LIFE CYCLE IMPACT ASSESSMENT OF AN ANAEROBIC DIGESTER PLANT FOR ORGANIC WASTES GENERATED FROM A UNIVERSITY CAMPUS IN ISTANBUL

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by

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ABSTRACT

In this thesis, life cycle impact assessment application for the utilization of food wastes through anaerobic digestion (AD) is carried out. For this purpose, characterization of the food wastes generated from selected campuses of Bogazici University is performed as first step. The average biogas potential is found as 0.140 m^3/kg wet waste. Around 0.66 m^3, 0.70 m^3 biogas, 0.36 m^3 methane can be obtained per kg of total solid (TS), per kg of volatile solid and per kg of TS, respectively.

The integrated AD plant is designed for the university as second stage. During the education period (EP), 55 m^3 biogas is generated by AD of ~82 kg of dry waste per day. Nearly 300 kWh energy can be produced by 28 kW cogeneration engine daily. Around 5.5 kWh and 10 kWh energy can be obtained per m^3 of biogas and methane, respectively. For the EP, electricity (E) and heat (H) requirements of the plant are determined as 14.95 % and 30.53% of the total E and H produced, respectively. The H requirement for the indoor swimming pool at Hisar Campus is designed to be supplied by the AD plant. Roughly, 16 % of the H requirement of the pool can be achieved.

In the last part of the study; the life cycle assessment (LCA) methodology has been applied. An integrated approach has been brought for AD plant through well known softwares of LCA such as GaBi 4 software. During LCA study, special emphasis is given to global warming (GW). Results showed that, AD technology is highly advantageous over current waste disposal and national energy production systems in terms of environmental protection capacity and renewable energy production. 97.8% reduction and ~85% reduction can be achieved in terms of GW and other relevant categories (acidification, photochemical ozone formation, aquatic eutraphication, terrestrial eutraphication), respectively. When utilization of the produced energy and overall energy requirement of the Hisar Campus is considered, the plant provides 7.23% reduction on GW and more than 4% reduction for other impact categories. Composting is only advantageous when it is considered as a waste management option, since volume reduction is achieved. However, when the energy need of the composting plant is considered, impact of composting scenario is assessed to be higher than other scenarios.

ÖZET

Bu çalışmada, yemek atıklarının oksijensiz ortamda çürütülmesi ile kullanımının yaşam döngüsü etki değerlendirilmesi gerçekleştirilmiştir. İlk olarak, Boğaziçi Üniversitesi'nin seçilen kampüslerinde oluşan yemek atıklarının karakterizasyonu yapılmıştır. Biyogaz potansiteli yaklaşık ~0,140 m^3/kg ham atık olarak belirlenmiştir. Bir kg toplam katı, bir kg uçucu katı ve bir kg toplam katı için, sırası ile yaklaşık 0,66 m^3, 0,70 m^3 biyogaz, 0,36 m^3 metan oluşumu sağlanabilmektedir.

İkinci olarak, üniversiteye uygun oksijensiz ortamda çürütme tesisi (OOÇT) tasarlanmıştır. Eğitim döneminde (ED) günde ~82 kg kuru atıktan 55 m^3 biyogaz oluşumu sağlanmaktadır. 28 kW'lık kojenerasyon motoru ile günlük, ~300 kWh enerji elde edilebilir. Sırası ile 1 m^3 biyogaz ve 1 m^3 metandan yaklaşık 5.5 kWh ve 10 kWh enerji üretilebilmektedir. Tesisin elektrik (El) ve ısı (I) enerjisi ihtiyacı, ED üretilen El ve I enerjisinin sırası ile %14,95'i ve %30,53'üdür. OOÇT ile elde edilen I, Hisar Kampüs'te bulunan kapalı yüzme havuzunun I ihtiyacının %16'sını karşılayabilir.

Çalışmanın son aşamasında, yaşam döngüsü analizi (YDA) metodolojisi uygulanmıştır. YDA'inin bilinen yazılımlarından GaBi 4 yazılımı ile OOÇT'ye entegre bir yaklaşım getirilmiş, küresel ısınma potansiyeline (KIP) önem verilmiştir. Sonuçlar, OOÇT'inin mevcut atık uzaklaştırma ve ulusal enerji üretim sistemlerine gore çevre koruma kapasitesi ve yenilenebilir enerji üretimi bakımından çok avantajlı olduğunu göstermiştir. KIP kapsamında, oksijensiz ortamda çürütme teknolojisi %97.8 oranında etki azaltımı sağlamaktadır. Diğer kategoriler için ise (asitleştirme, fotokimyasal ozon oluşumu, su ve kara ortamlarında ötrofikasyon) %85 oranında etki azaltımı sağlanabilmektedir. Üretilen enerjinin kullanımı ve Hisar Kampüs'ün tüm enerji ihtiyacı göze alındığında, oksijensiz ortamda çürütme tesisi KIP kapsamında, %7.23 etki azaltımı ve diğer kategorilerde %4'ün üzerinde etki azaltımı sağlamaktadır. Kompostlaştırma, hacim azaltımı sağladığından, sadece atık yönetimi kapsamında değerlendirildiğinde avantajlı olduğu görülmüştür. Fakat, kompostlaştırma tesinin enerji ihtiyacı göze alındığında, bu senaryonun küresel ısınma etki potansiyeli diğer senaryolardan yüksek bulunmuştur.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**	**Units used**
AD	Anaerobic Digestion	-
CH_4	Methane	-
CHP	Combined Heat and Power	-
CO_2	Carbon Dioxide	-
E	Electricity	-
EP	Education Period	-
H	Heat	-
FU	Functional Unit	-
HRT	Hydraulic Retention Time	hour
LCA	Life Cycle Assessment	-
LCI	Life Cycle Inventory	-
LCIA	Life Cycle Impact Assessment	-
ISO	International Organisation for Standardisation	-
GHG	Greenhouse Gas	-
GW	Global Warming	-
GWP	Global Warming Potential	kg CO_2- eq.
NMVOC	Non-methane volatile organic compounds	-
N_2O	Nitrous oxide	-
MC	Moisture Content	-
ODM	Organic Dry Matter	-
OECD	Organisation for Economic Co-operation and Development	-
STP	Standard Temperature and Pressure	-
TS	Total Solids	-
UES	Unprotected Ecosystem	m^2
VS	Volatile Solids	-

1. INTRODUCTION

Energy demand of the world has been increasing steadily for the last several decades. World energy consumption increases by nearly 50 percent from 2009 to 2035 and most of the growth occurs in emerging economies outside the Organisation for Economic Co-operation and Development (OECD). Total energy demand in non-OECD countries is increasing by 84 percent, compared with an increase of 14 percent in OECD countries as shown in Figure 1.1 (U.S. EIA, 2011).

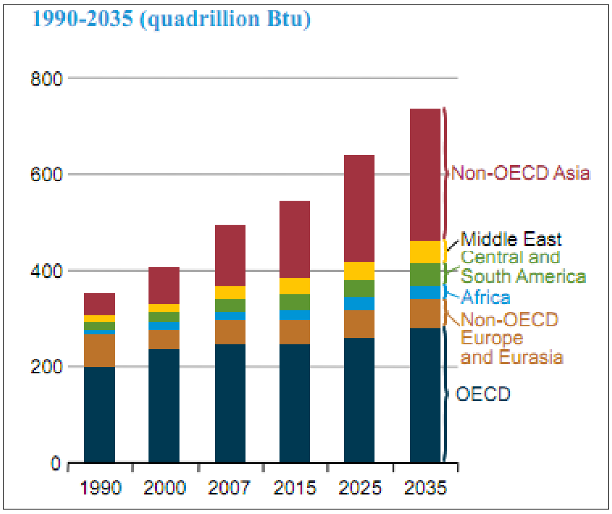

Figure 1.1. World marketed energy consumption (U.S. EIA, 2011).

The world's total primary energy supply was 11,059 Mtoe in 2004. Oil accounted for 32.32% of the total energy supply, followed by coal and gas by 25.1% and 20.92%, respectively. Renewables only accounted for 13.1% of the total energy supply (IEA, 2007). Since fossil fuels are limited and the production of energy from fossil fuel processes cause emissions that contribute to the global warming, the role of renewable energy sources becomes increasingly important.

Anaerobic digestion technology which enables energy production and waste reduction emerges as an attractive energy source, since many European countries are facing significant problems related with the overproduction of organic wastes (Seadi et al., 2008).

Energy production by anaerobic digestion has several important advantages over other renewable energy sources. First of all, it transforms waste material into a valuable resource by using organic wastes as substrates, which is a feasible organic waste utilization method. It reduces both water born diseases and greenhouse gas emissions, while contributing to the preservation of resources.

The major organic wastes generated from Bogazici University’s campuses are food wastes. For weekdays in education period, 87.18% of the food wastes are generated from South and North Campuses. The amount of waste generated per week from South and North Campuses are 2705 kg, 325 kg, 325 kg and 50 kg for winter education period, winter holiday period, summer education period and summer holiday period, respectively. For the time being, these wastes are disposed with other solid wastes and their transport is supplied by the Sarıyer Municipality for Kemerburgaz solid waste landfill side in Istanbul (Istanbul Metropolitan Municipality, 2012).

For utilization of food wastes generated from Bogazici University’s Campuses, an anaerobic digestion plant is designed for the university. Processes are determined according to the amount and characterization of food wastes. Generated energy from the plant is assumed to be supplied to the indoor swimming pool in Hisar Campus and Hisar Campus Building.

In order to bring an integrated approach for the utilization of organic wastes and production of energy from the food wastes, life cycle assessment which is used as a tool for estimating and assessing the environmental impacts attributable to the life cycle of products (Rebitzer et al., 2004), is implemented as a decision support mechanism for environmental management systems. The study is carried out by using GaBi 4 software, a program based on International Organisation for Standardisation (ISO) standards. Anaerobic digestion of food wastes scenario is compared with current waste disposal and energy production methods. The composting of food wastes, as a waste management scenario, is also compared with the anaerobic digestion technology and current waste disposal and energy production methods in the scope of global warming.

2. REVIEW OF THE LITERATURE

2.1. Life Cycle Assessment

2.1.1. Introduction

Life Cycle Assessment (LCA) is defined as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." (ISO, 2006a). It is used as an assessment tool to assess the potential impacts and environmental aspects associated with a product, process, or service (USEPA, 2011a). As a minimum requirement, an LCA should follow the ISO 14040 standards to be accepted in public discussions (European Commission, 2011). ISO 14040 describes the principles and framework of LCA analysis and includes the goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation phases (ISO, 2006a).

Following life cycle impact potentials can be obtained by using several impact assessment methodologies in GaBi database: Global Warming Potential, Abiotic Depletion, Acidification, Eutrophication, Ozone Layer Depletion, Photochemical Ozone Creation, Freshwater Aquatic Ecotoxicity, Human Toxicity, Marine Aquatic Ecotoxicity, Radioactive Radiation, Terrestric Ecotoxicity (GaBi, 2011).

2.1.2. Phases to Life Cycle Assessment

Since the complexity of LCA requires a fixed protocol to perform an LCA study, a protocol has been established by the ISO and is generally referred to as the methodological framework (Guinée et al., 2006). In accordance with the standard ISO 14040 , four interrelated phases of LCA; goal and scope definition, inventory analysis, impact assessment and interpretation are indicated in Figure 2.1.

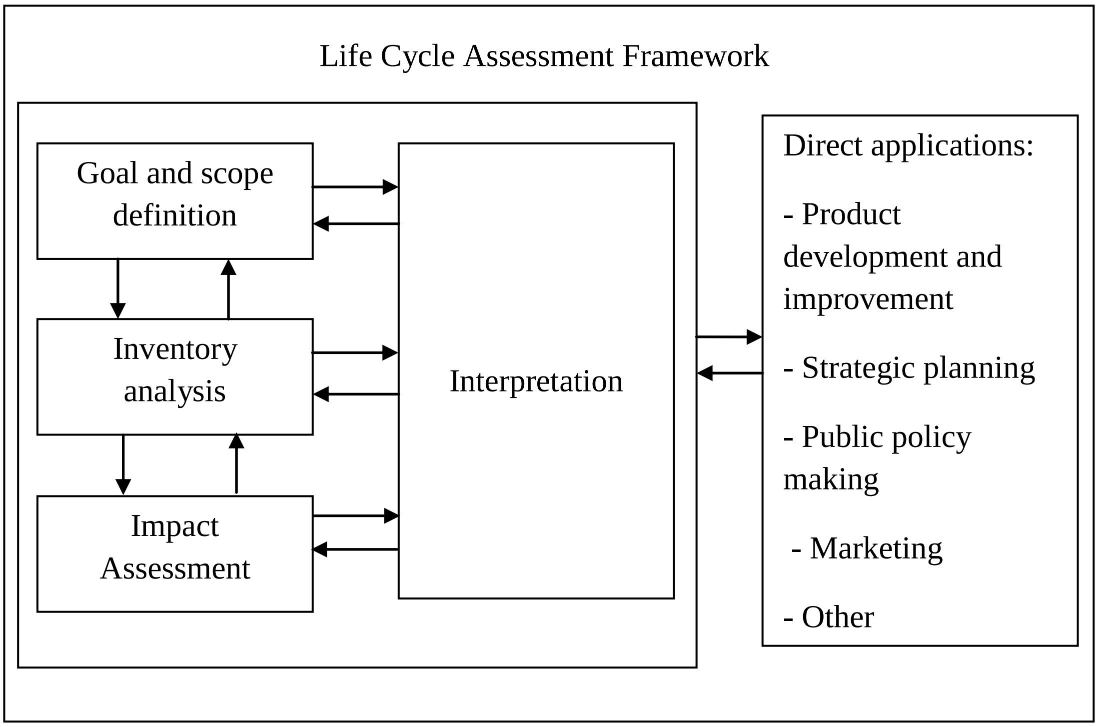

Figure 2.1. LCA framework (ISO, 2006a).

2.1.3. Goal and Scope Definition

The most important component of an LCA is possibly goal and scope definition, since the study is carried out according to the statements made in this step. The purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions are determined in this phase (Roy et al., 2009).

The unit processes that are included in the system are defined in system boundary. FU provides a reference to which the inputs and outputs are related (ISO, 2006a).

2.1.4. Life Cycle Inventory

The second phase of an LCA, life cycle inventory, deals with the collection and processing of data to quantify relevant inputs and outputs of a products system (Klüppel, 1997; ISO, 2006a).

Data collection should be presented in the study. In order to generate the results for each unit process and for the defined functional unit of the product system that is to be modeled, validation of collected data, relating of data to unit process, to the reference flow and to the functional unit is needed. When dealing with systems involving recycling or multiple products, the need for allocation procedures should also be considered (ISO, 2006a).

2.1.5. Life Cycle Impact Assessment

In this phase, potential environmental impacts are aimed to be evaluated. This process involves associating inventory data with specific environmental impact categories (ISO, 2006a). Figure 2.2. indicates the steps that should be carried out to transform the quantitative data collected into impacts.

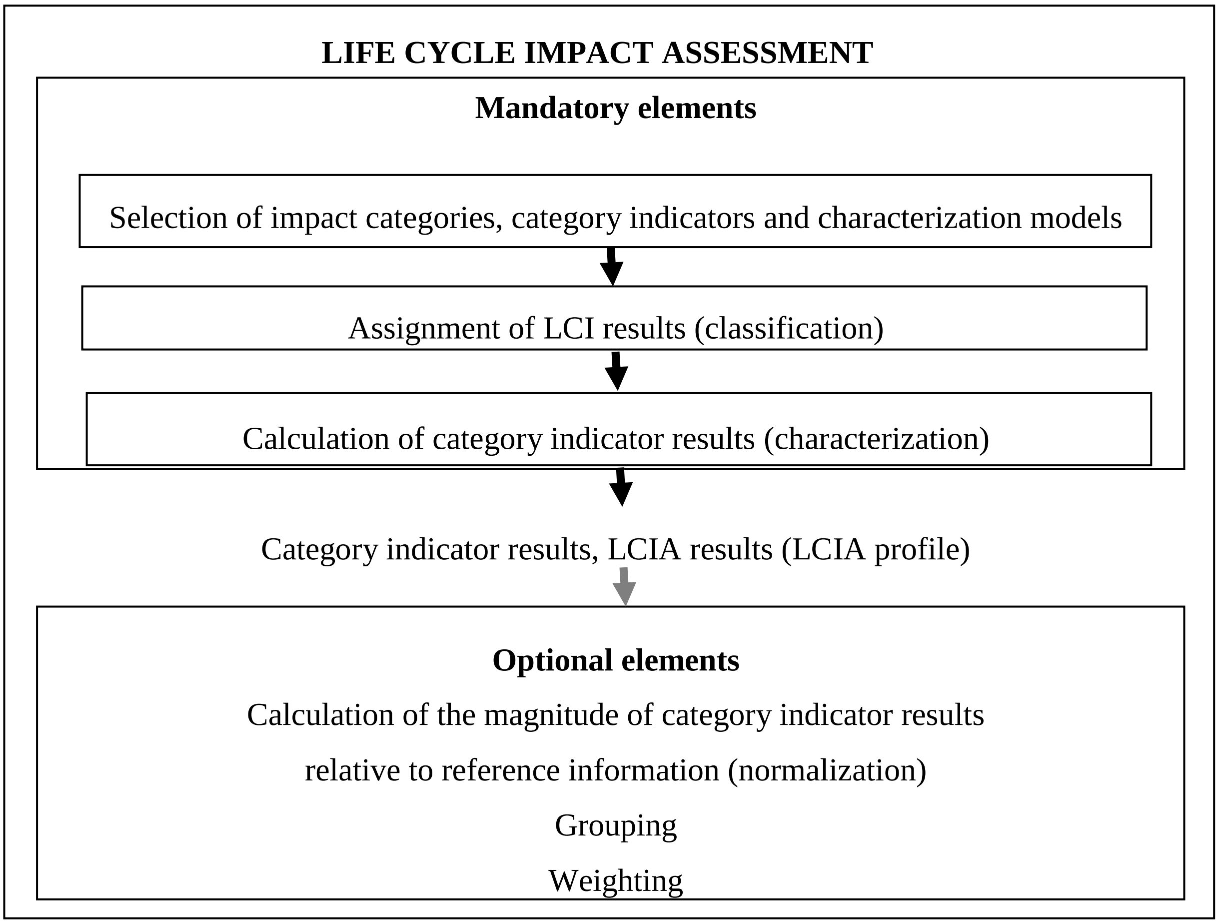

Figure 2.2. Elements of an LCIA study (ISO, 2006a).

Impact category determination is the first step of LCIA. In this step, the contribution of the emissions to the selected impact category is indicated. Commonly used life cycle impact categories are shown in Table 2.1.

Table 2.1. Commonly used impact categories (USEPA, 2006).

Impact Category	**Emissions**
Global Warming	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydro Cholorofluorocarbons (HCFCs) Methly Bromide (CH_3Br)
Acidification	Sulphur Oxide (SO_x) Nitogen Oxides (NO_x) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)
Eutrophication	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates and Ammonia (NH_4)
Ozone Depletion	Chlorofluorocarbons (CFCs) Hydro Chlorofluorocarbons (HCFCs) Halons Methly Bromide (CH_3Br)
Photochemical Smog	Non-methane Hydrocarbon (NMHC)
Terrestrial Toxicity	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Toxic chemicals with a reported lethal concentration to fish
Human Health	Total releases to air, water, and soil
Resource Depletion	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Quantity disposed of in a landfill or other land modifications
Water Use	Water used or consumed

Impact category determination is followed by classification and characterization. Classification provides guidance for assignment of life cycle inventory (LCI) results to impact categories (ISO, 2006b).

In this step, input and output parameters of the inventory are assigned to the impact categories. For instance CO_2, CH_4, N_2O is defined in terms of ‘global warming’ (Klöpffer, 1997).

According to the ISO 14044:2006, characterization involves ‘the conversion of LCI results to common units and the aggregation of the converted results within the impact category.' Potential contribution is transformed via characterization factors.

LCA study is followed by normalization and weighing which are optional steps. In normalization, the magnitude of an impact relative to the total effect of a given reference is calculated. An indicator result is divided by a selected reference value. Examples of reference value can be the total emissions or resource use for a given area which may be global, regional, national or local. Later, in weighting, indicator results of impact categories are converted by using numerical factors (ISO, 2006b). Weighting which indicates the impact potential of different impact categories, enables comparision of different impact categories.

Finally, interpretation, last step of LCA is carried out. In this step LCI and LCIA results are identified, quantified, checked and evaluated (USEPA, 2011b).

2.2. Importance of Anaerobic Digestion and Its Products from the Point of Renewable Energy Production

Anaerobic digestion has several important advantages. First of all, a reduction of emissions of; mainly CO_2, CH_4 and N_2O, can be achieved, when biogas displaces fossil fuels. Many European countries are facing significant problems related with overproduction of organic wastes. Anaerobic digestion transforms waste into valuable resources. Therefore, it emerges as an attractive energy source (Seadi et al., 2008). Moreover, anaerobic digestion provides better odor control, improved nutrient management flexibility and water quality protection (U.S EPA, 2011c).

One of the products of anaerobic digestion, biogas, is used to produce energy. It may be used for combined heat and power generation (CHP), or fed into natural gas grids, used as vehicle fuel or in fuel cells after upgrading. Other product of anaerobic digestion, digestate, a valuable soil fertilise which is rich in nutrients, can be applied on soils (Seadi et al., 2008).

The physical and chemical characteristics of food wastes are important parameters for anaerobic digestion process, since it effects biogas production. Some of these characteristics are moisture content, volatile solids content, nutrient contents, particle size, and biodegradability (Zhang et al., 2007). Some characteristics and methane yields of food wastes that have been reported in the literature are indicated in Table 2.2, Table 2.3.

The moisture content (MC) of food waste varies between 69% and 85%, and VS/TS ratio differs between 85% and 95%. Carbon, nitrogen ratio (C/N) is generally about 14 except the food waste that examined in India.

Table 2.2. Characterization of food wastes in literature.

Country	**Source**	**MC %**	**VS/TS**	**C/N**	**References**
Korea	Dining Hall	79.5	95	14.7	Han and Shin, 2004
Korea	University	80.03	93.55	-	Kwon et al., 2004
USA	Food leftovers of city of San Francisco	69.9	87	14.8	California Energy Commission, 2005
India	Food wastes emanating from fruit and vegetable markets, households, hotels and juice centres	85	88.5	36.36	Rao and Singh, 2004
USA	Restaurants, 50 food markets (grocery stores), and 150 commercial sources (hotels and businesses).	69.1	85.3	14.8	Zhang et al., 2007

Table 2.3. Methane yields of food wastes.

Feedstock	**Operating Condition**	**Gas Yield**	**References**
Vegetable wastes	Fed-batch laboratory scale reactor, mesophilic conditions (35^{O}C) 30 days of hdraulic retention time	0.387 l CH_4 /g VS	Velmurugan and Ramanujam, 2011
Food Waste	Batch tests performed at 50 °C	10 days: 0.348 l CH_4/g VS 28 days: 0.435 l CH4/g VS	Zhang et al., 2007
Fruit and vegetable wastes	Two coupled anaerobic sequencing batch reactors operated at mesophilic temperature	0.320 l CH_4/g COD	Bouallagui et al., 2004
Fruit market waste	Theorotical biogas yield determination Mesophilic conditions at 35°C	0.686 l biogas /g VS 0.65 CH_4 content	Cahyari and Putra, 2010

There is no significant difference observed on methane yields of food wastes in literature. More than 0.3 l CH_4 is produced per g of VS.

2.3. Anaerobic Digestion Process Definition with Its Energy Balance

A biochemical process during which complex organic matter is broke down in the absence of oxygen is defined as anaerobic digestion. This bacterial process of anaerobic digestion, as shown in Figure 2.3, is completed by various types of anaerobic microorganisms.

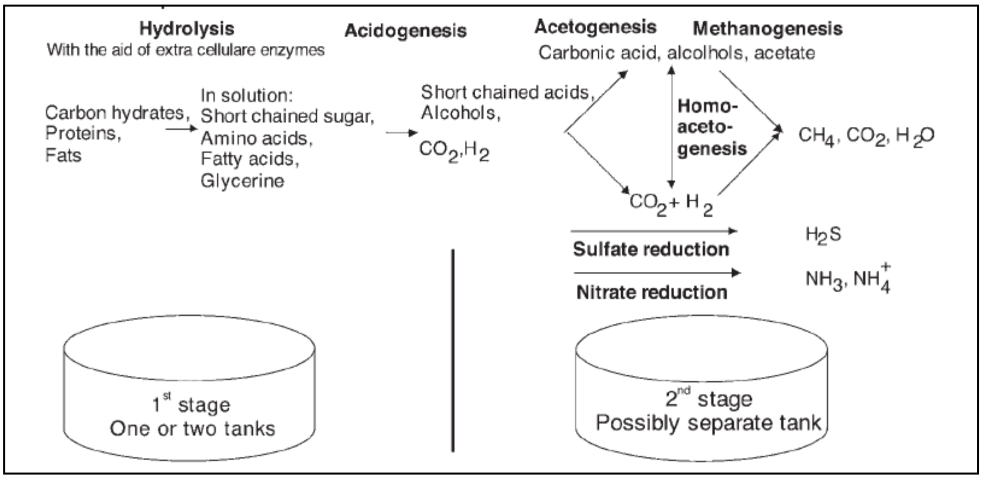

Figure 2.3. Biochemistry of methane gas production (Deublein and Steinhauster, 2008).

The two main products of this process are digestate and biogas which consists of methane, carbon dioxide and small amounts of other gases (Seadi et al., 2008). Suitable biowastes for anaerobic digestion is shown in Table 2.4.

Table 2.4. Biowastes suitable for anaerobic digestion (European Comission, 2001).

Waste Code	**Waste decription**	
02 00 00	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing
		Waste from the preparation and processing of meat, fish&other foods of animal origin
		Wastes from the fruit, vegetables,cereals, edible oils, cocoa, coffee, tea, tobacco preparation&processing; conserve production; yeast, yeast extract production, molasses preparation and fermentation
		Wastes from sugar processing
		Wastes from the dairy products industry
		Wastes from the baking, confectionery industry
		Wastes from the production of alcoholic and non-alcohol beverages (except coffee, tea and cocoa)
03 00 00	Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboar	Wastes from wood processing and the production of panels and furniture
		Wastes from pulp, paper and cardboard production and processing
04 00 00	Waste from the leather, fur and textile industries	Wastes from the leather and fur industry
		Wastes from the textile industry
15 00 00	Waste packaging; absorbents, wiping cloths, filter materials, protective clothing not otherwise specified	Packaging (including separately collected municipal packaging waste)
19 00 00	Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use	Wastes from anaerobic treatment of waste
		Wastes from waste water treatment plants not otherwise specified
		Wastes from the preparation of water intended for human consumption or water for industrial use
20 00 00	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Separately collected fractions (except packaging including separately collected municipal packaging waste)
		Garden and park wastes (including cemetery waste) and other municipal wastes

The energy balance calculation of a biogas plant is undoubtedly one of the most important steps of the design process, since it indicates the net energy value of the plant.

The operation of the biogas plant is generally the most energy-demanding process, corresponding to approximately 40–80% of the net energy demand (Berglung and Börjesson, 2006).

In a study which carried out in Japan, net energy is calculated according to the energy balance which is shown in Figure 2.4. The results showed that, the amount of tank heat losses in all temperature conditions in Japan were about 26-39% of total heat demand. When the temperature was highest, net energy was 84% of total energy produced. When the temperature was the lowest, net energy was 45% of the total energy produced (Basrawi et al., 2010)

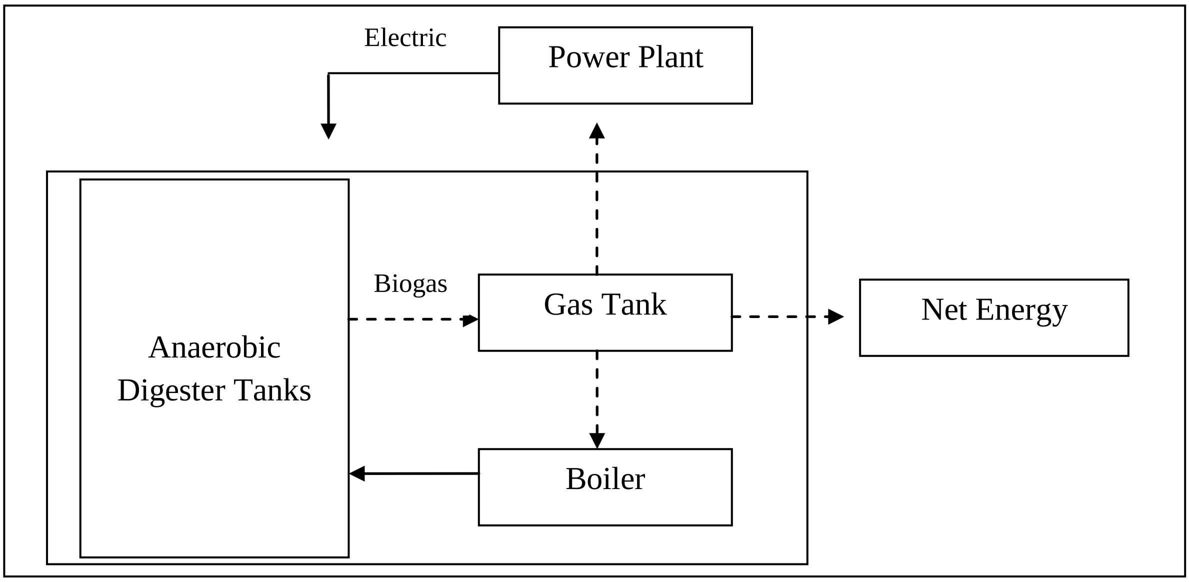

Figure 2.4. Energy balance in the anaerobic digestion plant (Basrawi et al., 2010).

