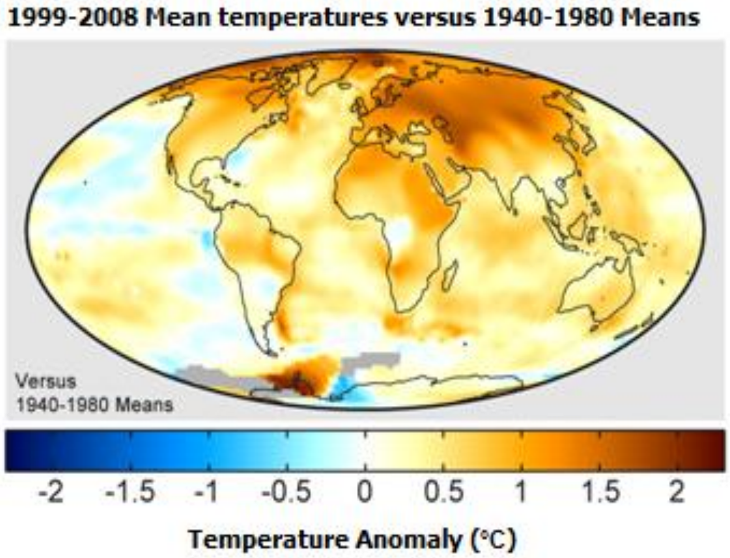


Figure 4.3 Global warming, temperature difference during a decade [40]

2. Stratospheric Ozone Depletion: decomposition of the stratospheric ozone layer resulted in increasing the incoming U-V radiation passing the atmosphere affecting the living components and the ecosystems on the globe [53]. This phenomenon caused by several halocarbons like CFCs, HCFCs, halons, etc. Figure 4.4 shows the Ozone hole in North Pole during 1984 (abnormally warm reducing ozone depletion) and 1997 (abnormally cold resulting in increased seasonal depletion).

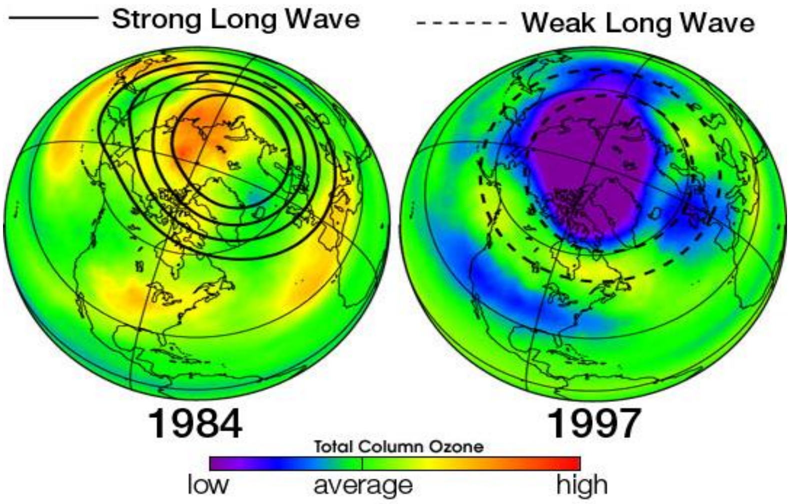


Figure 4.4 Ozone layer depletion from 1984-1997 [41]

3. Photochemical oxidant formation: also called "smog" is caused by the degradation of volatile organic compounds in the existence of light and nitrogen oxide NOx.
4. Acidification: Acidification is caused by the release of protons in the terrestrial or aquatic ecosystems. In the terrestrial ecosystem the effects are seen in softwood forests as weak growth and as a final consequence dieback of the forest. In the aquatic ecosystem the effects are seen as (clear), acid lakes without any wildlife. SO_2 and its acid formation potential are suggested as the reference substance in all lists submitted by different research groups.
5. Nutrient enrichment: also called "Eutrophication" can be defined as the enrichment of aquatic ecosystems by the nutrients leading to increased production of plankton, algae and higher aquatic plants resulting in a reduction in the value of the utilization of the aquatic ecosystem. Nitrogen and phosphorus are the main contributors of eutrophication occurrence. Figure 4.5 shows a satellite image of the Azov sea where the Eutrophication phenomenon clearly appears.

Figure 4.5 Shows the Eutrophication occurrence in the sea of Azov (Russia) [42]

6. Human toxicity: is a large group of different impacts on humans. Typically, this impact category includes all materials that are toxic to human beings. Substances contributing in this impact category are NOx, SO_2, some heavy metals and etc.
7. Ecotoxicity: Ecotoxicity includes in principle all substances that are toxic to the environment. Like eutrophication, ecotoxicity is often divided in two sections: one for terrestrial and the second for aquatic sections. The contributing substances in this impact category are mostly heavy metals and a number of organic components [39].

More impact categories are available in the lists of the mentioned researching groups, some of them are regional or less used by LCA practitioners, and the number of impact categories included in each group is not the same. Table 4.1 shows a long list of impact categories and related groups. The interaction between, emissions, environmental impacts and their consequences differ from one emitted substance to another. This interaction can be explained by CO_2 and CH_4 emissions as illustrative examples: The potential impact of the emission of CO_2 is global warming, which is considered as a global effect. Wherever CO_2 is emitted the potential impact of it will be the same; global warming. The results of global warming can be; loss of human lives, loss of crops and loss habitats and etc. The potential impact of CH_4 could be global warming as well as a photochemical ozone formation. The effects of photochemical ozone formation could be local when smog is formed and it can be regional when CH_4 is transported and ozone is formed.

Table 4.1 Compilation of different lists of Impact Categories [39].

List → / Impact Category ↓	The"Leiden list" SETAC-Europe (1992)	The" Nordic list" Lindfors et al. (1995)	SETAC, " default list " Udo de Haes (1996)	The " EDIP list" (Wenzel et al. 1997)	ISO Preliminary list (ISO 1999)
Global warming	Global warming CO_2-eq.	Global warming CO2-eq.	Global warming CO_2-eq.	Global warming CO_2-eq.	Global warming/ climate change
Depletion of stratospheric ozone	Depletion of stratospheric ozone CFC-11-eq.	Depletion of stratospheric ozone CFC-11-eq.	Depletion of stratospheric ozone CFC-11-eq.	Stratospheric ozone Depletion CFC-11-eq.	Stratospheric ozone Depletion
Photo- oxidant formation	Photo- oxidant formation C_2H_4-eq.	Photo- oxidant formation C_2H_4-eq.	Photo- oxidant formation C_2H_4-eq.	Photochemical oxidant formation C_2H_4-eq.	Photochemical oxidant formation (smog)
Acidification	Acidification SO_2-eq.	Acidification SO_2-eq.	Acidification SO_2-eq.	Acidification SO_2-eq.	Acidification
Nutrient enrichment - Eutrophication	Eutrophication - PO4- eq. - COD- (chemical oxygen demand) discharge	Eutrophication - N- emissions to air For aquatic systems: -Aggregation of P to water -Aggregation of N to water -Aggregation of N to water & to air -Aggregation of N & P to water and air	Eutrophication BOD (biological oxygen demand) discharge - PO4- eq. is suggested.	Nutrient enrichment - NO3-eq. -N- eq. - P- eq.	Nutrient enrichment
Ecotoxicity	Ecotoxicity -aquatic -terrestrial	Ecotoxicological impacts - acute - chronic - wastewater	Ecotoxicological impacts	Ecotoxicity - water, acute - water, chronic - soil - wastewater-plants	Ecotoxicity
Human toxicity	Human toxicity – water, air, soil	Human health, toxicological and non- toxicological	Human toxicological impact	Human toxicity - air, water, siol	Human toxicity
Occupational health and safety	Occupational safety - qualitatively	Human health impacts in work environment		Work environment -carcinogenicity -teratogenicity - allergy - neurotoxicity - hearing impairments - repetitive work - accidents	
Odor	Critical volume approach is suggested	Included in" Habitat alteration .."	Odor		
Noise	Worst case scenario is suggested	Included in" Habitat alteration .."	Noise		
Radiation			Radiation		
Waste	Final solid waste (hazardous) Final solid waste (non-hazardous)		Final solid waste	Waste - volume waste -hazard. waste - slags and ashes - radioactive waste	Waste

Table 4.1 Compilation of different lists of Impact Categories (continued)

List → / Impact Category ↓	The"Leiden list" SETAC-Europe (1992)	The" Nordic list" Lindfors et al. (1995)	SETAC, " default list " Udo de Haes (1996)	The " EDIP list" (Wenzel et al. 1997)	ISO Preliminary list (ISO 1999)
Resource consumption - water - land use	Energy and material - renewable & non- renewable Space requirement	Energy and material - scarcity Water Land, including wetlands	Depletion of abiotic resources Depletion of biotic resources	Resource consumption - renewable - non- renewable	
Habitat alterations and impacts on biological diversity		Habitat alterations and impacts on biological diversity			
Effect of waste heat on water			included		

4.2.4 Interpretation

ISO (International Standard Organization) defines the Interpretation phase of an LCA as the phase of the LCA where the findings and results of the previous phases, i.e. inventory and impact assessment phases, gathered or separately are combined in the frame of the goal and scope seeking to obtain consequent conclusions and final decisions. The interpretation phase of an LCA is conducted in order to find the solution for the given problem or to respond to the question that was mentioned at the early beginning of the study or in goal and scope phase [37]. The procedure of interpretation is further elaborated as: To analyze and report results, reach conclusions, explain limitations and provide recommendations for an LCI or an LCIA study. Related to waste management the common questions where LCA can help answer are:

- For more environmental improvement, what is the most important stage of the waste life cycle that should be focused on?
- If more than one solution scenario were concluded, a comparison between them would answer how good these solutions are.
- What are the total environmental impacts associated with different conceptual waste treatment alternatives and how are the performance of each one?

The main issues those are recommended to be included during the interpretation phase of a quantitative LCA can be summarized as follows:

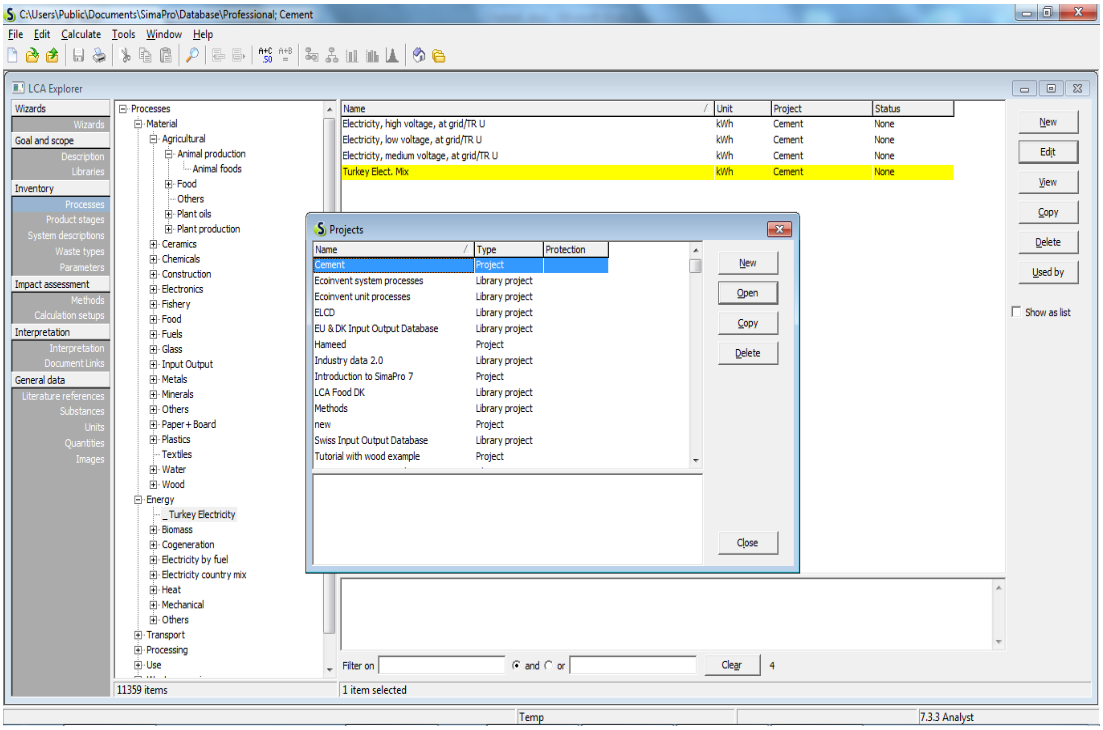
- Define the methodological choices that majorly affect the main performance of the studied system relying on knowledge about the system.
- Define data quality indicators and assess data quality. If possible, show uncertainty ranges.
- Completeness check; Determine if missing information, such as data gaps, data quality gaps, information gaps on technical methodological choices, are critical to the goal and scope of the study.
- Sensitivity analysis; Determine if a sensitivity analysis is necessary for your study. If yes, design a factorial scenario calculation plan. Conduct the calculations in a deterministic way, i.e. without considering data uncertainty.
- Uncertainty analysis. Determine whether or not an uncertainty analysis, i.e. replicate calculations of scenario with varying values of selected data elements, is necessary. If yes, make replicate calculations of at least one experiment with selected Y-parameters, representative of identified clusters. Determine if the spread of the replicates is larger than the variance between different scenarios.
- Conclude, from the uncertainty analysis, whether the data quality is sufficient or not. If yes, determine whether or not there are significant differences between the scenarios, and the cause of such differences.

