LIFE CYCLE ASSESSMENT OF THE BIOGAS PLANT PRODUCING ENERGY FOR MARMARA REGION

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ABSTRACT

LIFE CYCLE ASSESSMENT OF THE BIOGAS PLANT PRODUCING ENERGY FOR MARMARA REGION

Industrialization and overpopulation have been accelerating global energy consumption, and this situation increases the need for renewable energy sources more and more. In addition to the increasing energy demand, population growth leads to an increase in food consumption. Expired food products have been evaluated with various practices to meet the increased energy demand and to adopt sustainable waste management. For this purpose, many technologies have been developed and some facilities that carry out waste processing and recovery operations have been established. In this study, the transportation of various wastes, mostly expired food waste, into the specified biogas plant in the Marmara Region of Turkey, the energy production from these waste compositions and the utilization options of the produced energy were evaluated by Life Cycle Assessment Methodology. In this sense, the conversion of the produced biogas formed as a result of the anaerobic digestion process into electricity and heat was analyzed, and the utilization options of the produced energy were environmentally evaluated. The environmental performances of the specified biogas plant were determined through two different energy utilization options: on-site energy utilization and energy utilization from the electricity grid and natural gas. Within the scope of energy utilization from the electricity grid and natural gas, the revenues from the sale of electricity and profit margin were considered The results demonstrated that the decrease in the environmental impact categories was observed in the on-site energy utilization option. Furthermore, the entire energy requirements of the specified biogas plant were met by using some of the produced energy within the plant. In this sense, thanks to the on-site energy utilization option, fossil fuel consumption was eliminated, and thus the decrease in greenhouse gas emission was achieved.

ÖZET

MARMARA BÖLGESİ İÇİN ENERJİ ÜRETEN BİYOGAZ TESİSİNİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

Sanayileşme ve nüfus yoğunluğu, küresel enerji tüketimini hızlandırmakta ve bu durum yenilenebilir enerji kaynaklarına olan ihtiyacı her geçen gün arttırmaktadır. Artan enerji ihtiyacının yanı sıra, popülasyon artışı gıda tüketiminin de doğrudan artmasına yol açmaktadır. Son kullanma tarihi geçen gıda ürünleri, hem artan enerji talebini karşılamak hem de sürdürülebilir atık yönetimini benimsemek amacıyla çeşitli uygulamalarla değerlendirilmektedir. Bu amaçla, bir çok teknoloji geliştirilmekte ve atık işleme, geri kazandırma gibi faaliyetler yürüten tesisler kurulmaktadır. Bu çalışmada, son kullanma tarihi geçmiş gıda atıkları çoğunlukta olmak üzere çeşitli atık gruplarının, Türkiye'nin Marmara Bölgesi'nde bulunan belirlenmiş bir biyogaz tesisine getirilmesi, bu atıklardan biyogaz ve enerji üretimi sürecinin ele alınması, ve son olarak belirtilen biyogaz tesisi içerisinde üretilen enerjinin kullanım opsiyonları yaşam döngüsü değerlendirmesi (YDD) kullanılarak çevresel etki değerlendirilmesi yapılmıştır. Çalışma kapsamında, atıkların anaerobik (havasız) ortamda parçalanması sonucu oluşan biyogazın elektrik ve ısıya çevrilmesi incelenmiş, ve oluşan enerjinin kullanım opsiyonları değerlendirilmiştir. Biyogaz tesisinde üretilen enerjinin kullanım opsiyonları ise tesisin iç ünitelerindeki enerji ihtiyacının üretilen enerjiden karşılanması ve tesisin iç ünitelerindeki enerji ihtiyacının elektrik şebekesi ve doğal gazdan karşılanması olarak iki farklı durum çerçevesinde ele alınmıştır. Ayrıca, tesisin iç ünitelerindeki enerji ihtiyacının elektrik şebekesi ve doğal gazdan karşılanması durumunda üretilen enerjinin gelir olarak kazanımları ve kar marjı temel alınmıştır. Bu çalışmanın sonucunda; tesisin enerji ihtiyacının üretilen enerjiden karşılanması durumunda çevresel etki kategorilerinde azalma görülmektedir. Bunun yanı sıra, üretilen enerjinin bir kısmının tesis içinde kullanılması ile tesisin tüm enerji ihtiyacı karşılanmış ve böylece fosil yakıtların tüketimi ortadan kaldırılarak sera gazı emisyonlarında azalma sağlanmıştır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation	Unit
Cd	Cadmium	
CH_4	Methane	
CH_3Br	Methyl Bromide	
CFCs	Chlorofluorocarbons	
Co	Cobalt	
CO	Carbon monoxide	
CO_2	Carbon dioxide	
Cr	Chromium	
Cu	Copper	
DCB	Dichlorobenzene	
Fe	Iron	
H_2	Hydrogen gas	
HCFCs	Hydrochlorofluorocarbons	
HCL	Hydrochloric Acid	
HF	Hydroflouric Acid	
H_2S	Hydrogen sulfide	
H_2SO_4	Sulphuric acid	
Mo	Molybdenum	
NH_3	Ammonia	
Ni	Nickel	
NMHC	Non-methane hydrocarbon	
NMVOC	Non-methane volatile organic compound	
NO	Nitrogen monoxide	
NO_2	Nitrogen dioxide	
NO_{3-}	Nitrates	
NO_x	Nitrogen oxides	
N_2O	Nitrous oxide	
P	Phosphorus	
PO_4^{3-}	Phosphate	
SF_6	Sulphur hexafluoride	
SO_2	Sulphur dioxide	

SO_x	Sulphur oxide	
Zn	Zinc	

Abbreviation	**Explanation**	
AD	Anaerobic Digestion	
AP	Acidification Potential	kg SO_2-eq.
AMPTS	Automatic Methane Potential Test System	
BMP	Biochemical Methane Potential	
C/N	Carbon to Nitrogen Ratio	
CHP	Combined Heat and Power	
EP	Eutrophication Potential	kg Phosphate-eq.
FOS/TAC	Volatile Fatty Acids Content to Buffer Capacity	
GHG	Greenhouse Gas	
GWh	gigawatt hours	
GWP	Global Warming Potential	kg CO_2-eq.
HTP	Human Toxicity Potential	
IEA	International Energy Agency	
ISO	International Organization for Standardization	
ktoe	kilo ton of oil equivalent	
kWh	kilowatt hours	
LCA	Life Cycle Assessment	
LCI	Life Cycle Inventory	
LCIA	Life Cycle Impact Assessment	
MC	Moisture Content	
MJ	megajoule	
MWh	megawatt hours	
PM	Particulate Matter	
POCP	Photochemical Ozone Creation Potential	kg Ethene-eq.
RDF	Refuse Derived Fuel	
RT	Retention Time	
S1	Subsystem 1	
S2	Subsystem 2	
S3	Subsystem 3	
SRF	Solid Recovered Fuel	
TKN	Total Kjeldahl Nitrogen	
TS	Total Solid	

VOCs	Volatile Organic Compounds
VS	Volatile Solid
VS/TS	Volatile Solid to Total Solid Ratio
WTE	Waste-to-Energy

1. INTRODUCTION

The need for alternative energy resources has been growing since it is expected that continuous population growth entails a further increase in global energy requirement and consumption. As a consequence of the rising energy needs, fossil fuel consumption and the Earth's natural resources depletion have been accelerating (Bisht and colleagues, 2019). During the consumption of fossil fuel, not only an excessive amount of carbon dioxide is released into the atmosphere, but also climate change issue is triggered due to greenhouse gas emissions (Santagata and colleagues, 2017). To eliminate the negative impacts of fossil fuel consumption, the application of environmentally-friendly energy resources has been supporting on a global scale. In this sense, alternative energy resources have become essential to supply energy requirements without facing climate change. It is important to consider that bioenergy is accepted as one of the most effective alternative energy sources to generate energy (Bisht and colleagues, 2019). Bioenergy is generally defined as energy production by using biomass in such forms as forest, agricultural and waste residues (GBEP, 2005). Due to ongoing population growth and urbanization, waste generation has continually increased. Global municipal solid waste generation is expected to increase from 2.01 billion tonnes in 2016 to 3.40 billion tonnes in 2050 (The World Bank, 2021). Waste generation can lead to some environmental problems by contributing to greenhouse gas emissions (Cudjoe and colleagues, 2020). To overcome huge amounts of waste generation; waste reduction, reuse, recycling, energy recovery, treatment and disposal strategies have been improved to decrease the amount of waste disposed and to enhance energy recovery. Energy recovery, known as Waste-to-Energy (WTE), is one of the most suitable options to handle waste problems. Waste-to-Energy technologies are commonly used to actualize energy recovery from many kinds of waste biomass (Dong and colleagues, 2018). Anaerobic digestion, one of these Waste-to-Energy technologies, is a biochemical conversion of biomass to biogas in the absence of oxygen (Thomas and colleagues, 2017). Anaerobic digestion technology is commonly used to convert waste biomass into gas and it has been applied in many different countries such as Singapore, France, United Kingdom, Brazil, Germany, the Netherlands, the USA, Denmark in order to achieve electricity generation from agricultural and animal wastes (Shirzad and colleagues, 2019).

It is important to consider that resource efficiency, waste and energy management should be evaluated in these WTE technologies. Environmental impact assessment has an important role in Waste-to-Energy technologies since all processes cause some environmental impacts due to the utilization of resources. To this end, LCA methodology has been applied to compare the environmental aspects of waste treatment systems to specify more sustainable and environmentally-friendly options during the whole life cycle of a product or a system.

In this study, the utilization options of the produced energy in a specified biogas plant were compared in two different scenarios. In this sense, LCA methodology was applied to determine the environmental burdens along with the whole production processes by implementing extended allocation between the produced electricity and waste heat, and to evaluate environmental performances of a specified biogas plant through two different energy utilization options; on-site energy utilization (1) and energy utilization from the electricity grid and natural gas (2).

2. LITERATURE REVIEW

2.1. Life Cycle Assessment (LCA)

2.1.1. The Definition Life Cycle Assessment

Life Cycle Assessment is a holistic methodology that evaluates the whole life cycle of a product or service from cradle to grave (Ortiz-Reyes and colleagues, 2018). LCA methodology is an effective tool to define and assess some environmental effects about waste management options, to give useful information about the environmental performances of processes and to compare other alternative technologies (Lamnatou and colleagues, 2019). Besides, LCA provides some environmental indicators which are defined as impact indicators at the global and local level. With the help of these indicators such as global warming, freshwater eco-toxicity, human toxicity, etc., the possible impacts of human activities on the environment can be learned (Evangelisti and colleagues, 2015).