2.4. Anaerobic Digestion Process Design and Application

2.4.1. Conditioning

Feedstock conditioning influences the efficiency of anaerobic digestion process and contributes to digestion rates and biogas yields. The aim of feedstock conditioning is providing homogenized feedstock to the digesters. Since anaerobic digestion microorganisms have to adapt to new substrates and to changing conditions, large fluctuations of the supplied feedstock composition negatively efftects the anaerobic digestion microorganisms (Seadi et al., 2008).

First of all, impurities in feedstock should be removed by mechanical, magnetic or manual methods (Seadi et al., 2008). In addition, particle size shoud be decreased and the feedstock should be well mixed before supplying the feedstock into the digesters.

Most of the existing biogas plants operate at dry matter concentrations of 3 – 12 %, since this material can be directly pumped without any special equipment. So, it is easier to ensure proper mixing in the reactor (Poulsen, 2003). Moreover, the material that have more than 85% water content provides better exchange of material and heat, hygiene, better control of pH, dry matter concentration, NH_3 and volatile fatty acid content (Deublein and Steinhauster, 2008).

2.4.2. Digesters

Two-stage digesters have been developed to optimize the acetogenic and methanogenic stages, which are now becoming to spread. Two-stage digesters are ideally used for waste streams that decompose rapidly such as fruit and vegetable wastes.

In the one-stage plant, the experiments indicated a VS reduction of 80–85%, and a gas yield of 830–885 liter gas kg VS^{-1} at thermophilic temperatures, while a total VS reduction of 91% had been achieved in a two stage plant. The results suggest that two stage digesters are more effective than one stage digesters for municipal solid organic waste, particularly with kitchen wastes (Schober et al., 1999).

Most of the wet-fermentation processes are operated at mesophilic temperature conditions (30–38°C) whereas thermophilic temperatures (>55°C) are preferred mainly for dry-fermentation (Kern et al., 1999).

Mesophilic conditions have several advantages. Mesophilics are less sensitive to temperature than thermophilic methanogens. Moreover, the inhibition of ammonium is also reduced under mesophilic operating conditions. In addition, the energy balance is better in the mesophilic range than in the thermophilic range, since obtaining thermophilic conditions requires more heat energy (Deublein and Steinhauster, 2008).

The degradation of fruit and vegetable wastes according to the hyraulic retention time (HRT) is shown in Table 2.5 (Bouallagui et al., 2004).

Table 2.5. Effect of HRT and TS concentration on biogas yield, methane content and biogas production rate (Bouallagui et al., 2004).

TS (%)	**HRT (days)**	**TVS degradation efficiency (%)**	**Biogas Production rate (l/l day)**	**Biogas yield (l/kg VS fed)**	**Methane content (%)**
4	20	74.4	1.16	695.45	65
	15	67.55	1.41	629.49	60
	12	61.85	1.78	582.03	58
6	20	75.91	1.63	707.18	64
	15	69.24	2.19	641.1	61
	12	65.63	2.62	594.96	55
8	20	64.58	2.34	638.84	57
	15	61.24	3.1	614.91	54
	12	58.58	3.2	514.01	50

In East Bay Municipal Utility District’s Patented Food Waste Treatment Process, the HRT of food waste is determined as 10 days (USEPA, 2011d). The retention time for mesophilic conditions is suggested as 30 to 40 days (Seadi et al., 2008).

An experiment on anaerobic digestion of food waste in thermofilic conditions indicated that methane produced in a digester increased up to the 16th day since its initial loading. The amount of methane produced remained at a constant level until the end of the experiment, which was the 28th day. The methane yield during the digestion process can be found in Figure 2.8. It can also be concluded that the methane yields for 6.8 and 10.5 g VS/L loading rates which shows that, different loading rates does not effect the methane yield, respectively (Zhang et al., 2007).

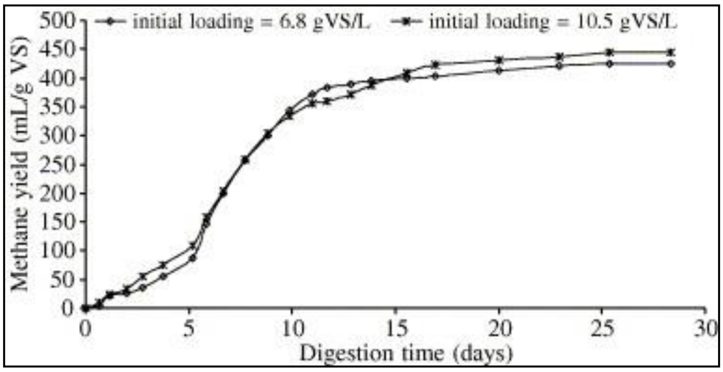

Figure 2.5. Methane yield according to the digestion time (Zhang et al., 2007).

Kannan et al. (2003), searched for the effect of height and diameter size of a digester on biogas generation. A study was carried out with three different feedstock; poultry droppings and donkey-dung combination, parthenium and donkey-dung combination, eucalyptus leaves and donkey-dung combination and only donkey-dung. The results of the experiments showed that 1:1.7 H/D scaled anaerobic digester performed best and resulted higher amount of biogas generation for all feedstock types that were experimented.

Since uniform feeding is very important for maintaining constant conditions in digester, feedstock should be pumped to the digester continuously or on a 30 min to 2 h time cycle (Tchobanoglous et al., 2010).

Energy can be obtained by the combustion of biogas in engines. Most of the conventional engines used for CHP requires biogas with H_2S content below 700 ppm, since H_2S causes corrosion and rapid deterioration of lubrication oil (Seadi et al., 2008).

In the biological desulfirization process, the H_2S is decreased biologically by Thiobacillus and Sulfolobus bacterias which are omnipresent. H_2S is decomposed to form sulfate and/or sulfur according to the equation 2.1, 2.2 and 2.3 (Deublein and Steinhauster, 2008).

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \quad (2.1)$$

$$2S + 2H_2O + 3O_2 \rightarrow 2H_2SO_4 \quad (2.2)$$

The direct reaction of H_2S to sulfate is also possible:

$$H_2S + 2O_2 \rightarrow H_2SO_4 \quad (2.3)$$

Air (2-8% of generated biogas) should be injected into the raw biogas for the removal of H_2S (Seadi et al., 2008).

2.4.3. Cogeneration

In recent years, for power generation the use of gas turbines has increased and it is supposed to increase in the medium term (Teppenstall, 1998).

The gas turbine engine has attractive features such as low cost, high efficiency, shorter lead-time and better environmental performance (GTA, 2012). A study carried out by Duval (2001), showed that widespread adoption of biomass cogeneration in Southeast Asia can significantly decrease the amount of greenhouse gas and other polluting air emissions in the region.

Cogeneration, is one of the types of gas turbines. The meaning of cogeneration is the production of power and thermal energy. The wasted energy in the exhaust gases is utilised in cogeneration systems. So, the thermal efficiency of the system is very high (Najjar, 2000). Cogeneration is commonly described as an energy conservation process because of this thermal recovery (Costa and Balestieri., 2001). Efficiencies of combined heat and power (CHP) and conventional systems are shown in Figure 2.6.

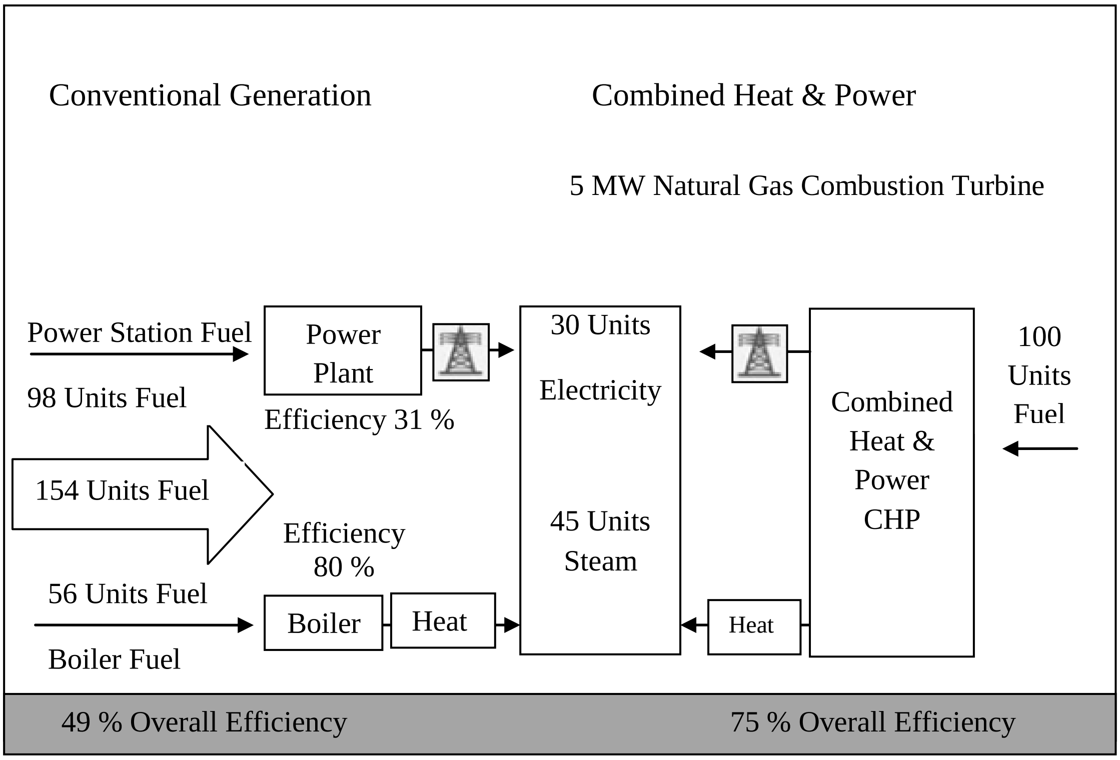

Figure 2.6. Comparision of CHP and conventional systems (USEPA, 2007a).

2.5. Composting as an Alternatived Technology for Organic Waste Utilization

Composting is the aerobic or oxygen-requiring, degradation of organic materials into a humus which is a rich nutrient-filled material under controlled conditions (Pace et al., 1995; Eitzen, 1995; Breidenbach, 2011). Composting may be a feasible method for managing organic wastes (Schaub and Leonard, 1996).

During the initial stages of composting, microorganisms degrades easily degradable components of the feedstock while consuming oxygen. The temperature of the raw material increases to 120-140 ^{O}F then, maintained constant for several weeks. Temperature drops until the compost reaches ambient air temperatures. After this active composting period, curing period starts where degradation continues slowly. Degradation continues until the last easily decomposed materials are consumed by microorganisims. When this stage is completed, the compost is stable and easy to handle. The composting process is indicated in Figure 2.7 (Government of Saskatchewan, 2008).

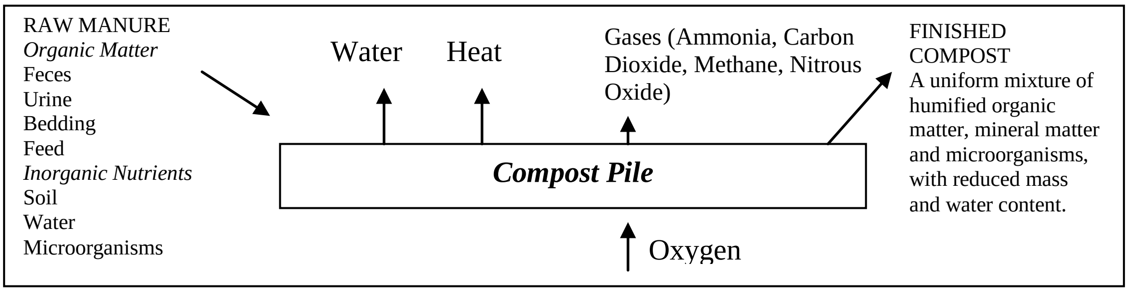

Figure 2.7. The composting process (Government of Saskatchewan, 2008).

Composting has many environmental benefits. The main advantage of composting is transforming waste into a valuable material. Compost, the product of composting, enriches soils, increases the nutrient content in soils and helps soils save their moisture content. It also reduces chemical fertilizer needs and suppresses plant diseases. Furthermore, compost absorbs odors, treats semivolatile, volatile organic compounds, binda heavy metals, helps remediation of contaminated soil. Since organic materials are diverted from landfills, production of methane and leachate is avoided. It contributes to the prevention of pollutants and erosion. Composting has also economic benefits. For instance, it reduces the need for water, fertilizer and pesticides (USEPA, 2011e).

2.6. Application of LCA Tools for Anaerobic Digestion and Composting Technologies

The environmental impact of biogas systems mainly depends on; the raw material digested, the energy efficiency in the biogas production, uncontrolled losses of methane, and the end-use technology (Börjesson and Berglung, 2006). Table 2.6 shows the fuel-cycle emissions from various biogas systems, including emissions from the biogas production environmental system analysis. The environmental impact and energy input differs significantly among biogas production systems. The energy input which differs between 15% and 50% of the energy content of biogas, depends on raw material, digestion technology, biogas production and if the biogas is upgraded or not. Biogas produced from food industry – without upgrading – has the lowest energy input.

Table 2.6. Summary of emissions in the production of biogas (Börjesson and Berglung 2006).

Raw material/biogas technology	Energy input (MJ)	Emissions						
		CO_2 (g)	CO (mg)	NO_x (mg)	SO_2 (mg)	HC (mg)	CH_4 (mg)	Particles (mg)
Ley crops								
Farm-scale	0.46	18	16	140	16	9.2	5.4	5
Large-scale	0.4	21	15	150	16	9.2	5.3	5
(incl. Upgrading)	0.51	27	18	170	16	9.6	6.6	5.3
Straw								
Farm-scale	0.46	11	13	74	3	5.1	2	1.7
Large-scale	0.35	14	12	85	2.9	5	1.8	1.7
(incl. Upgrading)	0.46	20	15	97	3.1	5.4	3.1	2
Tops and leaves of sugar beet								
Farm-scale	0.34	9.2	9.9	72	3.6	4.5	1.4	1.6
Large-scale	0.27	12	9.3	81	3.7	4.5	1.4	1.6
(incl. Upgrading)	0.38	18	12	93	3.9	4.9	2.7	1.9
Liquid Manure								
Farm-scale	0.42	7.9	9	49	1.8	3.2	2	1.4
Large-scale	0.31	11	7.8	63	1.9	3.3	1.8	1.3
(incl. Upgrading)	0.42	17	11	75	2.1	3.7	3.1	1.6
Food industry waste								
Large-scale	0.15	5.4	3.5	33	1	1.8	0.77	0.67
(incl. Upgrading)	0.26	11	6.5	45	1.2	2.2	2.1	0.97
Municipal organic waste								
Large-scale	0.26	12	14	85	2.8	6.1	1.1.	1.5
(incl. Upgrading)	0.37	18	17	97	3	6.5	2.4	1.8

The result of an life cycle assessment study of an anaerobic digestion plant operating with 50 m^3 slurry per day, indicates that operating energy of the plant is 1140 GJ fossil fuel which causes 78,000 kg CO_2 emissions (Ishikawa et al., 2006).

The results of life cycle assessment of food wastes for the comparison of different waste management technologies (composting, anaerobic digestion, incineration and landfilling applications) is indicated in Figure 2.8. The study was carried out both for fuel (Digestion f) and heat/electricity (Digestion h/e) production from anaerobic digestion. It is clearly seen that, the contribution of anaerobic digestion to global warming is less than the contribution of other utilization technologies. In other words, anaerobic digestion is preferable over incineration, composting and landfilling regarding energy use (Finnveden et al., 2005).

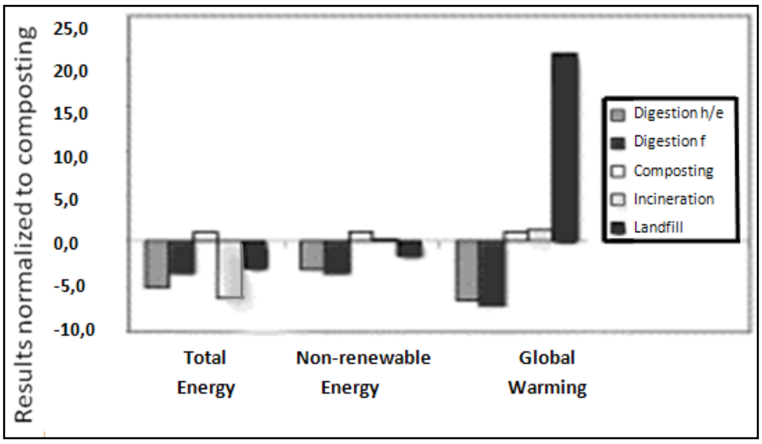

Figure 2.8. LCA of energy production from food waste (Finnveden et al., 2005).

The impact of composting of food and yard waste, generated from Eskişehir, Turkey was assessed. The system boundry of the study is shown in Figure 2.9. In this process, 77% of the waste is composting, while 15% is recyled and %8 is landfilled (Banar et al., 2009).

Nitrogen (N), phosphorus (P) values and CO_2, NH_3 emissions were calculated according to the chemical formula of the waste. 28.2 kg N and 3.9 kg P, 1.85 kg of CO_2 and 0.37 kg of NH_3 was assumed to be generated for per ton of waste in this study. Electrical demand of the process was assummed to be 54.4 MJ for per ton of waste, and diesel consumption is assumed to be 555.5 MJ for per ton of waste. Results showed that the global warming potential of organic treatment of a compostable waste is 1360 kg CO_2 eq/ton waste managed (Banar et al., 2009).

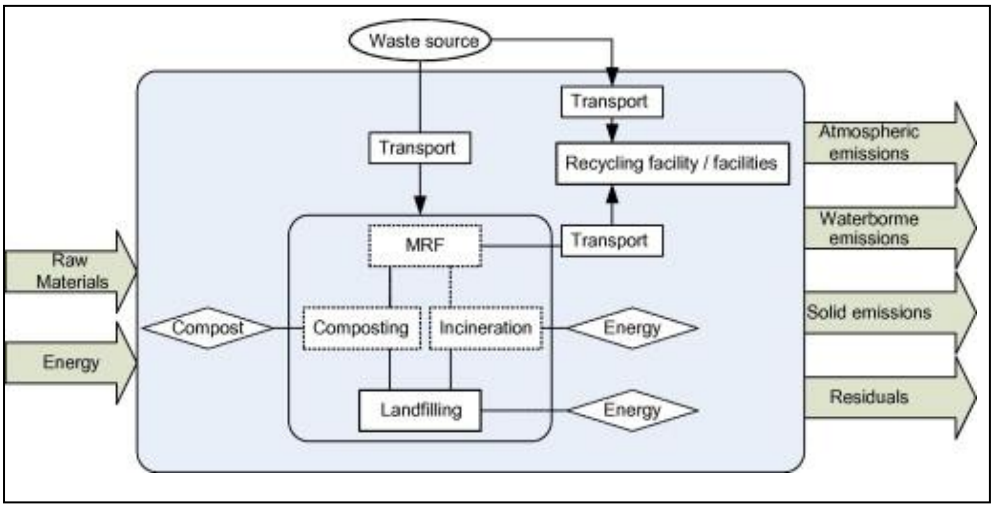

Figure 2.9. System boundry of composting process (Banar et al., 2009).

The environmental impact of three composting scenarios which are shown below are compared. Scenario 1: collection and disposal of wastes in conventional landfill, Scenario 2: collection of wastes; seperation of recylables while yard trimmings, food waste, and soiled paper are composted aerobically in-vessel, and residual wastes are disposed of in conventional landfill, Scenario 3: separate collection of commingled recyclables, yard trimmings, and residual wastes, yard trimmings are aerobically composted in windrows, and residual wastes are disposed of in bioreactor landfill. Results showed that, global warming potential of Scenario 2 is the lowest, while the potential of Scenario 1 is the highest. Composting of food residuals, soiled paper and yard trimmings caused 860 kg CO_2 eq/ton waste for in-vessel composting (Theresa et al., 2008).

Another study that compares the effect of two composting plants that operate with different technologies which are tunnels and confined.The global warming potential is found to be around 60 kg CO_2/ton waste for both plants. It is found that, gaseous emissions from the composting process represent the main contribution to eutrophication, acidification and photochemical oxidation impact categories, while energy consumption related emissions are the main responsible for global warming (Cadene et al., 2009).

3. MATERIALS AND METHODS

3.1. Introduction

The data obtained from waste characterization experiments are used to determine the suitability of the feedstock to anaerobic digestion process. According to the characterizations and the amount of food waste generated, which are collected from the Department of Cafetarias and Dining Halls of Bogazici University, the anaerobic digestion plant is designed. Data calculated in this part are used to carry out the life cycle assessment.

3.2. Food Waste Collection

Food wastes that have been collected seperately from 4 dining halls and restaurants of Bogazici University are considered. The distribution of the wastes generated are indicated below: 34.19% from North Campus Dining Hall, 17.09 % from South Campus Kennedy Lodge, 14.53% from South Campus Dining Hall, 21.37% from North Campus A La Carte Restaurant, 10.26% from Sarıtepe Campus Dining Hall and 2.56% from Kandilli Campus Dining Hall for during annual education period. It can be clearly seen that; North and South Campus wastes are responsible around 87.18% of the overall food wastes. Therefore, North Campus Dining Hall, South Campus Dining Hall, South Campus Kennedy Lodge Restaurant and North Campus A La Carte Restaurant are determined as sampling points.

For the time being, these wastes are disposed with other solid wastes and their transport is supplied by the Sarıyer Municipality for Kemerburgaz solid waste landfill side in Istanbul (Istanbul Metropolitan Municipality, 2012).

At each sampling point, approximately 2 kg of mixed waste were taken and later proportioned according to their percentage in total waste amount. Samples were stored at 4°C and transfered to the TUBITAK-MRC for analyses.

All samples were milled and homogenized to prepare the food waste for analyses. In order to conduct further experiments with the total phosphorus, heavy metals, and elemental analysis, samples were dried in the drying oven and milled again. This conditioned waste is used for analysis. For total Kjeldahl nitrogen, total phosphate and pH determination, wastes were centrifuged and the resulting filtrate was used for these analyses. All experiments were conducted in 2 to 5 parallels.

For the plant, a food waste collection plan is shown in Photograph 3.1. Boarding point of the truck is the parking area of North Campus, after collecting the food wastes from North Campus dining hall and A La Carte restaurant, truck goes to the South Campus dining hall, then to the Kennedy Lodge restaurant which is the final station. Finally, the collected wastes are transferred to the plant. Total calculated distance is 2.06 km.

Photograph 3.1. Waste management plan (developed by using Google earth Software).

3.3. Food Waste Characterization Experiments

The food wastes generated from Bogazici University are analyzed at Environment Institute and Energy Institute of TUBITAK-MRC for the determination of total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), pH and total phosphate is analyzed according to the standard methods of American Public Health Association (APHA, 1998). Total phosphorus (TP) was determined according to the method which is modified by TUBITAK-MRC. The method of United States Environmental Protection Agency (USEPA, 2007b) was applied for heavy metal determination. Elemental analysis was accomplished according to the American Society for Testing and Materials (ASTM, 2008) for all collected food waste samples.

3.3.1. Analytical Techniques and Characterization Results

The methodology of each experiment is shown in APPENDIX A. Photographs taken during the experiments is shown in APPENDIX B.

The results for the characterization of total solids, total volatile solids, pH, alkalinity, total phosphate, total phosphorus and total Kjeldahl nitrogen are shown in Table 3.1. Heavy metal contents of each sample can be found in Table 3.2. Total volatile solid (TVS) content is reported by considering the TS content of the feedstock in Figure 3.1.

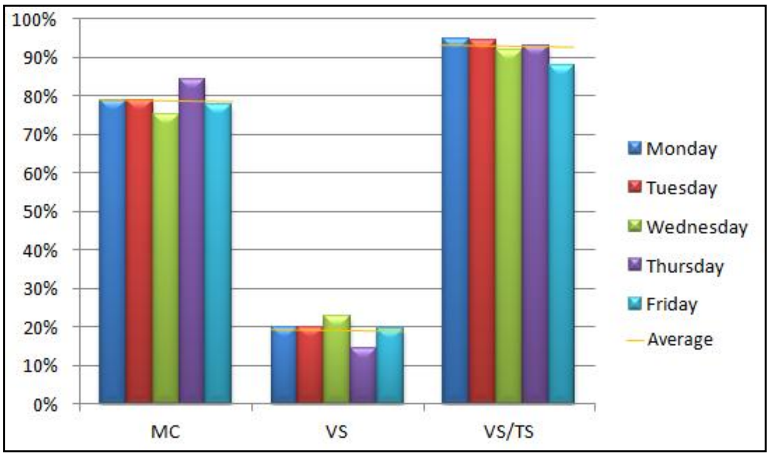

Figure 3.1. MC, VS and VS/TS according to the days.

The MC ranged from 75% to 84%, VS content ranges from 14% to 22% and VS/TS content ranged from 88% to 95%. The average values are; 79% for MC, 19% for VS, and 92% for VS/TS. MC and VS/TS remained nearly constant, however VS content of Thursday's sample show 14% VS content. No significant variation is observed among other samples. The measured values of MC, VS/TS and C/N are generally similar to the values reported for other food waste sources in different countries. Different values of MC can be seen, this could be due to the substances of the meals and the wheater conditions. The nutrients and trace elements are sufficient and the amount of heavy metals are not at inhibitory level for anaerobic digestion process (The AD Community, 2012; Deublein and Steinhauster, 2008; Chen et al., 2007). The digestates of the food wastes may be used as soil conditioner.

Table 3.1. Characteristics of food waste.

Sample	**TS (%)**	**MC (%)**	**VS (%)**	**pH**	**Alkalinity (mg $CaCO_3$/l)**	**Total Phosphate (mg/lt)**	**TP (g/kg)**	**TKN (g/kg)**
Monday	21.09	78.91	94.73	5	983.75	1439	2.23	34.813
Tuesday	21.2	78.8	94.35	5	815	1102	1.83	25.938
Wednesday	24.85	75.15	92.01	5.3	1270.63	1807	2.75	27.09
Thursday	15.54	84.46	93.14	5	871.25	1125	3.06	26.53
Friday	22.34	77.66	87.99	5	956.25	849	1.84	19.06
Average	21.004	78.996	92.444	5.06	979.376	1264.4	2.342	26.686

Table 3.2. Heavy metal concentrations of food waste.

Sample	**Na (ppb)**	**Mg (ppb)**	**Al (ppb)**	**K (ppb)**	**Ca (ppb)**	**Cr (ppb)**	**Mn (ppb)**
Monday	62450	6177	2180	71300	22860	53.99	94.67
Tuesday	70160	4995	2118	57500	5373	30910	72720
Wednesday	47550	5166	6668	78110	74080	45.61	133.6
Thursday	61260	8058	1950	91920	34770	28.78	126.3
Friday	63230	5457	13890	70410	118500	581.4	295.3
Average	60930	5970	5361	73848	51116	6323.956	14674

Table 3.2. Heavy metal concentrations of food waste (continued).

Sample	**Fe (ppb)**	**Ni (ppb)**	**Zn (ppb)**	**Cu (ppb)**	**Zn (ppb)**	**Cd (ppb)**	**Pb (ppb)**
Monday	5055	26.7	248.6	42.19	257.7	0.444	1.973
Tuesday	3973	18.66	31.72	31.72	180.4	0.126	2.047
Wednesday	5695	23.66	141.8	28.51	141.7	0.178	5.488
Thursday	1246	20.15	168.5	41.69	171.7	0.133	1.777
Friday	13970	204.8	191.1	47.08	181.8	0.219	10.94
Average	5987	58.794	156.344	38.238	186.66	0.22	4.445

3.3.2. Elemental Analysis and Oxygen Determination

The biogas potential of a feedstock and the gas composition of the biogas depend on the feedstock's chemical composition. In order to determine the biogas generation and the composition of the biogas, elemental analysis is carried out.

The percentages of each element are shown in Table 3.3. Methane and carbon dioxide yield of the feedstock can be calculated, if the chemical composition of organic matter is known with an uncertainty of about 5% using the simple relation by Buswell Equation (Buswell and Neave, 1930), which is shown in Equation 3.1. Buswell formula represents the maximal potential from complete degradation of the organic matter. The theoretical biogas potential was calculated for each biomass sample.