In the most cases of performing a sensitivity analysis, the variables in the sensitivity analysis were in some common subjects or issues, which should be given more care and attention in the interpretation phase of an LCA. The issues related to sensitivity analysis can be summarized as:

1. Input data (generic or specific)
2. Heat production from fuel (oil or biomass)
3. Transport distance.
4. Waste composition.
5. Used technologies [28].

4.3 SIMAPRO SOFTWARE

LCA is a time consuming process due to the large number of required data sets and other long series of analysis, test and checks. Therefore, several softwares were produced to facilitate and simplify the implementation of an LCA process. The world leading software amongst them is SimaPro [43]. SimaPro is a software program structured according to ISO 14040 and 14044, and all the stages of an LCA are included within this software. In addition, it is integrated with well-known Ecoinvent database related to a wide variety of material, products and processes from different geographical regions. SimaPro provides a professional, all-in-one tool for Life Cycle Management. It enables its users to make solid decisions regarding changing the product's life cycle in a positive direction. SimaPro is the most famous LCA software which used by industry, consultancies, and research institutes in more than 80 countries all over the world.



Name	Unit	Project	Status
Electricity, high voltage, at grid/TR U	kWh	Cement	None
Electricity, low voltage, at grid/TR U	kWh	Cement	None
Electricity, medium voltage, at grid/TR U	kWh	Cement	None
Turkey Elect. Mix	kWh	Cement	None

Projects

Name	Type	Protection
Cement	Project	
Ecoinvent system processes	Library project	
Ecoinvent unit processes	Library project	
ELCD	Library project	
EU & DK Input Output Database	Library project	
Hameed	Project	
Industry data 2.0	Library project	
Introduction to SimaPro 7	Project	
LCA Food DK	Library project	
Methods	Library project	
new	Project	
Swiss Input Output Database	Library project	
Tutorial with wood example	Project	

4

11359 items

1 item selected

Figure 4.6 An interface screen of analyst SimaPro version 7.3.3

The SimaPro LCA Software supports a professional tool to collect, assess, monitor and control the environmental performance of products and services. It enables scientists and researchers to easily model and analyze complex life cycles in a systematic and transparent method, responding to the ISO 14040 series recommendations. SimaPro is a proven, reliable and flexible tool was first released in 1990, used by the majority of industries, consultancies and universities [44].

With over a thousand users and practitioners, SimaPro continues to be the most successful LCA software worldwide. Several versions of SimaPro were released represented in SimaPro 7 and the latest version of SimaPro 8 which is equipped with Ecoinvent database v.3 [45].

4.4 CONCLUSIONS

Environmental issues became the most vital topics during the last couple decades, and accordingly a large number of analyzing and assessing tools have been released. One of these important tools used widely nowadays is LCA, which accounts for environmental burdens related to the different stages of product's or service's life, starting from early extraction, transportation, production, usage and final disposal.

LCA requires a huge effort in compiling input and output data related to product life cycle stages and analyzing, comparing and assessing these data. In addition, the final steps of an LCA, several uncertainty, sensitivity and completeness checks required, which means more time to be consumed.

In order to simplify this long procedure and reduce time consumption, several softwares was released. Amongst them, SimaPro software got a forefront rank due to its reliability, flexibility and huge available databases.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter, the datasets, limitations and assumptions related to the studied systems are described and applied to SimaPro software to evaluate the Lifecycle of the processes, aiming to get the best comparison between the studied cases from an environmental viewpoint. The comparison results will be shown as a set of graphical images to present a simplified way for understanding and interpreting the results.

5.2 THE GOAL AND SCOPE

This study aims to present and explain several thermal disposal options of sewage sludge, focusing on the most appropriate ones which match with Turkey's conditions and the city of Gaziantep in particular. The chosen options were: The incineration of sewage sludge (digested) in a fluidized bed incinerator and in a cement Kiln as a secondary fuel and a raw material. Both processes produce an equal amount of heat for the same quantity of incinerated municipal digested sludge (assumed to be 1 kg) with a water content of 95%. While for the second system (cement kiln) the sludge used as a secondary fuel and raw material, in the first system (Fluidized Bed Combustor) the heat is converted into electricity power by a gas turbine generating system. The boundaries of the first system comprise several processes, namely: dewatering, thermal drying, incineration, heat recovery, electricity generation and landfilling of the final residues. Transportation from GSSIP and landfill facility is neglected (short distance and little quantities). For second system the boundary comprises: dewatering, transportation to the cement factory's site, thermal drying and incineration in a cement kiln. The dewatering process of the digested sludge is applied to reduce the water content of the sludge from 95% to 73% , which result in removing about 820 g water from each kg of sludge and the final weight of the sludge with 73% water, will be180 grams.

Drying process reduces the water content of the sludge to 10% and it is considered as one of the most energy consuming processes in this regard.

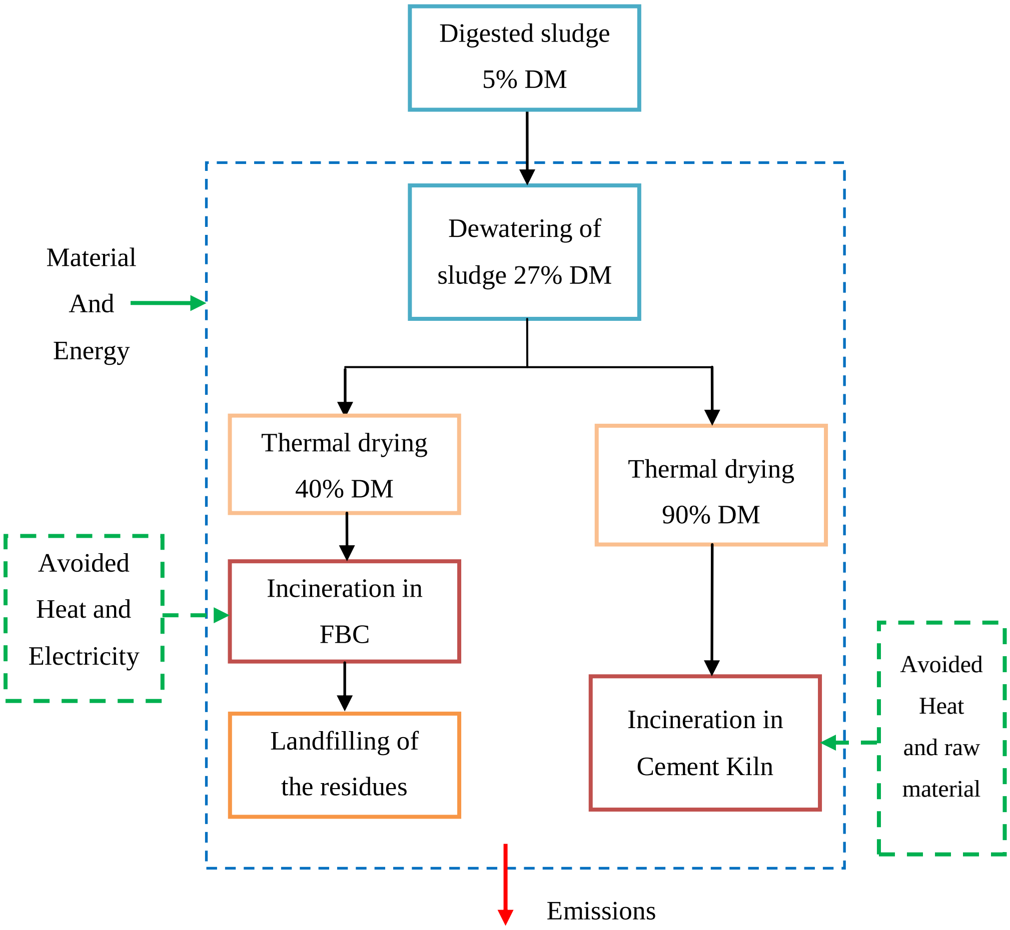


Figure 5.1 System boundaries for both scenarios.

As a result of the dewatering and drying processes, the transportation costs will be reduced. In addition, the treatment of the removed polluted liquid arises by the dewatering and drying processes is involved. The infrastructure of systems is included within this LCA and the transportation distance included in the second system is about 25 km between the WWTP and the cement factory, while the first system lies nearby the WWTP therefore the transportation process does not exist.

The heat and electricity for clinker production is not included in the cement kiln scenario. The lifetime of the systems is estimated by assuming the incineration of 100 million tons of sewage sludge, which can be fractioned into 10^{-11} point per each kg of wet sludge (the functional unit) [13].

5.3 LIFE CYCLE INVENTORY (LCI)

The specific data sets for the sewage sludge incineration plant in Gaziantep is hard to be acquired due to the fact that this plant has been recently installed and some of the basic components are not equipped yet. Therefore, the datasets of Ecoinvent which are supported by SimaPro software were taken as a life cycle inventory for both case study processes of concern, with some essential modifications and assumptions to keep the consistency with the Turkey context. These modifications are:

- The electricity mix inventory of Turkey was created depending on the data provided by EMRA (Energy Market Regulatory Authority) and the generic data sets of Ecoinvent. Figure 5.2 shows electricity mix / Turkey layout [46].
- The transportation distances between the WWTP and the nearest cement factory estimated to be 25 km.
- The type of the used furnace in Gaziantep incineration plant is a FBC [33].

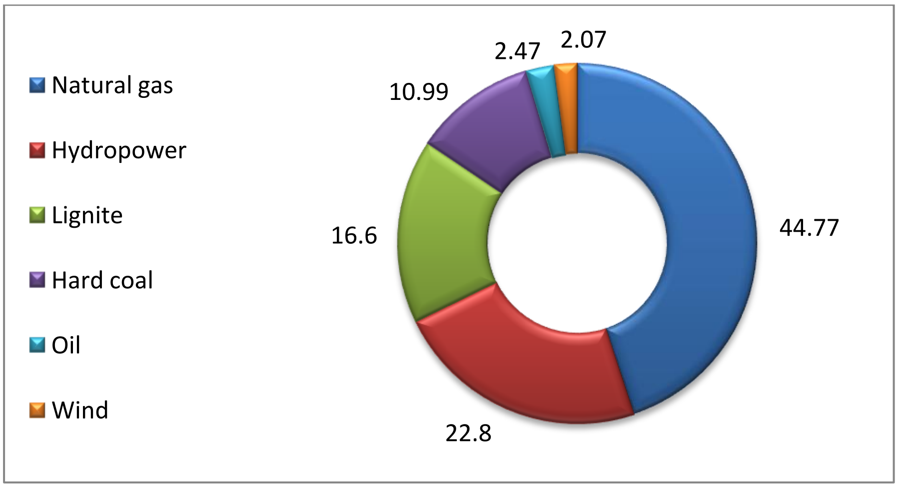


Figure 5.2 General Components of Electricity Production Mix in Turkey [46].