Globally, life cycle assessment is accepted as a methodology to evaluate the environmental impacts of a product or service and is following by the International Organization for Standardization (ISO) (Ramachandran and colleagues, 2017). As a means of integrating life cycle assessment procedures and methods, standards were developed as part of ISO’s standards on environmental management. Four ISO standards (ISO 14040-14043) were published in the years 1997-2000, all of which were replaced in 2006 with two standards, ISO 14040 (2006) and ISO 14044 (2006). These standards determine the required and recommended elements of environmental life cycle assessment (UNEP SETAC, 2009). ISO 14040 defines the principles and framework of life cycle assessment analysis and covers the goal and scope of the LCA, life cycle inventory (LCI), life cycle impact assessment (LCIA) and reporting of life cycle assessment (ISO 14044,2006).

GaBi, by PE INTERNATIONAL, is one of the life cycle assessment software program on the current market (Martínez-Rocamora and colleagues, 2016). Several impact assessment methodologies in GaBi software have been utilized to measure the following LCIA impact potentials:

- Abiotic Depletion
- Acidification
- Eutrophication
- Freshwater Aquatic Ecotoxicity
- Global Warming Potential
- Human Toxicity
- Marine Aquatic Ecotoxicity
- Ozone Layer Depletion
- Photochemical Ozone Creation
- Radioactive Radiation
- Terrestric Ecotoxicity (GaBi, 2018).

2.1.2. Phases of Life Cycle Assessment

In accordance with ISO 14040, an LCA study is carried out through four phases; goal and scope definition, inventory analysis, impact assessment, interpretation. These phases are shown in Figure 2.1.

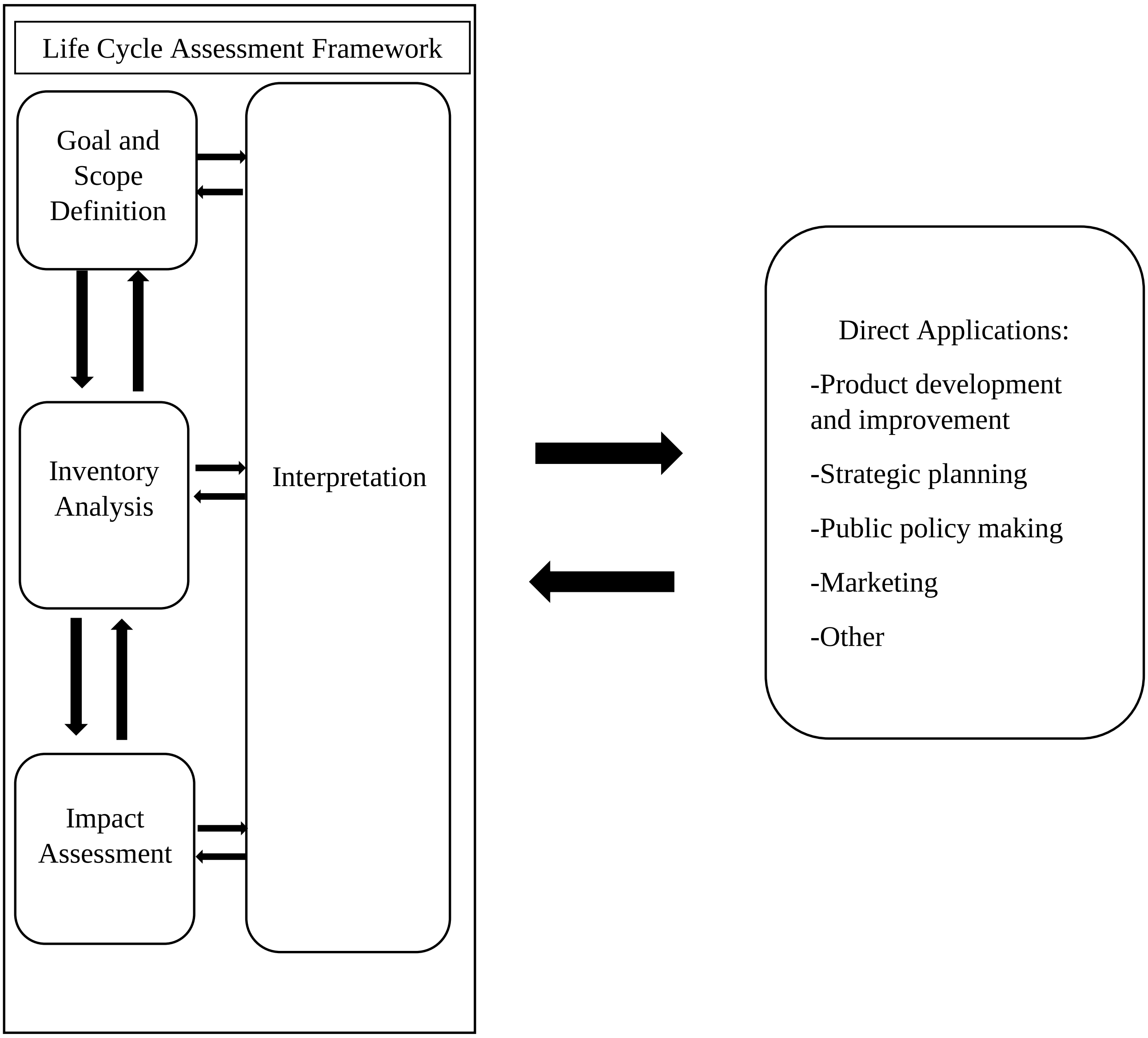


Figure 2.1. LCA framework (ISO 14040, 2006).

2.1.3. Goal and Scope Definition

Goal and scope definition, the first step of an LCA study, is the identification of the objective of an LCA study. It is important to specify the goal and scope of the LCA study because the methods are dependent on the objective of the study (Wenzel et al., 1997). Regarding the definition of the goal, the used environmental analysis and the scope of the study should be considered. The determination of functional unit, system boundaries, reference products, environmental assessment parameters, methodology, and the required data for the study are the steps of an LCA study (Wenzel et al., 1997).

The functional unit is a quantified description of the service or the performance of the product system. The objective of the functional unit is to give a reference to which the inputs and outputs can be relevant. This reference provides the comparison of LCA results and it enables to evaluate of different systems on a common basis (ISO 14040, 2006).

The purpose of system boundaries is to determine unit processes to be included in the LCA. According to the International Organization for Standardization, system boundaries determine which unit processes are part of a product system(ISO 14044, 2006).

2.1.4. Life Cycle Inventory

Life Cycle Inventory, abbreviated LCI, consists of all stages related to data collection, management and calculation for inputs and outputs of a product system. This includes:

- generation of unit data and the setting up of unit processes
- inventory of the environmental exchanges from the complete product system
- presentation of the information in a transparent form (Wenzel., 1997).
-

In accordance with ISO 14040/14044, transparency has to be considered to legitimate an LCA study (ISO 14044, 2006).

2.1.5. Impact Assessment

Impact Assessment is the third phase of LCA, following goal and scope definition and life cycle inventory. The goal of the impact assessment phase is to evaluate the potential contributions to the environmental impacts during the life cycle of the product or the system. This phase comprises associating inventory data with particular environmental impacts and understanding those impacts (ISO 14040, 1997). The goal and scope of the LCA study have an important role in the selection of methodologies and impacts. According to the ISO 14040 standard, impact assessment includes several mandatory and optional steps:

- selection of impact categories and characterisation methods
- classification
- characterisation
- normalisation
- weighting

2.1.5.1. The Impact Categories and Characterisation Method

The first step of impact assessment is the selection of impact categories. The selection of impact categories depends on the goal of the LCA study. In Table 2.1, some of the commonly used impact categories and emissions contributing to the selected impact categories are indicated (Curran, 2006).

Table 2.1. Commonly used life cycle impact categories.

Impact Category	Emissions
Global Warming	Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Methane (CH_4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH_3Br)
Eutrophication	Phosphate (PO_4^{3-}), Nitrogen Monoxide (NO), Nitrogen Dioxide (NO_2), Nitrates (NO_{3-}), Ammonia (NH_3)
Acidification	Sulphur Oxide (SO_x), Nitrogen Oxides (NO_x), Hydrochloric Acid (HCL), Hydroflouric Acid (HF), Ammonia (NH_3)
Photochemical Smog	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Toxic chemical with a reported lethal concentration to rodents
Aquatic Toxicity	Toxic chemical 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 fuel used
Land Use	Quantity disposed of in a landfill or other land modifications
Water Use	Water used or consumed

2.1.5.2. Classification

In this step, the results of the Life Cycle Inventory phase are combined with impact categories. While the LCI results and relevant impact categories are integrated, the cause and effect relationship should be considered. One LCI parameter can contribute only one impact category or parameters can have multiple impact categories. For example, CO_2 and CH_4 can be classified into the impact category named global warming potential. On the other hand, NOx emissions potentially affect acidification and eutrophication impact categories, so the total flow of NOx emissions is assigned to both of these life cycle impact categories (Curran, 2006).

2.1.5.3. Characterization

LCI parameters are evaluated according to the degree of the contribution to an impact (Hauschild et al., 2017). There is a characterization factor used for converting LCI results to an indicator of impact. This characterization factor provides to compare different LCI parameters within each impact category. For instance, relevant LCI results multiply by a CO_2 characterization factor, so all greenhouse gases can be explained as CO_2 equivalents and the overall indicator of global warming potential can be obtained (Curran, 2006).

2.1.5.4. Normalization

The aim of the normalization step is to calculate the magnitude of the impact indicator results relative to reference values. Normalization enables to compare the impact category results with references to find what is normal or not (Gabi, 2012). Normalization provides:

- to control characterization values, inventory data and potential errors
- a better evaluation of the characterized impact values
- a starting point for the next step named weighting (Lee and colleagues, 2004).

2.1.5.5. Weighting

The weighting step is used to compare impact category results based on the importance of the results (Gabi, 2012). In other words, this step enables to determine the most important impacts (Hauschild et al., 2017). The weighting process is stated with weighting factors.

2.1.5.6. Interpretation

Interpretation, the last step, provides to draw conclusion on the LCA process. The results of the inventory analysis and the impact assessment are evaluated to monitor the consistency with the goal and scope definition. The interpretation step has three key elements:

1. Identification: Structure the results of the inventory analysis and the impact assessments to specify significant issues

2. Evaluation: Evaluation is to generate the reliability of all results from LCI analysis, impact assessment and determine significant issues
3. Conclusion: This step is the determination of conclusions by making recommendations (Gabi, 2012).