Buswell Equation

$$C_cH_hO_oN_nS_s + 1/4(4c - h - 2o + 3n + 2s)H_2O \rightarrow 1/8(4c - h + 2o + 3n + 2s)CO_2 + 1/8(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \qquad (3.1)$$

Table 3.3. Elemental Analysis for Each Element in Mixed Food Waste of Bogazici University.

Sample	**Carbon (%)**	**Sulfur (%)**	**Nitrogen (%)**	**Hydrogen (%)**	**Ash Dry (%)**	**Oxygen (%)**
Monday	50.655	0.2225	4.2392	6.3087	5.7100	32.8647
Tuesday	49.513	0.1430	3.4331	6.2558	5.7700	34.8851
Wednesday	52.402	0.1613	3.5576	6.7170	7.7150	29.4470
Thursday	50.815	0.1615	3.3134	6.2097	6.6100	32.8904
Friday	45.777	0.1084	2.2900	5.8306	11.5750	34.4190

Carbon content of the feedstock is one of the most important parameters, since it effects the methane content of the biogas. The amount of the electricity and heat produced by the cogeneration unit, in which biogas is burned to produce electricity, depends on the methane content. According to the experimental results, the carbon content is found about 50%, which indicates the half of the fuel input can be considered to determine electrical and heat outputs.

Sulfur content is another important parameter, since it determines the H_2S content of the biogas, which may cause corrosion in the cogeneration unit. A biological removal system is implemented inside the digester even though the H_2S content is low in the biogas.

NH_3 which may cause to inhibition is another product of anaerobic degredation. N content of the feedstock determines the NH_3 content of the biogas. N content of the feedstock is below 5%. The ash dry content of the feedstock is used to determine the oxygen content of the feedstock.

The chemical formula of the feedstock according to the elemental analysis is: $C_{313}H_{39}O_{207}N_{21}S$. According to the chemical formula gas compositions are calculated by using the Buswell Equation. The percentages of each type of gas in biogas is shown in Table 3.4.

Table 3.4. Percentages of each gas in biogas.

Gas	Monday	Tuesday	Wednesday	Thursday	Friday
CO_2	41.217	43.997	41.219	43.583	44.808
CH_4	51.942	50.292	53.174	51.013	50.996
NH_3	6.688	5.609	5.499	5.291	4.112
H_2S	0.153	0.102	0.109	0.112	0.085

The methane content which determines the efficiency of the cogeneration engine, is observed over 50%. It is observed that H_2S and NH_3 contents are low. These gases are removed before the combustion of biogas as decribed in the design part. The percentages of CO_2 and CH_4, after removal of H_2S and NH_3 are indicated in Table 3.5.

Table 3.5. Percentages of CO_2 and CH_4 in biogas.

Gas	Monday	Tuesday	Wednesday	Thursday	Friday
CO_2	44.244	46.662	43.668	46.073	46.771
CH_4	55.756	53.338	56.332	53.927	53.229

For composting, minimum required C/N ratio is 12:1 (Wisconsin Department of Natural Resource, 2006) and 10:1 for anaerobic digestion (Schattauer and Weiland, 2004), which indicates that there would be no inhibition because of the C/N ratio of the feedstock. However, the optimum C/N ratio for anaerobic digestion and composting is 16:1 to 25:1 (Deublein and Steinhauster, 2008) and 20:1 to 40:1 (Wisconsin Department of Natural Resource, 2006), respectively. Therefore, low C/N ratio may lead to increased ammonia production (Deublein and Steinhauster, 2008), which negatively effects methane production in anaerobic digestion process and cause undesirable odors in composting.

3.3.3. Biogas Potential Calculation

Calculation steps of the volume of the biogas produced can be found in Table 3.6. The amount of carbon in organic dry matter (ODM) is found by using the results of following experiments: total solid content, volatile solid content and elemental analysis. Then, the amount of carbon that converted to biogas is calculated. By considering the studies carried out by Zhang et al. (2007), USEPA, (2011d), Cahyari and Putra. (2010), the volatile solid destruction is determined as 80%. Weight of methane is determined by using weight of methane carbon. By considering standard temperature and pressure (STP) conditions, the volume of each gas is calculated. Results shows that, 138.6 l biogas is produced per kg of wet waste and 54.52% of this biogas is methane.

The biogas yield is determined as 0.66 l/g VS and the methane yield is determined as 0.36 l/g VS. The biogas and methane yields of the food wastes are similar to the values reported in Table 2.3.

Table 3.6. Biogas potential calculation.

Sample	Organic Dry Matter (%)	Carbon in Organic Dry Matter (%)	Carbon in Wet Waste [1] (kg)	Carbon Converted into Biogas [1] (kg)	CH_4 Content of Biogas (%)	CO_2 Content of Biogas (%)	Volume of CH_4 After Digestion of Waste[1] (m^3)	Volume of CO_2 After Digestion of Waste[1] (m^3)	Volume of Biogas After Digestion of Waste[1] (m^3)
Monday	19.9596	50.655	100.111	80.088	55.756	44.244	80.4113	60.6746	150.086
Tuesday	20.0022	49.513	90.9037	70.923	53.338	46.662	70.8819	60.8953	140.777
Wednesday	22.8645	52.402	110.981	90.585	56.332	43.668	100.071	70.8067	170.877
Thursday	14.474	50.815	70.3549	50.884	53.927	46.073	50.9181	50.0562	100.974
Friday	19.657	45.777	80.9984	70.199	53.229	46.771	70.1467	60.2797	130.426

[1] For 1 ton of wet food waste

3.4. Design of Anaerobic Digestion Plant

For utilization of food wastes, an anaerobic digestion plant with a biogas recovery system is designed. Operation conditions of the plant and digester dimensions are determined according to the literature data in accordance with the amount and the characterization of food wastes generated from Bogazici University.

Since the amount of waste generated during the education period is significant when compared with the holidays, the plant is designed by considering the education period. The plant can also operate during holidays. All electrical devices in the plant are explosion-proof. Installed power of each electrical unit of the plant is shown in Table 3.11.

The plant consists of following units; a primary storage tank, a 5 meter long conveyor, a grinder, a conditioning tank, two digesters, a flare, a separator, two last storage tanks and a control unit.

The dimensions and capacity of each unit/equipment are shown in Table 3.7. In order to illustrate the designed biogas plant which can be seen in Figure 3.2 and 3.3, KitchenDraw software is used.

Table 3.7. Dimesions of each unit in the plant.

Name	**Dimensions**	**Capacity**
Dumping Area	Length: 3.75 m, Width: 2.5 m	> 9000 kg
Primary Storage Tank	Height: 1 m, Diameter: 2 m	~700 kg
Conditioning Unit	Conveyor - Height: 1 m, Length: 5 m,Width: 1 m	-
	Grinder	400 kg/h
	Conditioning Tank (with grinder) - Height: 2.3 m, Diameter: 1 m	~1500 kg
Digester 1	Height: 1.8 m, Diameter: 3.06 m	~10000 kg
Digester 2	Height: 1.8 m, Diameter: 3.06 m	~10000 kg
Flare	Height: 0.5 m	> 55 m^3 biogas/day
Cogeneration Unit	Cogeneration Motor Cogeneration Room- Height: 2 m, Length:2.5 m, Width: 1.8 m	14.3 m^3/h
Separator	-	8 ton/h
Liquid Digestate Storage Unit	Height: 1m, Diameter: 1.2 m	~1100 kg
Solid Digestate Storage Unit	Height: 1 m, Length: 1 m, Width: 1 m	~1000 kg
Control Unit	Height: 2.5 m, Length: 2.5 m, Width: 2 m	-

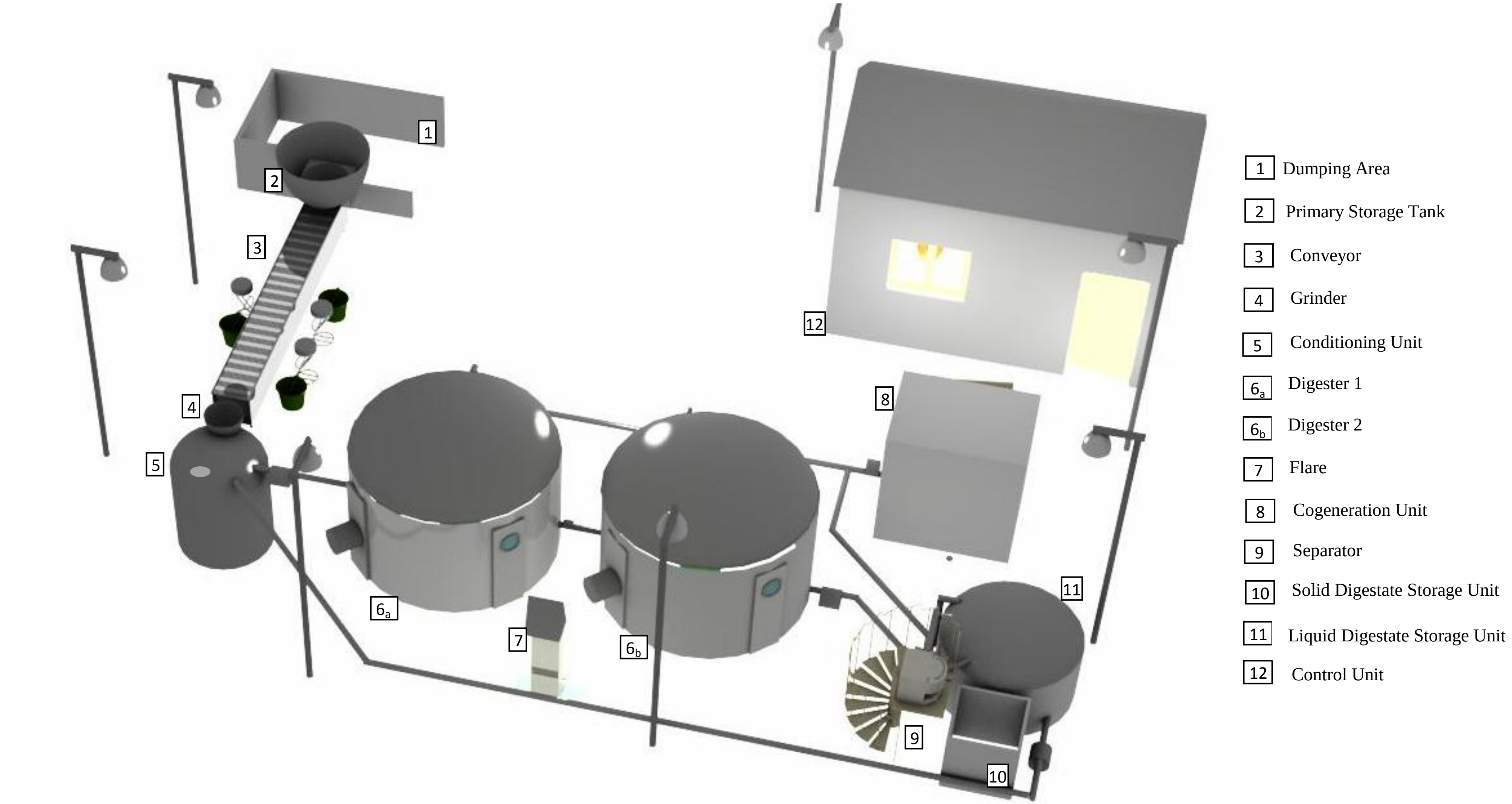

Figure 3.2. 3D view of the designed biogas plant (developed by using KitchenDraw Software).

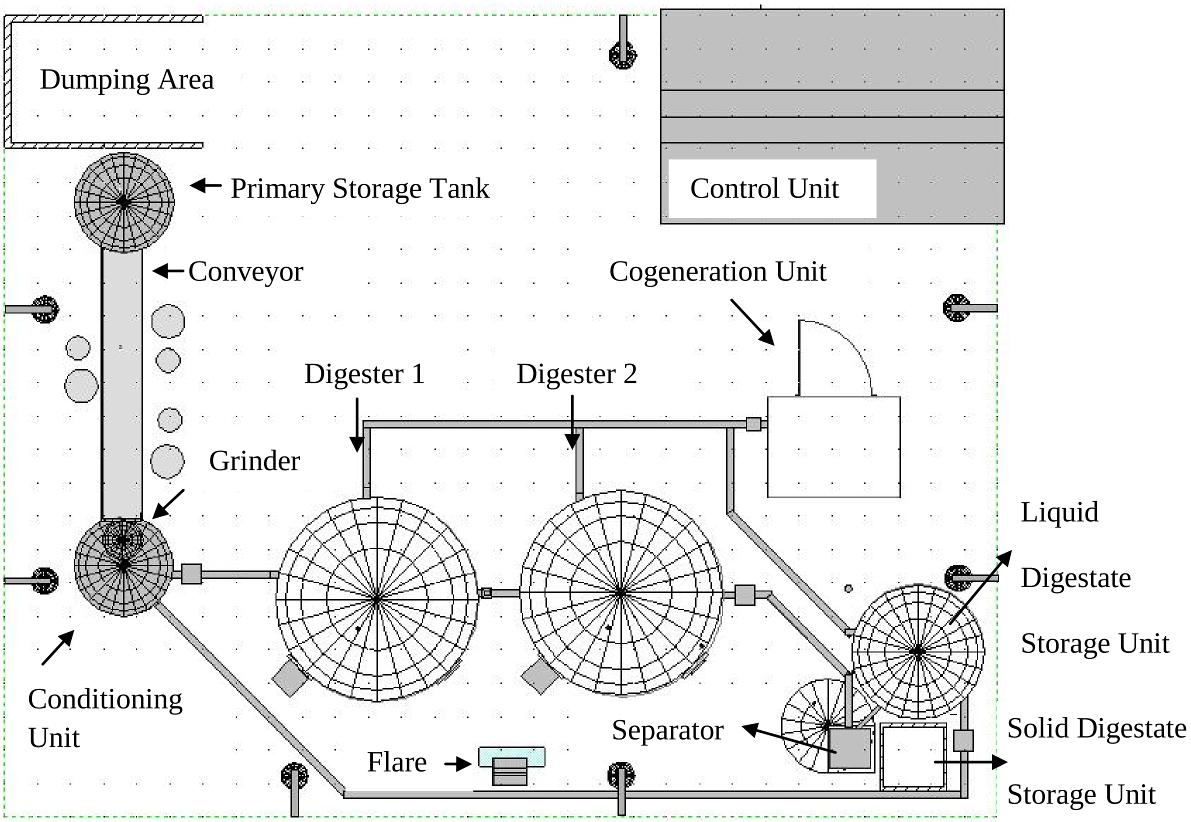

Figure 3.3. Plan of the designed biogas plant (developed by using KitchenDraw Software).

3.4.1. Primary Storage Tank

Food wastes are transferred by a digging machine to the storage tank from the dumping area where food wastes are discharged from the transportation truck. The dumping area is sufficient to store over 9000 kg of wastes in order to prevent feedstock loss in case of having a problem in one of the units of the plant.

The primary storage tank is conic-shaped and made of steel. The height of the storage tank is 1 m and the diameter is 2 m. Pressure, level and pH sensors are implemented into the storage tank.

For the education period, 510 kg of food waste is generated per day for week days and 155 kg for weekends, in order to allocate the same amount of feedstock, 386,429 kg of food waste will be fed to the digester per day for 6 days. The final 386,426 kg of waste will be allocated to the digester for the 7th day.

3.4.2. Feedstock Conditioning

Feedstock conditioning consists of; a moving belt, a grinder and a conditioning tank. Various impurities in food waste may cause damage on digesters, block pipes and pumps (Seadi et al., 2008). Therefore, in order to remove the impurities, a moving belt which is 5 meter long is placed. The impurities, mainly cans and napkins, are removed manually by hand. The velocity of the moving belt which can also be adjusted by engine speed control equipment is 0.25 m/s.

At the end of the moving belt, a grinder is stated. In order to obtain a homogenized feedstock, food waste is grinded and mixed in the conditioning unit which is stated in underground. In the grinder, food waste is torn to pieces by screws. The details of a grinder that is suitable for grinding food wastes can be found in APPENDIX C.

After being grinded, waste is transfered to the conditioning tank. In order to adjust the dry matter concentration, water is added in this unit. Since minimum addition of water is preferred because of the cost, the concentration of dry matter is determined as 10%. 0.426 m^3 water is added daily and waste is mixed. By the addition of water, the pH rises to 5.3. Since the pH inside the digester is higher and the amount of the feedstock inside the digester is about more than 10 times the amount of feedstock supplied, new feedstock will have a little effect on the pH. When needed, the adjustment of pH may be achieved by adding lime powder. From this unit, feedstock is transferred to the digester.

3.4.3. Digesters

Since two stage biogas production is more effective than one stage biogas production, two digesters are stated in the plant. The pump system is designed for operating the plant both as two-stage and one-stage alone. The pump system can be converted from a two-stage digester to one-stage digesters. The suction collectors and supply manifolds are adjustable to run the plant as two-stage or one-stage. This pump system is outlined in Figure 3.4.

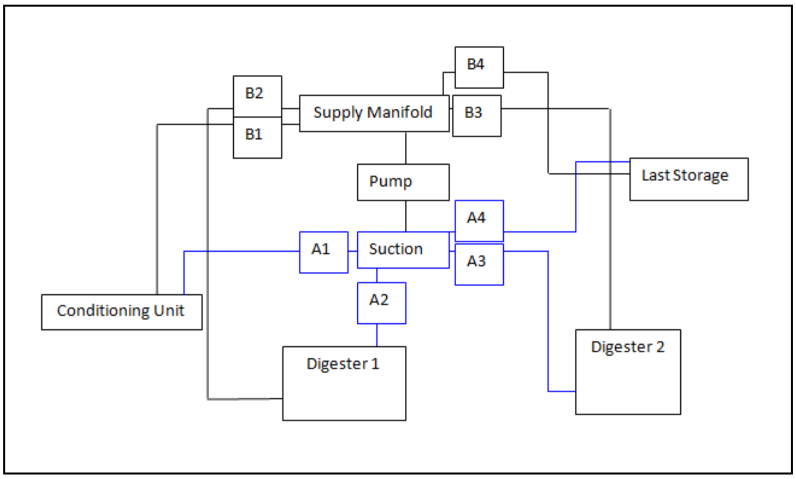

Figure 3.4. The pump system.

The pump system illustrated in Figure 3.3. has three pumps, the first one pumps the feedstock into the digester from the contioning unit, the second one pumps the digestate to the separator, and the third one enables the liquid digestate to be pumped to the conditioning unit.

Digesters are operated in mesophilic range (35-40°C) and heat exchangers are used to provide the required temperature range. In order to obtain homogeneous feedstock inside the digester, submersible horizontal impeller mixer is placed inside each digester.

The retention time for mesophilic conditions is suggested as 30 to 40 days (Seadi et al., 2008). 20 days or less would be also enough according to (USEPA, 2011d; Bouallagui et al., 2004; Zhang et al., 2007) for food waste digestion. The retention time of the feedstock inside the digesters is determined as 36 days. First of all, degradation rate may be higher. Secondly, there may be an increase in the amount of food wastes in the future, so, the capacity of the plant can be increased without any modifications. Lastly, 10 m^3 concrete digester may be easier to build. Since anaerobic digestion will be carried out as two stage digestion, the retention time for each digester is determined as 18 days. 8.0505 kg of waste is pumped to the digester every 30 minutes.

In order to prevent heat loss, concrete digesters are covered with styrapor, an isolation material that helps to prevent heat loss through surfaces.

Biogas is collected in membrane gas holding units located at the top of each digester. Since the gas holding membranes expand, a protective safeguard is put in place to prevent them from tearing if there is too much gas.

Literature survey (Kannan et al., 2003) showed that, 1:1.7 (H/D) scaled digester performed best among different feedstocks, 1:1.7 (H/D) is determined for the digesters. The dimensions of each digester are shown below:

Mid-depth = 1.8 m
Side-depth= 1.2 m
Diameter (D) = 3.06 m
Volume (m^3) ~ 10.29 m^3

A wooden layer is also implemented inside the digester. This layer is placed at the top of the digester, just below the gas holding membrane. Air is injected over this layer. The wooden layer also provides a medium for the bacterias. The oxygen will be provided by injection of air through oxygen feeding point which is placed above the wooden layer. Approximately 4% air is injected into the digester.

Hydrostatics sensors are implemented inside the digester. In addition, the digesters have two windows each with 10 cm diameters for observation. For ammonia removal, biogas is passed through a slightly acidic solution. Ammonia remains liquid in the form of ammonium. For safety reasons, a pressure relief is attached to digesters. When pressure increases, biogas is released to adjust the pressure inside the digester.

In order to remove the moisture in biogas, a recuperator is stated. Biogas is transferred to the cogeneration unit after the removal of moisture from biogas. A blower is also stated to provide the needed pressure for cogeneration unit. Volatile fatty acids and ammonia should be monitored during digestion process, since they may cause inhibition.

3.4.4. Cogeneration Unit

Efficient use of energy and cost effectiveness can be achieved by using cogeneration systems. A gas sensor is implemented in a room where the cogeneration engine is placed to detect gas leaks.

In the biogas plant, the cogeneration unit consisting of a gas engine, is used to produce electricity and heat from the biogas produced in the anaerobic digesters. The volumetric content of the biogas is given below:

Methane content : 53-55%
CO_2 content: 43-46 %
H_2S content: < 700 ppm

In case of having a problem in cogeneration unit, biogas is burned in the flare.

3.4.5. Seperation and Final Storage Unit

Digestate is transferred to a separator after the digester. In this unit, liquid and solid phases are separated. Each phase is stored in the concrete tanks. Biogas generated from the liquid digestate tank is also collected and sent to the cogeneration unit. The dimensions of each tank is indicated below.

Liquid storage tank; height: 1 m, diameter: 1.2 m, Solid storage tank; height: 1 m, width: 1 m, length: 1 m. Level sensors are implemented inside the last storage units.

Pasteurazition is not necessary to apply the food waste digestate as fertilisers. Therefore, solid and liquid digestates may be applied as fertilisers (Wrap, 2011). Liquid digestate may also be recirculated to the conditioning unit.

3.5. Process Design and Energy Balance

The selected feedstock is the organic waste produced from dining halls, Kennedy Lodge Restaurant and A La Carte Restaurant of the University Campuses for periods of winter education, winter holiday, summer education and summer holiday. The production rate of organic wastes show variation on seasonal bases as winter, summer and 2 springs.

The amount of generated wastes, without impurities, per week is shown below:

- Winter and Springs (education): 2705 kg
- Winter (holiday): 325 kg
- Summer (education): 325 kg
- Summer (holiday): 50 kg

For summer holiday period, the amount of waste generated decreases significantly, since there are not many students in campus in this period. The plant can still operate at the same capacity during the year, assuming that Sarıyer Municipality will provide the required 379 kg/day waste for the summer period, and 340 kg/day for the winter holiday period.

3.5.1. Mass Balance for the Anaerobic Digestion Plant

Mass balance for the anaerobic digester plant includes the mass analyses of the digesters and the seperation unit. The amount of the food waste supplied per day to digester is 386.429 kg for the education period. The TS content and ODM content of the food waste are, 21.004% and 19.4%. The other input is water which is added in order to adjust the dry matter content in the digester. For the education period, addition of 426 kg water is required.

Since 80% destruction is achieved during the digestion, the amount of non-degradable solid is found to be 15.006 kg. By considering the MC in the feedstock, the amount of output is found as 320.269 kg for the education period. By the addition of the water that is used to adjust the dry matter content, the amount of output is found as 746.269 kg.

According to the data taken from the separator manufacturer, dry matter content of the solid digestate is 28%.

Liquid digestate may be re-circulated and can be used to adjust the dry matter content of the feedstock. Solid digestate may be applied as soil conditioner. De-watering processes can also be applied for the output from the digester.

3.5.2. Net Energy Determination

The general lay out for anaerobic digestion plant considered for Bogazici University is shown in Figure 3.5. Heat and electricity production is achieved by combustion of biogas in cogeneration unit. The energy required for the units of the anaerobic digestion process that is indicated in Table 3.9 is supplied by the produced heat and electricity in the plant. The remained energy is considered as ‘net energy’.

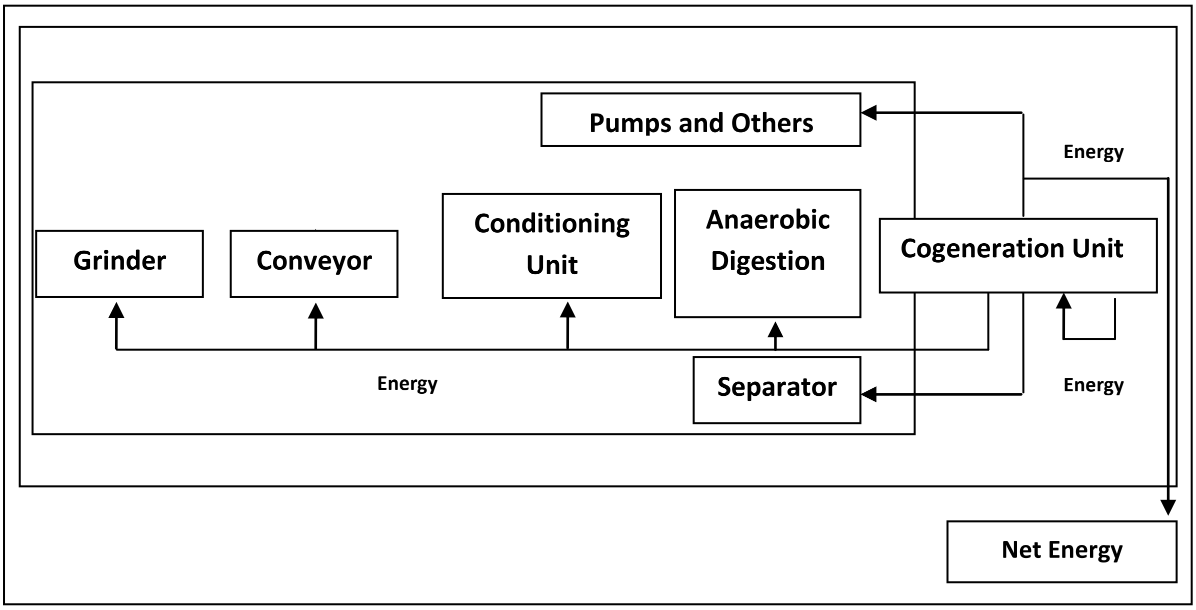

Figure 3.5. Energy balance of the plant.

Since the amount of waste generated varies, energy balance of each period that is shown below is calculated to find out the feasibility of the plant. According to the periods, generation of heat and electricity can be found in Table 3.8.

Table 3.8. Generation according to the periods.

Periods	**Period 1 (Education Period)**	**Period 2 (Winter Holiday)**	**Period 3 (Summer School)**	**Period 4 (Summer Holiday)**
Calendar[1]	27.09 to 18.01, 21.02 to 09.06	19.01 to 20.02	24.06 to 08.08	10.06 to 23.06, 09.08 to 26.09
Electricity Generation (kWh/day)	92.613	11.127	11.127	1.712
Heat Generation (kWh/day)	188.905	22.697	22.697	3.492

[1] Periods are determined according to the academic calendar of 2010-2011.

In order to determine the net energy, following data are required; energy production and consumption according to periods, which are shown between Table 3.9 and Table 3.11.

Table 3.9. Energy consumption of the plant.

Name of the Unit	Installed Power (kW)	Period 1		Period 2 - 3		Period 4	
		Working Duration (hr)	kWh	Working Duration (hr)	kWh	Working Duration (hr)	kWh
Grinder							
Motor	2.237	0.966	2.161	0.116	0.26	0.018	0.04
Conveyor							
Motor	1	1.932	1.932	0.232	0.232	0.036	0.036
Conditioning Unit							
Mixer	1	1.333	1.333	0.16	0.16	0.025	0.025
Atex Fan	0.09	0.049	0.004	0.006	0.001	0.001	Neglectable
Digester 1							
Mixer	1	1.333	1.333	0.16	0.16	0.025	0.025
Sulphide Removal	0.003	24	0.06	0.112	Neglectable	0.017	Neglectable
Heating Demand	Please see Table 3.11.						
Digester 2							
Mixer	1	1.333	1.333	0.16	0.16	0.025	0.025
Sulphide Removal	0.003	24	0.06	0.112	Neglectable	Neglectable	Neglectable
Heating Demand	Please see Table 3.11.						
Cogeneration Unit							
Blower	0.22	1.032	0.227	0.124	0.027	0.019	0.004
Motor	0.006	3.899	0.023	0.468	0.003	0.072	0
Flare							
Blower	0.22	1.032	0.227	0.124	0.027	0.019	0.004
Others							
All sensors and lighting system	0.464	Lights[1] Sensors[2]	4.415	Lights[1, a], Sensors[2,a] Lights [3,b], Sensors[2,b]	4.415 [a] 3.380 [b]	Lights[3] Sensors[2]	3.38
Separator							
Motor	2.2	0.04	0.088	0.006	0.013	0.001	0.002
Pump							
Motor	1.1	0.8	0.88	0.188	0.207	0.029	0.032

[1] For 12 hours, [2] For 24 hours, [3] For 9 hourS, [a] Period 2, [b] Period 3

Heat loss determination is carried out according to the periods. General data that is used to calculate heat requirements is shown in Table 3.10. Heating demand of the plant can be seen in Table 3.11.