The sludge used in this study is digested sewage sludge generated from the anaerobic digestion of the mixed sludge. Table 5.1 shows the composition of typical digested sewage sludge. Dry matter (DM) and volatile matter (VM) are the most important measurement in thermal treatment of sludge. While the first refers to the dry matter content of the sludge (implicitly the water content), other parameter shows the sludge organic content which controls the calorific value of the sludge [23]. For achieving an efficient dewatering, within required dryness limit 27% DM, several flocculation agents are required to be added to the sewage sludge, and by using of a mechanical dewatering equipment, i.e. press belts, the dewatering process proceeds. Typical flocculation agents are (quick lime, ferric chloride and polyelectrolyte). Table 5.2 shows the flocculation agents and the quantities which were used. The average electrical energy demand for this process is estimated to be about 0.0015 kWh per kilogram of wet sludge input. The removed liquid of 1 kg of wet sludge by dewatering process to achieve a dryness ratio of 27% DM is about 820 grams. This liquid is rich in ammonia and it is recycled into a WWTP [13].

Table 5.1 Composition of digested sludge [23]

Component	Unit	Digested sludge (DS)
Dry Matter (DM)	g/L	30
Volatile Matter (VM)	% DM	50
C	% VM	49
H	% VM	7.7
O	% VM	35
N	% VM	6.2
S	% VM	2.1
P	% VM	2
Cl	% VM	0.8
K	% VM	0.3
Al	% VM	0.2
Ca	% VM	10
Fe	% VM	2
Mg	% VM	0.6

In the fluidized bed plant scenario (GSSIP), the sewage sludge is incinerated after the dewatering and drying process to a dryness ratio of 40%, and the final residuals are taken to be landfilled. In the cement kiln scenario, the dewatered sludge is dried to a higher dryness ratio of 90% to avoid affecting the quality of produced clinker. The average energy demand for drying process is estimated to be 4.9 KJ and 0.468 kWh for each kg of removed liquid [13].

Table 5.2 The specific input flocculation agent for dewatering process [13].

Flocculation agent	Kg agent / kg wet sludge input
CaO	0.00233
$FeCl_3$	0.00125
Polyelectolyte / polymer	0.0002625

5.3.1 Energy Model

The energy input and output of the chosen systems were calculated depending on some essential data from Ecoinvent inventories. The lower heating value (LHV) for the digested sludge with a 84.4% water content is assumed to be 3.142 KJ/kg [33]. The gross heat efficiency of the incineration plant is 63% and the gross electricity efficiency is 22% [4]. The thermal efficiency of the cement kiln is 80.5% (no electricity generation) [33]. The energy forms of both systems were quantified with respect to the main functional unit of 1 kg of wet digested sludge with 95% water content. To dehydrate 1 kg of sludge with 95% - 73% water content, the removed liquid will be calculated as below:

At (95% w) solid matter = 0.050 kg, Liquid weight = 0.950 kg

At(23% w)solid matter=0.050 kg, Liquid weight=0.1293 kg, total weight=0.1793 kg

LHV of Dried sludge = 3.142 KJ/kg [33].

LHV for (0.050 kg/f.u)$= 3.142 \times 0.05 = 0.1571\ MJ/fu$ (Sludge input energy)

<u>Incineration Plant:</u>

Used diesel= 0.00333 kg/$kg_{sludge,}$ diesel LHV=43.4 MJ/kg Calculation and [33]

Diesel heat$= 0.00333 \times 43.4 = 0.0145\ MJ/fu$ (heat input)

Total input heat$= 0.1571 + 0.0145 = 0.1716\ MJ/fu$

Total output heat$= 0.1716 \times 0.63 = 0.1081\ MJ/fu,$

Plant thermal efficiency is 63% (0.63), and plant electricity generation is 22% (0.22)

Electricity generated$= 0.1716 \times 0.22 = 0.03775\ MJ/fu$ = 0.0105 kWh

<u>Cement kiln:</u>

Heat input = 16.4 GJ/t DM = 16.4 MJ/ kg For drying [21]

Heat input (light diesel oil) $= 16.4 \times 0.05 = 0.82\ MJ/fu$

Total Heat input $= 0.1571 + 0.82 = 0.9771\ MJ/fu$

Heat output = 0.8492 MJ/ f.u Calculation and [21]

Thermal efficiency $= 0.8492 \div 0.9771 = 0.87 = 87\%$

Tables 5.3 and 5.4 show the energy inventories for both systems.

Table 5.3 The energy inventory for the Incineration Plant scenario.

Item	Unit	Quantity	Energy category	Reference
Incineration plant				
Potential energy (LHV of sludge)	MJ / kg DM	3.142	Heat	[33]
Generated energy (0.05kg DM)	MJ / f.u	0.1571		Calculated
Consumed energy	MJ / f.u	0.0145		[13]
Avoided energy	MJ / f.u	0.1081		Calculated
Generated electricity	KWh / f.u	0.0105	Electricity	[13]
Consumed electricity	KWh / f.u	0.018		[13]
Avoided electricity	KWh / f.u	0.01064		Calculated

Table 5.4 The energy inventory for Cement Kiln scenario.

Item	Unit	Quantity	Energy category	Reference
Potential energy (LHV of sludge)	MJ / kg DM	3.142	Heat	[33]
Generated energy from sludge	MJ / f.u	0.1571		Calculated
Consumed energy (Drying)	MJ / f.u	0.820		[13] and calculation
Net generated energy (avoided)	MJ / f.u	0.8492		[13]
Electrical consumption Low voltage	KWh / f.u	0.06423	Electricity	[13]
Electrical consumption Medium voltage	KWh / f.u	0.01443		[13]

5.3.2 Allocation and Substitution

Many processes usually perform more than one function or produce more than one output. Allocation based on an economical key value concept is the commonly used procedure in the Ecoinvent datasets which is used in this study, this because of the multi-output nature of the most of the processes, including the incineration of sewage sludge. As an economical key value, the current disposal fees and energy prices of Swiss municipal incinerators were used [13]. The allocation percentage of each expected output was calculated and tabulated in Table 5.5. These percentages were adopted for the allocation of corresponding flows and emissions on each expected product of the main process in SimaPro datasets. The substitution concept was used to avoid the allocation traces, and apply the positive environmental effects of the co-products on the main product performance. Substitution leads to subtract an equal amount an equivalent value of the co-product with its relevant emissions and flows from the main product's burdens improving its environmental performance.

Substitution was applied by adding both avoided heat and electricity production sub-processes to the first system, and avoided raw material and heat production sub-processes to the second system [47].

Table 5.5 Allocation percentages calculated based on economical key value [13].

Per f.u	Disposal service	Sold heat	Sold electricity
Valued amount	1 kg	0.2264 MJ	0.00739 MJ
Fees and prices	0.0401 CHF/kg	0.09 CHF/MJ	0.2628 CHF/MJ
Generated revenues	0.0401 CHF	0.0204 CHF	0.00208 CHF
Allocation keys for this dataset	64.1 % disposal service	32.6 % heat production	3.3 % electricity production

5.4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Life Cycle Impact assessment is an integral part of any LCA, due to the difficulty faces the interested parties in the LCA from understanding the inventory results analysis. Therefore, the LCIA phase is conducted to solve these difficulties in understanding LCI results. To apply the LCIA on a specific product or service, many methodologies have been developed, and each method has its own policy in the degree of aggregation of assessment results, starting from the LCI results, midpoint categories and ends with endpoint categories [36]. In this study, the method of (IMPACT2002+) was used which links LCI results to both midpoint and endpoint impact categories, it includes14 potential midpoint, 14 damage midpoint and 4 endpoint damage categories [48]. The selection of this method was based on two criteria, first; The IMPACT2002+ is a developed method published by the "Industrial Ecology & Life Cycle Systems Group, Swiss Federal Institute of Technology Lausanne", therefore to make the best match between the LCI which basically relied on Ecoinvent database (Swiss made database) and the assessing method Impact 2002+ (Swiss made method) this method was chosen and secondly, because the IMPACT2002+ combines both the classical method of one stage quantitative modelling of cause and effect chain and the damage oriented method which tries to model the cause-effect chain up to a higher stage, in spite of the high rate of uncertainty occurrence. The characterization factors for this method of each impact category related to any substance belong to the category of concern is a long series of data tabulated by the developers of the method [49]. After characterization of the potential impacts by multiplying the potentials by characterization factors, damage impacts can be obtained by applying the same procedure with damage factors. Normalization, a higher stage of impact assessment can be performed by dividing the damage results by the damage normalization factors. Normalization can be applied on either the midpoint damage results or the endpoint damage results to get the normalized damage impacts. Often, the normalization factors of Western Europe are used to this LCIA method. These factors normally compare the scores of the given impact categories by the share of the same impact category of person in Western Europe during a year.

Table 5.6 presents the normalization factor for damage impacts at endpoint approach, whereas Table 5.7 shows the damage and damage normalization factors at midpoint adopted by IMPACT2002+ method. The procedure of determining the scores of any substance within the associated impact category, commonly called the environmental mechanism of the specified substance.

Table 5.6 Normalization factors for damage categories (endpoint) in Western Europe [49].

Damage categories	Normalization factors	Units
Human Health	0.0071	DALY / pers / yr
Ecosystem Quality	13700	PDF. m^2.yr / pers / yr
Climate Change	9950	Kg CO_2 / pers / yr
Resources	152000	MJ / pers / yr

Table 5.7 Damage factors for characterized impacts (midpoint) in Western Europe [49]

Midpoint Category	Damage factor	Unit	Endpoint Category
Carcinogens	2.80E-6	DALYs/kg	Human Health
Non-Carcinogens	2.80E-6		
Respiratory inorganic	7.0E-4		
Ozone layer	1.05E-3		
Respiratory organic	2.13E-6		
Radiation	2.10E-10	DALYs/Bq	
Aquatic ecotoxicity	5.02E-5	PDF*m2*yr/kg	Ecosystem Quality
Terrestrial ecotoxicity	7.91E-3		
Terrestrial Acidification./nutrition	1.04		
Land occupation	1.09	PDF*m2*yr/m2*yr	
Global warming	1.0	DALYs/kg	Climate Change
Mineral extraction	5.10E-2	MJ/ kg extraction	Resources
Non-renewable energy	45.8	MJ/ kg oil	

The life cycle inventories results of the systems of concern in this study were classified and characterized to their corresponding potential life cycle impact categories by the aid of SimaPro software. Hence, for characterization, the characterization factors of IMPACT2002+ method were used and GWP for 500 years were used which imposes less global warming effects for some emissions and flows due to this long time span.

Finally, the damage scores of each category were normalized according to the IMPACT2002+ method, as recommended by the author of the method [50]. A general layout of IMPACT2002+ method is shown in Figure 5.3.

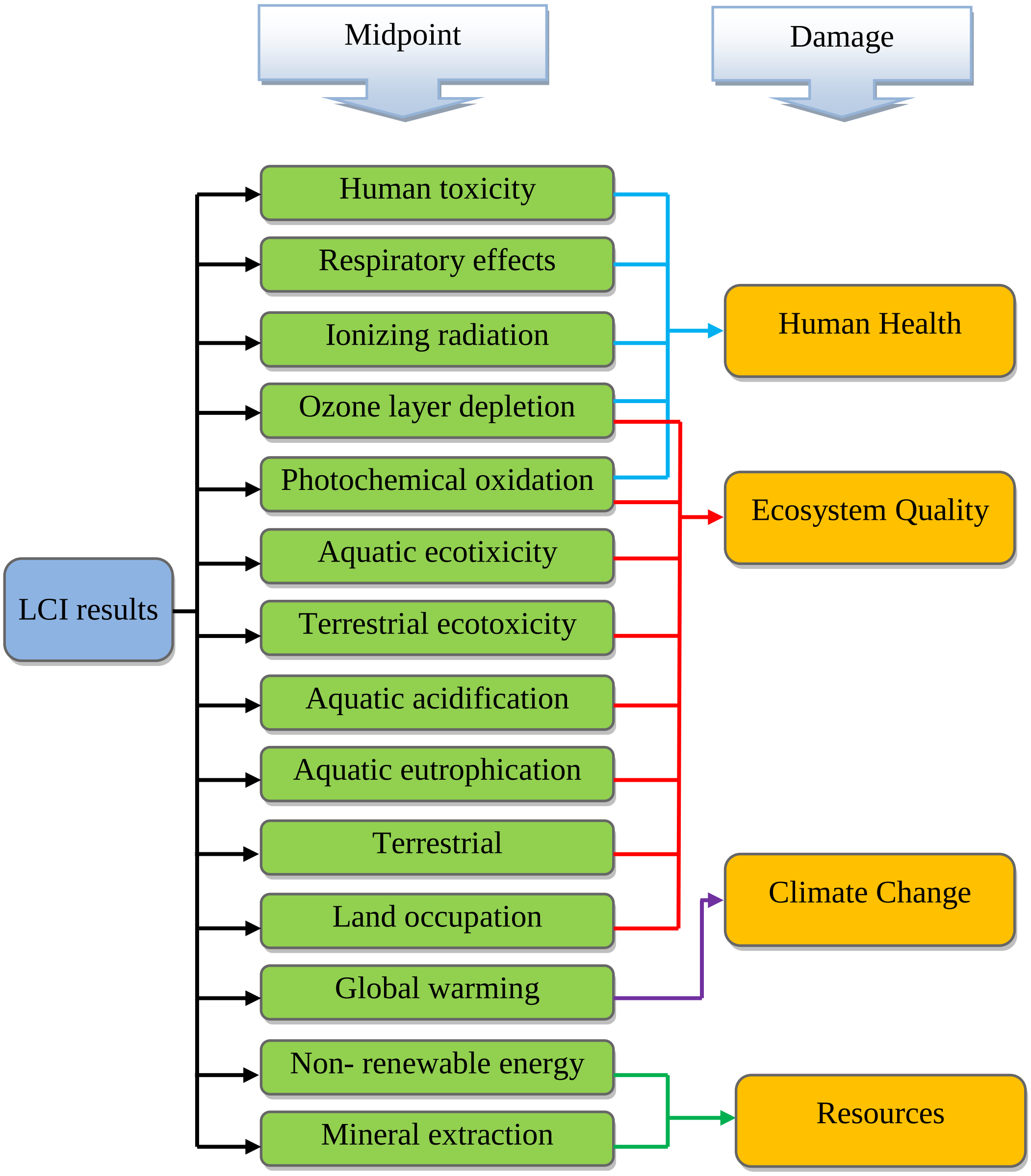


Figure 5.3 IMPACT2002+ impact assessment method framework [52].