2.2. Life Cycle Assessment Software

GaBi 9.2 is an assessment software program that performs whole stages of an LCA study and monitors all material, emission and energy flows. GaBi database includes various standard LCA methods and life cycle inventory datasets updated regularly (Li and colleagues, 2018). It allows users to generate their models manually by using energy and material flows. The calculation of the LCA study is carried out by a sequential algorithm based on the input. This calculation system provides to work a partial model without completing a full model and provides to take any feedback more easily (Sinha and colleagues, 2016).

GaBi software empowers users:

- to visualize the environmental impacts for the entire life cycle of a product,
- to develop the design of a product,
- to compare various scenarios,
- to make an interactive report about the environmental and social impacts of a product,
- to find the best transportation method, components and the most sustainable energy source.

2.3. Turkey′s Electricity Situation

Because of the direct impacts of overpopulation, industrialization and urbanization, the demand for energy particularly for electricity has enormously increased in Turkey. According to the International Energy Agency (IEA), Turkey′s electricity final consumption in 2018 was 272.53 TWh and industry was the largest electricity consuming sector (Turkey - Countries & Regions - IEA, 2020).

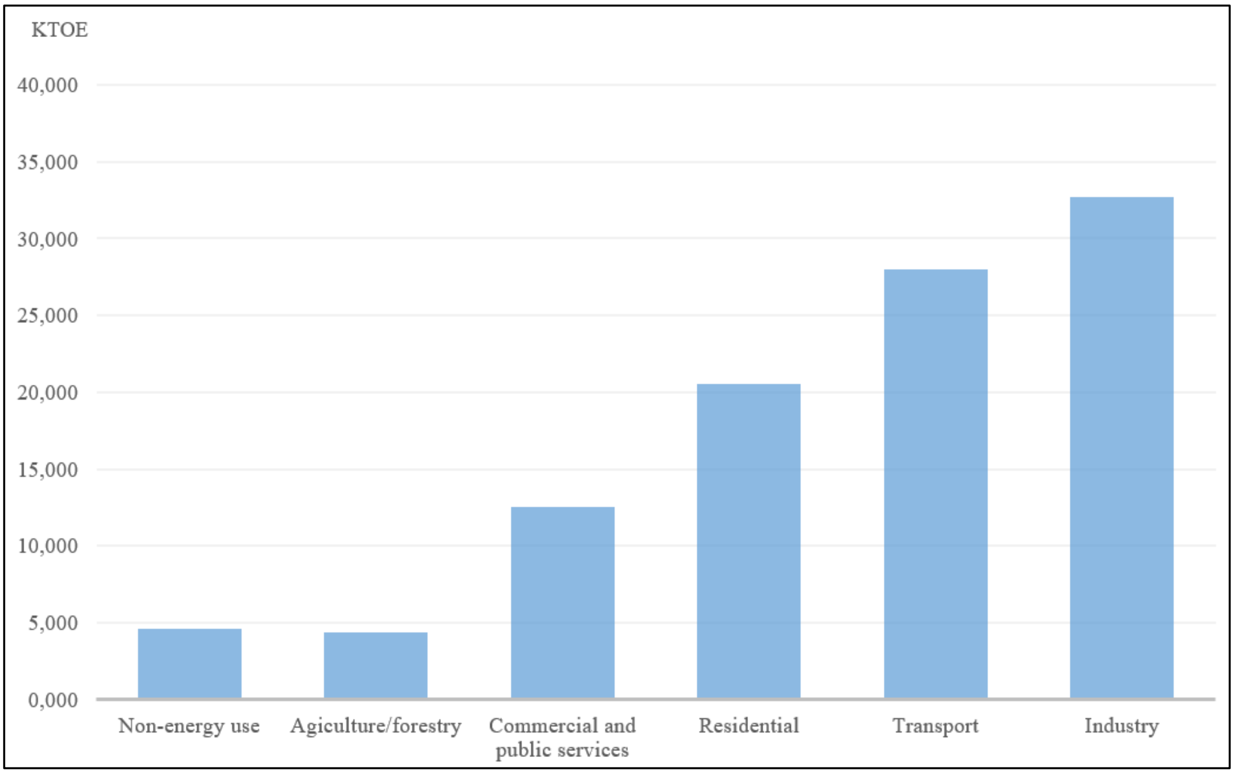


Figure 2.2. Total final consumption in Turkey by sector in 2018.

Electricity generation in Turkey is based on coal, natural gas, hydro, and renewable energy and wastes sources (Yuksel, 2013). The majority of electricity generation is derived from natural gas and coal fuel sources since 1990. Renewable energy and wastes sources are one of the lowest contributor to electricity production, when compared with natural gas and other fossil fuel base sources.

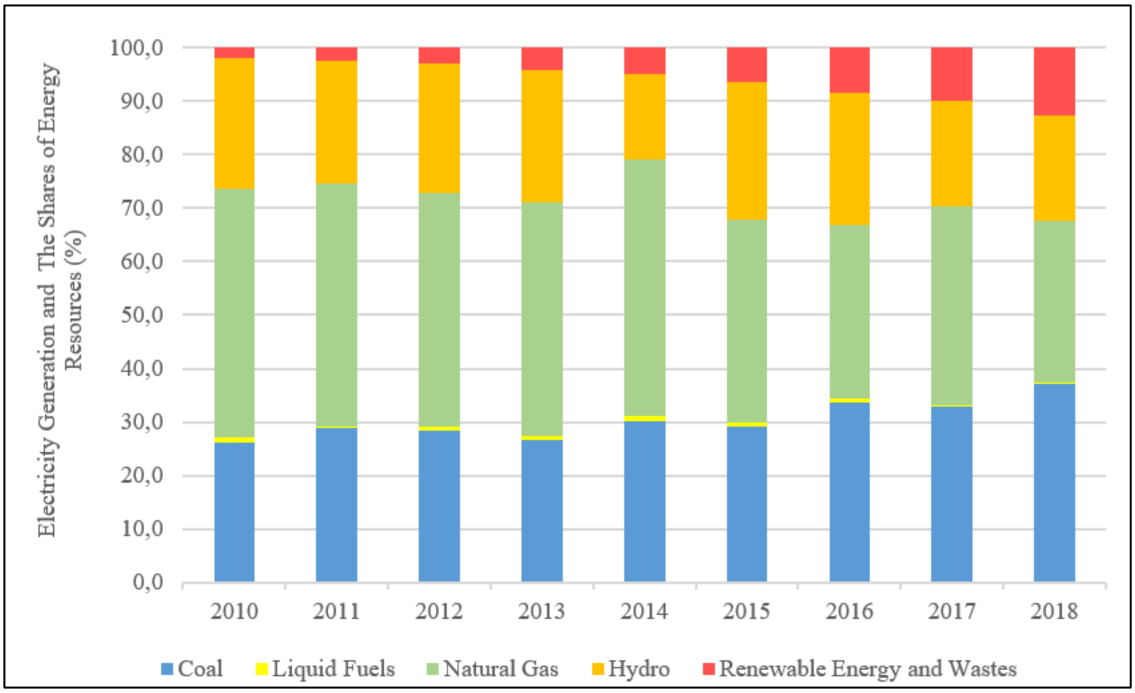


Figure 2.3. The profile of electricity generation for Turkey between 2010 and 2018.

When it comes to renewable energy sources, hydro, wind, geothermal, solar and biomass are considered. While hydro has the biggest share of other renewable resources in electricity generation, the contribution of hydro is still less compared to fossil fuel resources. Because of the crucial environmental issues caused by fossil fuel resources, expanding renewable sources usage have been evaluating by researchers all around the world. In addition to the negative impacts of fossil fuel resources on the environment, Turkey also has a dependency problem on foreign suppliers of natural gas and this problem can lead to some financial problems like a foreign account deficit (Bilgili, 2010).

2.4. Biogas Situation and Potential in Turkey

Renewable energy comes from renewable sources including solar, geothermal, wind, hydropower and biomass. The use of renewable sources to produce electricity, in essence to transit less carbon-intensive and more sustainable energy systems, provides to save significant amounts of greenhouse gas emissions and protect the environment.

Bioenergy term is utilized to refer to renewable energy produced from biomass which comprises carbon, oxygen, nitrogen and hydrogen (Bisht and colleagues, 2019). Bioenergy can be converted into solid, liquid or gaseous biofuels that may be used as heat production, electricity or transportation fuel (Strzalka and colleagues, 2017). Biogas, a type of biofuel, arises from the anaerobic digestion process of a variety of organic materials by microorganisms. After the conversion of organic matters, biogas can be used to generate heat, electricity or vehicle fuel (Scarlat and colleagues, 2018).

Turkey has important biogas potential thanks to huge amounts of biomass sources such as wood biomass, agricultural crop residues, municipal and industrial wastes. In 2018, 2638 GWh electricity was generated from biofuels in Turkey (Turkey - Countries & Regions - IEA, 2020). It is clear to see that the majority of heat generation from renewable resources and wastes stems from biogas in 2018 and the shares of each different renewable resources are indicated in Figure 2.4 (Renewable Information - IEA, 2020).

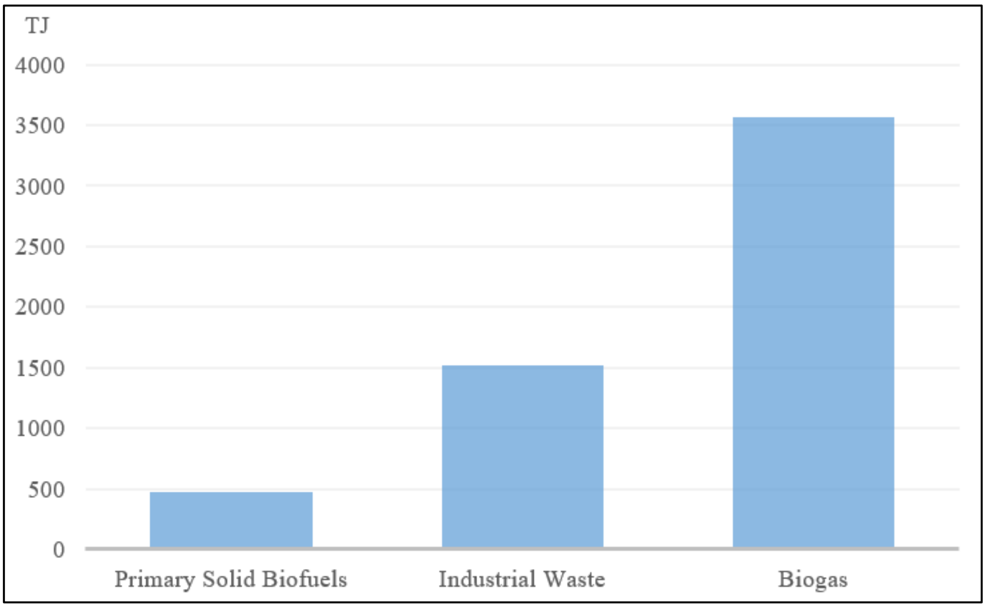


Figure 2.4. Heat generation from renewables and waste by source in Turkey.