Table 3.10. General data for heat requirement determination.

Specific heat capacity of organic matter [1]	0.89	J/g °C
Specific heat capacity of water [2]	4.186	J/g °C
Heat transfer coefficient for concrete wall with insulation[2]	0.7	$W/m^2 °C$
Heat transfer coefficient for concrete floor in contact with moist earth[2]	0.625	$W/m^2 °C$
Heat transfer coefficient for floating cover[2]	1.874	$W/m^2 °C$

[1] (Stabnikova et al., 2008)

[2] (Tchobanoglous et al., 2010)

Table 3.11. Heating demand of the plant.

Periods		**Period 1**	**Period 2**	**Period 3**	**Period 4**
Total Organic Matter in Feedstock	(kg/day)	75.03	9.02	9.02	7.14
Total Water in Feedstock	(kg/day)	305.26	36.68	36.68	1.39
Total Inorganic Matter in Feedstock	(kg/day)	6.13	0.74	0.74	5.64
Desired temperature	(°C)	37	37	37	37
Inlet temperature	(°C)	11.77	6.1	23.53	23.61
Heat Requirement of Organic Matter in Feedstock	(kWh/day)	0.51	0.08	0.03	0.01
Amount of water to be added	(kg/day)	426	50.91	50.91	7.86
Total Water in Feedstock	(kg/day)	305.26	36.68	36.68	5.64
Heat Requirement of Water	(kWh/day)	21.46	3.15	1.37	0.21
Total Heat Requirement for Feedstock	(kJ/day)	89237	10689.09	6245.69	962795
	(kWh/day)	21.96	3.22	1.41	0.22
Temperature of air	(°C)	11.77	6.1	23.53	21.61
Temperature of earth below floor	(°C)	12.74	5.35	28.89	25.5
Incoming feedstock	(°C)	11.77	6.1	23.53	21.61
Feedstock in digester	(°C)	37	37	37	37
Heat Loss from wall	(kJ/day)	19905.18	33969.42	11630.54	11630.5
Heat Loss from floor	(kJ/day)	10341.44	19905.179	5490.9	5490.9
Heat Loss from cover	(kJ/day)	33969.42	13492.79	19848.24	19848.2
Total Heat Loss from a Digester	(kJ/day)	64216.05	67367.39	36969.68	36969.7
	(kWh/day)	17.85	18.73	10.28	10.28
Total Heating Requirement	(kWh/day)	57.67	40.68	21.96	20.77

In order to determine the net energy, energy consumption of the plant should be subtracted from the energy produced. Net energy is determined according to the education and seasonal periods, since the electrical and heat requirement of the plant depends on the outside temperature and the waste amount. Since amount of waste generated is low during period 2,3 and 4, calculations are also done for one stage digesters. Summary of the energy balance of the plant is shown in Table 3.12. Since the amount of food wastes decrease in period 2 and 3, and the volume of one digester is enough, plant is operated as one stage digester for these periods. In period 4, the heat and electricity requirement of the plant is higher than total produced energy. Therefore, it is not feasible to run the plant on period 4.

Table 3.12. Summary of energy balance of the plant.

Periods		**Period 1**	**Period 2**		**Period 3**		**Period 4**	
Number of Digesters		**Two Stage**	**Two Stage**	**One Stage**	**Two Stage**	**One Stage**	**Two Stage**	**One Stage**
Electricity Produced	(kWh/day)	92.613	11.127		11.127		1.712	
Heat Produced	(kWh/day)	188.905	22.697		22.697		3.492	
Electricity Requirement of the Plant	(kWh/day)	13.849	5.635	5.478	4.600	3.405	4.007	3.544
	(%)[1]	14.954	50.643	49.232	41.341	30.601	-	-
Heat Requirement of the Digesters	(kWh/day)	57.667	40.680	21.952	21.960	11.683	20.771	10.493
	(%)[1]	30.527	-	96.718	96.753	51.474	-	-
Net Electricity Produced	(kWh/day)	78.764	5.492	5.649	6.527	7.722	-	-
	(%)[1]	85.046	49.357	50.768	58.659	69.399	-	-
Net Heat Produced	(kWh/day)	131.238	-	0.745	0.737	11.014	-	-
	(%)[1]	69.473	-	3.282	3.247	48.526	-	-

[1] Total Electricity/Heat Produced

3.6. Utilization of the Produced Energy

Produced heat from anaerobic digestion plant, is assumed to be supplied to the indoor swimming pool in Hisar Campus and the electricity produced is assumed to be consumed by the Hisar Campus Buildings. According to the data gained from Construction and Technical Affairs of Bogazici University, the heat requirement of the pool is 819.9 kWh/day and the electrical consumption of Hisar Campus Buildings is 1913.1 kWh/day. The dimensions of the pool are: Width: 15 m, Lenght: 33 m and depth: 1.75 m *(*Bogazici University, 2011).

Utilization of food wastes by anaerobic digestion can provide 23.04 % of the heating demand of the pool when overall heat requirement of the pool is considered. When the heating requirement of the pool is considered, 16.00 % of the heating demand of the pool can be achieved. It is assumed that the addition of food waste is provided by Sarıyer Municipality for periods 2, 3 and 4.

In order to determine energy produced in terms of energy consumption of a residential building, following calculations and assumptions have been applied. The electrical consumption of a family with four members is assumed to be 230 kWh/month (TMMOB Elektrik Mühendisleri Odası, 2009) and heat requirement of a 100 m^2 flat is 11200 kcal/h (adopted from Kaya, 2009). So, 10 families can meet their electrical and heating requirement for Period 1. Since the heating requirement of a house in Istanbul is nearly zero in period 4 and the amount of energy produced in the plant is very low for holiday periods, no calculation is carried out for these periods.

4. POTENTIAL ENVIRONMENTAL IMPACT ASSESSMENT FOR ANAEROBIC DIGESTION PLANT

4.1. Introduction

The objective of this study is to assess energy production from food wastes of Bogazici University's Campuses and utilization of organic wastes and production of energy in the scope of environmental management systems.

The laboratory experiments provided the initial data to determine the process design and conditions for the plant. The study covers the evaluation of utilization of food wastes of Bogazici University by an anaerobic digestion plant. Environmental impacts of utilization of food wastes by anaerobic digestion plant with a biogas recovery system are compared with the current waste disposal method and energy production method.

In addition, since compost is also one of the beneficial methods of utilization of organic wastes, a compost scenario is also considered in the scope of global warming potential. The composting plant is assummed to be an in-vessel plant because it minimizes the effects of composting upon the environment. Moreover, it accelerates the process through the maintenance of optimum conditions (UNEP, 2012). The advantages and disadvantages of in-vessel composting is shown in Table 4.1.

Table 4.1. Advantages and disadvantages of in-vessel composting (Government of Saskatchewan, 2008).

Advantages	**Disadvantages**
Space-efficient	High capital cost
Good control of composting process	Careful management required
Predictable, uniform products	Less flexibility in operation
High degree of pathogen and week seed kill	
Potentially good odour control	
Protection from climate	

The given name of each scenario for this study is shown in Table 4.2. The anaerobic digestion and composting scenario are compared in the concept of global warming. Since energy is produced in anaerobic digestion system, the composting scenario is assessed by including current energy production methods to make the results comparable.

Table 4.2. Name of the scenarios.

Scenario	**Given Name**
Utilization of food wastes by anaerobic digestion plant with a biogas recovery system	Scenario A
Utilization of food wastes by composting in the scope of waste disposal	Scenario B
Current waste disposal and energy production methods	Scenario C

The LCA study covers; identification of air emissions of the plant, comparision environmental effects of the plant with current waste disposal and energy production methods, comparison of the environmental effects of the plant with composting process in the scope of waste disposal methods.

LCA study consists of two assessments. First one focuses on the production of energy, and the second one focuses both on production of energy and the utilization of the energy. In the assessment of production of energy, the amount of food wastes generated from the university and the amount of energy that can be obtained by the anaerobic digestion of the food wastes are considered. In the assessment of production of energy and the utilization of the energy in the scope of Sustainable and Green Campus Program, it is assumed that continous supply of the food waste is provided by Sarıyer Municipality for period 2, 3 and 4, totally for 142 days. The overall heat requirement of the pool and the overall electricity requirement of the buildings are considered. Since, the produced energy is not sufficient to meet the need of the energy required, the rest of the energy required is assumed to be supplied by the current energy production methods.

As it can be seen from the Table 4.3. that functional unit of this study is ‘benefits of utilization of waste generated from the university campuses per year.’ The secondary services of each period are also indicated in the Table 4.3. In order to supply continous feedstock to digester, 340 kg/day food waste is needed for Period 2 and 3, 379 kg/day food waste is needed for Period 4.

Table 4.3. Data for functional unit, secondary services and requirements for continuous supply.

Period No	**Duration of the Period (days)**	**Waste Generated[1] (kg/day)**	**Secondary Services**		**Waste Requirement for Continous Supply (kg/day)**
			Biogas Generation (m^3/day)	**Digestate Generation[2] (kg/day)**	
Period 1	223	386.429	55.76	15.006	-
Period 2	33	46.429	6.699	0.360	340.00
Period 3	46	46.429	6.699	0.360	340.00
Period 4	63	7.143	1.031	0.277	379.29

[1] Data used for functional unit

[2] Without water content, reported as unbiodegradable content

4.2. Goal and Scope Definition

The purpose of the LCA for this study is to determine the environmental benefits of using an anaerobic digestion plant to utilize food wastes generated from an universities' campuses.

Energy is obtained by utilization of biogas that occurred during anaerobic degradation process. Since, energy production is possible, anaerobic digestion technology can also be considered as one of the solutions for the energy problem. The other product of anaerobic degradation; digestate can also be used as fertilizer, since it contains required nutrients for soil microorganisms.

Goals of this study are as follows: reduction of the waste that required to be transported to landfill side in Istanbul, utilization of food wastes, meeting 10% of the heating requirement of the indoor swimming pool in Hisar Campus from the produced heat in the plant, decreasing electricity consumption from the grid for Hisar Campus Buildings by supplying electricity from the plant, saving in global warming potential, decreasing the impact of acidification, aquatic eutrophication, terrestrial eutrophication and photochemical ozone formation-impact on vegetation

4.3. System Boundary

The process includes the assessment of potential environmental impact assessment of the designed plant. In this plant, wastes are degraded in anaerobic conditions and, biogas and digestate occur as products of anaerobic degradation. The construction of the plants is not included, while the operation of the plants is considered in LCA.

The system boundary of the Scenario A can be explained as follows:

- The transportation distance of wastes is 2.06 km to collect the food wastes from restaurants and dining halls.
- The operation of the plant is 302 days. Since the amount of food wastes is only 10 kg per day in period 4, plant is not working for this period which is 63 days.
- For period 1, plant is running as two-stage digesters. Since the amount of food wastes decrease in period 2 and 3, and the volume of one digester is enough, plant is operated as one stage digester for these periods.
- Energy demand of the plant is met by the energy produced in the plant.
- Energy production is calculated for utilization of 90173.517 kg of waste for 1 year (The amount of the waste is calculated according to the academic calendar by considering the possible arrival and leaving dates of the most students).
- Digestate is transferred to Sarıyer Municipality Parks Department which is 6.11 km away from the university.
- The truck used to transport the wastes has the capacity of 7 tons.
- In the scope of LCA of utilization of produced energy, overall heat requirement of the pool and overall energy requirement of the buildings are considered.
  - Continous supply of food waste is assumed to be provided by Sarıyer Municipality for period 2, 3 and 4, totally for 142 days.
  - The amount of waste to be transferred is assumed as 5 km.

Production of food waste, transportation of energy and grid connection, and application of digestates are excluded from the system boundry. The flowchart of Scenario A is shown in Figure 4.1.

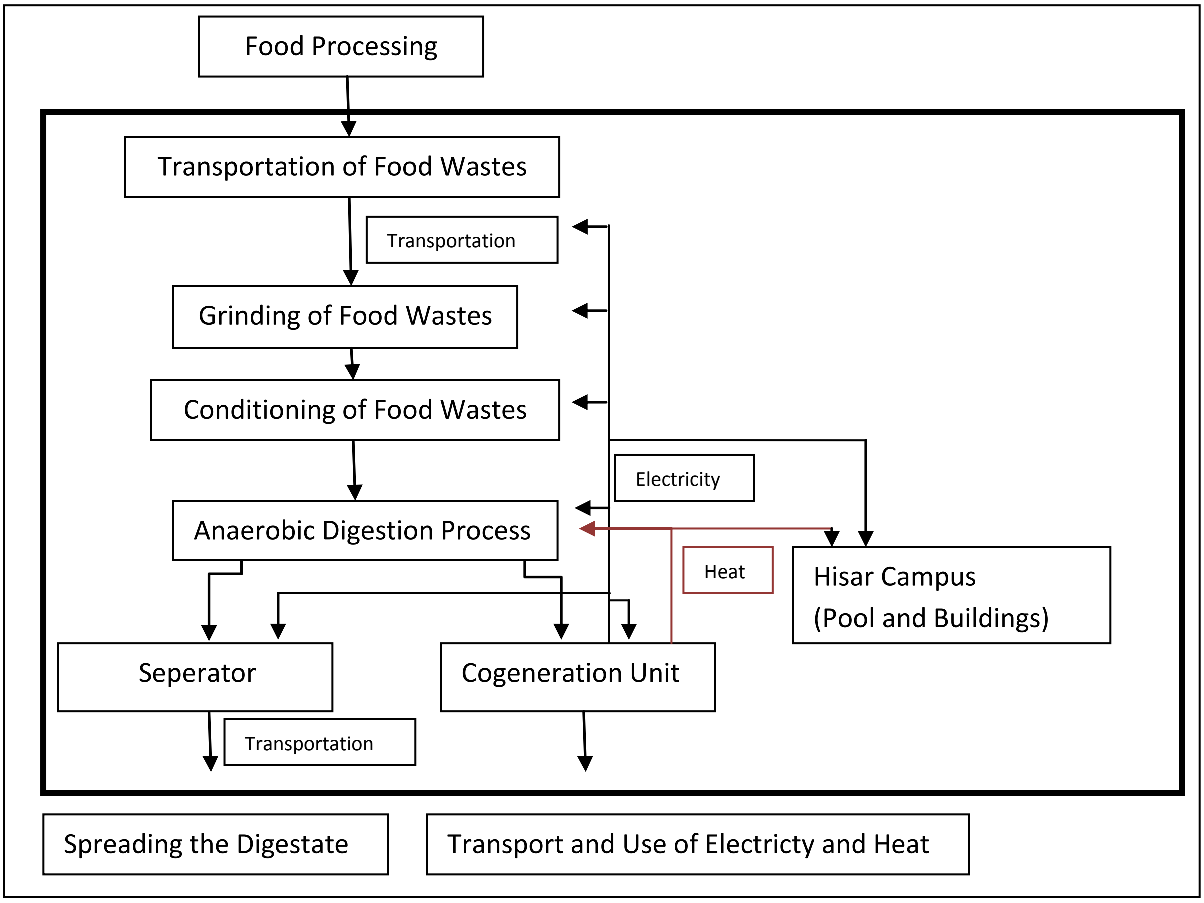

Figure 4.1. System boundary of anaerobic digestion of food waste.

The system boundary of the Scenario C can be explained as follows:

- In order to make the results comparable, current waste disposal and national energy production methods are included in this scenario.
- Before being disposed to landfill side in Odayeri, wastes are collected in waste collection center in Baruthane, Şişli.
- The total transportation distance of wastes is 32.57 km to landfill side in Odayeri in Istanbul.
- The truck used to transport the wastes has the capacity of 7 tons.
- The amount of electricity consumption from the grid mix is same as the electricity produced in anaerobic digestion plant.

- Natural gas consumption which provides the same amount of heat that is produced in anaerobic digestion plant, is adjusted from GaBi 4 software, since the process of GaBi 4 software is used for natural gas consumption.
- In the scope of LCA of utilization of produced energy, overall heat requirement of the pool and overall energy requirement of the buildings are considered.
    - Electrical and heating requirements are assumed to be same as the produced electricity and heat in anaerobic digestion plant in continous supply conditions.
    - The amount of waste that required to be transferred from Sarıyer Municipality to Bogazici University, to provide continous supply conditions, is assumed to be transferred to landfill side in Odayeri, Istanbul.

Transportation of energy and grid connection, and landfilling operation of wastes are excluded from the system boundry.

The system boundary of the Scenario B can be explained as follows:

- In order to make the results comparable, current energy production methods are included in this scenario.
- The transportation distance of wastes is 2.06 km to collect the food wastes from restaurants and dining halls, and transfer the wastes to the plant.
- Electrical consumption of the compost plant is supplied from the grid mix.
- Mass reduction in waste is assumed to be 80% according to the literature (Faucette, B., 2000; Fehr, 2007).
- Digestate is transferred to Sarıyer Municipality Parks Department which is 6.11 km away from the university.
- The truck used to transport the wastes has the capacity of 7 tons.
- The amount of electricity consumption from the grid mix is same as the electricity produced in anaerobic digestion plant.
- Natural gas consumption which provides the same amount of heat that is produced in anaerobic digestion plant, is adjusted from GaBi 4 software, since the process of GaBi 4 software is used for natural gas consumption.

- The operation of the plant is 302 days. Since the amount of food wastes is only 10 kg per day in period 4, plant is not working for this period which is 63 days.
- In the scope of LCA of utilization of produced energy, overall heat requirement of the pool and overall energy requirement of the buildings are considered.
    - Continous supply of food waste is assumed to be provided by Sarıyer Municipality for period 2,3 and 4, totally for 142 days.
    - The amount of waste to be transferred is assumed as 5 km.
- The energy requirement of the composting plant is indicated in APPENDIX D.

Production of food waste, transportation of energy and grid connection, and application of compost is excluded from the system boundry. System boundary of the composting plant is shown in Figure 4.2.

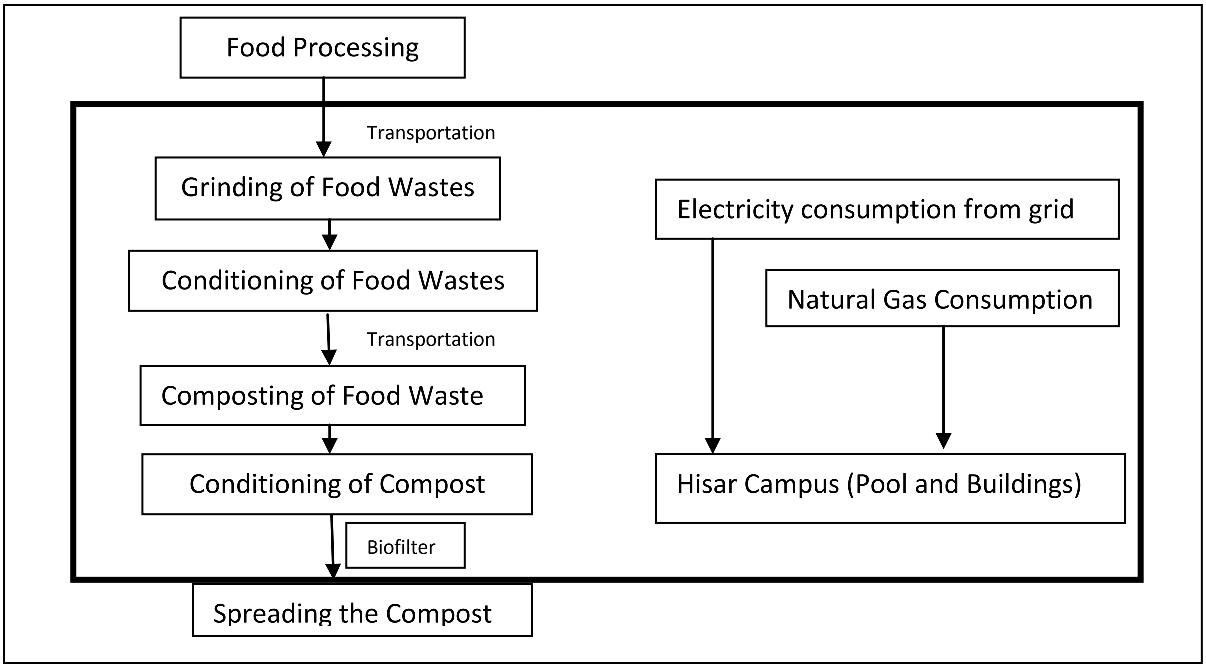

Figure 4.2. System boundry of composting plant.

4.4. Inventory Analysis

In this study, the inventory data regarding the designed plant was gathered from the laboratory experiments carried out in TUBITAK – MRC, industry and literature. The inventory tables regarding energy use are indicated between Table 3.8 and Table 3.12.

4.4.1. Scenario A

The designed plant has following units; a dumping area, a primary storage unit, a conveyor, a grinder, a contidioning unit, two digesters, a cogeneration engine, a flare, a separator, a liquid digestate tank, a solid digestate tank and a control unit. The flow diagram of the pilot plant for the main scenario is given in Figure 4.3.

The wastes are transported to the dumping area from the campuses. Data in GaBi 4 database is used to determine the emission generated from the transportation process.

Secondly, wastes are transported to primary storage unit. Since the retention time in storage tank is not significant, it is assummed that there is no emission released from the storage.

Wastes are transferred to the conveyor on which the impurities are removed. The installed power of the conveyor motor is 1 kW. After removal of the impurities, wastes are grinded. The installed power of the grinder is 2.237 kW. The grinder is selected by considering the amount of waste generated, the content of the waste and the availability of the grinder in Turkey. Technical drawing of Schutte Buffalo Hammermill that grinds food waste can be found in APPENDIX C.

Wastes are transferred to conditioning unit in which total solid content of the feedstock is adjusted and the feedstock is homogenized before supplied to the digesters. There is a mixer with 1kW installed power inside the conditioning tank. It is considered that tap water is added daily to adjust the dry matter content of the feedstock. A fan is also attached to the unit for safety reasons.

After conditioning tank, feedstock is pumped to digesters. The installed power of the pump is 1.1 kW. There is a mixer with 1 kW installed power inside each digester. The installed power of air injection motors is 0.003 kW.

The heat requirement of the digesters are calculated by the sum of heat loss from the digesters and heat requirement of food waste according to the periods, since significant difference is observed for heat losses between periods. The heat loss calculations can be found in Table 3.11.

In order to calculate heat losses according to the periods, data in Table 4.4 and Table 4.5 are also considered. The average of air temperature and soil temperature is determined for each period.

Table 4.4. Average soil temperatures in Istanbul (TBS Madencilik Sanayi Ticaret A.Ş., 2010).

Months	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Average Soil Temperature (at 5 cm depth) (^{o}C)	5	6	9	14	21	26	30	29	23	17	11	7

Table 4.5. Average air temperatures in Istanbul (Türkiye Cumhuriyeti Meteoroloji Genel Müdürlüğü, 2012).

Months	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Average Air Temperature (^{o}C)	6	6	7	12	16	21	24	24	20	16	11	8

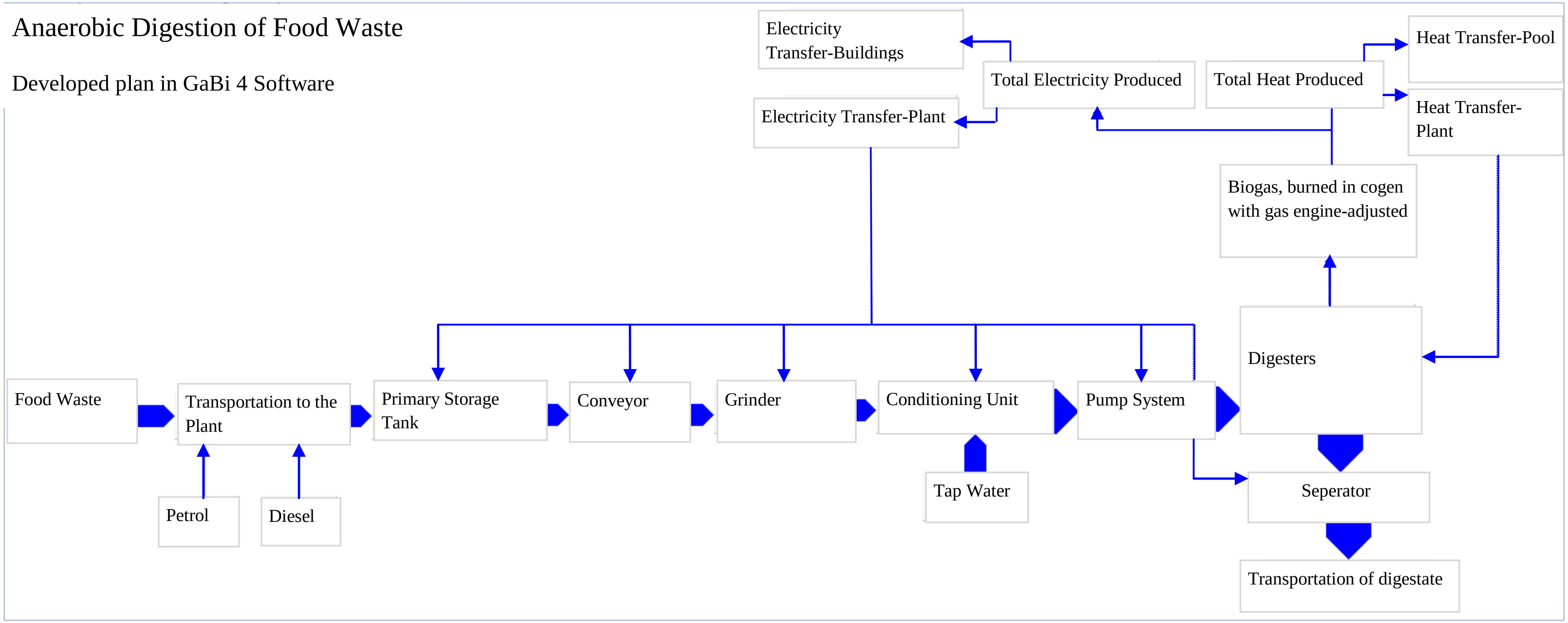

Figure 4.3. Anaerobic digestion of selected biomass.

According to the elemental analysis of food waste, 55.755 m^3 biogas is produced for period 1 and 6.669 m^3 biogas is produced for period 2 and 3. The process ‘biogas, burned in cogen with gas engine’ in GaBi 4 database is adjusted according to the selected biogas engine. The installed power of the cogeneration is 28 kW. The brand of the cogeneration engine is TEDOM and technical drawing can be found in APPENDIX D.

The data in Table 4.6 represents the outputs for biogas with 65% methane. Therefore, this data is adjusted according to the biogas that generates from handled food waste. Energy production data is adjusted in ‘biogas, burned in cogen with gas engine’ process.
The basic technical data of the cogeneration unit is shown in Table 4.6.

Table 4.6. Data for cogeneration engine (obtained from Arke Enerji Sistemleri Sanayi ve Ticaret Limited Şirketi).

Nominal Electrical Output	28 kW
Maximal Heat Output	57 kW
Fuel Input	92.5 kW
Electrical Efficiency	30.20%
Heat Efficiency	61.60%
Total Efficiency (fuel use)	91.80%
Gas Consumption at 100% output	14.3 Nm^3/h

The heating demand of the digesters and electricity demand of the plant is supplied from the produced energy.

After digestion process, the digestate is pumped to 2.2 kW separators. Since, digestion may continue, biogas is collected from the liquid storage tank.

The electricity requirement of lighting system, sensors and control panels are also considered in LCA.

4.4.2. Scenario B

Waste is collected in a storage tank and then grinded by a 2.237 kW grinder. In order to remove the impurities, waste is transferred to the reactor by a conveyor. The installed power of the conveyor motor is 0.75 kW. The reactor is rotating drum and the power of the motor to rotate the reactor is 2.2 kW. Two blowers are stated in order to prevent bad smell.

The installed power of the blowers is 0.22 kW. One blower is installed to provide air in order to obtain aerobic conditions, and the second one transfers the air of the composting area to biofilter. The electrical consumption of this plant is supplied by power grid mix.

Direct emissions from the composting process that contributes to global warming are; CO_2, N_2O, CH_4. CO_2 from collection and transportation of the organic materials are taken into account while, biogenic CO_2 resulting from decomposition of organic wastes is not counted since it is not considered as a GHG (USEPA., 2005). According to (Federasl Environment Agency, 2009) N_2O production is 83 g per ton of wet kitchen waste. CH_4 is not generated, if aerobic conditions are achieved. The CH_4 at the center of the compost pile, is likely to be oxidized when it reaches the surface of the pile which is rich in oxygen. So, CH_4 is converted to CO_2, when it reaches the surface (USEPA, 2002).

The compost is transferred to Sarıyer Municipality. Data in GaBi 4 database is used to determine the emission generated from the transportation process.

In order to obtain comparable results, current energy production methods that are described in Scenario C, are included in this Scenario. The flow diagram of the composting plant for this scenario is given in Figure 4.4.

4.4.3. Scenario C

Scenario C is created for calculating the emissions caused by current waste disposal method and current heat production by natural gas consumption and national electricity production methods. Wastes are transported to landfill side in Odayeri.