5.5 RESULTS AND INTERPRETATION

In consistency with the goal and scope of this LCA study and by adopting a modified ECOINVENT database version 2.0 and using the SIMAPRO software computer program, both of systems of concern (case study) were modeled with all their relevant input and output, starting from the raw material extraction, processed material, infrastructure, transportation, processing, emissions and ending by the final destiny of the residues. Functional unit of both systems was the disposal of 1 kg of wet digested mixed sludge from the municipal waste treatment plant of Gaziantep (GASKI). All the inputs and outputs and processes associated with each system were compiled quantitatively with respect to this functional unit.

5.5.1 System Analysis (GSSIP, First Scenario)

Each system (scenario) has its own positive and negative burdens at every impact category, and this burden varies depending on the sub-process which gives this burden. Table 5.8 gives the characterization scores for GSSIP, while Figure 5.4 represents the percentage of these burdens at each impact category at midpoint.

Table 5.8 Characterization scores for GSSIP (first scenario).

Category	Unit	Total Score
Carcinogens	kg C2H3Cl eq	2.40E-03
Non-carcinogens	kg C2H3Cl eq	1.27E-02
Respiratory inorganics	kg PM2.5 eq	1.57E-05
Ionizing radiation	Bq C-14 eq	1.46E-01
Ozone layer depletion	kg CFC-11 eq	6.43E-10
Respiratory organics	kg C2H4 eq	7.17E-06
Aquatic ecotoxicity	kg TEG water	1.61E+00
Terrestrial ecotoxicity	kg TEG soil	2.20E-01
Terrestrial acid/nutri	kg SO2 eq	6.37E-04
Land occupation	m2org. arable	7.71E-05
Aquatic acidification	kg SO2 eq	8.31E-05
Aquatic eutrophication	kg PO4 P-lim	2.41E-05
Global warming	kg CO2 eq	-1.24E-03
Non-renewable energy	MJ primary	-7.07E-02
Mineral extraction	MJ surplus	1.92E-04

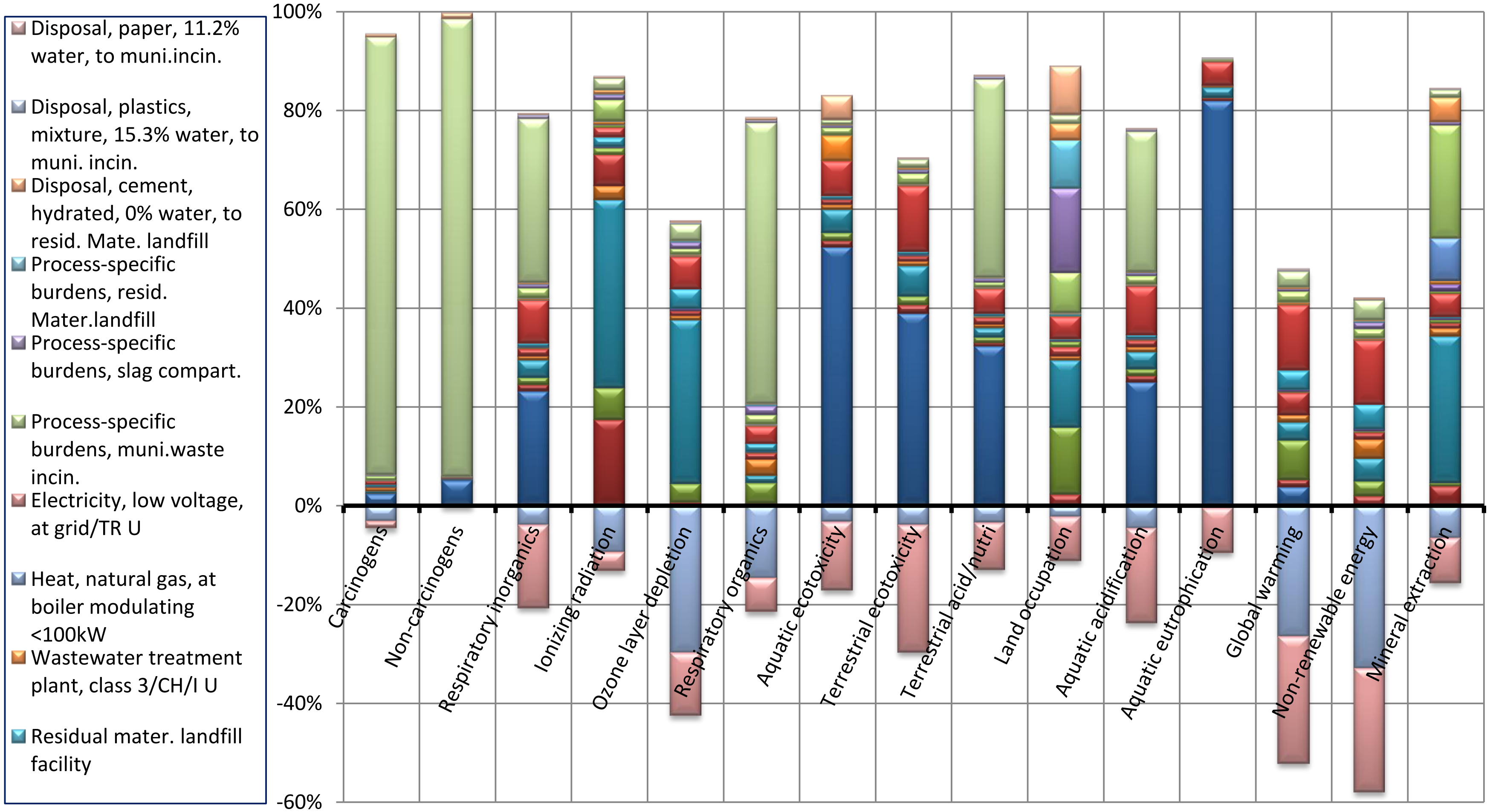


Figure 5.4 GSSIP – IMPACT2002+ method / Characterization

Figure 5.4 is the percentage depiction of the Table 5.8. What is obvious in this Figure is that for Carcinogens and Non-Carcinogens impact categories the main cause for their high scores is the concentration of heavy metals in the landfill residues and the formation of some dioxins. The effect of these residuals and emissions in Respiratory (organic and non-organic) and Acidification (Aquatic and terrestrial) categories is less than that of the previous categories. The most interesting points in this scenario are the negative signed burdens, which totally belongs to the effects of the avoided heat and electricity. The larger the effect of the avoided energies (fossil energy in particular) the highest the influence the climate change corresponding categories.

5.5.2 System Analysis (Cement Kiln, Second Scenario).

For the second scenario, Table 5.9 and Figure 5.5 show the impact category structure composed by various sub-processes.

Table 5.9 Characterization scores for Cement Kiln (second scenario).

Category	Unit	Total Score
Carcinogens	kg C2H3Cl eq	1.9801E-05
Non-carcinogens	kg C2H3Cl eq	2.4158E-03
Respiratory inorganics	kg PM2.5 eq	1.0765E-04
Ionizing radiation	Bq C-14 eq	2.9001E-01
Ozone layer depletion	kg CFC-11 eq	6.0898E-10
Respiratory organics	kg C2H4 eq	1.6466E-05
Aquatic ecotoxicity	kg TEG water	2.7493E+00
Terrestrial ecotoxicity	kg TEG soil	7.1083E-01
Terrestrial acid/nutri	kg SO2 eq	3.7644E-03
Land occupation	m2org. arable	1.3030E-04
Aquatic acidification	kg SO2 eq	6.2434E-04
Aquatic eutrophication	kg PO4 P-lim	2.5973E-05
Global warming	kg CO2 eq	6.4316E-03
Non-renewable energy	MJ primary	-1.3943E-01
Mineral extraction	MJ surplus	6.0629E-04

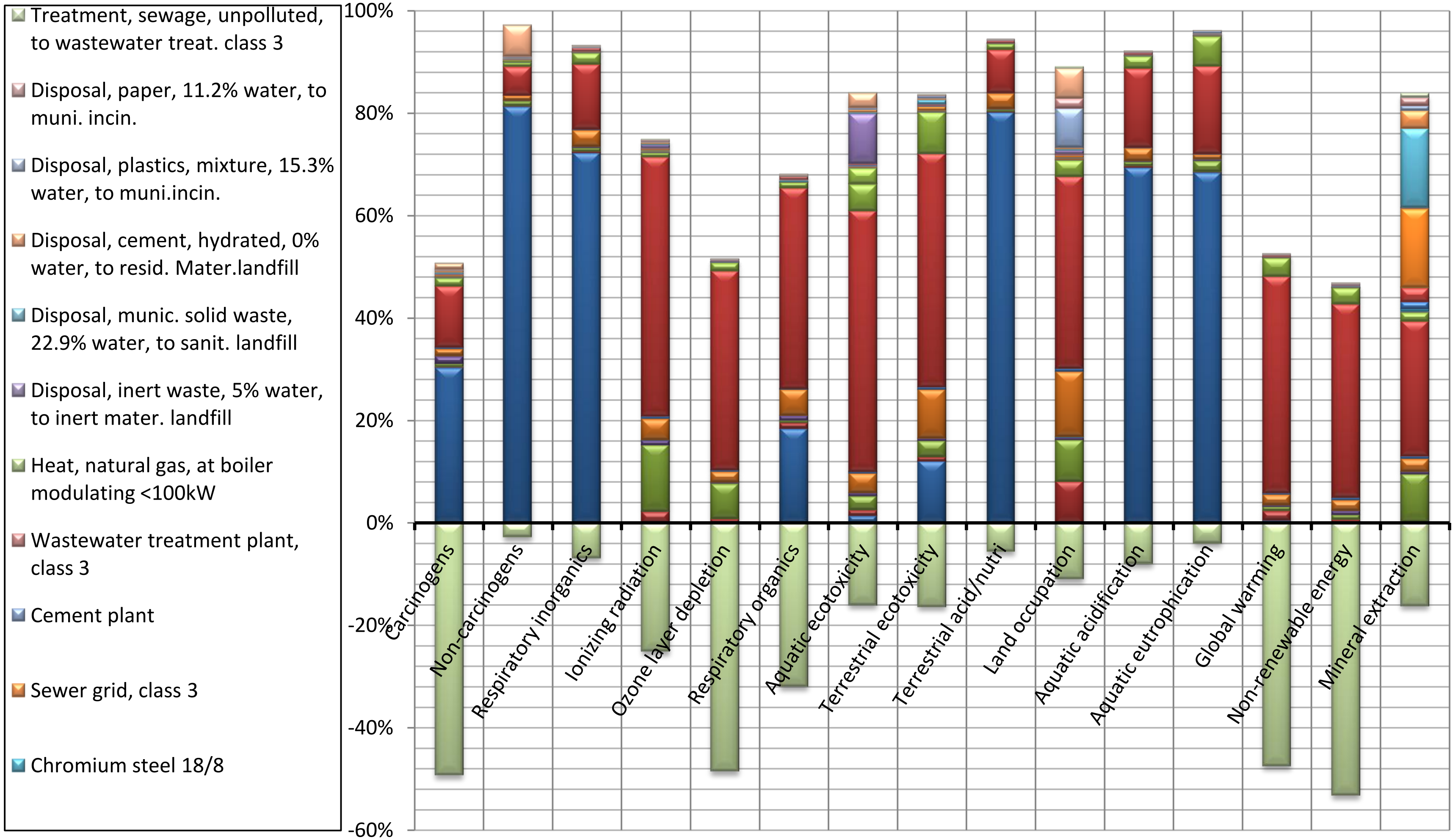


Figure 5.5 Cement Kiln – IMPACT2002+ method / Characterization

As it can be noticed from Figure 5.5, the avoided heat process (Heat, natural gas, at boiler…) contributes positively to reduce the environmental burdens at different impact categories, especially in Global Warming, Non-renewable energy, Carcinogens and Ozone depletion categories. This effect can be attributed to the fact that the avoided energies substitute the fossil fuel energy which would be used if no substitution were applied. The positive performance of different categories is not originated to the avoided energy alone, but the reduced landfill residues in this scenario (most of residual materials immobilized to the clinker matter) plays a high role in this aspect, typically in human health categories.