2.5. Overview of the Anaerobic Digestion Process

Anaerobic digestion (AD) is a biochemical process in which complex organic matters are converted into simpler compounds. The main products of the anaerobic digestion process are digestate and biogas mainly containing methane, carbon dioxide small amount of other gases (Holm-Nielsen and colleagues, 2009). The conversion of organic materials occurs in the absence of oxygen. Anaerobic digestion process is divided into four stages that are hydrolysis, acidogenesis, acetogenesis and methanogenesis (Meegoda and colleagues, 2018). Figure 2.5. demonstrates the various steps of the anaerobic digestion process (Náthia-Neves and colleagues, 2018).

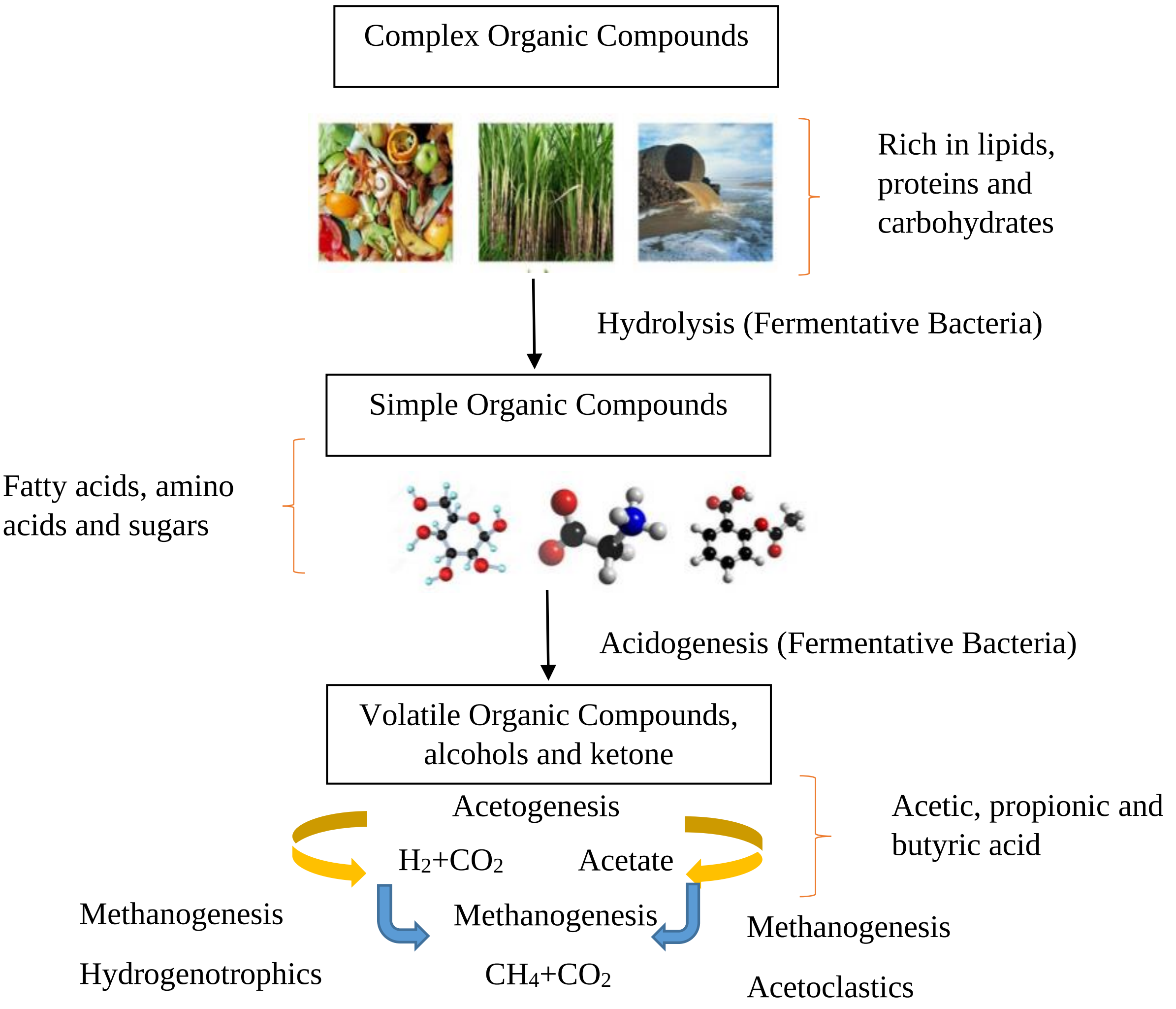


Figure 2.5. The main steps of anaerobic digestion.

Environmental benefits of the anaerobic digestion process include:

- the conversion of different types of wastes into digestate which is an organic residue generating subsequent to anaerobic digestion. Digestate can be utilized as a fertilizer or soil amendment because it has nutrient-rich substances (Kumar and colleagues, 2020).
- the reduction of greenhouse gas emissions to the atmosphere. It provides to trap greenhouse gases which results from the uncontrolled decomposition of wastes (Kumar and colleagues, 2020).
- the production of renewable energy that enables to decrease rising fossil fuel energy demand (Environmental Benefits of Anaerobic Digestion US EPA, 2021).
- being more cost-effective compared to the other biological processes, thanks to its low environmental impacts and high energy recovery (Kothari and colleagues, 2014).
- the production of a source of carbon-neutral energy called biogas (Náthia-Neves and colleagues, 2018).

- Less sludge production is an advantage over aerobic processes (Ward and colleagues, 2008).
- pathogen removal via pasteurization stage of AD process (Ward and colleagues, 2008).
- the reduction of odour problem through minimizing and controlling of biodegradable components of organic wastes (An Introduction to Anaerobic Digestion of Organic Wastes Final Report, 2003).
- the destruction of weed seed and the decrease in the requirement of herbicide use (An Introduction to Anaerobic Digestion of Organic Wastes Final Report, 2003).

Some factors have an important effect on the anaerobic digestion process:

- Temperature is a critical factor for the growth of microbial communities, the formation of methane, biogas production and substrate utilization (Khalid and colleagues, 2011). In accordance with microbial activity, three distinct temperature ranges can be utilized for biogas production:
- Psychrophilic temperature from 10 to 20 °C with optimum at 25 °C
- Mesophilic temperature from 20 to 45 °C with optimum at 35 °C
- Thermophilic temperature from 50 to 65 with optimum at 55 °C

Anaerobic digestion that is operating in thermophilic conditions provides faster biogas production compared to the other conditions owing to the increase in the metabolic rate of microorganisms. Furthermore, thermophilic systems enable more pathogens removal. Despite all advantages of thermophilic temperature, there is an important drawback that should be considered. The cost to continue high operating temperature and to reach constant temperature in the digester is more than the cost of mesophilic systems (Náthia-Neves and colleagues, 2018). Because of the negative impact of thermophilic systems on energy cost, mesophilic systems are the most popular for biogas production. Besides, thermophilic systems are mostly applied in large-scale biodigester (Kothari and colleagues, 2014).

- pH

Keeping Ph range of the digester between 6.8 and 7.2 is crucial especially for methanogenic bacteria. The metabolic rates of these bacteria are negatively affected by ph value outside of this range because methanogenic bacteria are ph-sensitive (Náthia-Neves and colleagues, 2018).

- Retention Time

The time which is needed for complete degradation of organic matter is described as retention time (RT). In other words, RT is defined as the time that is the organic matter stays in the digester (Kothari and colleagues, 2014). Temperature and waste composition are the parameters that affect retention time. The RT in mesophilic conditions ranges from 10 to 40 days, while in thermophilic conditions is usually 14 days.

- Loading Rate

Loading rate is expressed as the amount of organic material that is fed daily to the digester. According to the loading rate, the anaerobic digestion process is categorized:

- Low solid contents (containing less than 15% total solids)
- Medium solid contents (total solid content ranging from 15 to 20%)
- High solid contents (total solid content ranging from 20 to 40%)

The reactor faces an overloading problem derived from the accumulation of some inhibitory substances such as fatty acids, when the feeding rate of organic material is excessive. Consequently, biogas production decreases due to that the feeding is not suitable for the system (Kwietniewska and colleagues, 2014).

- Moisture

The two main types of anaerobic digestion process are classified into dry and wet anaerobic digestion. Dry solid content in the reactor varies from 10 to 15% in a wet anaerobic digestion system. In the dry anaerobic digestion process, organic materials with 25-40% dry solid content are operated (Luning and colleagues, 2003). AD process is usually eased by high moisture content but the conservation of the same availability of water during the anaerobic digestion cycle is difficult (Khalid and colleagues, 2011). In Table 2.2, various moisture contents based on different wastes are demonstrated by utilizing some studies.

Table 2.2. Characterization of various feedstocks in literature.

Feedstock Material	Source	Moisture Content (%)	VS/TS (%)	References
Food waste	Restaurants, Hotels and Groceries	70	83	(Zhang and colleagues, 2010)
Food waste, Yard waste and waste sewage sludge	Supermarkets, industries and schools	73.9	-	(Lee and colleagues, 2020)
Dairy cow manure	Animal farm	87	85	(Debruyn and colleagues, 2007)
Food waste	Restaurants	76.98	89	(Nguyen and colleagues, 2017)

- Carbon to nitrogen ratio (C/N)

Carbon to nitrogen ratio is the ratio between the amount of carbon and nitrogen in organic material (Kothari and colleagues, 2014). C/N ratio is a crucial parameter in anaerobic digestion. Kwietniewska and colleagues obtained an optimal C/N ratio between 20 and 35. Nitrogen is necessary especially for protein synthesis and microbial growth, and also utilized as a nutrient for microorganisms in the anaerobic digestion process (Náthia-Neves and colleagues, 2018). Besides, carbohydrates in municipal solid wastes have great importance for biogas production and are accepted as the most essential component (Khalid and colleagues, 2011). The meaning of high carbon to nitrogen ratio is that carbon content is dominant, whereas a low ratio is that the materials are high in protein (Kwietniewska and colleagues, 2014). Low C/N ratio leads to the accumulation of ammonia in the system and causes to reach ph values of more than 8.5 which is toxic levels for bacteria in the digester (Rocamora and colleagues, 2020). In the case of the high ratio, it means that low gas yield occurs due to consuming nitrogen more quickly (Náthia-Neves and colleagues, 2018).