The indoor swimming pool in Hisar Campus is heated by combustion of natural gas. The electricity is provided by grid mix. The inventory tables are gathered from the GaBi 4 database regarding the heat production from natural gas, the national electricity consumption from the grid and the transportation.

The source of grid mix in Turkey is shown in Table 4.7. The grid mix is mainly consists of natural gas by 44.7%, followed by hydraulic energy, lignite and coal by 23.0, 21.8 and 7.6%, respectively.

Table 4.7. Electrical energy sources and their contributions in Turkey (Banar et al., 2009).

Energy sources	**Contribution of energy sources (%)**
Fuel-oil	2.9
Coal	7.6
Lignite	21.8
Natural gas	44.7
Hydraulic energy	23

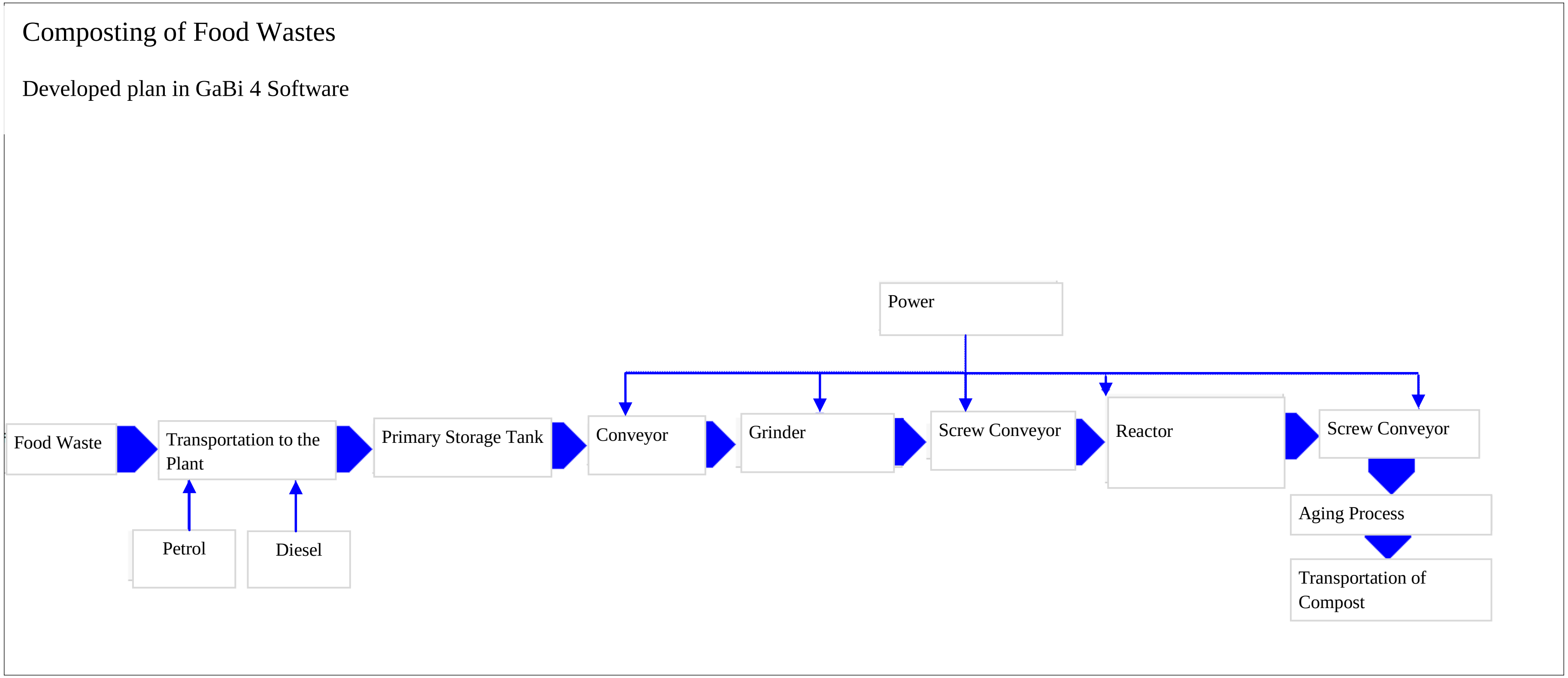

Figure 4.4. Composting of selected biomass.

4.5. Impact Assessment

4.5.1. Classification

In this step, impact categories are determined. Since the main environmental concern regarding energy use is global warming, special emphasize is given to global warming impact category. Following impact categories are also assessed: acidification, aquatic eutrophication, photochemical ozone formation- impact on vegetation and terrestrial eutrophication. The other methods available on EDIP 2003, photochemical ozone formation-impact on human health and stratospheric ozone depletion are also considered. However, the impacts of these categories are insignificant. Classification results of scenario A and C can be seen in Figure 4.5, 4.6 and 4.7.

Following results are obtained from classification step;

The amount of emissions that released to air is higher than the emissions released to fresh water and sea water as shown in Figure 4.5 and Figure 4.6. Emissions to air are over 95% of total emission released in both Scenarios. Chloride and Sodium +1 are the main emissions that contribute to emissions to fresh water, and suspended solid is the emission that contributes to emission to sea water.

In Scenario A, the amount of each emission category is as follows: emissions to air: 359.883 kg, emissions to fresh water: 10.677 kg, emissions to sea water: 1.956 kg, emissions to agricultural soil: 0.28126 kg and emissions to industrial soil: 0.087 kg.

For Scenario C, the amount of each emission category is as follows: emission to air: 253,302 kg, emissions to fresh water: 243.396 kg, emissions to sea water: 18.597 kg, emissions to agricultural soil: 0.548 kg, emissions to industrial soil: 1.89 kg.

Since the amount of emissions to air is significant, main contributors of air emissions of each scenario are shown in Figure 4.7.

The largest amount of emission for Scenario A is carbon dioxide. Carbon dioxide is mainly generated by cogeneration unit, followed by transportation process and tap water consumption.

The main emissions for Scenario C are exhaust and steam emissions. These emissions are mainly generated by current energy production methods. Consumption of natural gas to produce heat contributes to exhaust and steam emissions about 60% of the total exhaust and steam emissions. Remaining part comes from electric consumption from grid mix. Carbon dioxide is caused by consumption of natural gas about 53%, electricity consumption from grid about 44% and transportation about 2.2% of the total emissions, respectively.

When scenarios are compared in terms of main emission generated from their processes, all emissions are higher in Scenario C. In addition, there is no exhaust generation from Scenario A and steam generation is negligible in Scenario A when compared to Scenario C.

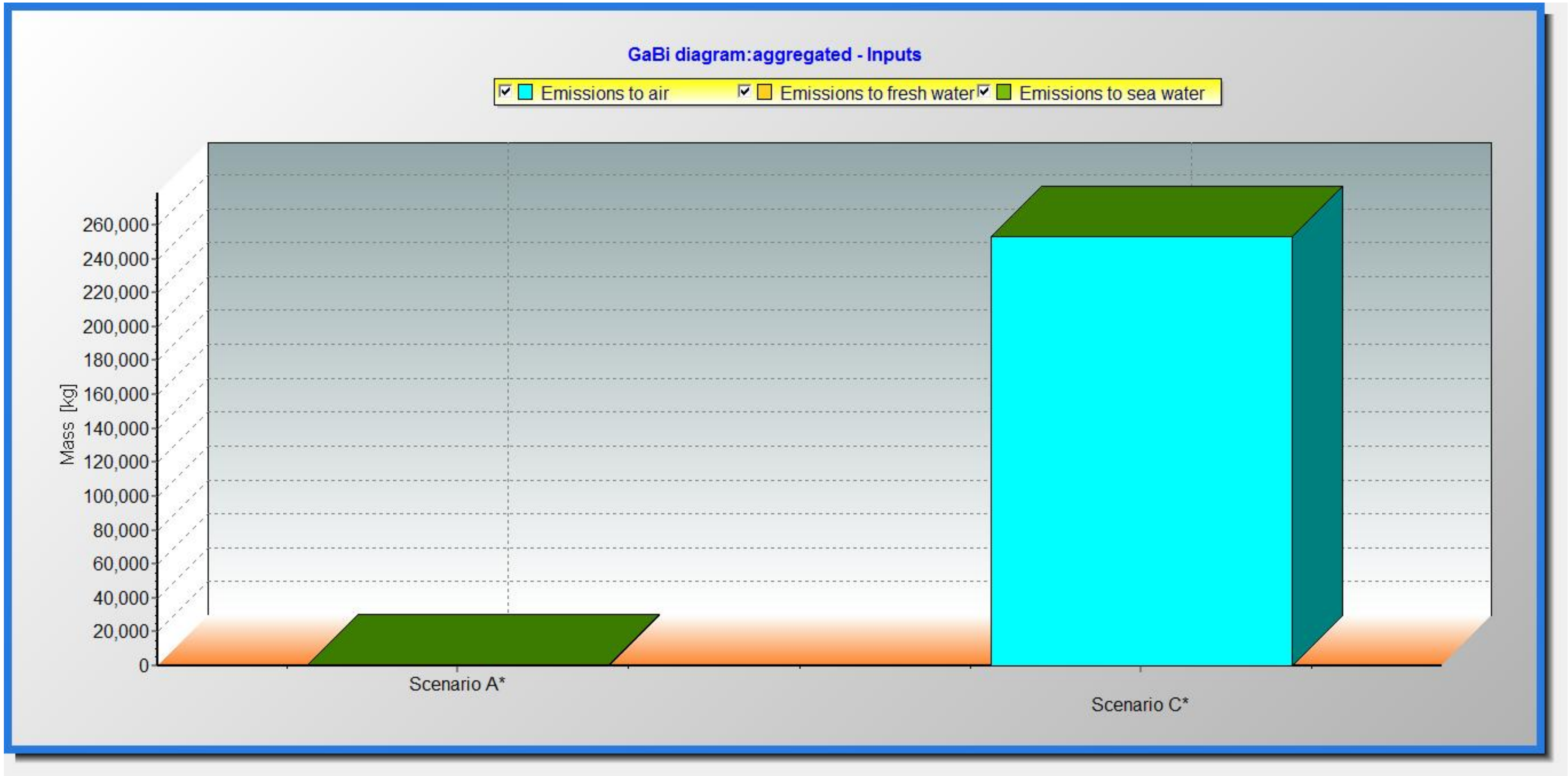

Figure 4.5. Emissions of scenario A and C according to the effect area.

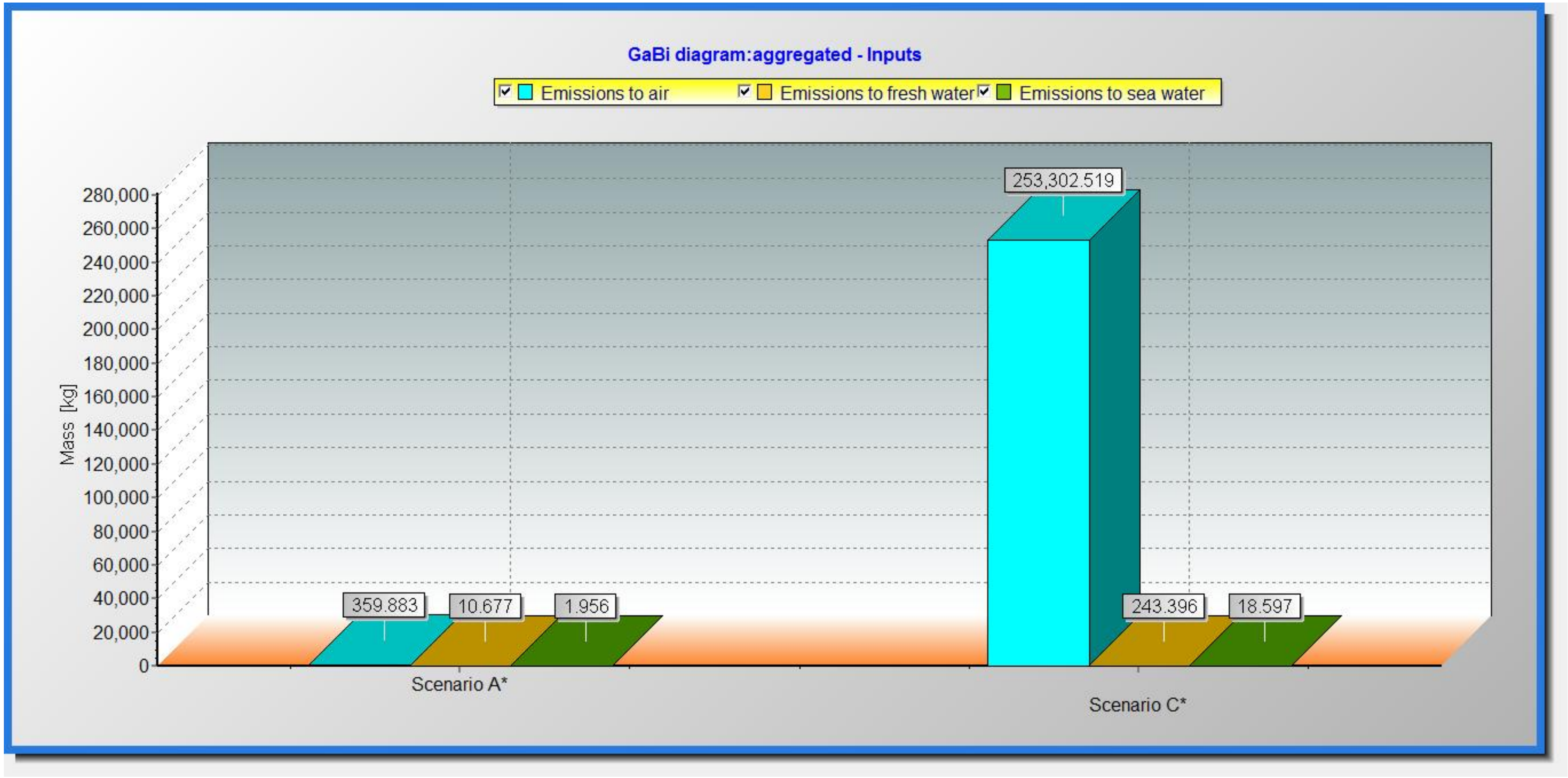

Figure 4.6. Amount of emissions of scenario A and C according to the effect area.

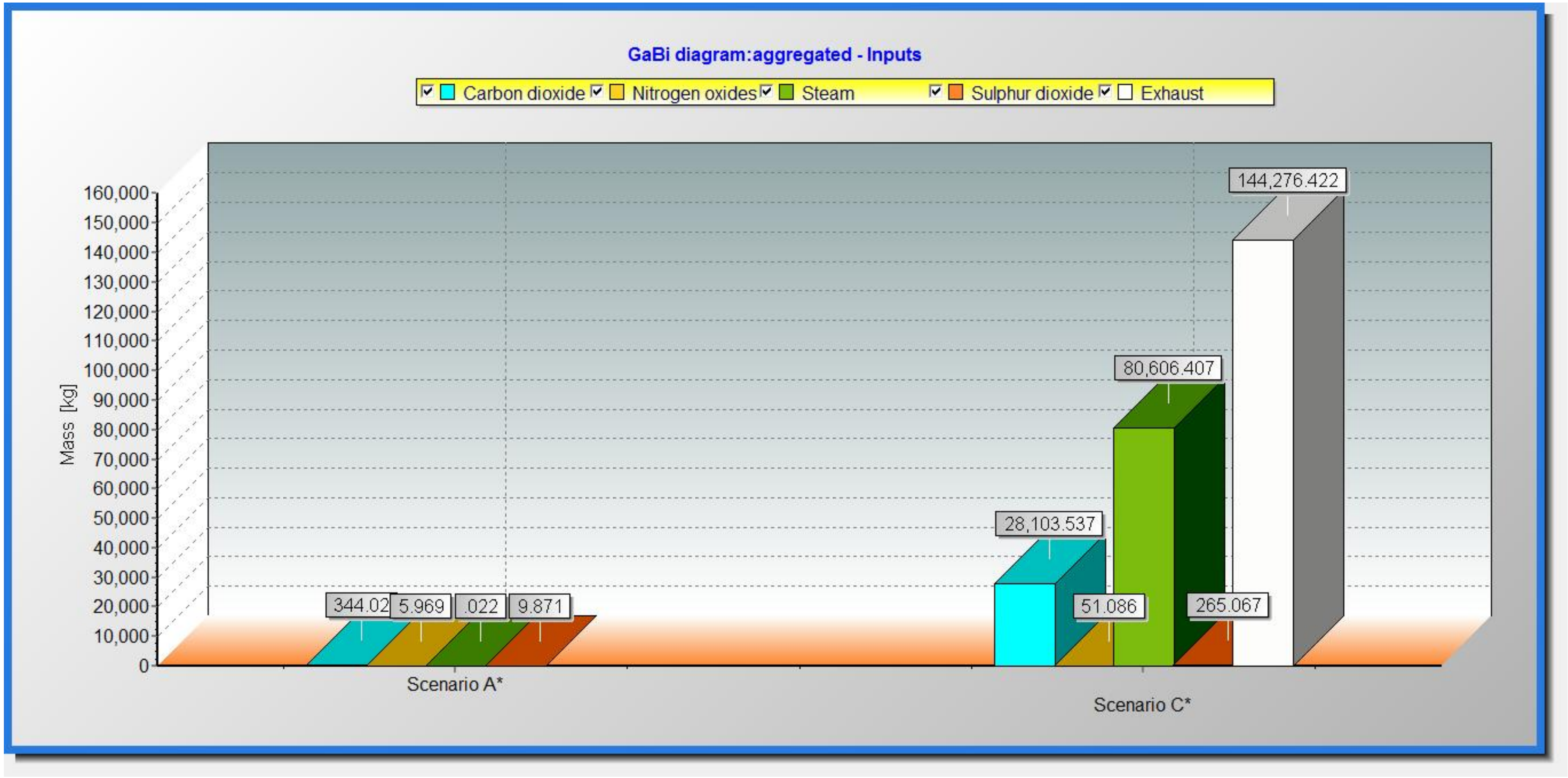

Figure 4.7. Amount of air emissions of scenario A and C.

4.5.2. Characterization

4.5.2.1. Global Warming. Characterization results are seen between Figure 4.8 and Figure 4.21. The main sources of global warming potential in Scenario A, which can be found in Figure 4.8., are carbon dioxide, followed by nitrous oxide emissions. Nitrous oxide is mainly generated from cogeneration process, transportation processes and usage of tap water. The amount of carbon monoxide and methane, totally accounts for 0.045%, which is negligible when compared with other emissions.

In Scenario B, N_2O emissions which are the product of aerobic degradation, is the main contributor to global warming potential as shown in Figure 4.9. It can be stated that the prevention of most of the N_2O emissions which have a significant effect on global warming, can be achieved by anaerobic digestion. Further comment can be done, if the landfilling emissions are known. It can not be concluded that Scenario B has the highest impact on global warming potential. In Scenario C, carbon dioxide is the main contributor of global warming potential as shown in Figure 4.10. by 94% contribution. The source of carbon dioxide emissions are the current energy production methods; consumption of natural gas and electrical power from the grid. Transportation has also a little contribution to carbon dioxide emissions. Methane is the second highest contributor of GWP in this scenario, responsible for 5.43% of total emissions.

When scenario A and C are compared, it can be stated that, anaerobic digestion technology is highly advantageous over current waste disposal and energy production methods in global warming category. The comparison is indicated in Figure 4.11. However, an integrated comparison can not be done for Scenario B, since other scenarios do not include emissions released during land filling processes. It is possible to state that highest amount of global warming emissions are released during treatment of wastes, is in composting process.

- The global warming potential of anaerobic digestion scenario is 637.27 kg CO_2-equivalent, while it is 29,820 CO_2-equivalent for the current waste disposal and energy production scenario. Anaerobic digestion scenario provides about 97.8% reduction compared to current waste disposal and energy production scenario.

When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 7.2% reduction on global warming can be achieved.

Figure 4.12 shows the comparison of each scenario according to the emissions regarding energy use and transportation process. Scenario B has higher GWP than Scenario C. The reason of that is in Scenario B, an addition of energy is required for the operation of composting plant. In scenario C, the transportation distance is higher, since the waste amount is higher and wastes are disposed to landfill side in Odayeri. In order to assess the effect of mass reduction and utilization of wastes, the effect of transportation processes of each scenario is compared. As seen from Figure 4.13, composting is advantageous over other scenarios in the scope of waste disposal. Current energy production and energy consumption of composting plant is not included for this assessment.

- The global warming potential of composting scenario provides about 95% reduction compared to current waste disposal and energy production scenario and of anaerobic digestion scenario provides about 79% reduction compared to current waste disposal and energy production scenario in the scope of waste disposal method only. However, when the energy demand of the compost plant is considered, GWP of this scenario becomes the highest contributor of GWP. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, composting scenario provides about 88% reduction compared current waste disposal and energy production scenario in the scope of waste disposal method only and anaerobic digestion scenario provides about 86% reduction compared to current waste disposal and energy production scenario in the scope of waste disposal method only in terms of GWP. However, when the energy demand of composting plant is considered, the GWP of composting scenario becomes the highest contributor to GWP.

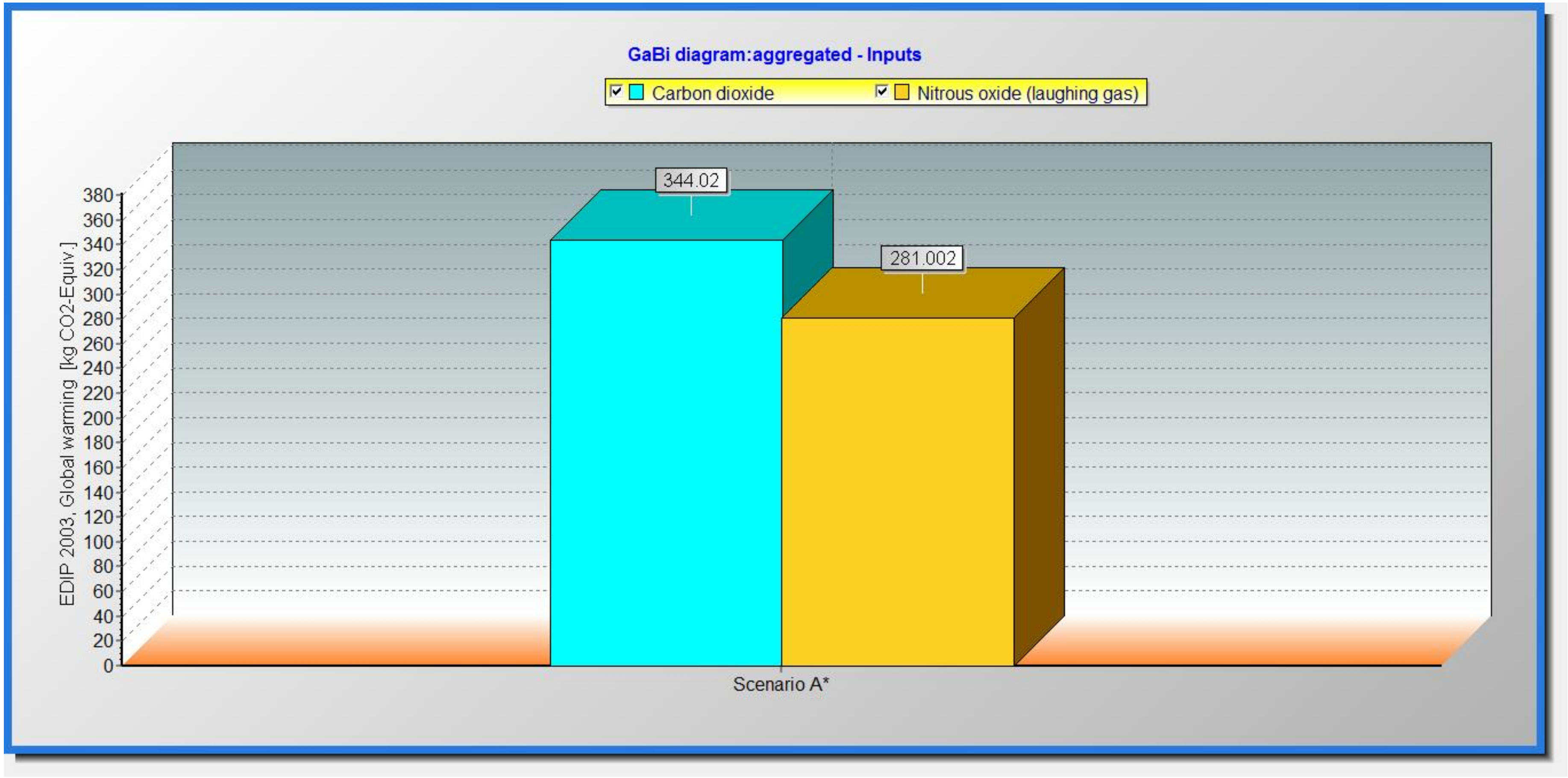

Figure 4.8. Main contributors to GWP caused by scenario A.

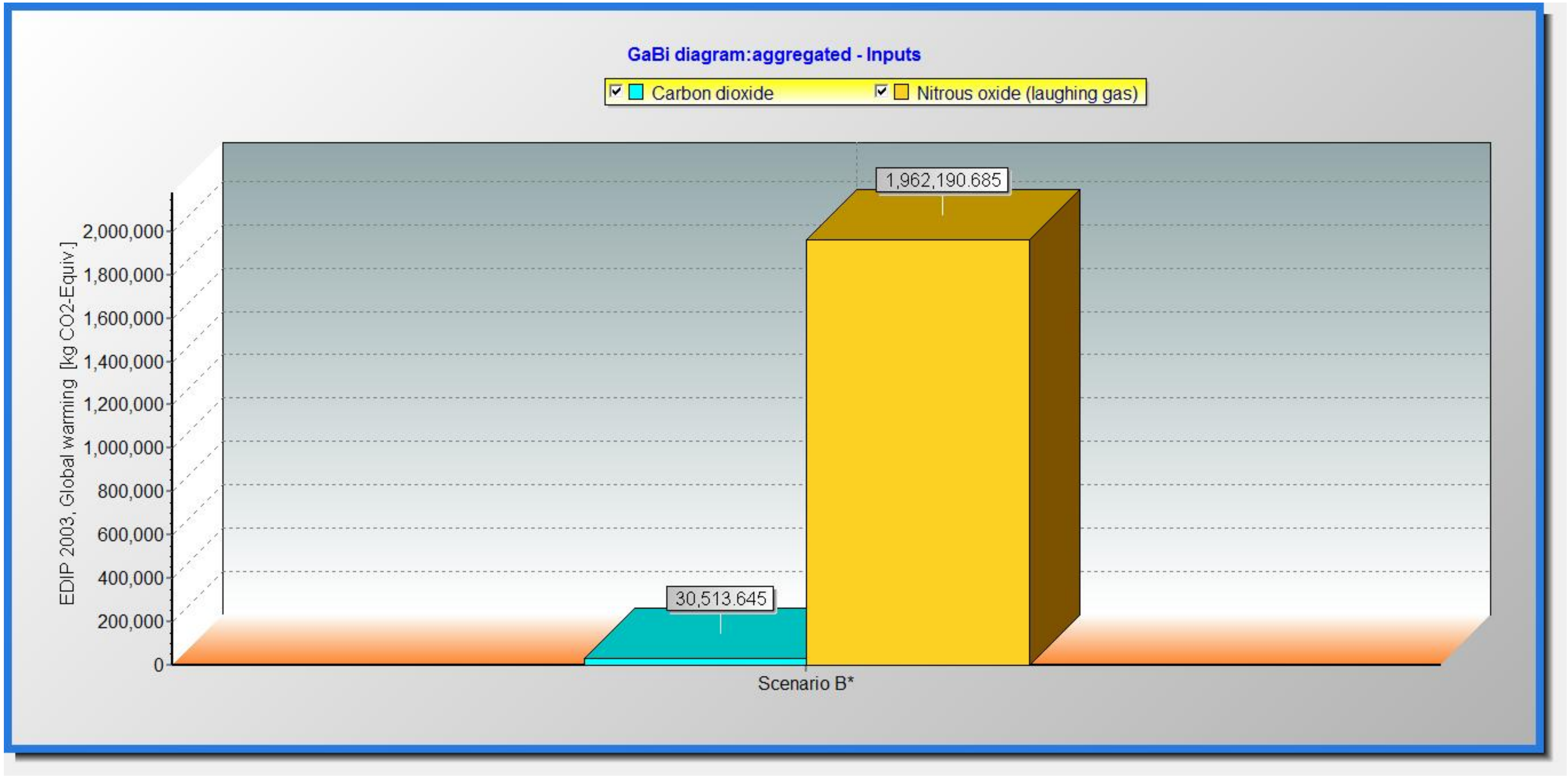

Figure 4.9. Main contributors to GWP caused by scenario B.