The most effective processes which control the comparison between both scenarios are the consumed and avoided energies. The large amount of energy spent in the drying process for the cement kiln scenario and the formation of NOx emissions enables the incineration plant (first scenario) to acquire the first rank in this comparative analysis from the climate change and ecosystem quality viewpoints while the second scenario environmental scenario dominates in resources category perspective.

5.5.3 Comparing Systems (Scenarios)

Referring to Table 5.10 and Figure 5.6, the value next to each impact category represents the total score of each flow or process contributing in the same category of impact within the whole system. These values are the characterization of LCI results of both scenarios (the total score multiplied by the characterization factors of the impact assessment method). It is obvious, in the mentioned Table and Figure, the environmental burden in the scenario of incineration of sludge in the fluidized bed combustor (GSSIP) is less if compared with the scenario of incineration of the same sludge in the cement kiln, especially in Global warming potential category. The reason beyond this improvement represents in less dependency of the GSSIP scenario on fossil fuel rather than the other scenario, especially when it is known that the biogenic CO_2 does not worsen the global warming effect. For other impact categories (except Carcinogens, Non-carcinogens, Ozone depletion and Non-renewable energy categories), the first scenario precedes in various rates, mostly due to lower NOx emissions in fluidized bed incinerator technology. In contrast, the Cement kiln option shows a better environmental performance in Non-renewable energy, carcinogens, Non-carcinogens, and Ozone depletion categories.

The precede of this scenario at the ozone depletion category can be ascribed by the less formation of the dioxins due to the high incineration temperature (about 1400 °C), which contributes in the ozone depletion process, while the better performance of this scenario at human toxicity versus the other scenario, belongs to the process of immobilization of heavy metals in cement clinkers. The Non-renewable energy impact category score can be obtained by the addition of all embodied energies (feedstock, extraction, transportation and production energies) that accompany the whole life cycle stages of each material and flow contributing to the main product, subtracting the related substituted energies. Accordingly, the cement kiln scenario records a better performance in this regard in comparing with the first scenario, in which an additional energy required in the landfill facility for the disposal of the final residual material.

Table 5.10 IMPACT2002+ method / Characterization scores for both scenarios.

Impact category	Unit	GSSIP	Cement kiln
Carcinogens	Kg C2H3Cl eq	2.40E-03	1.98E-05
Non-Carcinogens	kg C2H3Cl eq	1.27E-02	2.42E-03
Respiratory inorganic	kg PM2.5 eq	1.57E-05	1.08E-04
Ionizing radiation	Bq C-14 eq	1.46E-01	2.90E-01
Ozone layer	kg CFC-11 eq	6.43E-10	6.09E-10
Respiratory organic	kg C2H4 eq	7.17E-06	1.65E-05
Aquatic ecotoxicity	kg TEG water	1.61E+00	2.75E+00
Terrestrial ecotoxicity	kg TEG soil	2.20E-01	7.11E-01
Terrestrial Acidi./nutrition	kg SO2 eq	6.37E-04	3.76E-03
Land occupation	m2org. arable	7.71E-05	1.30E-04
Aquatic acidification	kg SO2 eq	8.31E-05	6.24E-04
Aquatic eutrophication	kg PO4 P-lim	2.41E-05	2.60E-05
Global warming	kg CO2 eq	-1.24E-03	6.43E-03
Non-renewable energy	MJ primary	-7.07E-02	-1.39E-01
Mineral extraction	MJ surplus	1.92E-04	6.06E-04

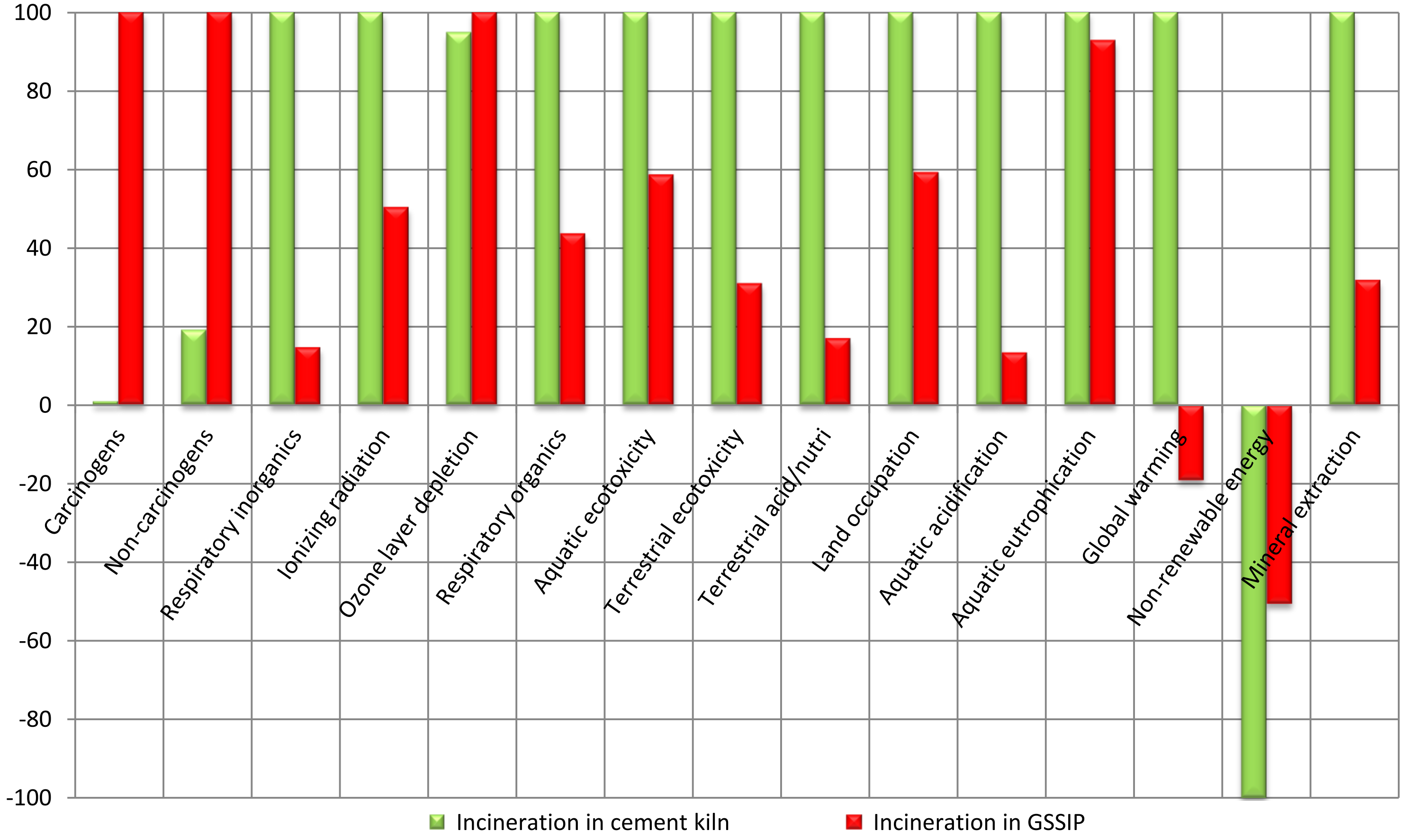


Figure 5.6 Comparing I kg of sludge in GSSIP with 1kg sludge in Cement Kiln. IMPACT2002+ /Characterization

Later, the life cycle inventory results for processes of concern were normalized to the normalization factor (given in Table 5.6). Referring to Table 5.11 and Figure 5.7, these points can be noticed: The normalization was taken at endpoint categories (damage categories), namely; Human Health, Ecosystem Quality, Climate Change and Resources categories. The results of the normalization show a good environmental performance for the fluidized bed incinerator against the performance of the cement kiln at categories of climate change and ecosystem quality, while as it was expected from characterization stage, the cement kiln scenario precedes the competent scenario at resources and human health categories. The more remarkable positive environmental burdens can be seen in Resources and Climate change categories. This can be resulted from the less non-renewable energy usage in cement kiln scenario and less fossil fuel dependency of the incineration plant in comparison with the typical high fossil fuel usage for the cement kiln option. Regarding the Climate change, the biogenic emissions from the combusted sludge in the incineration plant, grants the climate change category some minus environmental bonuses. The high human health category scores are due to the heavy metal concentration in the incineration residual materials and the formation of NOx emissions, especially in cement kilns, because of the high working temperature.

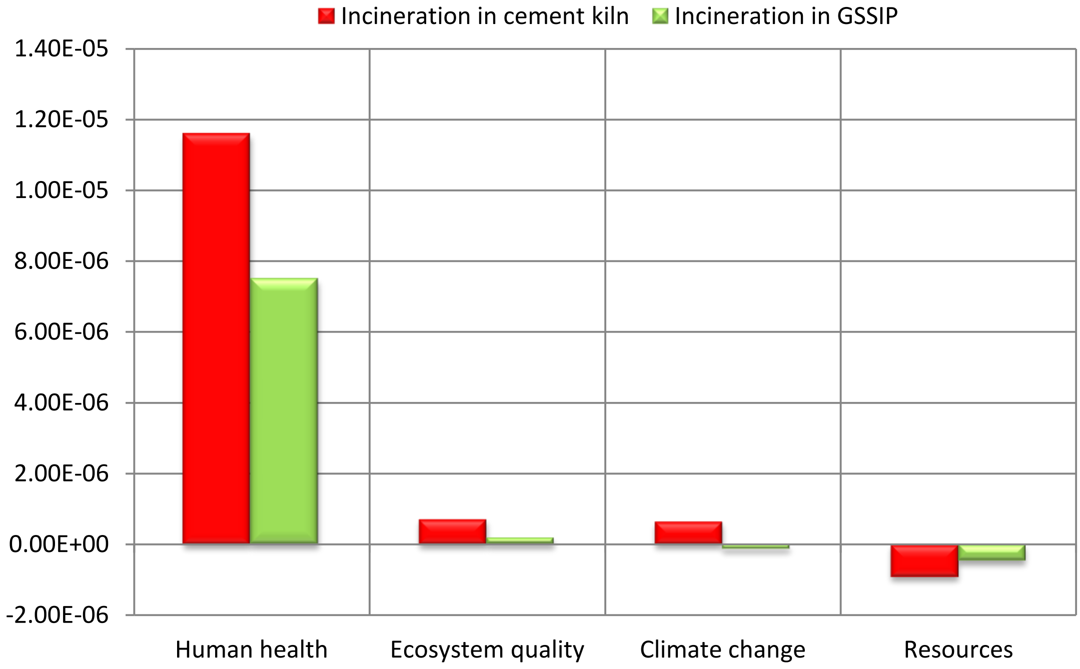


Figure 5.7 Comparing 1 kg sludge in GSSIP with 1 kg sludge in Cement Kiln IMPACT2002+ method / Normalization at endpoint.