It is important to consider that all feedstocks used for the anaerobic digestion process have different characteristics. The composition and characteristics of feedstocks have great importance on the conditions of the process and biogas production (Rocamora and colleagues, 2020). The following table details the types of waste that can be used as a feedstock of the anaerobic digestion process (Verheugen, 2005).

Table 2.3. Feedstocks for anaerobic digestion process.

The Type of Waste	**Waste Description**
Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, the fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation
Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard	Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard production and processing
Waste from the leather, fur and textile industries	Wastes from the leather and fur industry
	Wastes from the textile industry
Waste packaging; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	Packaging (including separately collected municipal packaging waste)
Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Garden and park wastes (including cemetery waste), and other municipal wastes
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

2.6. The Main Components of the Biogas Plant

A biogas plant mainly consists of the following components single-stage or multi-stage digesters, gas holder with gas cleaning systems and a cogeneration unit. These units play an important role in the plant operations and the process control of these units have to be managed by a control panel in the plant room. Furthermore, pretreatment technologies are another important step to make heterogeneous biomass substrates ready for anaerobic digestion. It is important to consider that complex biomass feedstocks can be a challenge for the controlling of a biogas plant (Jens Bo Holm-Nielsen and colleagues, 2013). For this reason, pretreatment technologies provide a better controlled and homogeneous biomass feedstocks before the digestion process.

2.6.1. Pretreatment Technologies for Feedstocks

Because of complex reactions by anaerobic bacteria, it is hard to control of anaerobic digestion process (Atelge and colleagues, 2020). In addition, the characteristics of feedstocks for digestion have a significant influence on the effectiveness of anaerobic digestion (Millati and colleagues, 2020).

Prior to anaerobic digestion, numerous substrates need pretreatment processes such as the removal of non-degradable materials, grinding or homogenizing and they profit from the advantages of these processes (R. and colleagues, 1998).

To enhance the performance of substrates for anaerobic digestion, different pretreatment technologies have been recently improved. Physical (grinding, milling, extrusion), chemical (acidic, alkaline, advanced oxidation processes, etc.), biological (enzymatic, fungal, bacterial) and combined pretreatment methods are the four main pretreatment methods (Sabeeh and colleagues, 2020).

By the end of the pretreatment process, the decrease in the molecular size of the substrate occurs and the availability of smaller and less complex composition of the substrate is achieved. In this way, the composition of the substrate becomes appropriate for bacteria in the anaerobic digestion process (Atelge and colleagues, 2020). Thanks to pretreatment, the surface area of the substrate, substrate solubility and enzymatic activity increases and in some cases, the extent of biodegradability enhances. Besides, pretreatment is a useful technology to achieve higher methane yield and less digestion time by facilitating the hydrolysis phase and improving substrate characteristic (Dasgupta and colleagues, 2019).

2.6.2. Digesters

Anaerobic digesters are typically designed as single-stage, two-stage or multi-stages digesters. This means that the stages of the anaerobic digestion process including hydrolysis, acidogenesis, acetogenesis and methanogenesis are performed in the same or separate digesters. The acid-forming and methane-forming bacteria have different properties in terms of the sensitivity to changes in environmental factors such as temperature and pH, the specific growth rate and the nutritional requirements. In addition to the differences between acid-forming and methane-forming bacteria, a single-stage anaerobic digestion system may lead to the decrease in pH value in the digester and the failure in the process due to the accumulation of volatile fatty acids (Lovato and colleagues, 2020).

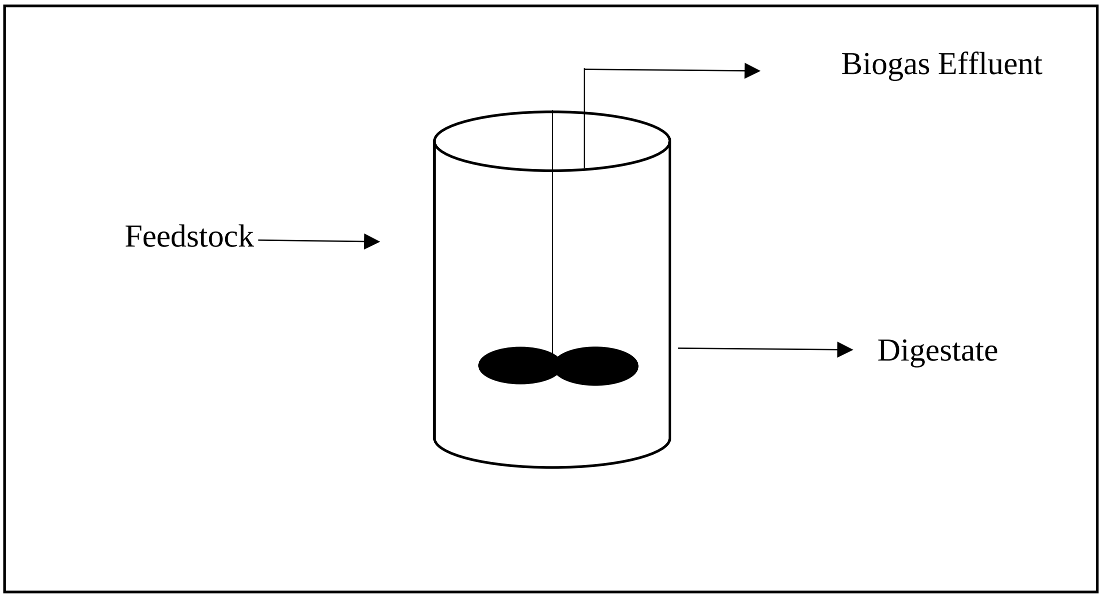


Figure 2.6. Traditional single-stage digester.

On the other hand, many studies have concluded that two-stage digestion has higher methane yield and anaerobic digestion performance than one-stage (Lovato and colleagues, 2020). It is important to know that separated fermenters ease process control and they enable to optimize operational conditions for each stage of the anaerobic digestion process (Rabii and colleagues, 2019).

Air (or oxygen) is considered a toxic substance for anaerobic digestion but, small amounts of oxygen may also be a solution that removes hydrogen sulfide (Duangmanee, 2009). A small amount of air is dosed into the upper part of the digester in order to remove hydrogen sulfide (H_2S) and to prevent the corrosive effect of hydrogen sulfide on metals (Akbulut, 2012). Besides, hydrogen sulfide has a corrosive property on engines and piping systems. In this sense, hydrogen sulfide is removed by air injection from the oxygen feeding point located at the upper part of the digester with 0.1 to

0.2% oxygen input. Apart from air injection to the anaerobic digester, many different methods, which are mainly categorized as chemical, physicochemical and biological gas cleaning processes, are utilized for the removal of hydrogen sulfide from biogas.

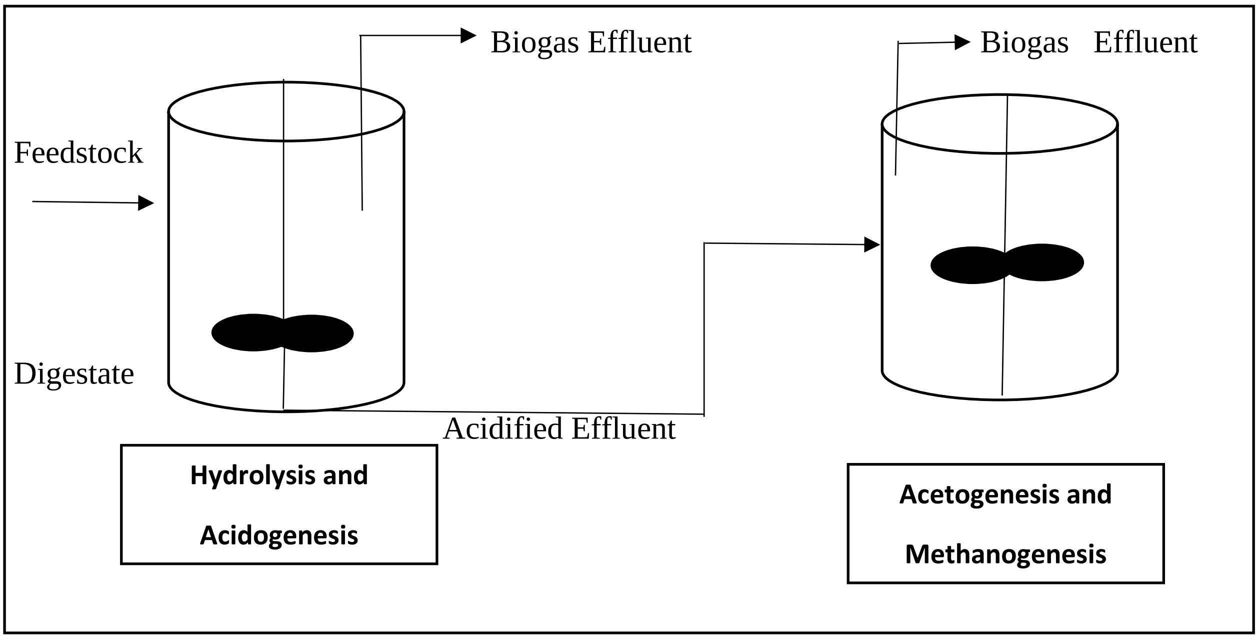


Figure 2.7. Two-stage digesters.

2.6.3. Gas Cleaning Systems

Biogas generated by the anaerobic digestion process is mainly composed of CH_4 and CO_2, also includes slight amounts of, hydrogen sulfide (H_2S), ammonia, moisture and other trace gases. The removal of some components especially for H_2S and water vapour in biogas is necessary to prevent corrosion in the system equipment. Thus, some gas cleaning technologies can be utilized to improve the quality of biogas produced in the plant and to remove some corrosive components from biogas before the biogas application into the CHP unit.

Biogas generally contains about 5 to 10 percent of water vapour and the concentration level of water vapour in biogas changes with feedstock composition. Due to the negative effects of excess water vapour concentration on the biogas plant, various gas cleaning technologies such as activated carbon, chiller system, molecular sieves, refrigeration and glycerol can be applied to eliminate moisture. Besides, H_2S is an important gas for all pipes and instruments in the biogas plant because it can damage the pipelines while biogas is transferred from the membrane gas holder unit to the CHP. The concentration of H_2S in biogas is between 0 and 10000 ppm and this corrosive gas can be removed by activated carbon adsorption, biological treatment and absorption (Kapoor and colleagues, 2020).