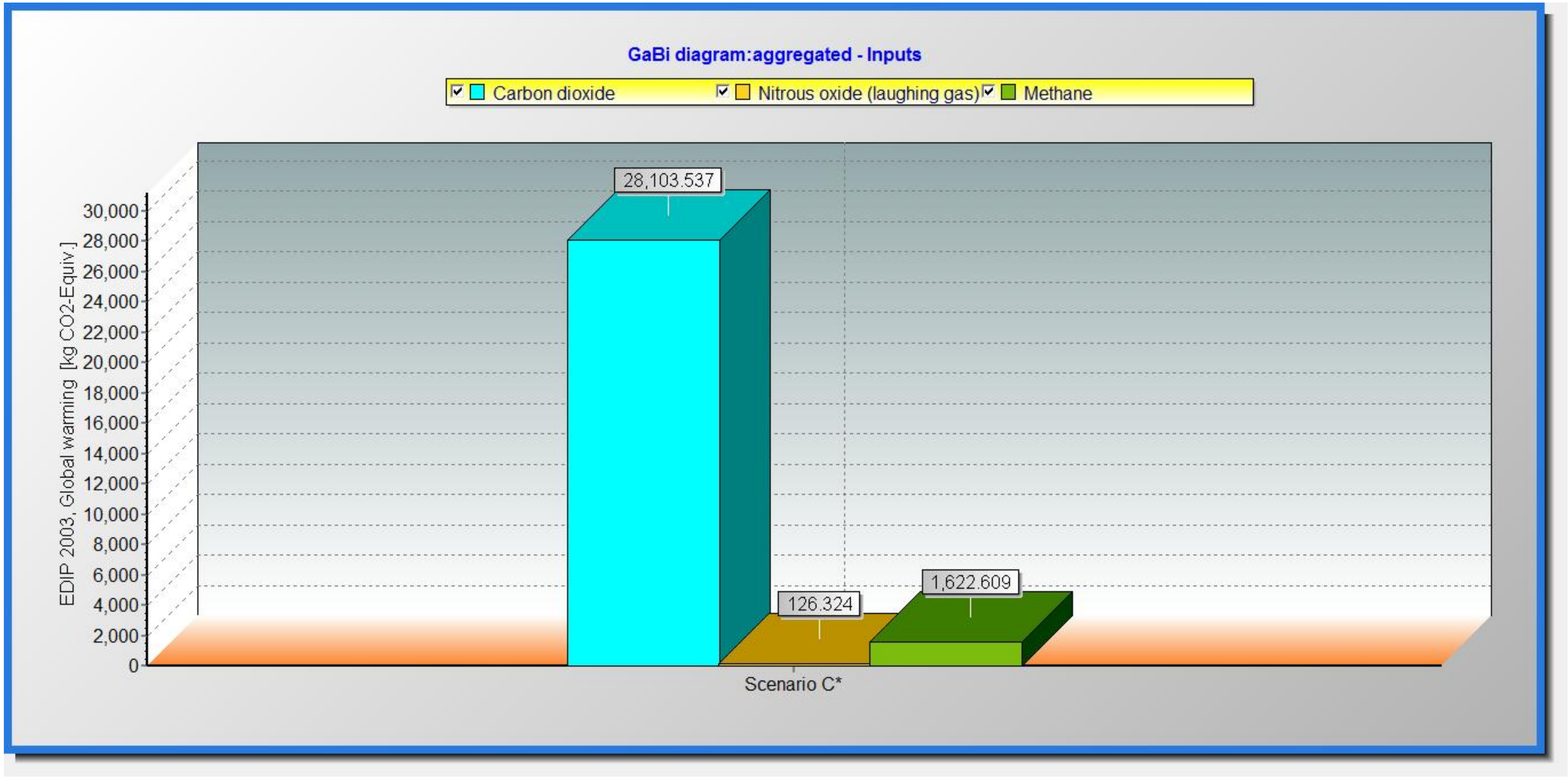

Figure 4.10. Main contributors to GWP caused by scenario C.

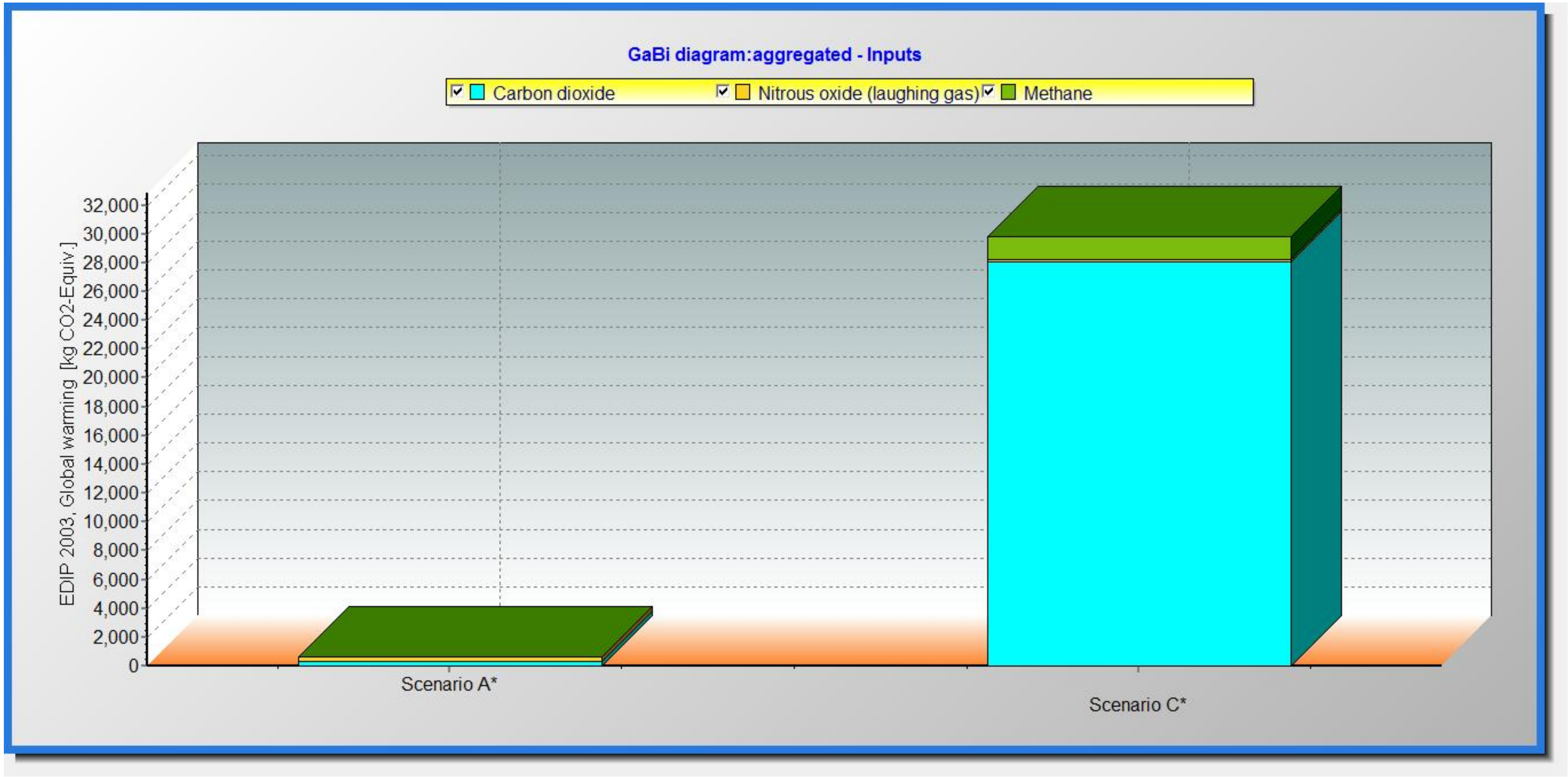

Figure 4.11. GWP of scenario A and C.

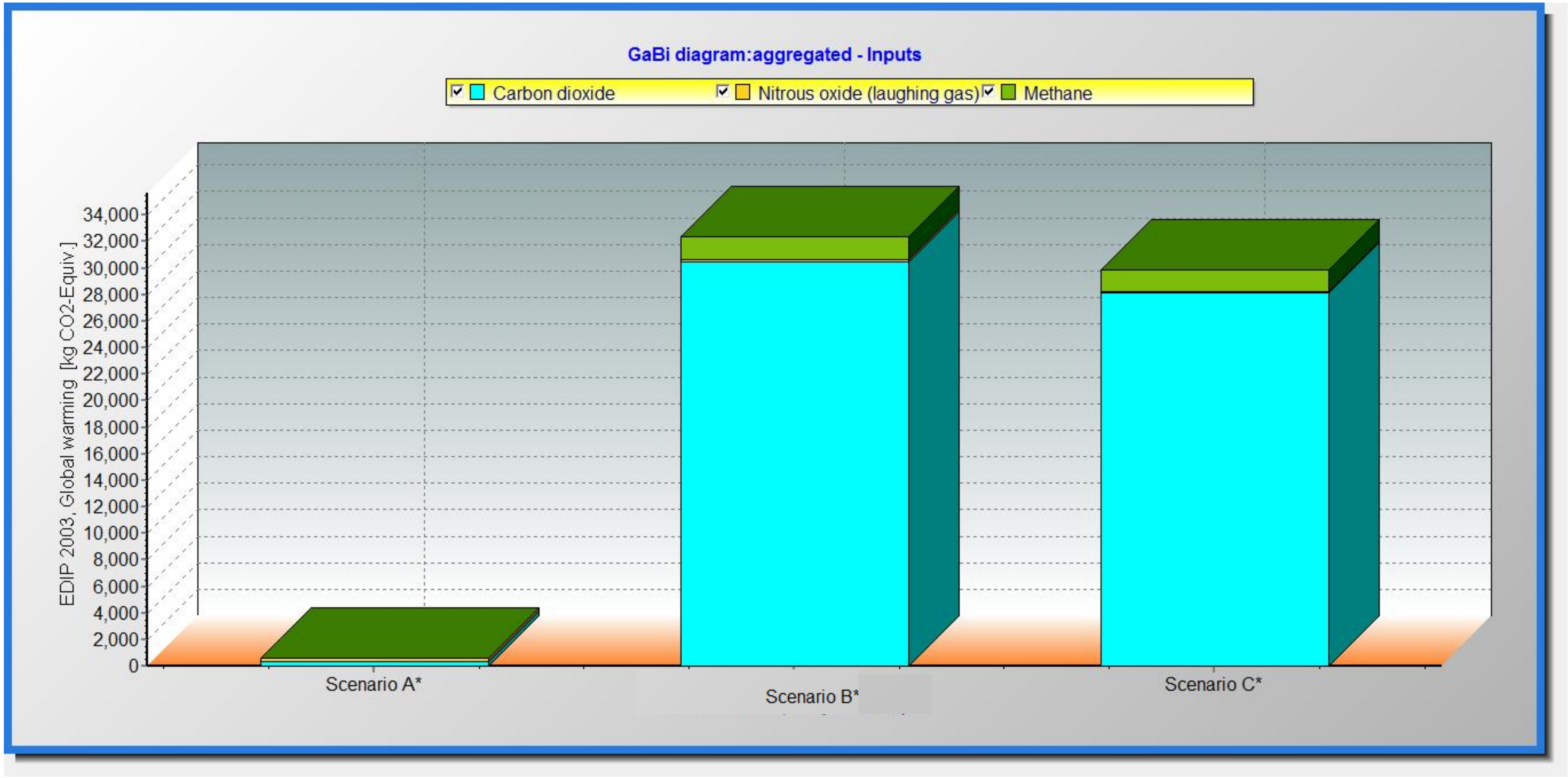

Figure 4.12. GWP of scenario A, C and B without N_2O emissions.

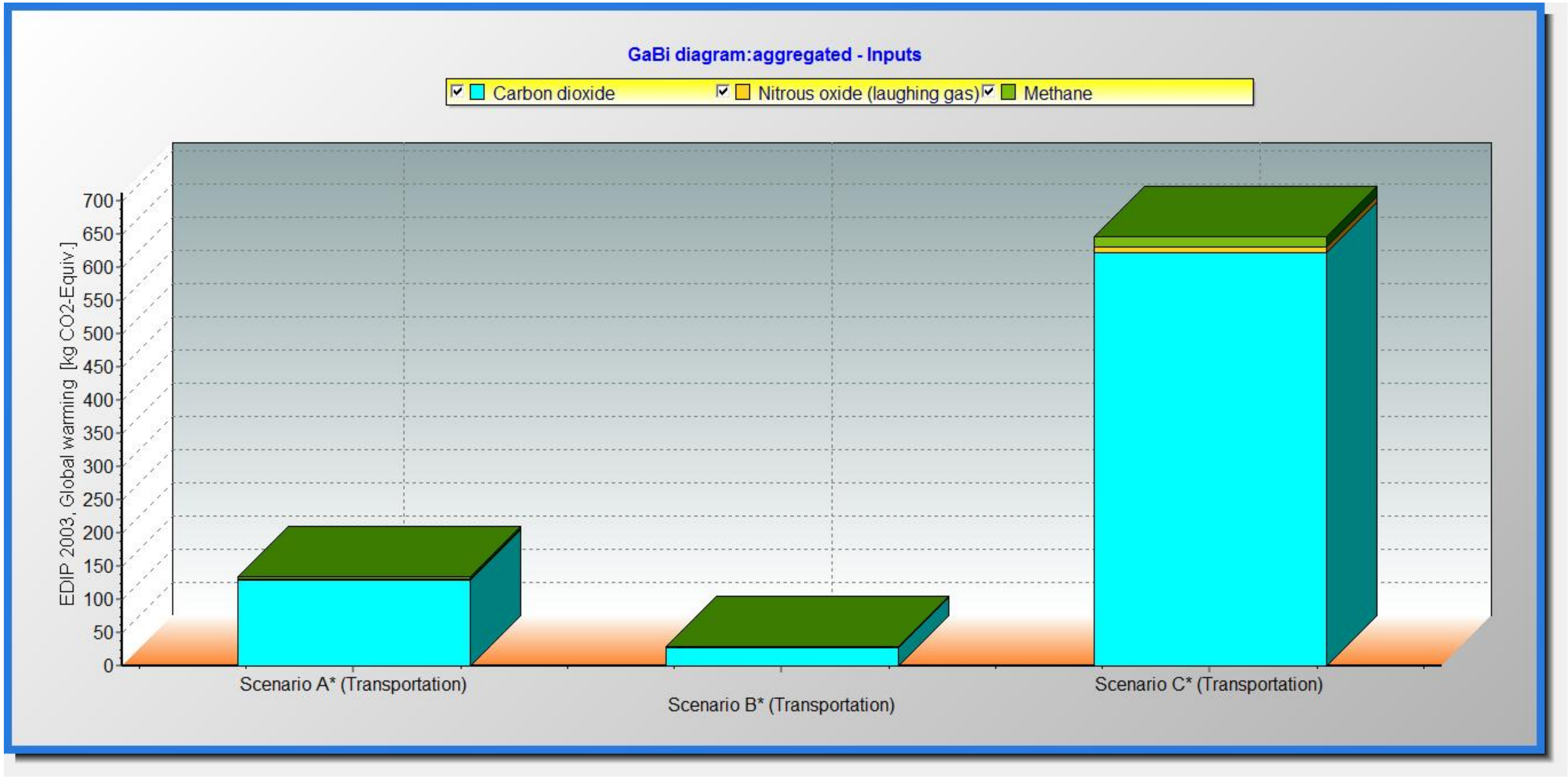

Figure 4.13. GWP of the transportation processes of scenario A, B and C.

4.5.2.2. Acidification. As shown in Figure 4.14 and Figure 4.15, sulfur dioxide emissions are the main contributor to acidification for Scenario A and B. In Scenario A, sulfur dioxide emissions are responsible for 77% of total impact and nitrogen oxides for 22.6%, respectively. The main source of sulfur dioxide emissions is cogeneration unit which is responsible for 73.7% of sulfur dioxide emissions.

In Scenario C, 88.6% of acidification potential is caused by sulfur dioxide emissions, followed by 8.3% of nitrogen oxides emissions and 2.7% of hydrogen chloride emissions. The source of sulfur dioxide emissions is electrical consumption from grid which contributes 86.6% of total sulfur dioxide emissions.

- The acidification potential of anaerobic digestion scenario is 227.02 m^2 (Unprotected Ecosystem) UES while it is 5,294.3 m^2 UES for the current waste disposal and energy production scenario. So, anaerobic digestion scenario provides about 95.7% impact reduction on acidification potential compared to current waste disposal and energy production scenario. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 4.14 % impact reduction on global warming can be achieved.

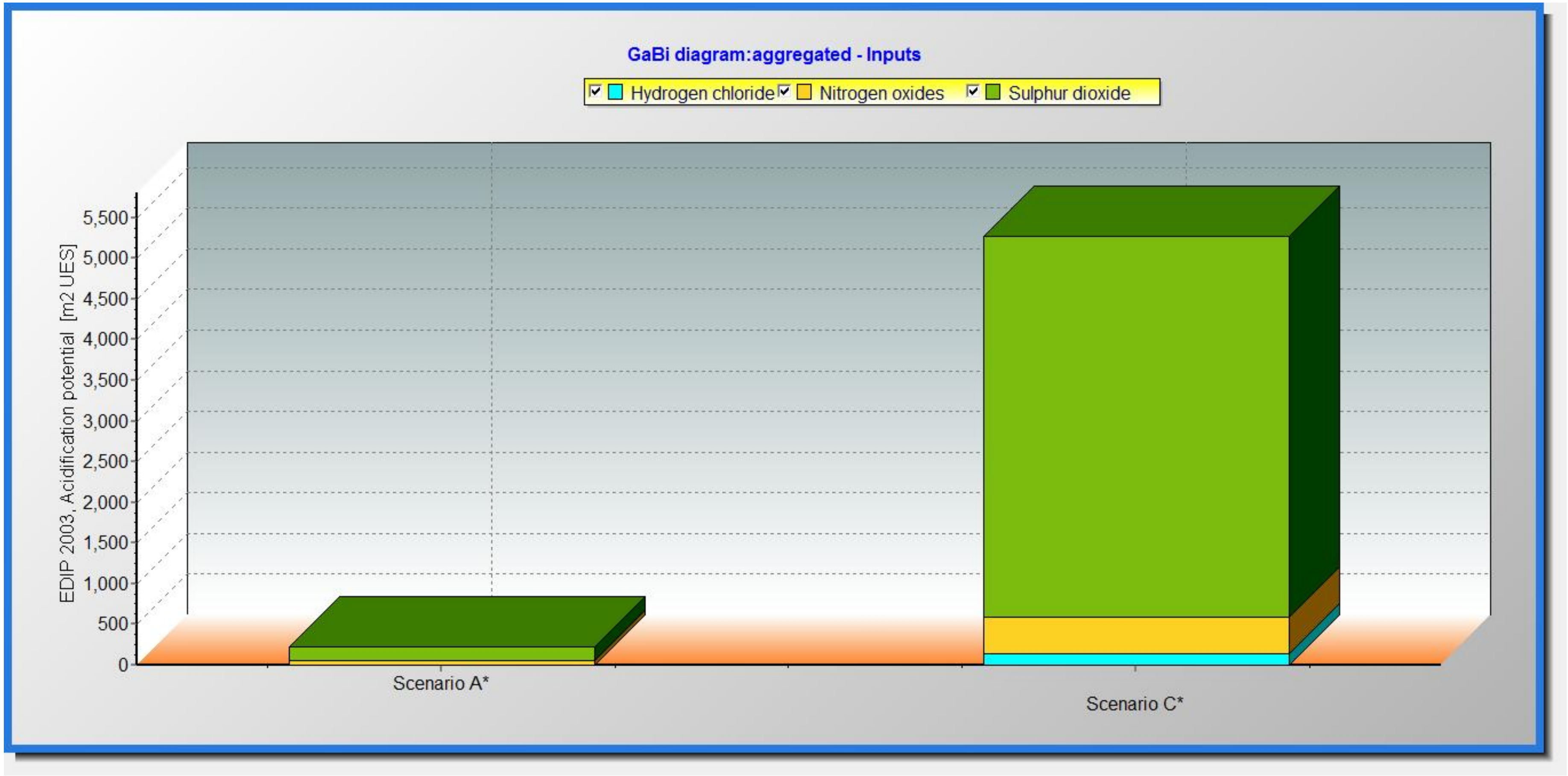

Figure 4.14. Acidification potential of scenario A and C.

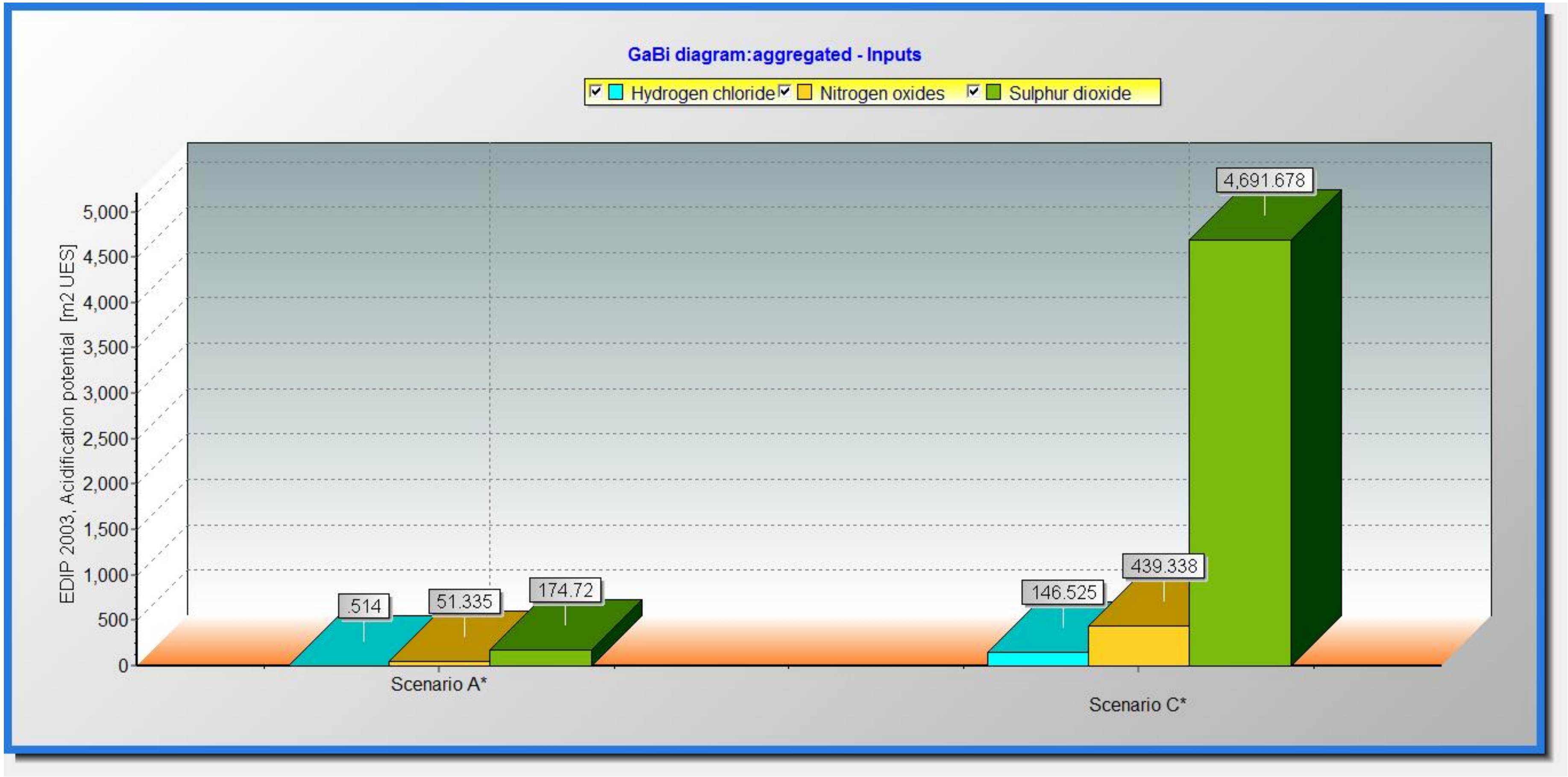

Figure 4.15. The amount of main contributors to acidification potential of scenario A and C.

4.5.2.3. Aquatic Eutrophication. Nitrogen oxides emissions are the main contributor to aquatic eutrophication by 92.1% for Scenario A, and by 98.1% for Scenario C as shown in Figure 4.16 and Figure 4.17.

For aquatic eutrophication, combustion of biogas in cogeneration engine is the highest contributor to nitrogen oxides emissions by 80.4% of 92.1%. Second contributor is transportation process by 5.32% of 92.1% for Scenario A. For Scenario C, 72.25% of %98.1 nitrogen oxides emissions are caused by electrical consumption from grid. Consumption of natural gas causes 21.6% of %98.1 nitrogen oxides emissions. Phosphate and ammonia-ammonium emissions effects fresh water, while others cause air emissions.

- Aquatic eutrophication potential is determined as 2.8011 kg NO_3-equivalent for anaerobic digestion scenario and 22.491 kg NO_3-equivalent for current waste disposal and energy production scenario. So, anaerobic digestion scenario provides about 87.55 % impact reduction on aquatic eutrophication compared to current waste disposal and energy production scenario. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 4.14 % impact reduction on aquatic eutrophication can be achieved.

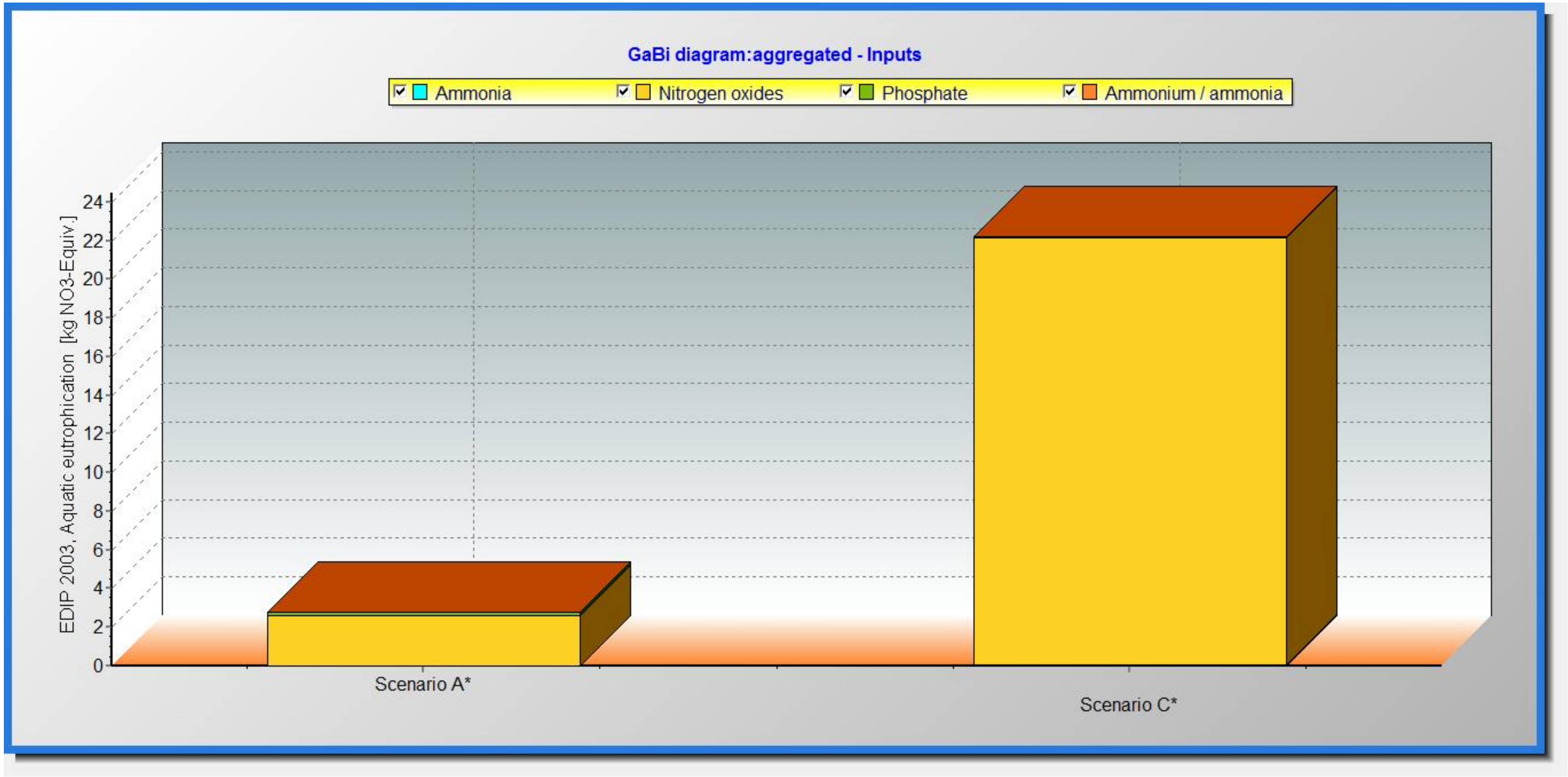

Figure 4.16. Aquatic eutrophication potential of scenario A and C.