Table 5.11 Normalization scores at endpoint for both scenarios.

Scenario	Human Health	Ecosystem Quality	Climate change	Resources
GSSIP	7.51E-06	1.87E-07	-1.25E-07	-4.64E-07
Cement Kiln	1.16E-05	7.17E-07	6.50E-07	-9.13E-07

As an intermediate stage between characterization and normalization, the Damage assessment can be an additional viewing option for the potential damages that could be result from both systems. Figure 5.8 shows a comparison based graph for the categories included within the IMPACT2002+ method. It is worthy to be mentioned that the damage scores (Table 5.12) of the chosen categories are different than that calculated in characterization stage, but the graphical Figure still the same as the characterization, because for both systems the same damage factors were used. In addition, there is no damage factors are recently available for both Aquatic Acidification and Eutrophication categories in the current method, so the damage assessment for these two categories is not exist in Figure 5.8.

Table 5.12 Damage assessment at midpoint categories.

Impact category	Cement Kiln	GSSIP
Carcinogens	5.54E-11	6.72E-09
Non-carcinogens	6.76E-09	3.55E-08
Respiratory inorganics	7.54E-08	1.10E-08
Ionizing radiation	6.09E-11	3.06E-11
Ozone layer depletion	6.39E-13	6.75E-13
Respiratory organics	3.51E-11	1.53E-11
Aquatic ecotoxicity	1.38E-04	8.08E-05
Terrestrial ecotoxicity	5.62E-03	1.74E-03
Terrestrial acid/nutri	3.91E-03	6.62E-04
Land occupation	1.42E-04	8.40E-05
Global warming	6.43E-03	-1.24E-03
Non-renewable energy	-1.39E-01	-7.07E-02

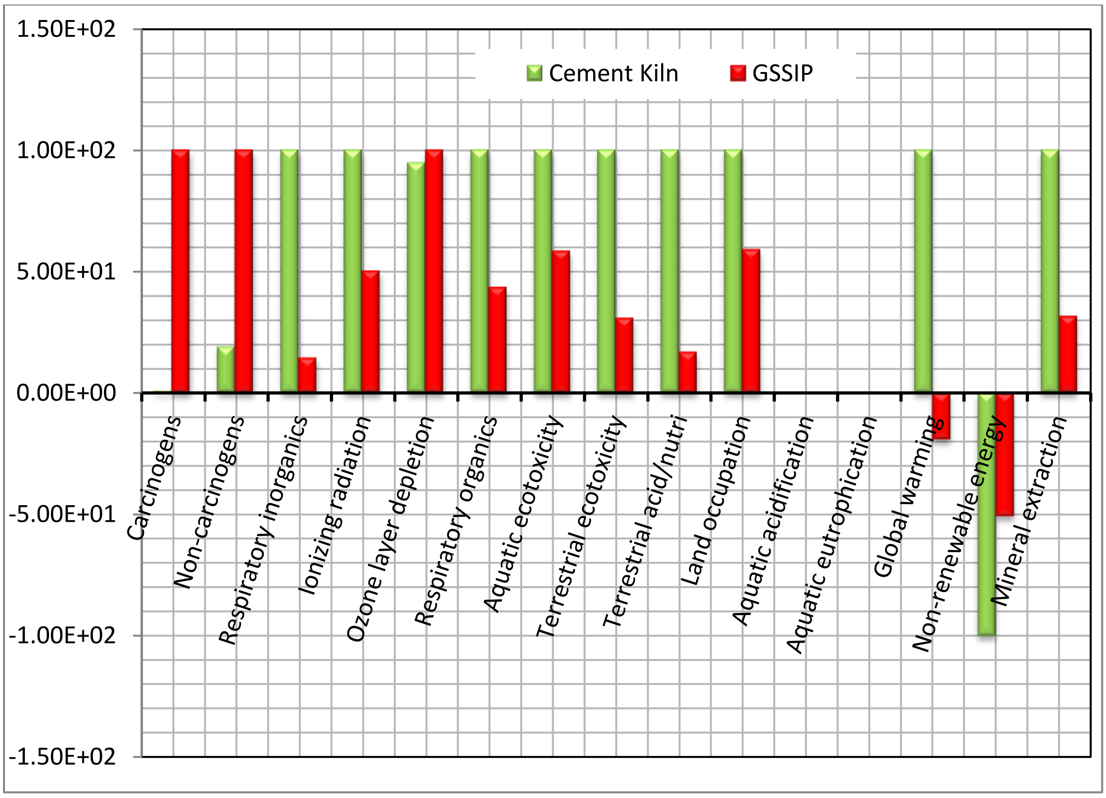


Figure 5.8 Comparing 1 kg of sludge in GSSIP, with 1 kg sludge in Cement kiln, IMPACT2002+ method / Damage assessment at midpoint

To give more details about the contribution of each substance within the same environmental impact category, and to show these details in a comparable manner for both systems, the next Figures (5.9-5.14) show the effect percentage of each substance included in each category for both systems. These Figures cover the most effective impact categories, namely; Carcinogens, Non-carcinogens, Ozone Depletion, Eutrophication, Global Warming and Non-Renewable categories respectively. The second group of Figures (5.15-5.18) shows the effective contribution of each substance included within the same impact category in the normalization stage, which give a comparative view for a specific substance to that the same substance gives in a specified geographical region (Western Europe was taken as a normalization factor).

It is worthy to mention that the scores of each impact category are affected by a large number of substances, and some of these substances contribute in more than one impact category. To avoid a long series of substances on each graph, a cut-off ratio of 1% was adopted in drawing the mentioned Figures, i.e. any substance has an effect less than 1% is neglected.

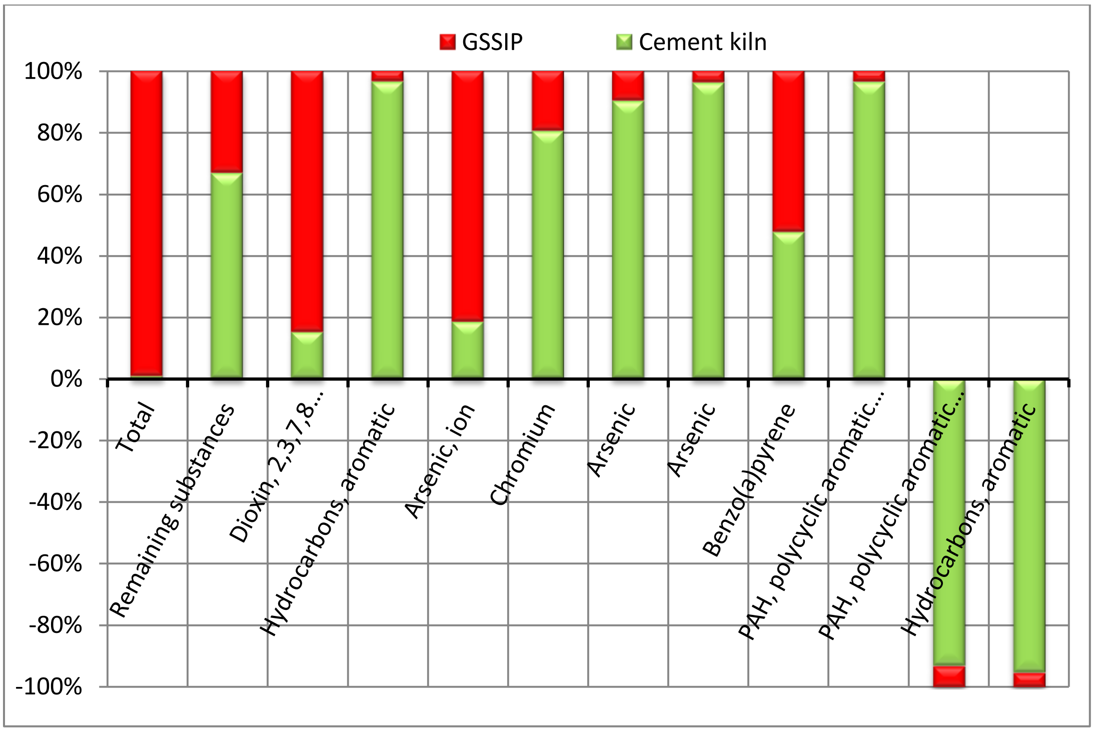


Figure 5.9 Comparing GSSIP and Cement kiln options. IMPACT2002+ method Characterization Carcinogens Constitutes percentages.

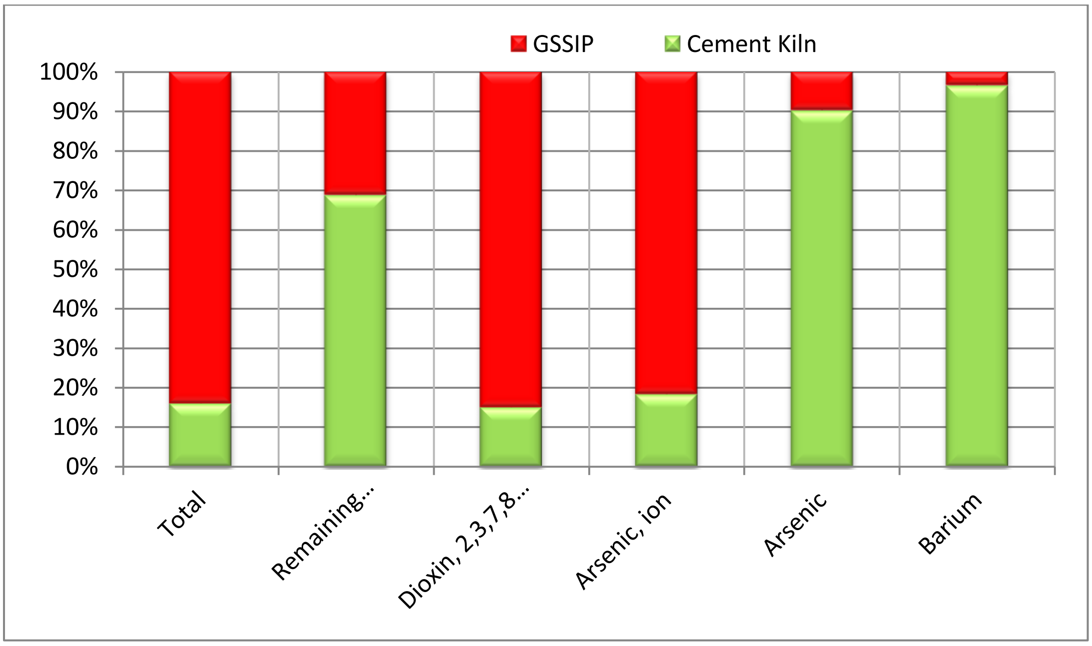


Figure 5.10 Comparing GSSIP and Cement Kiln systems. IMPACT2002+ method Characterization Non-Carcinogens Constitutes percentages.