2.6.4. Cogeneration

Cogeneration or combined heat and power (CHP) is a technology that generates both electricity and heat. Combined heat and power is a technique for wasted energy in exhaust gases and engine cooling (Dalpaz and colleagues, 2020). CHP technology has great importance on the mitigation of the climate change issue by using primary energy resources efficiently and decreasing carbon dioxide emissions (Wittmann and colleagues, 2013).

Biogas generated by anaerobic digestion of organic substrates can be utilized for the production of power and thermal energy in a CHP plant (Akbulut, 2012). Greenhouse gas emissions produced by the biogas plant are less than half in comparison with fossil fuel sources (Torquati and colleagues, 2014). A study carried out by Martens (1998), indicated that CHP is an efficient and clean technology for energy production, and provides to gain 20% energy efficiency compared to separate production of power and thermal energy (Martens, 1998).

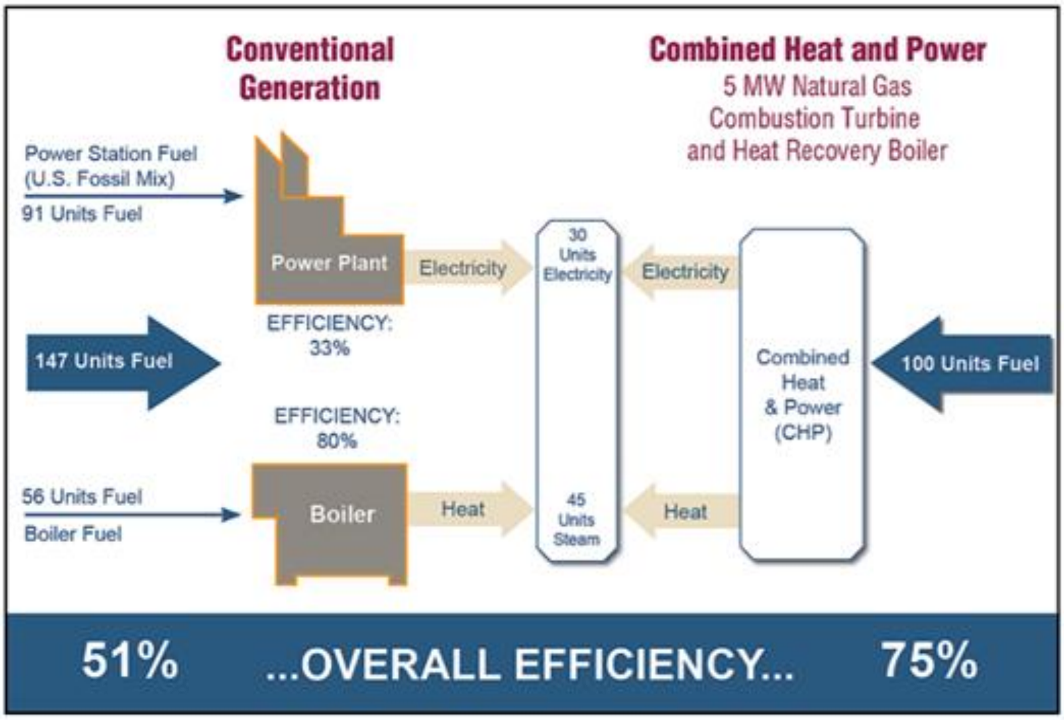


Figure 2.8. The comparison of the conventional generation and the CHP system (Environmental Protection Agency, 2015).

Regarding a simple example shown in the figure above, it is clearly seen that the traditional system utilizes 147 units of energy inputs to generate 75 units of electricity and heat, whereas the combined heat and power system only requires 100 units of energy inputs for the production of the same amount of energy. In conclusion, it is obvious that the CHP system is more efficient than the conventional system if the total system efficiency is considered.

2.7. Application of LCA Methodology for Anaerobic Digestion Process

Life Cycle Assessment is an effective environmental management method used for the evaluation of environmental impacts, comparing the environmental impacts of different processes and obtaining a comprehensive analysis that contains GHG emissions, the utilization of resources, etc. (Rajendran and colleagues, 2019).

There are numerous studies that have been conducted researches on the life cycle assessment of the anaerobic digestion process, the evaluation of biogas utilization in several ways. In this sense, it is easy to understand how to environmentally evaluate a biogas plant and how to measure impact potentials via these various studies.

The studies focusing on the importance of co-digestion have mostly preferred to compare conventional anaerobic digestion and anaerobic co-digestion processes. Regarding co-digestion impact, a study found that anaerobic co-digestion has more advantages than mono-digestion in terms of the increase in biogas production yield and the performance of anaerobic digesters (Rabii and colleagues, 2019).

In addition to the studies related to mono-digestion and co-digestion, some studies have highlighted the performances of the single-stage and multi-stage anaerobic digestion process. In a study, co-digestion of end-of-life dairy products and agro-industrial waste is evaluated according to the two-stage and single-stage anaerobic digestion process. The results showed that higher energy productivity is observed in the two-stage digestion.

A study that is related to the life cycle assessment of electricity and heat generation from mixed farm wastes by using the anaerobic digestion process aims to estimate the environmental impacts of the cogeneration of electricity and heat by using biogas. In the anaerobic digestion plant, mixed farm wastes comprise manure, maize silage, cheese whey and fodder beet. In addition, the AD-CHP plant is compared with a fossil-fuel system and significant reductions in global warming potential (GWP) is observed by 34% compared to the natural gas CHP. Besides, the results indicate that the AD-CHP plant is the best option in terms of some positive impacts including abiotic depletion potential, global warming potential, human and eco-toxicity potential, ozone depletion potential, marine aquatic eco-toxicity potential compared to the other fossil-fuel alternatives such as electricity-boiler systems and natural gas CHP system. On the contrary, the other important result is that acidification and eutrophication potentials of the AD-CHP plant are higher than the other alternative systems because the ammonia which is in the liquid digestate produced in anaerobic digestion process releases when the digestate is stored in an open-air lagoon (Whiting and colleagues, 2014).

3. MATERIALS AND METHODS

3.1. A Specified Biogas Plant Description and Application

In this study, an anaerobic digestion plant located in the Marmara Region of Turkey is specified. The specified plant which was established in 2003 is one of Turkey's first private integrated waste management company. The specified anaerobic digestion plant has been performing a controlled waste management system and biogas production since 2018. Apart from biogas production, many different field activities are actualized and the plant is met all of the needs of customers through energy recovery. For this reason, a variety of wastes have been handled and recovered for the control and use of resources.

Activity fields of the specified plant are indicated below.

- Fuel preparation from hazardous and non-hazardous waste
- Refuse Derived Fuel (RDF) preparation
- Solid Recovered Fuel (SRF) preparation
- The collection and separation of packaging waste
- The collection and separation of non-hazardous waste
- The collection and separation of scrap waste
- Interim storage of wastes
- Household waste management
- Evaluation of inorganic wastes as alternative raw materials
- Interim storage of hazardous waste
- Sludge drying applications
- Landfill
- Biogas process
- Recovery of electronic waste
- Transportation of hazardous and non-hazardous waste
- The temporary storage of waste batteries

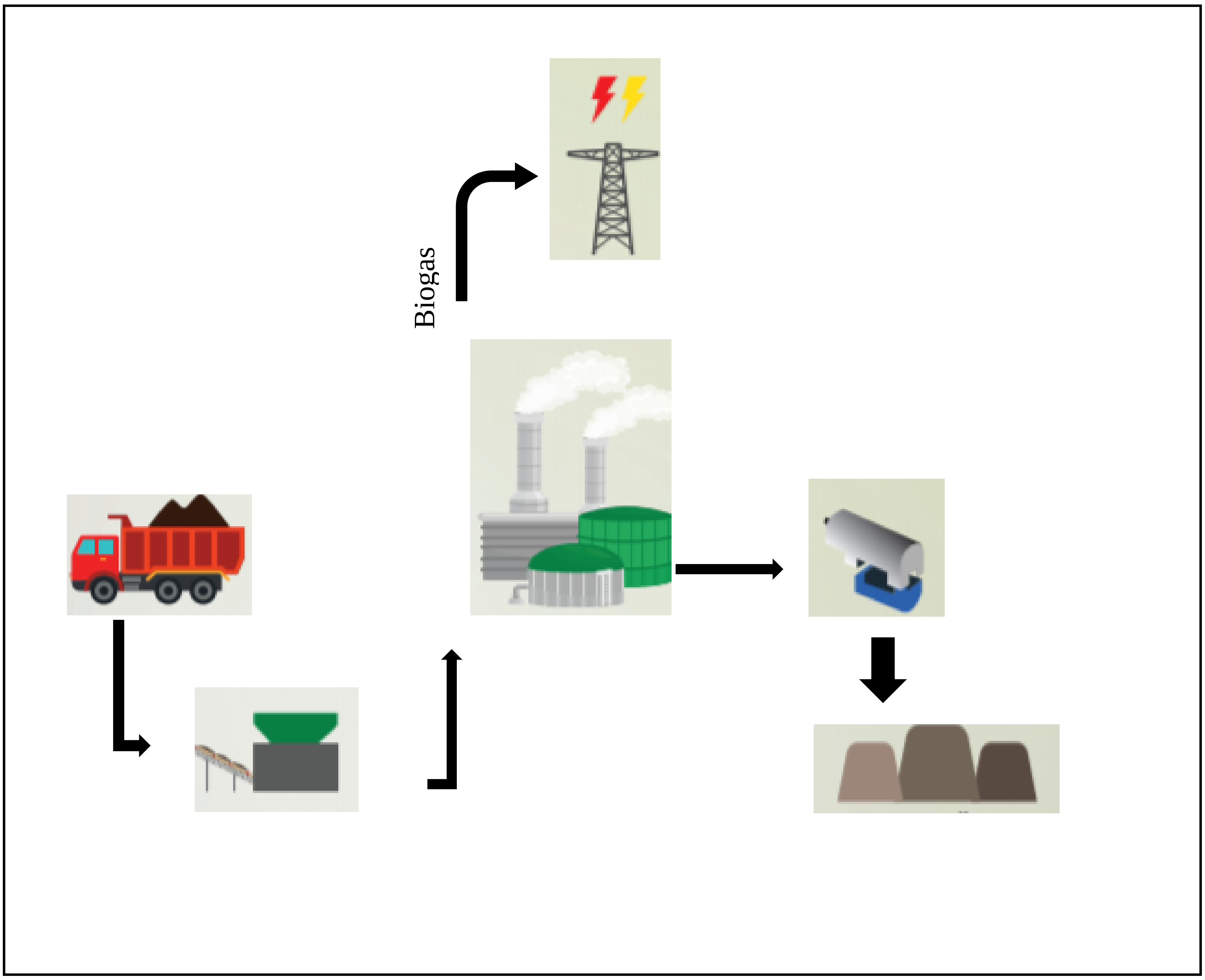


Figure 3.1. The plan of the specified biogas plant.