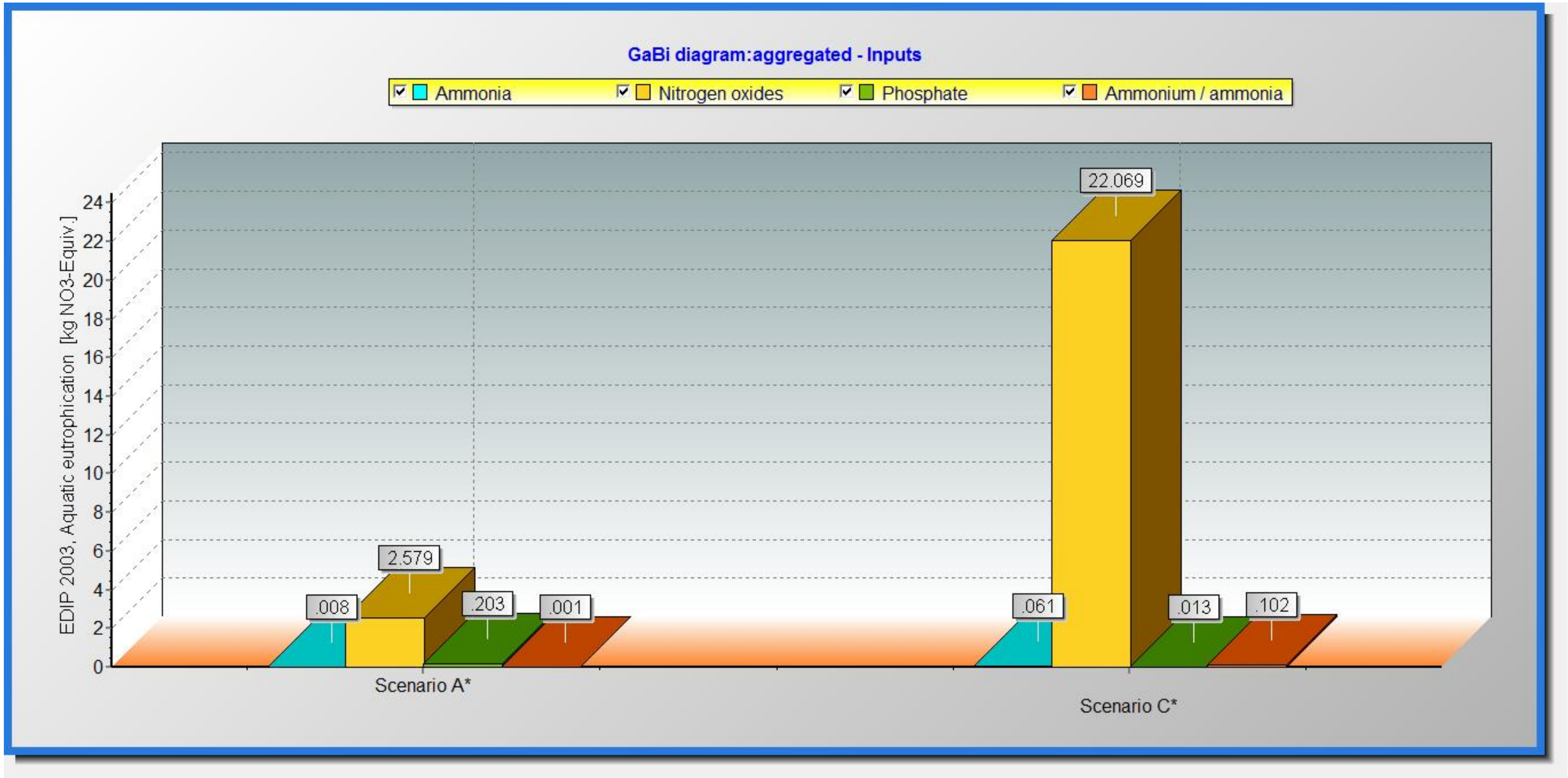

Figure 4.17. The amount of main contributors to aquatic eutrophication potential of scenario A and C.

4.5.2.4. Photochemical Ozone Formation - Impact on Vegetation. Nitrogen oxides emissions are the main contributor to photochemical ozone formation - impact on vegetation impact categories by 68.6% for Scenario A, and by 76.4% for Scenario C, respectively. The comparison of each scenario is indicated in Figure 4.18 and Figure 4.19.

For Scenario A, nitrogen oxides emissions are mainly caused by combustion of biogas in cogeneration engine. For Scenario C, electrical consumption from grid mix is the main contributor for nitrogen oxides emissions. Methane is the second contributor to photochemical ozone formation impact category for Scenario C. For Scenario A, Group NMVOC emissions are the second contributor.

- The vegetation potential of anaerobic digestion scenario is 11,838 m^2 UES*ppm*hours, while it is 119,460 m^2 UES*ppm*hours for the current waste disposal and energy production scenario. So, anaerobic digestion scenario provides about 90% photochemical ozone depletion impact reduction compared to the current waste disposal and energy. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 5.26 % impact reduction on photochemical ozone formation-impact on vegetation can be achieved.

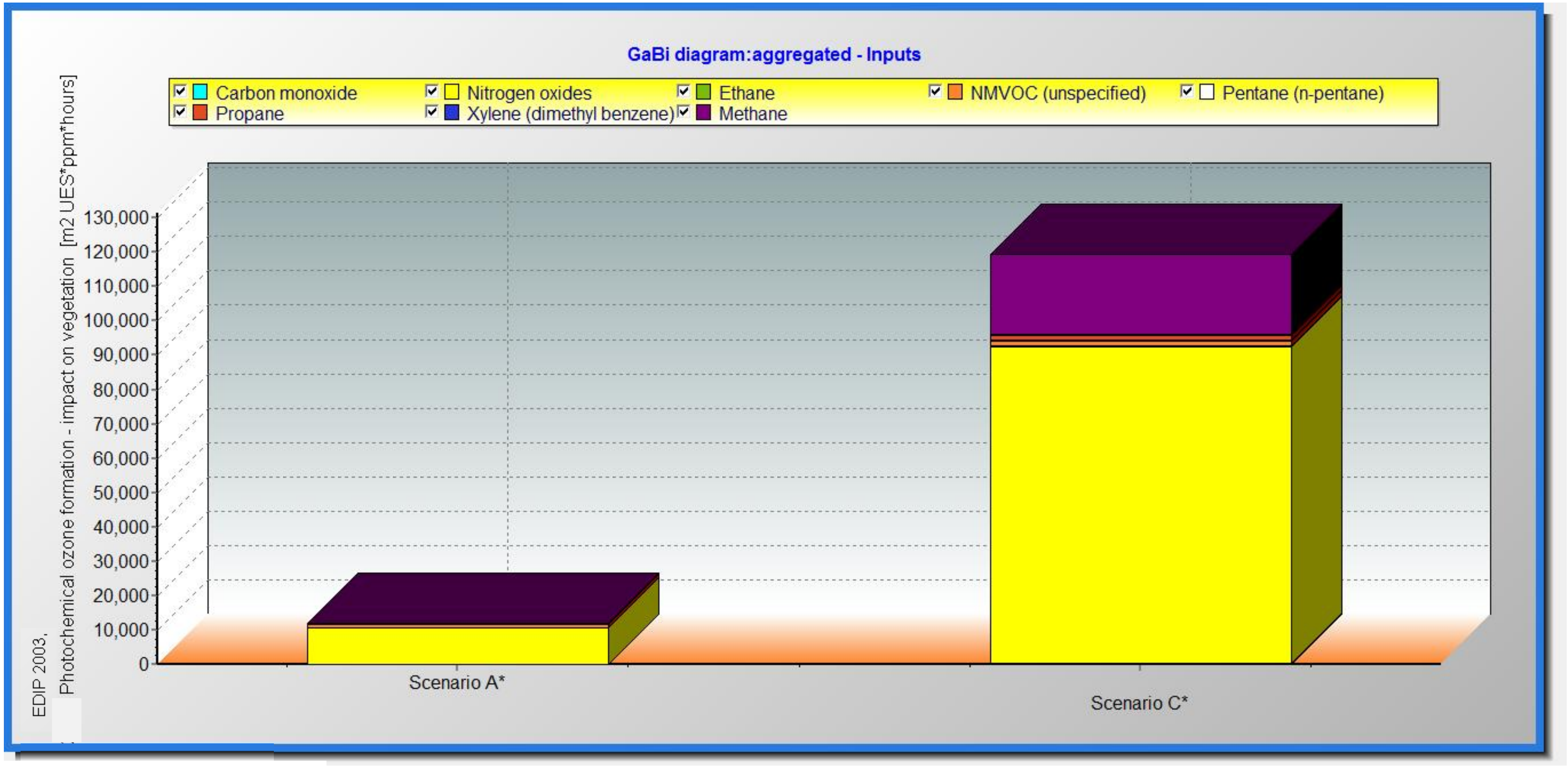

Figure 4.18. Photochemical ozone formation - impact on vegetation potential of scenario A and C.

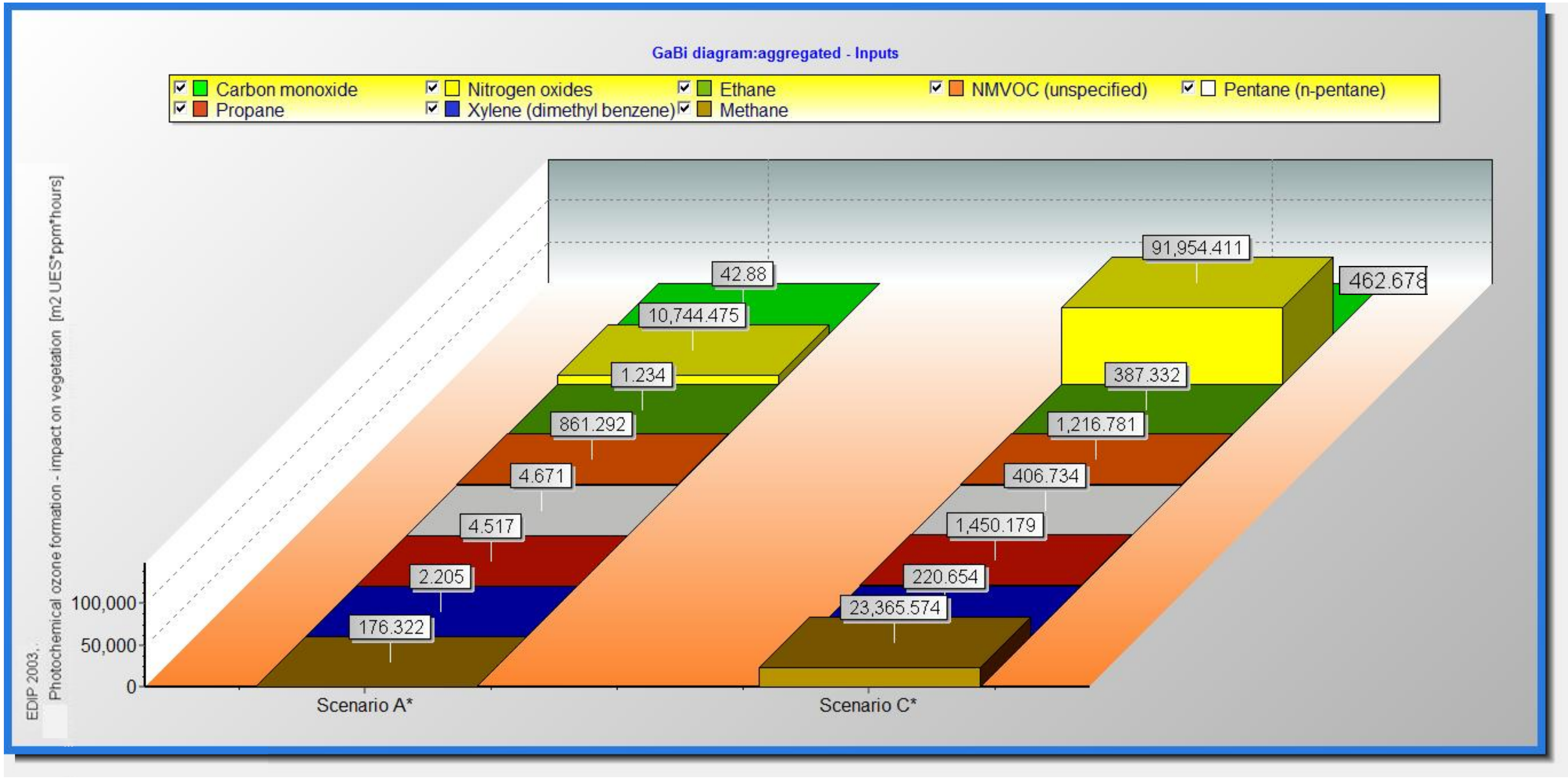

Figure 4.19. The amount of main contributors to photochemical ozone formation - impact on vegetation potential of scenario A and C.

4.5.2.5. Terrestrial Eutrophication. Nitrogen oxides emissions are the main contributor to terrestrial eutrophication, by 99.4%for Scenario A, and 99.4%, for Scenario C, respectively The comparision of each scenario is shown in Figure 4.20 and Figure 4.21.

Ammonia is the second contributor of terrestrial eutrophication impact category, however; it is only 0.625% of total emission released in Scenario A and 0.566% of total emissions in Scenario C. There are no other emissions that contribute to terrestrial eutrophication potential.

- The terrestrial eutrophication potential of anaerobic digestion scenario is 152.56 m^2 UES, while it is 1,305 m^2 UES for the current waste disposal and energy production scenario. So, anaerobic digestion scenario provides about 88 % reduction compared to the current waste disposal and energy. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 4.85 % impact reduction on terrestrial eutrophication can be achieved.

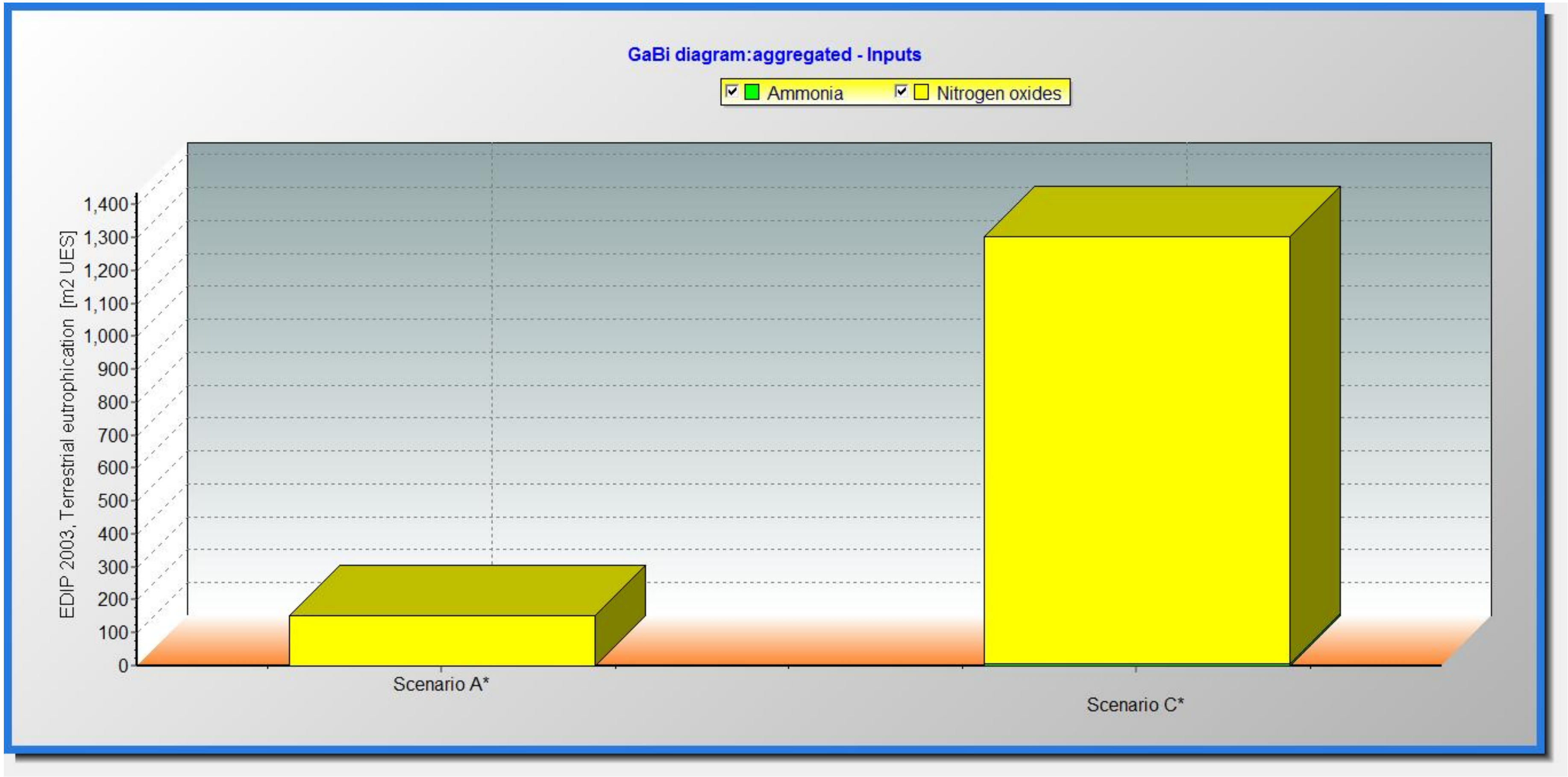

Figure 4.20. Terrestrial eutrophication potential of scenario A and C.

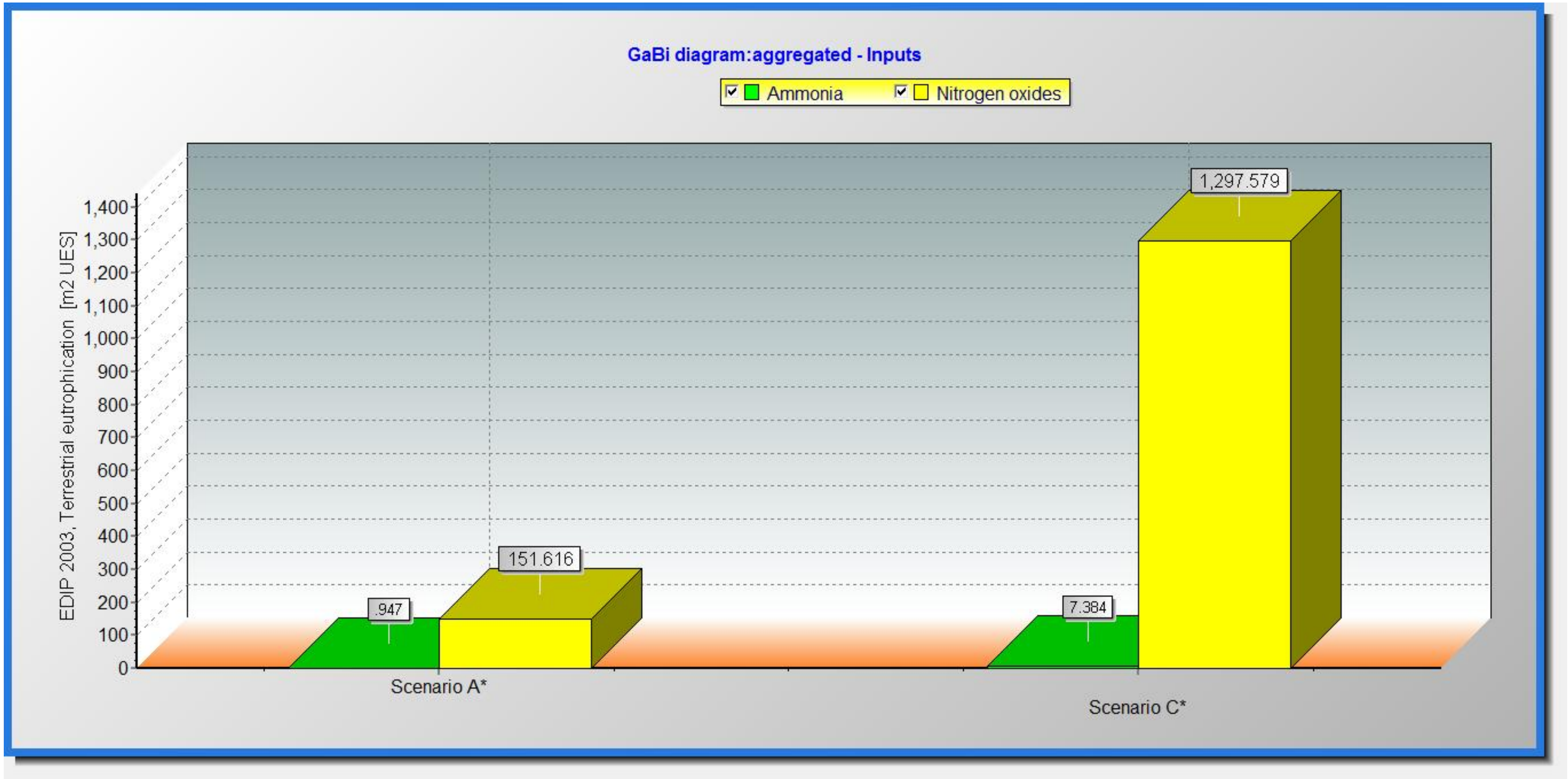

Figure 4.21. The amount of main contributors to terrestrial eutrophication potential of scenario A and C.

4.5.3. Normalization

The normalization results of Scenario A and Scenario C which shows current waste disposal and energy production methods is shown in Figure 4.22.

The biggest environmental impact of Scenario A comes from acidification potential. For Scenario C, global warming has the highest environmental impact among other assessed impacts. For Scenario A, photochemical ozone formation-impact on vegetation is the second highest impact category, while it is acidification potential for Scenaerio C.

4.5.4. Weighting

According to the weighted environmental impact potential results, Scenario C has the highest contribution to the environmental pollution. All assessed impact categories showed that the impact of Scenario C is higher than the impact of Scenario A. Weighting results are shown in Figure 4.23 and Figure 4.24.

For Scenario A, the highest weighted environmental impact potential comes from the acidification potential followed by photochemical ozone formation-impact on vegetation, terrestrial eutrophication, global warming and aquatic eutrophicaion with 26.4%, 22.7%, 17.8%, 16.6%, 11.9% contribution, respectively.

For Scenario C, the highest weighted environmental impact potential comes from the global warming, acidification potential, photochemical ozone formation-impact on vegetation by 40.5%, 32.4%, 12.1% contribution, respectively. The terrestrial eutrophication contributes only 8.04% and aquatic eutraphication contributes only by 5.05% of the total weighted environmental impact potential.

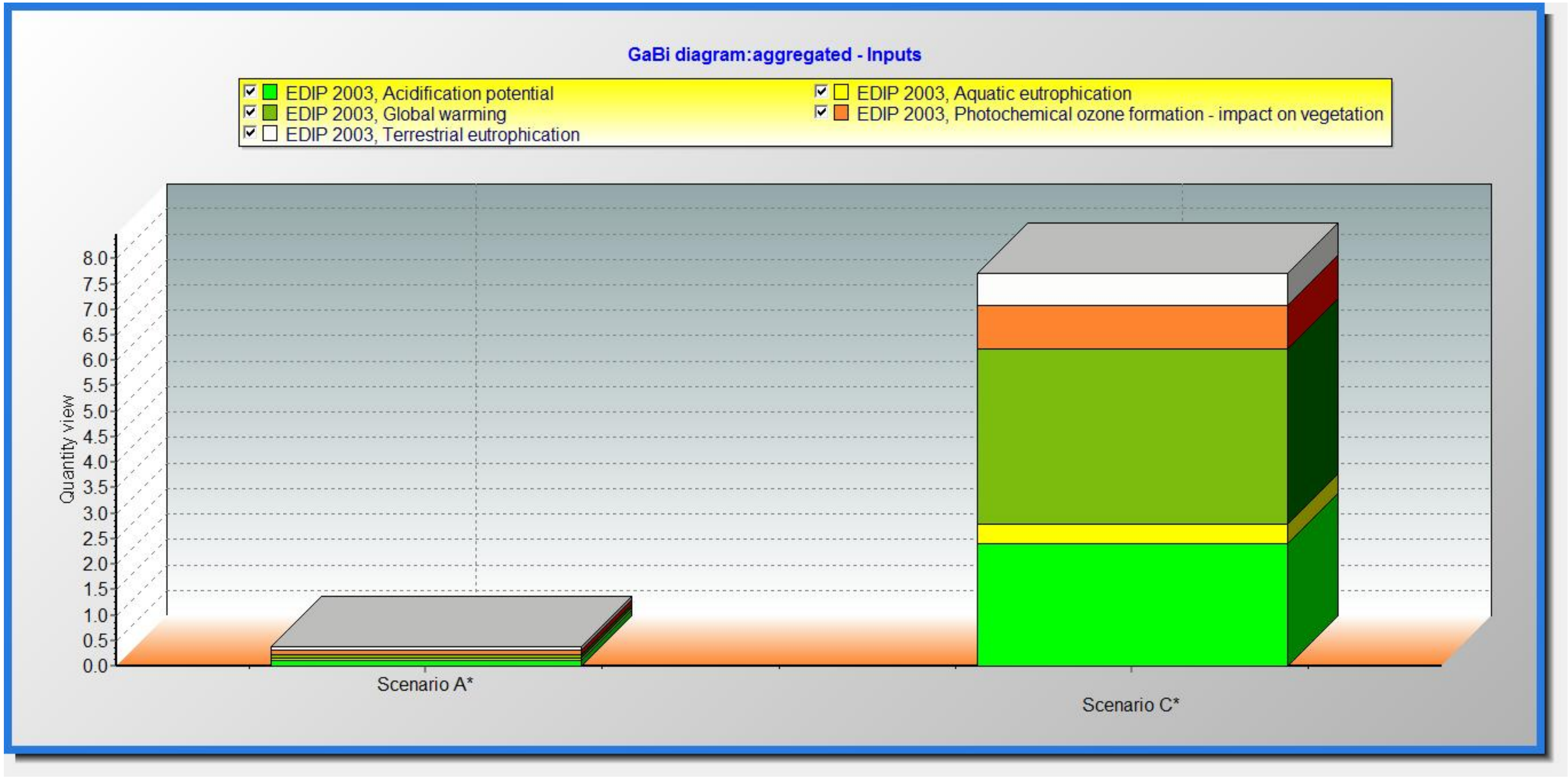

Figure 4.22. Normalization results for scenario A and C.

In terms of the sources of these emissions, the biggest environmental impact potential results from combustion of biogas in cogeneration unit, with a total of 20.2 % to acidification potential, %19.1 to photochemical ozone formation, 15.5 to terrestrial eutrophication, 9.52% to aquatic eutrophication, 7.25% to global warming for Scenario A.

For Scenario C, global warming potential is mainly caused by natural gas consumption by 22% and electricity consumption from grid by 17.9%. Only 0.885% contribution comes from the transportation process. Acidification potential is mainly caused by electricity consumption by 31%, %1.22 and 0.174% results by natural gas consumption and transportation, respectively. Electricity consumption from grid and natural gas consumption contributes to photochemical ozone formation –impact on vegetation by 8.07% and 3.59% respectively. 5.9% contribution comes from electrical consumption for terrestrial eutrphication and 3.66% comes from electrical consumption for aquatic eutrophication.

When Scenarios are compared, impact reductions of scenario A over scenaerio C are shown below:

95.7% environmental impact potential reduction on acidification potential, 87.5% reduction aquatic eutrophication potential, 97.8% reduction on global warming potential, 90.1% reduction photochemical ozone formation – impact on vegetation and 88.3% reduction on terrestrial eutrophication can be achieved.

When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, impact reductions of scenario A over scenaerio C are shown below: 4.15% reduction on acidification potential, 4.85% reduction on aquatic eutrophication potential, 7.23% reduction on global warming potential, 5.26% reduction on photochemical ozone formation – impact on vegetation and 4.85% reduction on terrestrial eutrophication can be achieved.