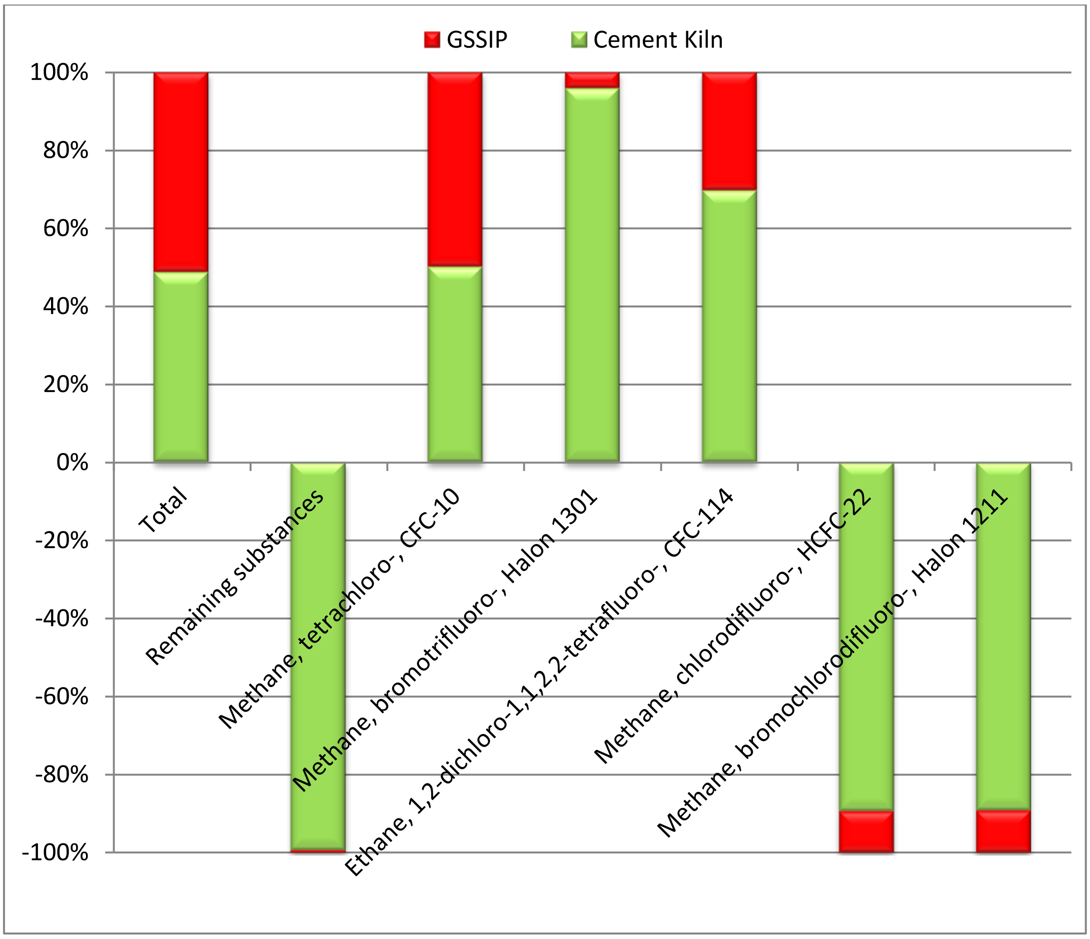


Figure 5.11 Comparing GSSIP and Cement kiln. IMPACT2002+ method Characterization Ozone Depletion Constitutes percentages.

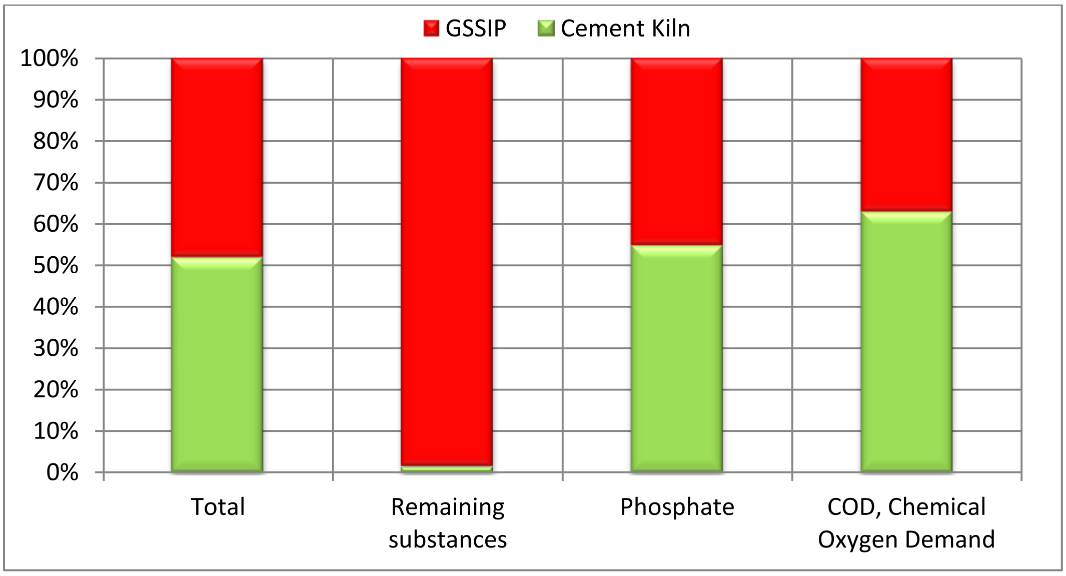


Figure 5.12 Comparing GSSIP and Cement kiln. IMPACT2002+ method Characterization Eutrophication Constitutes percentages.

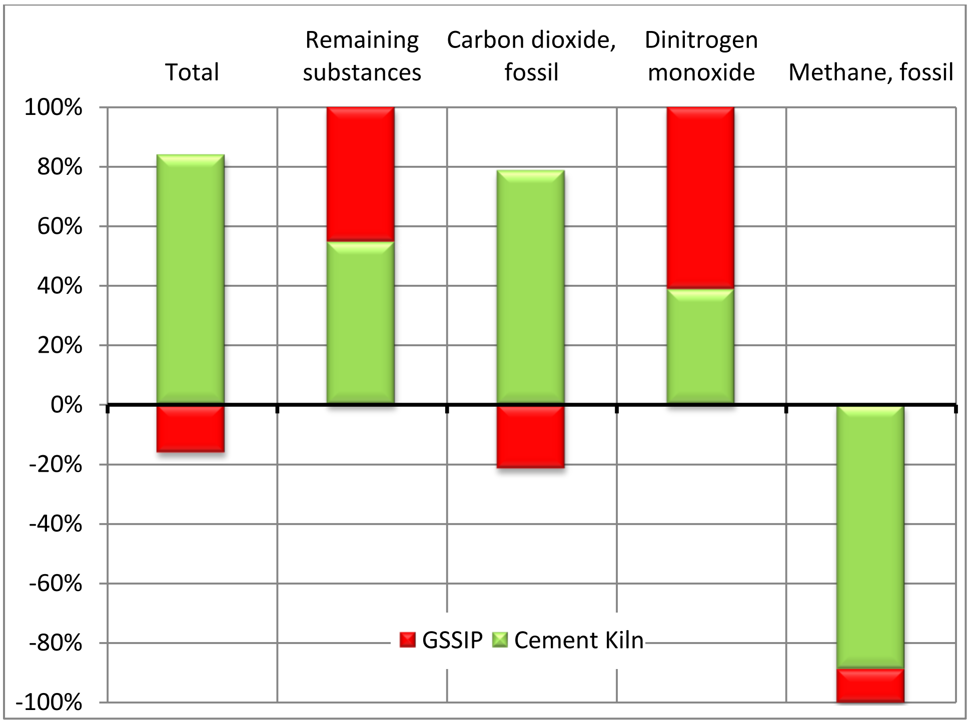


Figure 5.13 Comparing GSSIP and Cement kiln. IMPACT2002+ method Characterization Global Warming Constitutes percentages.

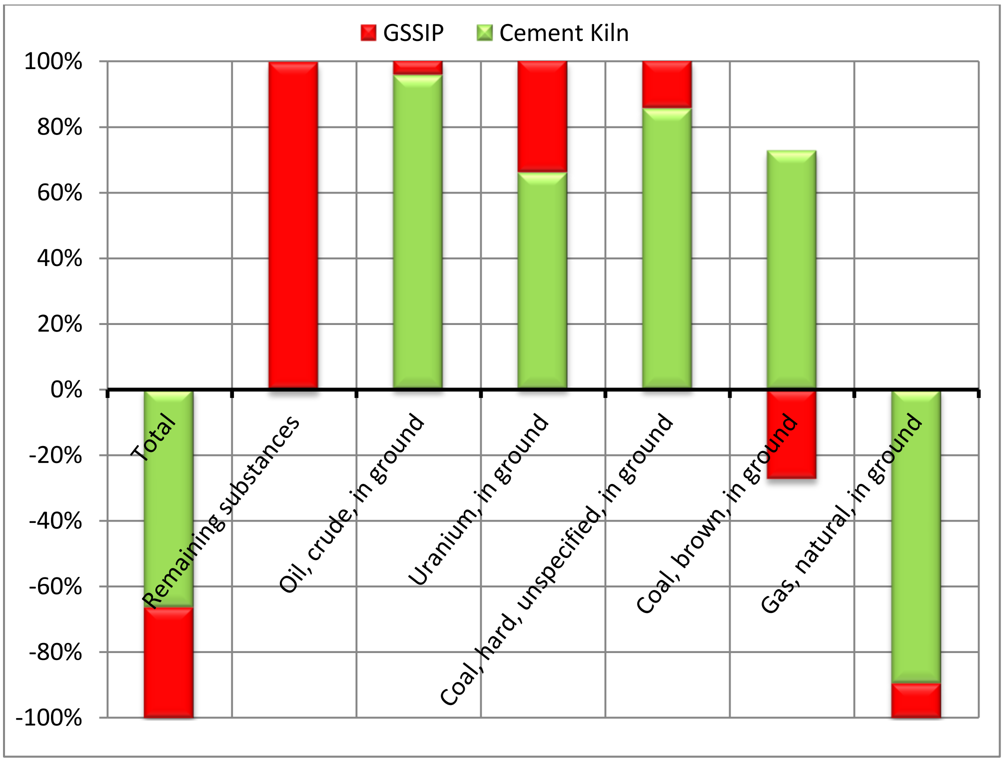


Figure 5.14 Comparing GSSIP and Cement kiln. IMPACT2002+ method Characterization Non-Renewable Energy Constitutes percentages.

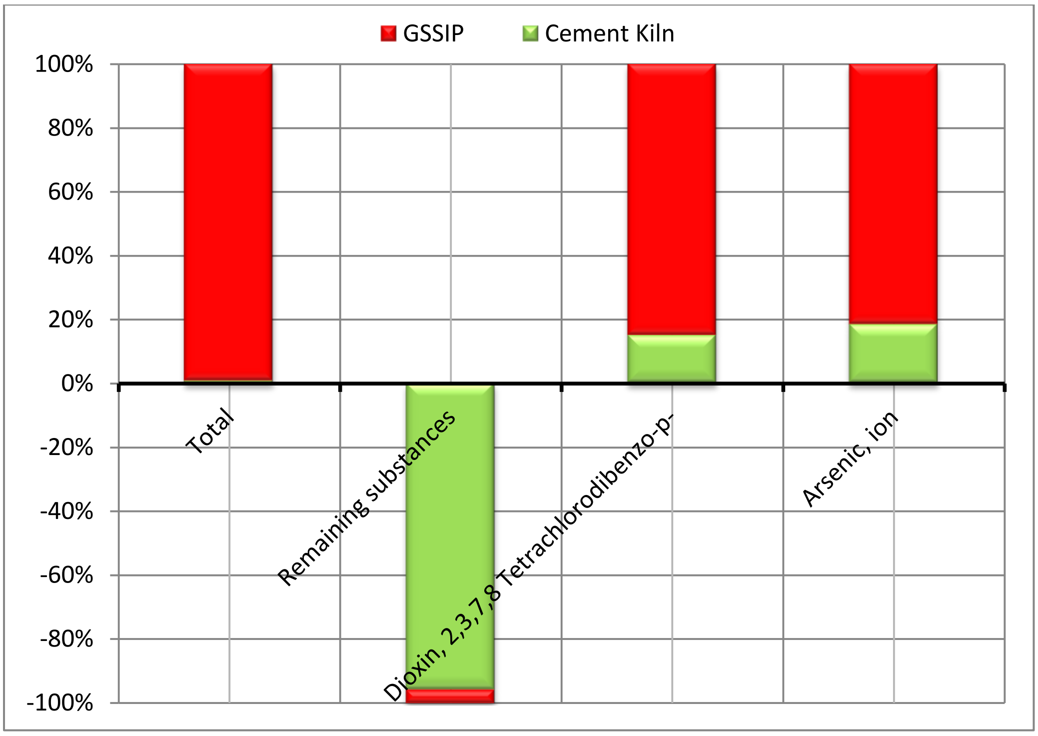


Figure 5.15 Comparing GSSIP and Cement kiln. IMPACT2002+ method Normalization Carcinogens Constitutes percentages.