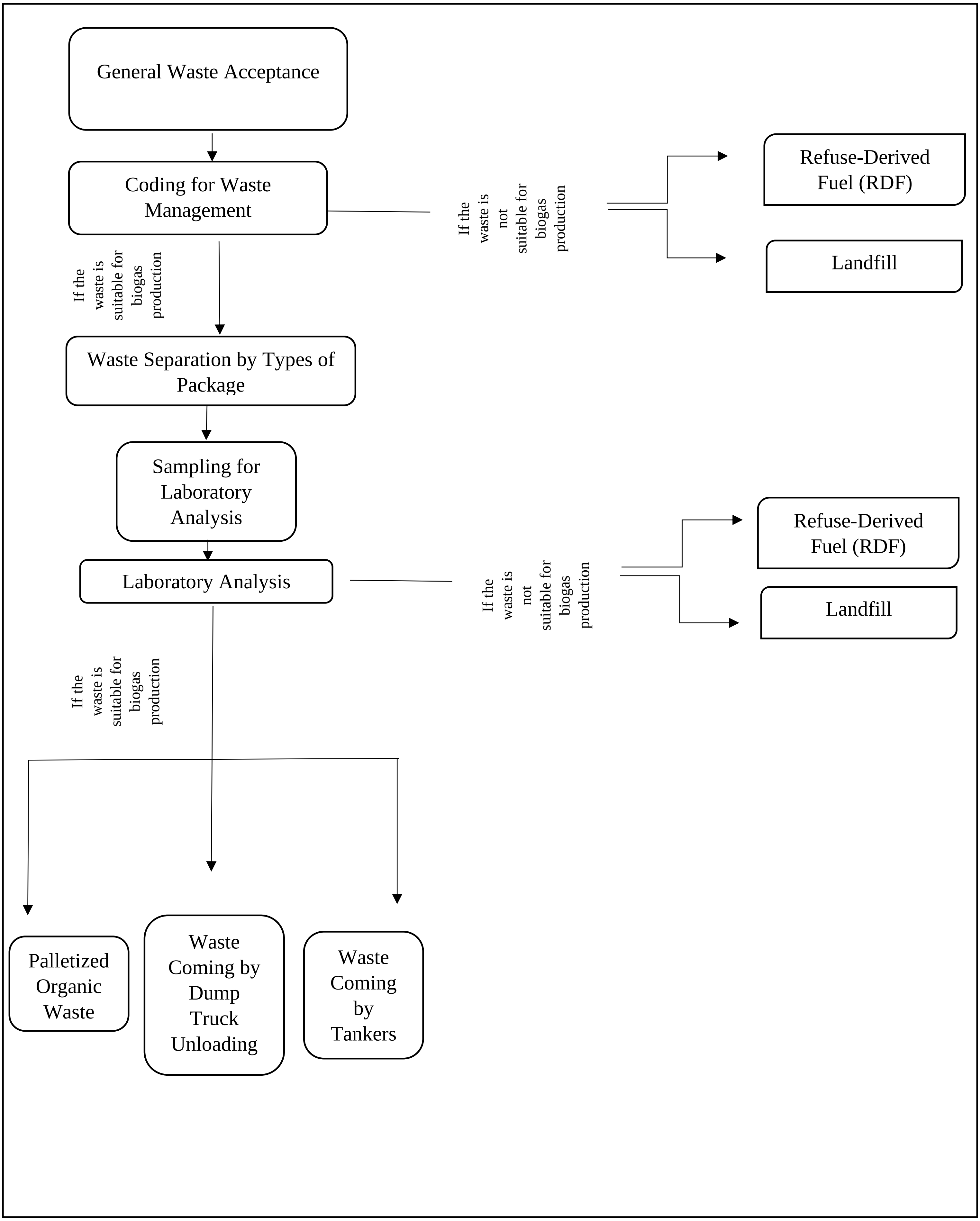
The specified biogas plant comprises the following units which are one dumping area, one primary storage tank, one conveyor, one waste shredder, five conditioning units, one pasteurization unit, three digesters, one chiller unit, one activated carbon unit, one cogeneration unit with two different engines, one separator, one pasteurization unit, one liquid digestate storage tank, one solid digestate storage tank and one control unit.

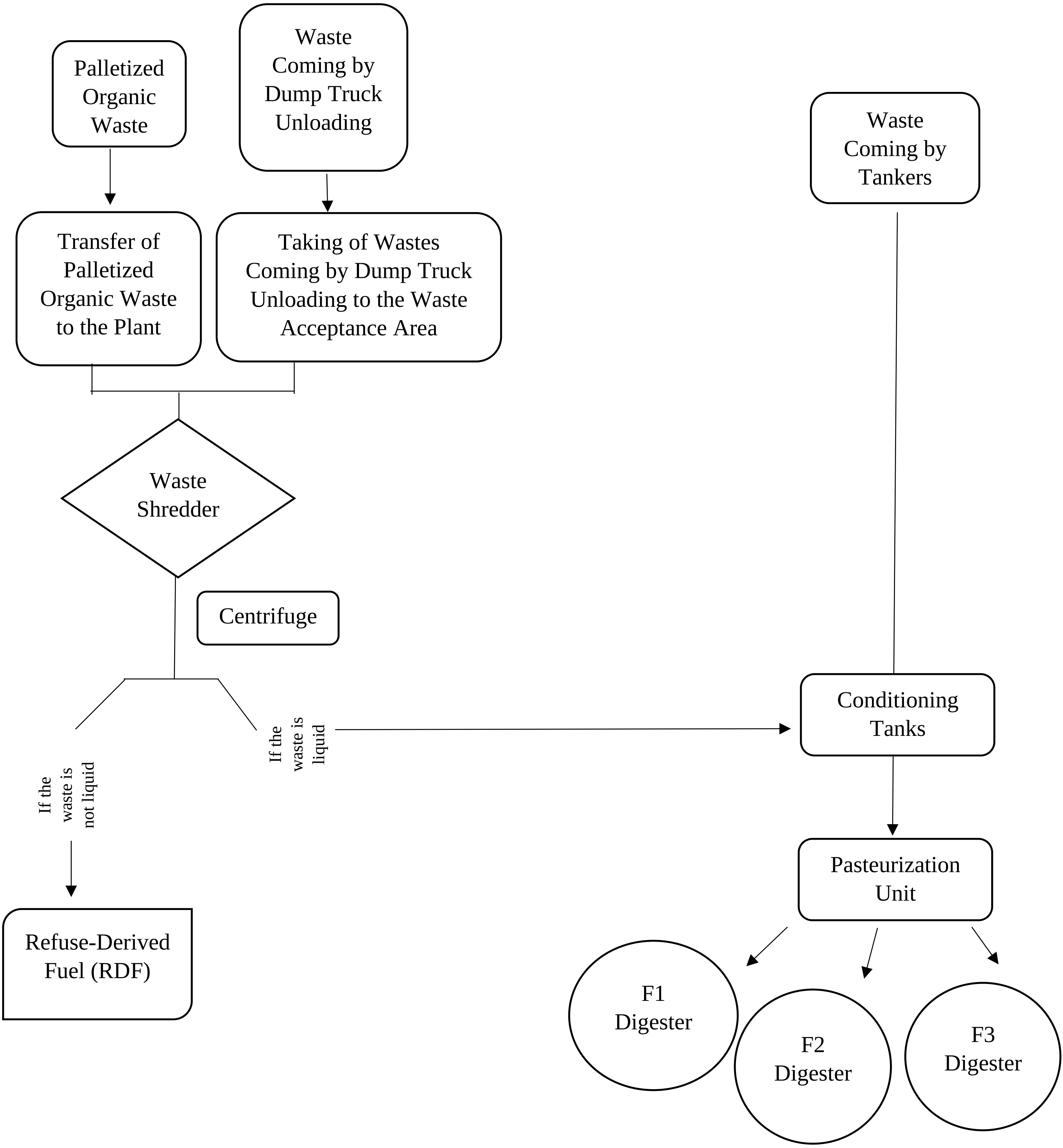
The procedure of the biogas production process is outlined below:

- Transportation of wastes to the specified anaerobic digestion plant with suitable vehicles,
- Taking samples from incoming wastes for laboratory analysis and controlling of them,
- Transferring incoming wastes to the manual sorting platform,
- Papers and cardboards are sorted out at the manual sorting platform and transferring incoming wastes to the waste shredding machine for eliminating packaging materials,
- Separating some suitable packaging materials for the recycling process and disposal step,

- Transferring non-recyclable packaging materials to refuse-derived fuel unit after required laboratory analysis,
- Transferring the rest of the incoming wastes to conditioning units and then pasteurization unit,
- After the pasteurization process at 70 ^{o}C for 1 hour, transferring wastes to anaerobic digesters in order to produce biogas,
- Removing of moisture and some trace gases in biogas by chiller unit and activated carbon technology,
- After the gas cleaning process, the conversion of the mechanical energy generated by burning biogas in gas engines into electrical energy,
- Returning the waste heat from the cogeneration unit to the digesters in order to provide the required temperature conditions for bacteria,
- Returning electricity generated by CHP to gas engines, waste shredder, centrifuge, transfer pumps and supply manifolds, chiller unit, separator for the internal usage,
- Obtaining and separating the solid and liquid fractions of digestate by using a separator unit,
- Transferring liquid fractions of the digestate into the pasteurization unit at 70 ^{o}C for 4 hours before the usage of liquid digestate as a solid amendment.

In Figure 3.2, the whole processes of the specified biogas plant are shown. It is clearly seen how to evaluate the suitable waste compositions after their acceptance into the specified biogas plant.