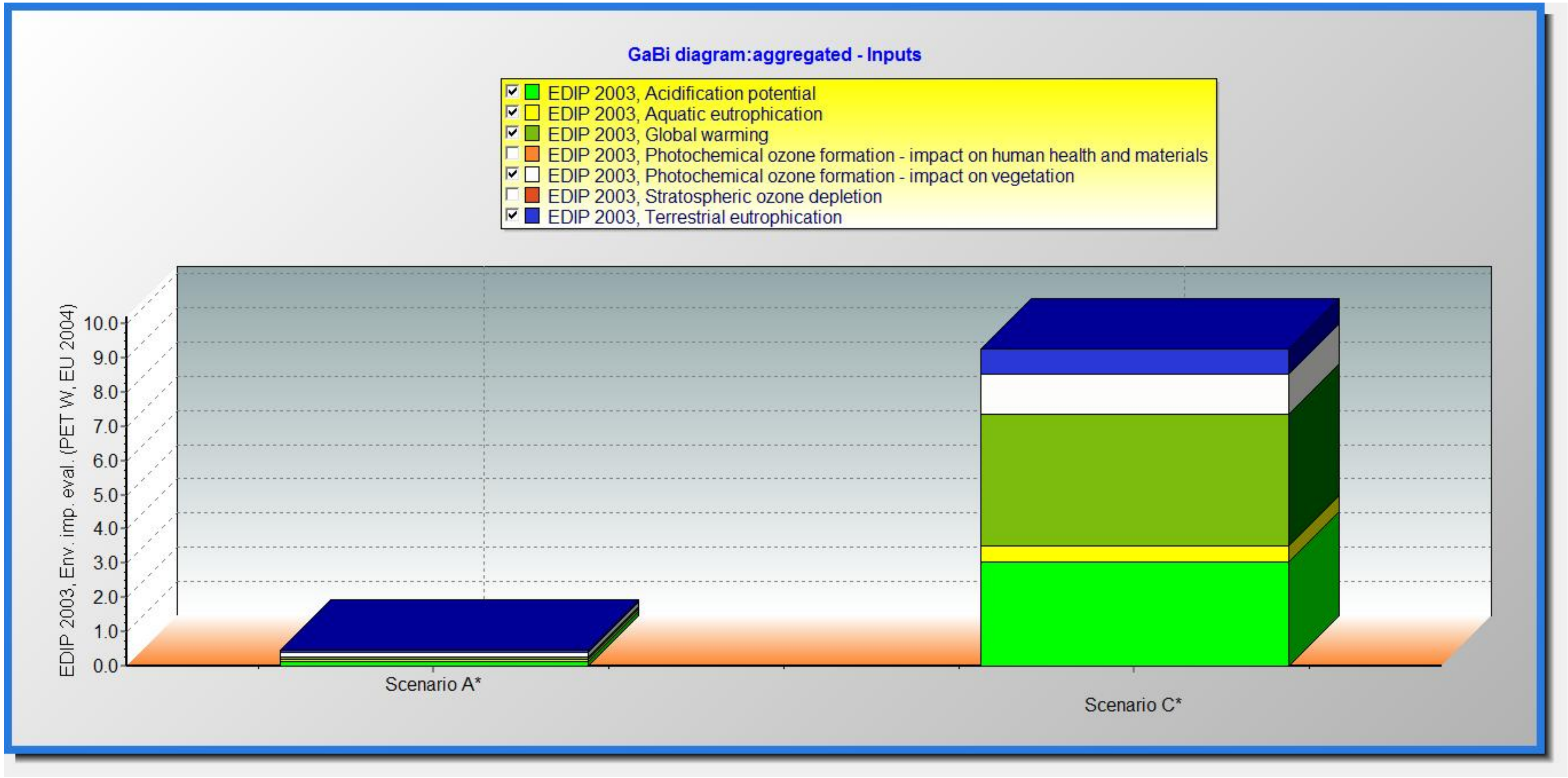

Figure 4.23. Weighting results for scenario A and C.

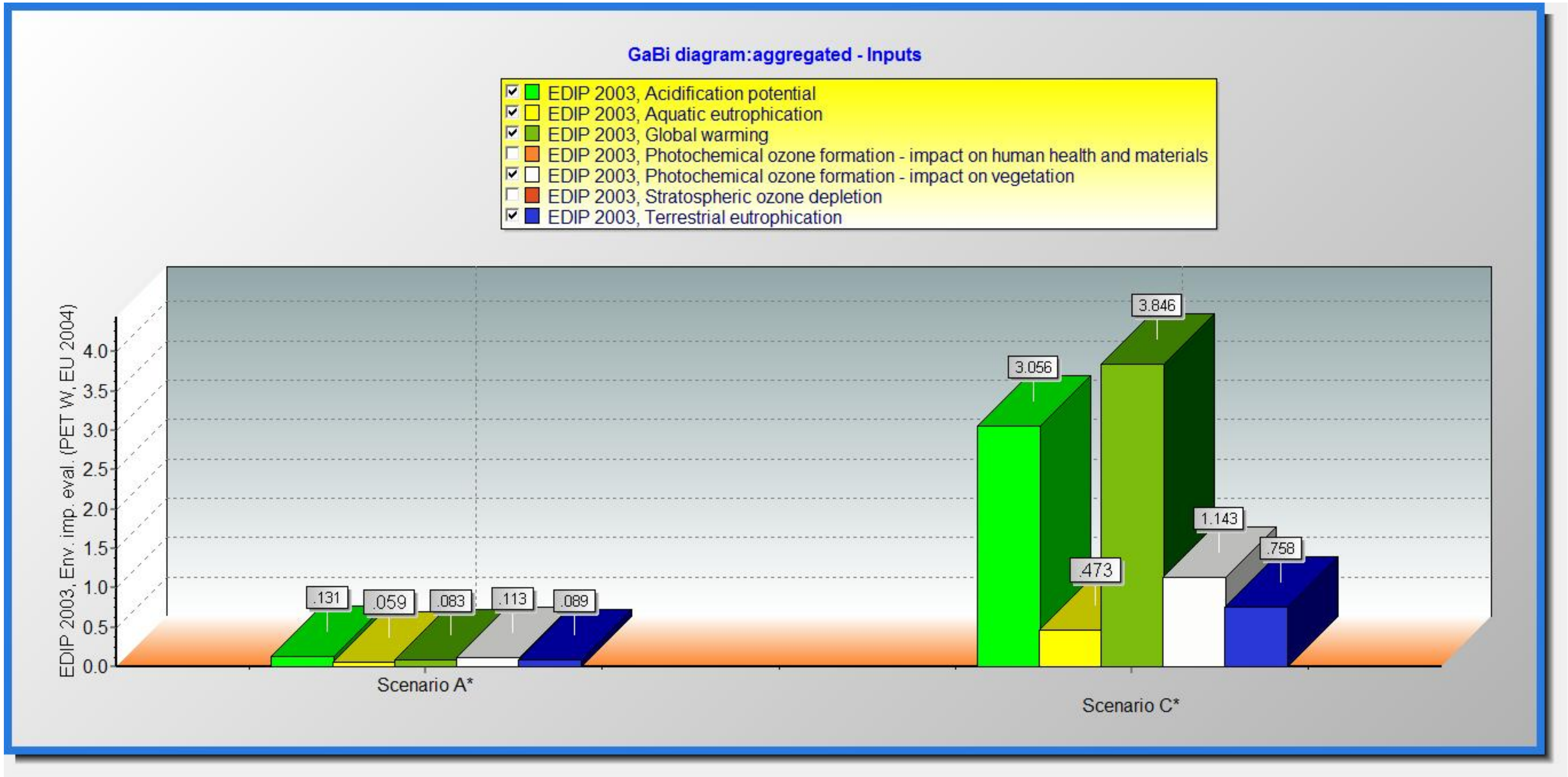

Figure 4.24. Amount of weighting results for scenario A and C.

5. CONCLUSIONS

Considering the whole life cycle assessment (LCA) of organic waste management technologies, an integrated approach has been brought to an anaerobic digestion plant which was scaled up for a university campus in Istanbul.

The main idea beyond the LCA application in the university is to enhance the importance of organic wastes for renewable energy production – no matter what the size is – and to conclude anaerobic digester systems as one of the applicable energy recovery technologies for a sustainable campus life.

The LCA interpretation is particularly developed for the digester and its correlated unit processes designed for the food wastes of the university for the education period. The summarized characterization results and the design parameters of the digester revealed that nearly 300 kWh energy can be obtained daily. Electricity will be supplied to the buildings. Regarding the heating energy, the indoor swimming pool at Hisar Campus will be the possible area for renewable energy consumption.

LCA characterization results showed that, anaerobic scenario is highly advantageous over current waste disposal and national energy production scenario. Operation of the anaerobic digestion plant causes 637.27 kg CO_2-equivalent emissions, while current waste disposal and national energy production methods cause 29,820 CO_2-equivalent emissions on global warming potential. Therefore, digestion scenario provides about 97.8% reduction in the scope of global warming. Over 87% reduction on other assessed impact categories (acidification, photochemical ozone formation, aquatic eutraphication, terrestrial eutraphication) can be achieved when compared to current waste disposal and energy production scenario. When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 7.2% reduction on global warming and over 4% reduction on other impact categories can be achieved. Composting scenario is only advantageous when it is considered as a waste management option, since volume reduction is achieved. It provides about 95% and 79% reductions in terms of global warming when compared with anaerobic digestion and current waste disposal and energy production scenarios, respectively. However, when N_2O emissions that are released during composting process are considered, anaerobic digestion scenario becomes advantageous because prevention of N_2O emissions can be achieved. Also, when the energy requirement of the composting plant is considered, GWP of composting scenario is assessed to be higher than other scenarios.

The biggest environmental impacts of anaerobic scenario and national waste disposal and energy production scenario comes from acidification potential and global warming potential, respectively. 20.2% of acidification potential in anaerobic scenario is caused by the combustion of biogas in cogeneration unit. For current waste disposal and energy production scenario, global warming potential is mainly caused by natural gas consumption by 22% and electricity consumption from grid by 17.9%.

Finally it can be summarized from the weighing results of the LCA that, utilization of food wastes of the university by anaerobic technology provides about 95.7% environmental impact potential reduction on acidification potential, 87.5% reduction on aquatic eutrophication potential, 97.8% reduction on global warming potential, 90.1% reduction on photochemical ozone formation – impact on vegetation and 88.3% reduction on terrestrial eutrophication can be achieved when compared with current national energy production and waste disposal methods.

When both the production and utilization of the produced energy and overall energy requirement of the pool and the buildings are considered, 4.15% environmental impact potential reduction on acidification potential, 4.85% reduction on aquatic eutrophication potential, 7.23% reduction on global warming potential, 5.26% reduction on photochemical ozone formation – impact on vegetation and 4.85% reduction on terrestrial eutrophication can be achieved when compared with current national energy production and waste disposal methods.

It can be stated that, anaerobic digestion technology provides emission savings and provides impact reductions on global warming, acidification, aquatic eutrophication potential, photochemical ozone formation – impact on vegetation and terrestrial eutrophication impact categories.

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APPENDIX A: METHODOLOGY OF EACH EXPERIMENT

A.1. Total Solids

Aluminium dish was weighed on an analytical balance before and after addition of sample to be analyzed into the dish. The mass of dish, dish and sample were measured and recorded. Afterwards, the sample was kept in VWR Dry Line drying oven at 105°C till the sample reaches to a constant weight. Then, sample was transferred to a desiccator. Lastly, sample was weighed on an analytical balance and the mass of sample was recorded. Total Solid amount was calculated by using following formula:

$$\text{Total Solids, \%} = 100*(A-B)/(D-B) \qquad (A.1)$$

Where:
A= weight of dish + dry sample (g)
B= weight of dish (g)
D= weight of dish + wet sample (g)

A.2. Volatile Solids

The dried sample was ignited in a Nabertherm muffle furnace at 550° C till the sample reaches to a constant weight. The sample was cooled in a desiccator and weighed on an analytical balance. Mass was recorded.

Total Volatile Solid amount was calculated by using following formula:

$$\text{Volatile Solids, \%} = (A-C)/(A-B) \qquad (A.2)$$

Where:

A= weight of dish + dry sample (g)
B= weight of dish (g)
C= weight of dish + sample after ashing or ignition (g)

A.3. pH

After the calibration of the pH probe of pH 720 ino Lab, pH of the sample was measured.

A.4. Total Kjeldahl Nitrogen

0.05 gr dried sample was placed in a kjeldahl flask. Sample was boiled for 2 hours at 250 ^{o}C and for 1 hour at 400 ^{o}C, after addition of borate buffer and NaOH until pH reaches to 9.5.

Sample was cooled and 6.7 mL H_2SO_4, 6.7 g K_2SO_4, and 0.365 g $CuSO_4$ were added and sample was boiled until white fumes are observed. Then digestion was continued for an additional 30 minutes. After digestion, sample was diluted to 300 mL with water, and mixed. 50 mL sodium hydroxide-thiosulfate reagent to form an alkaline layer at flask bottom was added. Flask was connected to a steamed-out distillation apparatus and swirled to insure complete mixing. Distilation was made and 200 mL distillate was collected. 50 mL indicating boric acid was used as absorbent solution when ammonia is to be determined by titration.

A.5. Total Phosphorus

Sample was placed on digestion apparatus and 30 ml perchloric acid and 5 ml nitric acid was added. Sample was digested till white color is observed. After waiting the sample to be cooled, sample was diluted to 250 ml with distilled water. Then, ammonium molybdate vanadate was added to 10 ml sample that was taken from the dilution. Sample was diluted to 50 ml with distilled water. After 10 minutes, total phosphorus content of the sample was measured by using HACH-LANGE DR/3800 Spectrophotometer at 400nm.

A.6. Total Phosphate

Sample was diluted with distilled water and placed into auto sampler. Total phosphate content of the sample was read from the software of the autosampler.

A.7. Metal Concentrations

Sample was digested in order to set metals free into liquid solution. 9 ml nitric and 3 ml hidrochloric acid was added to sample. Then, sample was microwaved in Ethos Touch Control Advanced Microvawe Labstation. Afterwards, sample was placed in autosampler and the metal concentrations was measured by using Thermo X Series ICP-MS equipment.

A.8. Carbon, Nitrogen and Hydrogen Analysis

Elemental analysis was carried out by using LECO TruSpec CHN Series. After calibration of the equipment, sample was weighted into 502-186 Tin Foil Cup which was placed into LECO CHN. By using the software of the equipment, carbon, nitrogen and hydrogen contents of the sample was measured.

A.9. Sulfur Analysis

Sulfur analysis was carried out by using LECO TruSpec S Series. After calibration of the equipment, sample was weighted into a 528-203 Crucible. 1 gr of 502-321 Com-Cat was added and the crucible was slided into the combustion tube when "Load Sample into Furnace" message appears on the display. By using the software of the equipment, sulfur content of the sample was measured.

A.10. Oxygen Calculation

Ash content of the sample was measured by LECO TGA701 Thermogravimetric Equipment and the percentage of the oxygen was calculated with the following equation.

$$\% \text{ Oxygen} = 100 - (\text{Carbon } \% + \text{Hydrogen } \% + \text{Nitrogen } \% + \text{Sulfur } \% + \text{Ash } \%) \quad (A.3)$$

APPENDIX B: PHOTOGRAPHS TAKEN DURING THE EXPERIMENTS

Some photographs taken during sampling and experiment period are shown below:

Figure B.1. Food Waste Generated From South Campus Dining Hall.

Figure B.2. Food Waste Generated From North Campus Dining Hall.

Figure B.3. Food Waste Generated From Kennedy Logde Restaurant.

Figure B.4. Total Solid Determination Experiment.

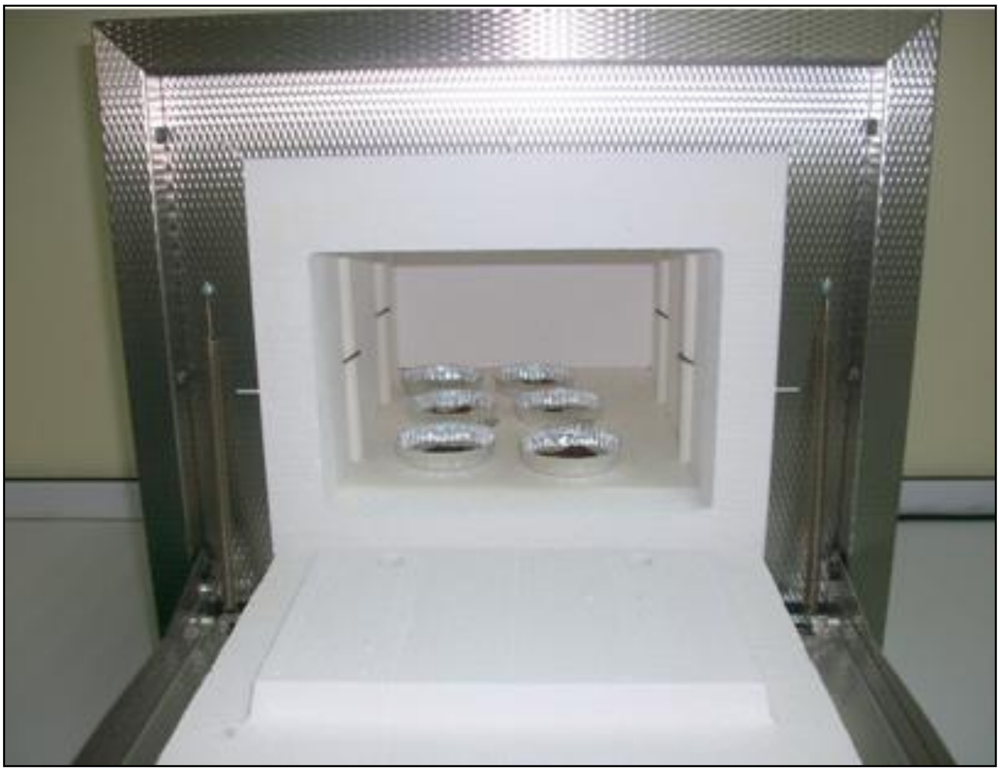


Figure B.5. Total Volatile Solid Determination Experiment.

Figure B.6. Elemental Analysis 1.

Figure B.7. Elemental Analysis 2.

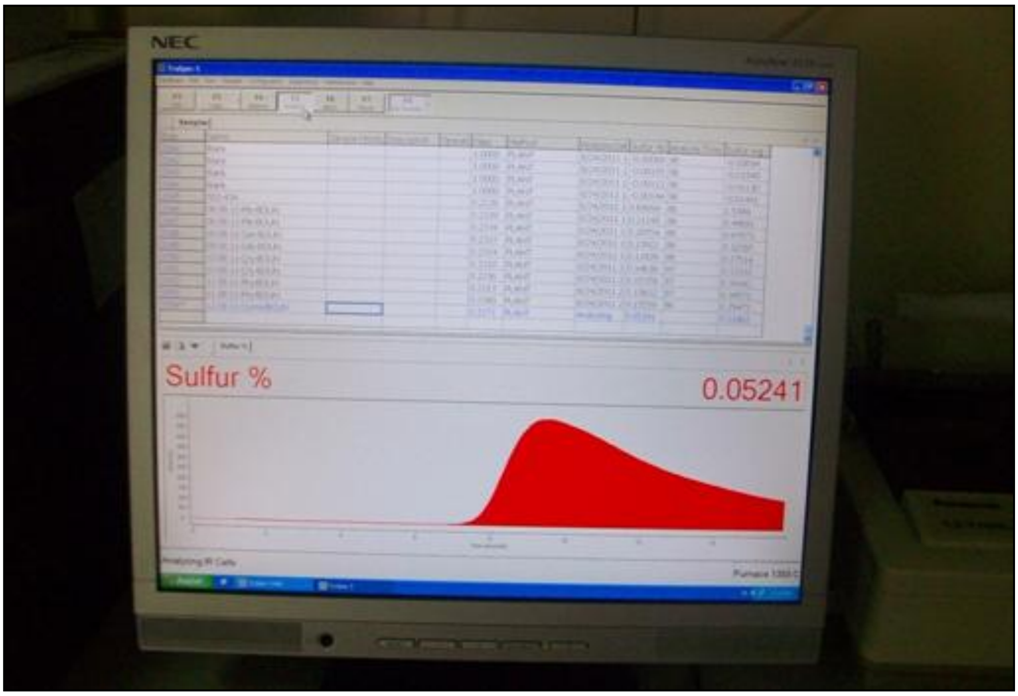


Figure B.8. Elemental Analysis 3.

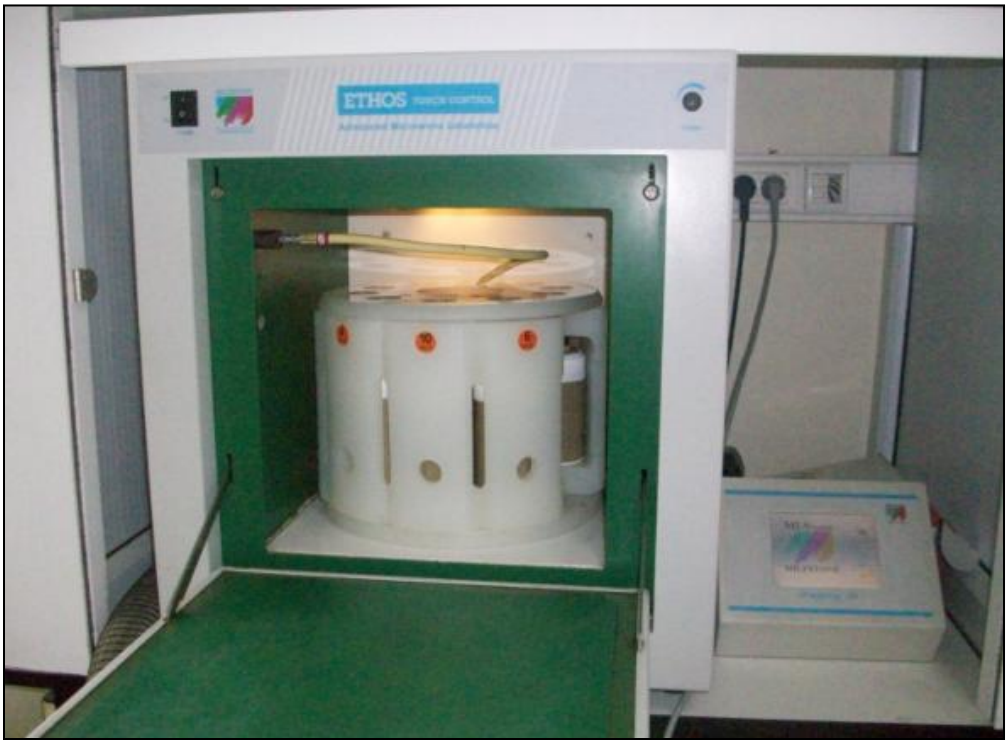


Figure B.9. Heavy Metal Determination.

Figure B.10. Metal Analysis.

Figure B.11. Grinder.

Figure B.12. Grinded and Dried Samples.

Figure B.13. Filtrate.

Figure B.14. Phopshorus Determination.

APPENDIX C: TECHNICAL DRAWINGS

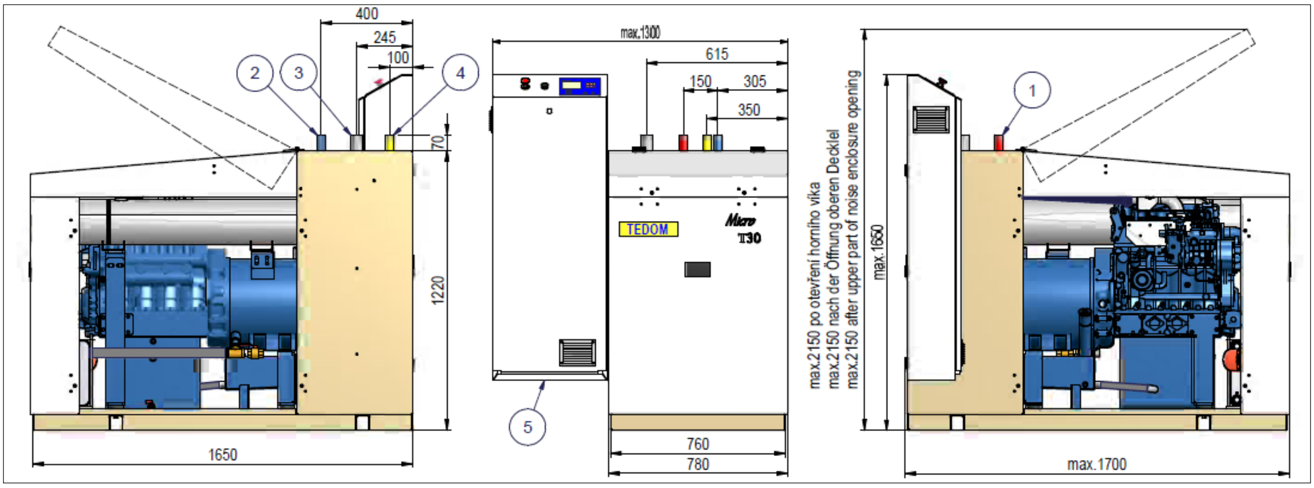
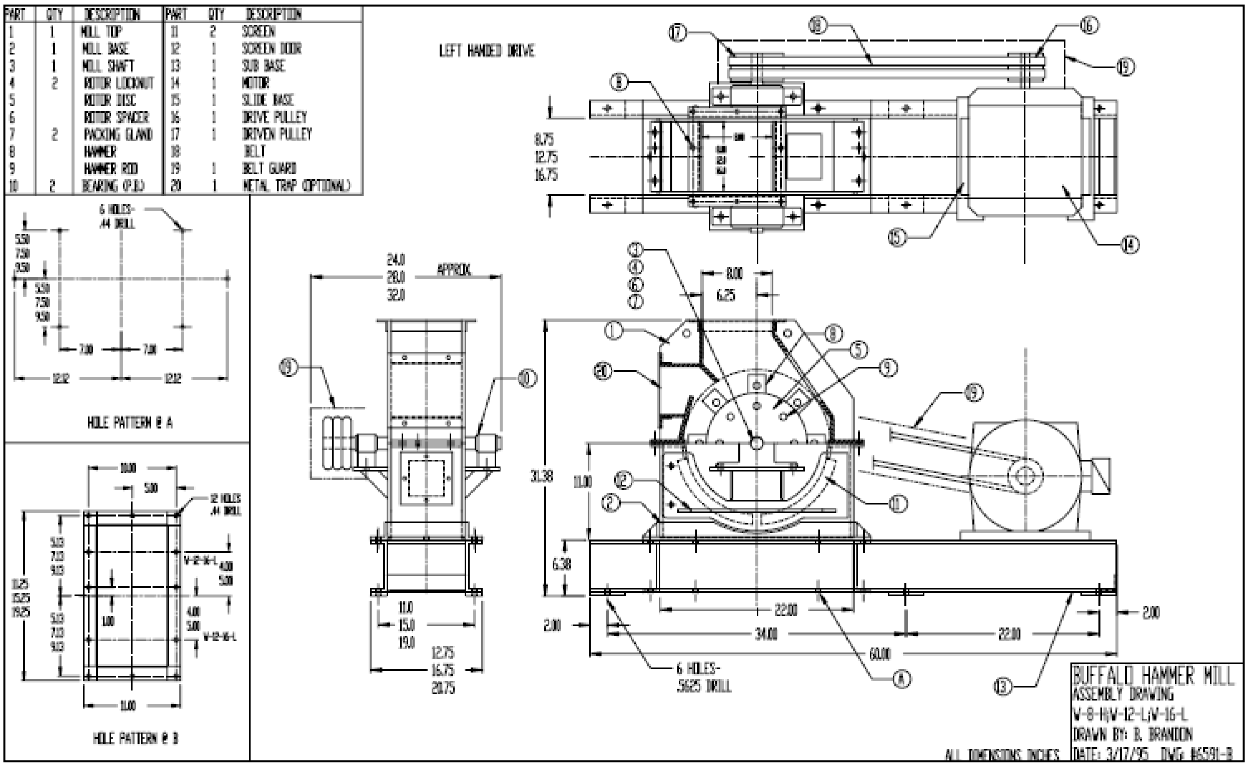


Figure C.1. TEDOM T-30 Micro Cogeneration (obtained from Arke Enerji Sistemleri Sanayi ve Ticaret Limited Şirketi).



PART	QTY	DESCRIPTION	PART	QTY	DESCRIPTION
1	1	MILL TOP	11	2	SCREEN
2	1	MILL BASE	12	1	SCREEN DOOR
3	1	MILL SHAFT	13	1	SUB BASE
4	2	ROTOR LOCKNUT	14	1	MOTOR
5		ROTOR DISC	15	1	SLIDE BASE
6		ROTOR SPACER	16	1	DRIVE PULLEY
7	2	PACKING GLAND	17	1	DRIVEN PULLEY
8		HAMMER	18		BELT
9		HAMMER ROD	19	1	BELT GUARD
10	2	BEARING (P.B.)	20	1	METAL TRAP (OPTIONAL)

Figure C.2. Schutte Buffalo Hammermill (obtained from S. Buffalo Hammermill, LLC).

APPENDIX D: ENERGY REQUIREMENT OF THE COMPOSTING PLANT

Table D.1. Energy Requirement of the Composting Plant.

Name of the Unit	Installed Power (kW)	Period 1		Period 2-3		Period 4	
		Working Duration (hr)	kWh	Working Duration (hr)	kWh	Working Duration (hr)	kWh
Grinder							
Motor	2.237	0.966	2.161	0.116	0.260	0.018	0.040
Conveyor	1.000	1.932	1.932	0.232	0.232	0.036	0.036
Reactor							
Motor	2.200	1.600	3.520	0.192	0.423	0.030	0.065
Screw Conveyor - Supply	0.750	1.932	1.449	0.232	0.174	0.036	0.027
Screw Conveyor - Discharge	0.750	1.932	1.449	0.232	0.174	0.036	0.027
Blower	0.220	8.889	1.956	1.068	0.235	0.164	0.036
Biyofiltre							
Blower	0.220	11.111	2.444	1.335	0.294	0.205	0.045
Others							
All sensors and lighting system	0.260	Lights[1] Sensors[2]	3.120	Lights[1, a] Sensors[2,a] Lights[3,b] Sensors[2,b]	3.120 [a], Period [b]	Lights[3], Sensors[2]	2.640

[1] For 12 hours.

[2] For 24 hours.

[3] For 9 hours.

[a] Period 2

[b] Period 3