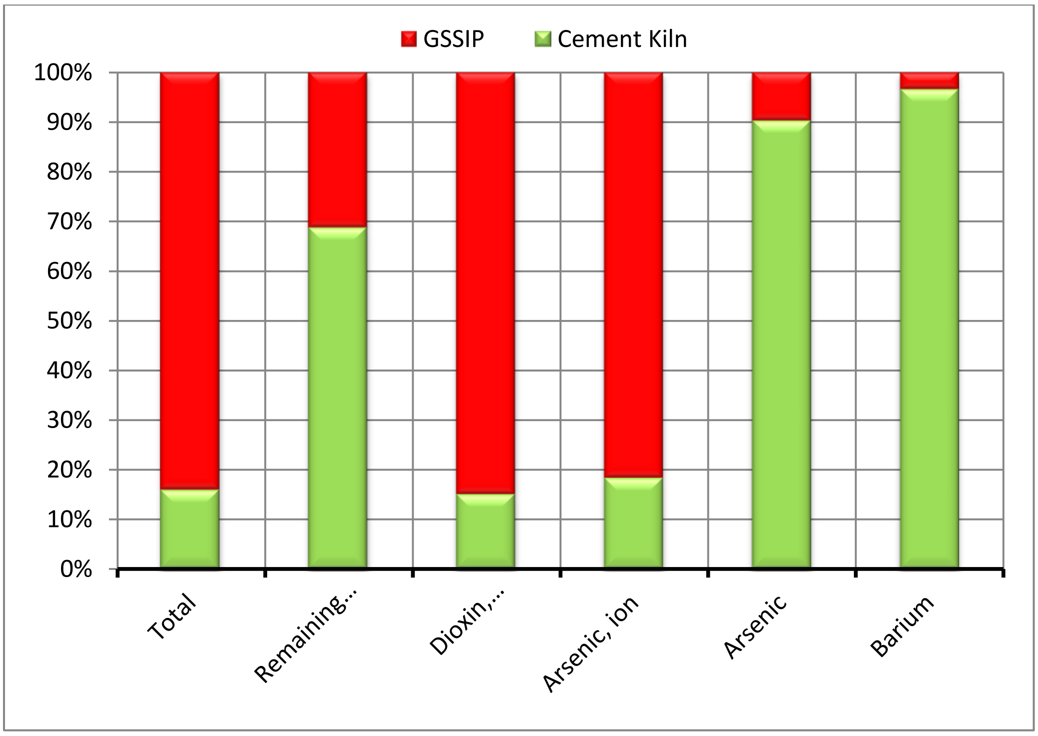


Figure 5.16 Comparing GSSIP and Cement kiln. IMPACT2002+ method Normalization Non-Carcinogens Constitutes percentages.

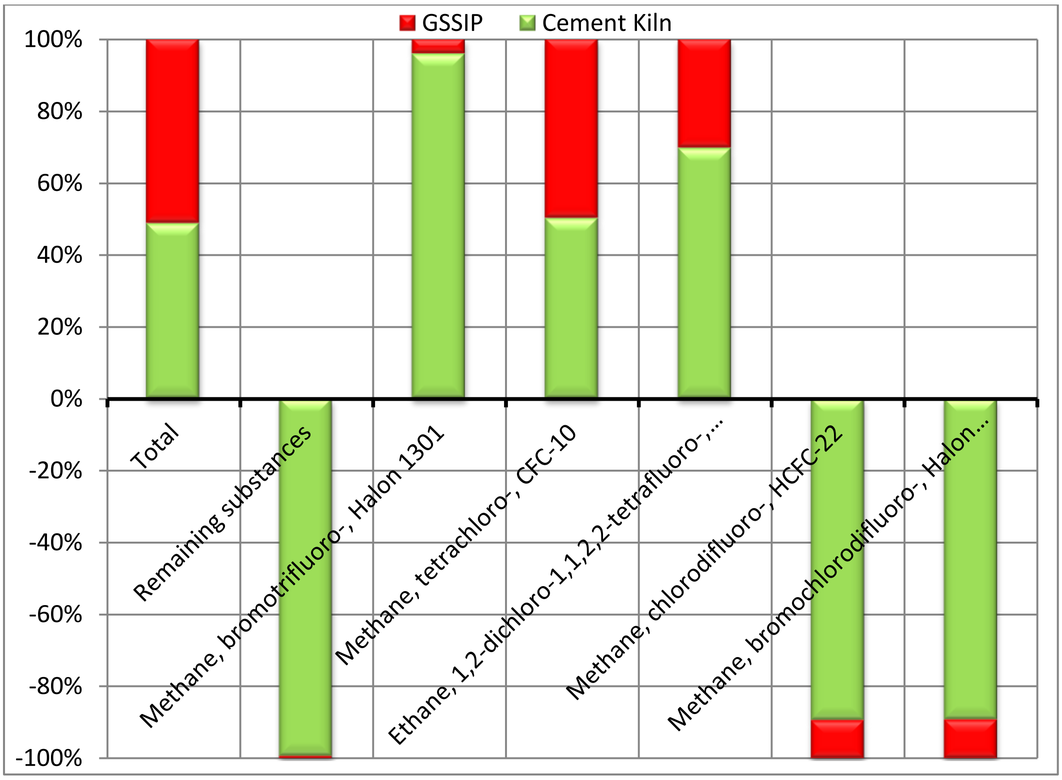


Figure 5.17 Comparing GSSIP and Cement kiln. IMPACT2002+ method Normalization Ozone Depletion Constitutes percentages.

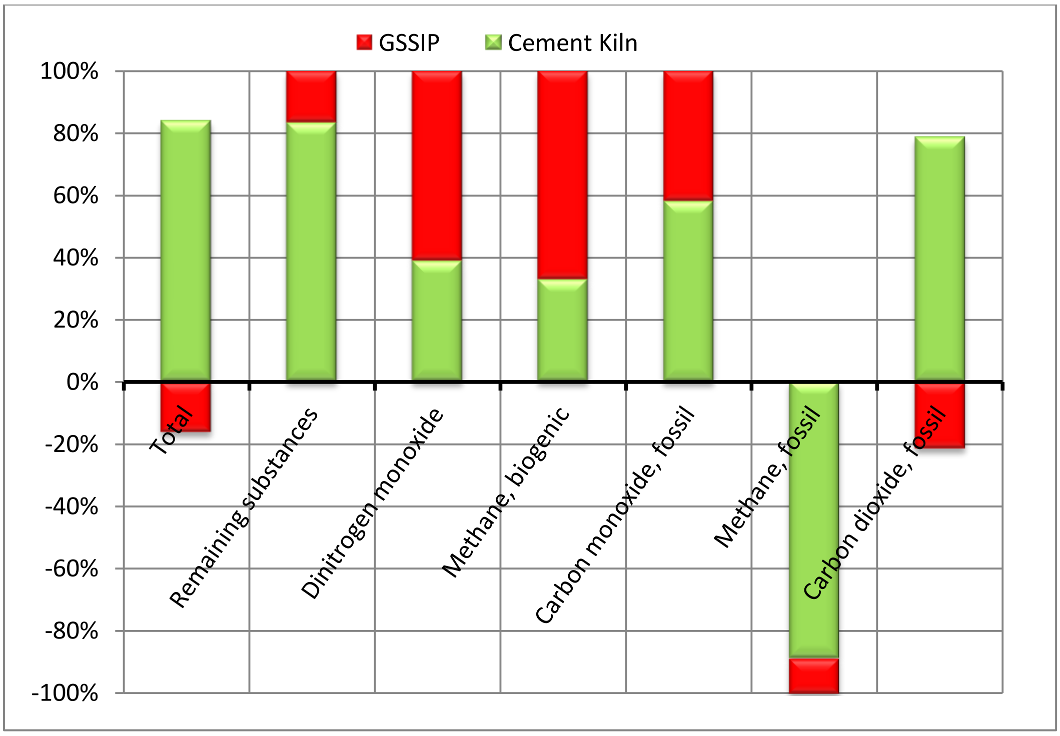


Figure 5.18 Comparing GSSIP and Cement kiln. IMPACT2002+ method Normalization Global Warming Constitutes percentages.

5.6. CONCLUSIONS

Each system has been evaluated separately by the IMPACT2002+ method with the total impact categories given in this method. Later, in a comparative manner, studied systems were assessed at different stages (midpoint and endpoint). Furthermore, systems in concern were compared at a single impact category for several significant impact categories like, Carcinogens, Non-carcinogens, Ozone depletion and Global warming. Ahead conclusions can be obtained from this chapter:

1. At midpoint categories:

   - For Human health categories (Carcinogens and Non-carcinogens) and Ozone depletion categories, Cement kiln option gives better environmental performance than the other option.
   - For Non-renewable energy impact category, the Cement kiln option precedes the other option performance.
   - From the rest of the impact categories given by IMPACT2002+ method perspective, the GSSIP system gives a better environmental performance than Cement kiln option, especially at global warming category.

2. At endpoint categories:

   - The GSSIP system option gives better environmental performance than Cement kiln option in Human health, Ecosystem quality and Climate change categories.
   - While Cement kiln (CK) option shows better performance in the Resources impact category (Damage category).

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 CONCLUSIONS

One of the biggest challenges faces the human community in recent century is the potency of energy resource depletion. This problem can be encountered from different aspects. The use of the renewable energies and the legislation of a sustainable energy handling policy represent a significant benchmark in this aspect. In this field, LCA is an effective tool to draw out the general layout of a sustainable energy handling policy. As a contribution in this regard, an LCA was applied to the process of the incineration of digested sewage sludge in two disposal facilities, namely: Gaziantep Sewage Sludge Incineration Plant (GSSIP) and a Cement factory (Rotary Kiln). The study aimed to evaluate the energy output potential from each facility and assess each scenario's environmental life cycle burdens in a comparable manner.

The most remarkable difference between both scenarios can be summarized as follows:

- In the first system (GSSIP), the digested sludge is delivered to the facility with a dry matter ratio of 5%, then dehydrated to get a 27% dry matter ratio, dried to 40 % DM ratio and incinerated with some supplementary fuel in a Fluidized Bed Incinerator at a temperature about 830-900 ° C and finally the residual material appropriately landfilled.
- While those working conditions were applied to the above mentioned system, the second scenario working conditions and stages was different from these aspects; the sludge drying process is maintained till 90% DM ratio to prevent any variation in the produced cement quality, and the second characterization factor in this scenario is the high working temperature when compared with the first scenario (1400 ° C).

- One more difference between both options is the transportation distance between the cement factory and the WWTP, which is taken in this study as 25 km, whereas for the first option, transportation assumed to be neglected.

When comparing these two scenarios, the bellow conclusions can be reached:

1. From an energetic transaction viewpoint:
    - GSSIP consumes less fossil energy for the disposal of the specified quantity of digested sewage sludge, while much more energy required in the cement kiln for the same disposed sludge. Consequently, the first option acquired better performance in the global warming category field which is normally affected by fossil carbonic emissions..
    - GSSIP recovers energy in two forms, but the total sum of it is less than that recovered in the cement kiln, because some of this recovered energy comes from the energy of the clinker production process.
    - More energy in the form of electricity is used for incineration of sludge in the cement kiln (kiln rotation energy requirement), but this energy was left outside the system boundary of this scenario and assumed to be allocated to the clinker production process.
    - The last two points led to grant a better performance for the second scenario in Non-renewable energy category regard.
2. From human health categories viewpoint:
    - GSSIP scenario gives more environmental burdens in this regard, while the cement kiln scenario shows a good performance in the mentioned categories.
    - The destination of the human health damage causer (mostly the heavy metal) in the first scenario is obvious (landfilled), while for the second scenario is suspended or postponed (immobilized with the clinker).

3. Except the Ozone Depletion category and the above mentioned categories, in the rest categories of the used methods, first scenario records better performance than the second scenario in different rates.

The performance of each scenario can be improved by reducing the fossil fuel usage in cement kiln by using solar drying for the sludge if applicable, whereas for the fluidized bed scenario, its performance can be promoted by reusing the residual material in any practicable production process like construction material production.

The scenario of the fluidized bed incineration for sewage sludge can be applied anywhere, whereas the cement kiln scenario is limited by the existence of cement factories in the vicinity. In contrast, from an economic perspective, the cement kiln option has less primary costs due to the fact that the cement kilns are already available for cement production, and thus the costs of purchasing, transporting and installing of the facility are eliminated and limited to the addition of a sludge drying system to the existed facility.

6.2 FUTURE STUDIES

As a recommendation for future studies, it would be useful to study the effects of the dryness ratio of the used sewage sludge, and the benefits obtained from using flue gas heat of cement factories to dry the used sludge. Furthermore, the investigations of the effect of using non-digested sewage sludge on both environmental aspects and of the energy balance, are also recommended. In addition, and to enlarge the scope of the study, it would be better to include more thermal disposal methods like pyrolysis and gasification in the suggested studies.

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