General Waste Acceptance
Coding for Waste Management
If the waste is not suitable for biogas production
Refuse-Derived Fuel (RDF)
Landfill
If the waste is suitable for biogas production
Waste Separation by Types of Package
Sampling for Laboratory Analysis
Laboratory Analysis
If the waste is not suitable for biogas production
Refuse-Derived Fuel (RDF)
Landfill
If the waste is suitable for biogas production
Palletized Organic Waste
Waste Coming by Dump Truck Unloading
Waste Coming by Tankers


Palletized Organic Waste
Waste Coming by Dump Truck Unloading
Waste Coming by Tankers
Transfer of Palletized Organic Waste to the Plant
Taking of Wastes Coming by Dump Truck Unloading to the Waste Acceptance Area
Waste Shredder
Centrifuge
If the waste is not liquid
If the waste is liquid
Conditioning Tanks
Pasteurization Unit
Refuse-Derived Fuel (RDF)
F1 Digester
F2 Digester
F3 Digester

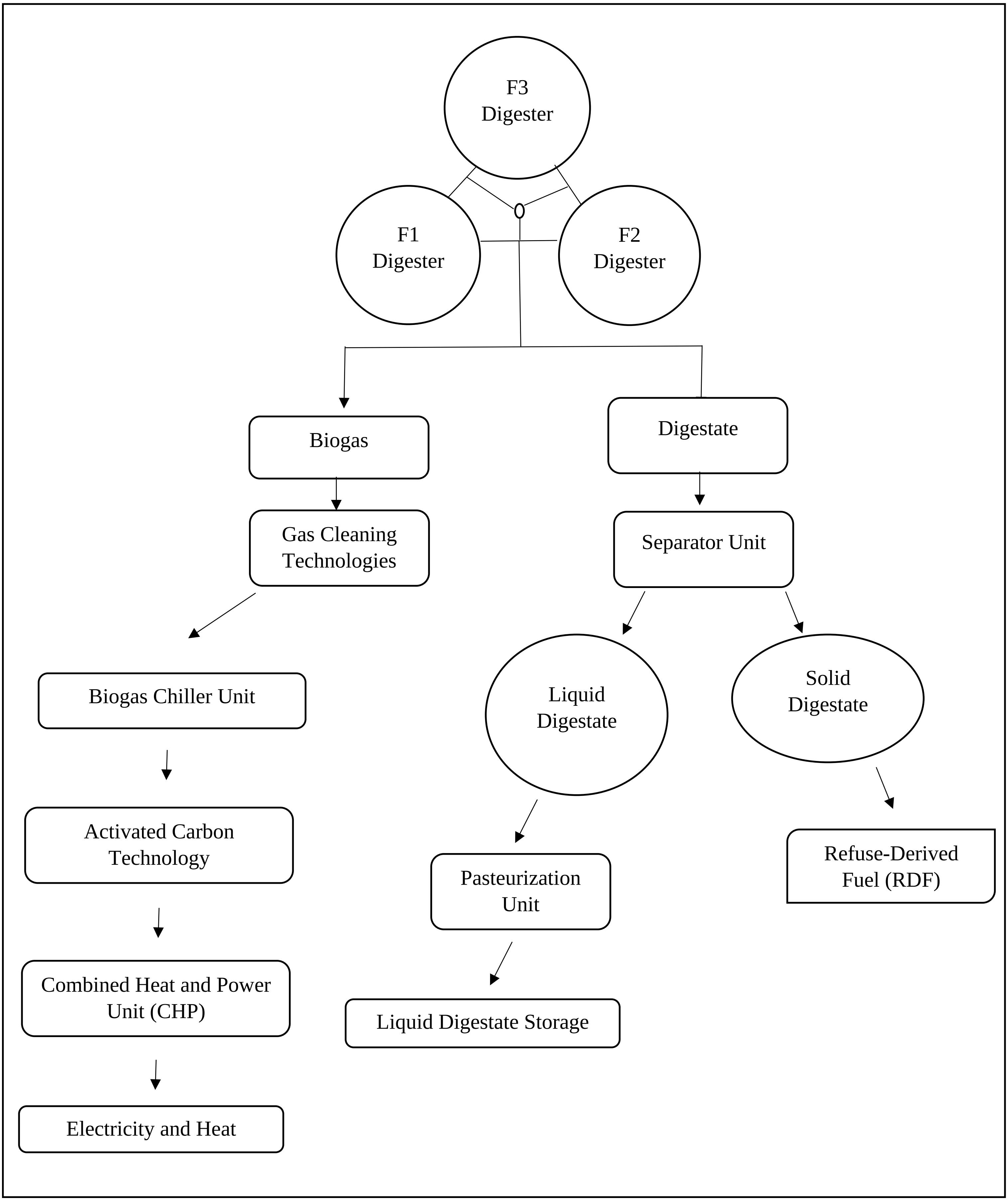


Figure 3.2. The diagram of the specified biogas plant.

The dimensional and physical properties of every unit are detailed in Table 3.1. Besides, operation time is a crucial point to be emphasized because the calculation procedure of electricity consumption for every stage in the plant is based on operation time.

Table 3.1. Properties of each unit in the specified biogas plant.

Unit Name of The AD Plant	**Dimensions of Unit**	**Unit Capacity**	**Working Duration**
Dumping Area	-	200-250 ton	24 hours
Waste Shredder	Height: 1.5 m Width: 0.8 m Length: 1.1 m	-	7.5 hours
Conditioning Tanks	First Conditioning Tank	296 m^3	24 hours
	Second Conditioning Tank	100 m^3	
	Third Conditioning Tank	84 m^3	
	Fourth Conditioning Tank	84 m^3	
	Fifth Conditioning Tank	215 m^3	
Digester 1	Height: 8.5 m Diameter:28 m	5000 m^3	24 hours
Digester 2	Height: 8.5 m Diameter: 18 m	2000 m^3	24 hours
Digester 3	Height: 8.5 m Diameter: 18 m	2000 m^3	24 hours
Flare	Height: 0.5 m	> 60 m^3 biogas/day	-
Cogeneration Unit	Cogeneration Motors, Cogeneration Room Height: 2.5 m Width: 2 m Length: 3 m	-	-
Storage Tank for Liquid Digestate	-	1000m^3	-
Biogas Holder	-	5000 m3	24 hours

To begin with, the waste transportation and characterization, anaerobic digestion stage, the combined heat and power unit, the separation of the produced digestate processes are so crucial in this LCA study. The characterization of waste collected from various areas has an important role because it determines the potential usage as a feedstock for the anaerobic digestion process. In this sense, several waste characterization experiments have been carried out by the laboratory which is located in the specified biogas plant. These whole measurements in this part are used to determine the appropriateness of each type of waste for the anaerobic digestion process and methane production.

3.2. Waste Collection

The following list details the types of waste that can be used as a feedstock for the specified biogas plant.

- Vegetable wastes
- Poultry wastes
- Food wastes
- Dairy products
- Edible oils
- Sauces (ketchup, mayonnaise, dib roman sauce, etc.)
- Coffee and tea
- Ice cream
- Confectioneries, candies and chocolates
- Packaged bread
- Pastry materials (cream, yeast, etc.)
- Meat products (sausage, salami, fermented sausage, etc.)
- Wastewater sludge

In the context of waste characterization, two different procedures are applied. In this sense, it is important to consider a coding system for waste management. The procedure of waste characterization analysis depends on the wastes used before in the specified biogas plant for biogas production. Waste characterization analysis is performed by taking a sample from the only waste grinder, conditioning units, three digesters and liquid digestate storage tank, if the waste has been previously used in the plant for biogas production.

Some types of wastes mainly vegetable, dairy, meat and packaged products have been collected from supermarkets located in different districts of the Marmara Region. On the other hand, food wastes have been collected specifically from a military base in Tekirdağ. Besides, some ice cream, confectionery and candy manufacturers have transferred their expired products to this specified plant. Animal slurry has also been collected from several chicken farms and transported in order to generate biogas. In addition, wastewater sludge that is generated in a wastewater treatment plant has been picked up by truck-trailers and waste vegetable oil from oil factories active in the regions of Marmara has been collected by tankers.

Truck-trailers, lorries and tankers are mainly utilized to collect various types of wastes which are generated by supermarkets, factories and animal farms in the Marmara Region. It is noteworthy that the great majority of waste composition in the specified biogas plant has consisted of expired wastes. Thanks to the collection of these expired wastes, both waste minimization and energy production via waste utilization have been handled. Besides, the loading capacities of truck-trailer and lorry are different from each other. For truck-trailers, the loading capacity is between 34 and 40 tons, whereas it is lower in lorries. In other words, each lorry is able to carry approximately 22 tons of cargo.

3.3. Waste Characterization Experiments

All wastes collected from several supermarkets, factories, wastewater treatment plants and animal farms are analyzed at the laboratory of the specified biogas to determine total solids (TS), moisture content (MC), the percentage of volatile solids within total solid (VS), total Kjeldahl nitrogen (TKN), heavy metal concentrations, pH and conductivity. It is important to consider that these whole analyses are implemented according to standard methods of the United States Environmental Protection Agency (USEPA, 2001)

In accordance with the frequency of waste use in biogas production, two different procedures are utilized for waste characterization analysis. The waste previously used in the specified biogas plant are subjected to daily experimental analysis such as pH, total solids, volatile solids, etc. Apart from routine analysis, a biomethane potential (BMP) test is also performed for wastes that will be utilized for the first time in the plant. Based on the BMP test of collected waste samples, it is easy to estimate the anaerobic digestibility of different feedstocks. Biomethane potential test generally lasts more than 30 days. In the context of a BMP test, the automatic methane potential test system (AMPTS), which is a lab equipment, provides to measure the biogas potential of any waste sample.

3.3.1. The Results of Waste Characterization Analysis

In Appendix A, the methodology of each experiment is presented. Besides, Appendix B includes some photographs that show the whole steps of the experimental analysis and laboratory instruments utilized during waste characterization experiments.

All experiments are carried out for first and second conditioning units, and three digesters. The results for the characterization of moisture content, total solids, volatile solids and total Kjeldahl nitrogen are shown in Table 3.2 and Table 3.3 Total volatile solid (VS) content is observed through the total solid content of the feedstock. The weekly measurements of moisture content, volatile solid content and VS/TS ratio by percentage are shown in Figure 3.3 and Figure 3.4.

Table 3.2. Characteristics of waste sample from the first conditioning unit.

Sample From The First Unit	**Moisture Content (%)**	**TS (%)**	**VS (%)**	**TKN (%)**
Monday	89.7	10.26	68.38	0.410
Tuesday	90.2	9.84	65.82	0.40
Wednesday	86.5	13.53	48.19	0.40
Thursday	93.25	6.75	72.53	0.46
Friday	91.7	8.3	48.34	0.46
Saturday	91.34	8.67	84.46	0.442
Sunday	88.43	11.58	61.05	0.424
Average	90.16	9.85	64.110	0.430

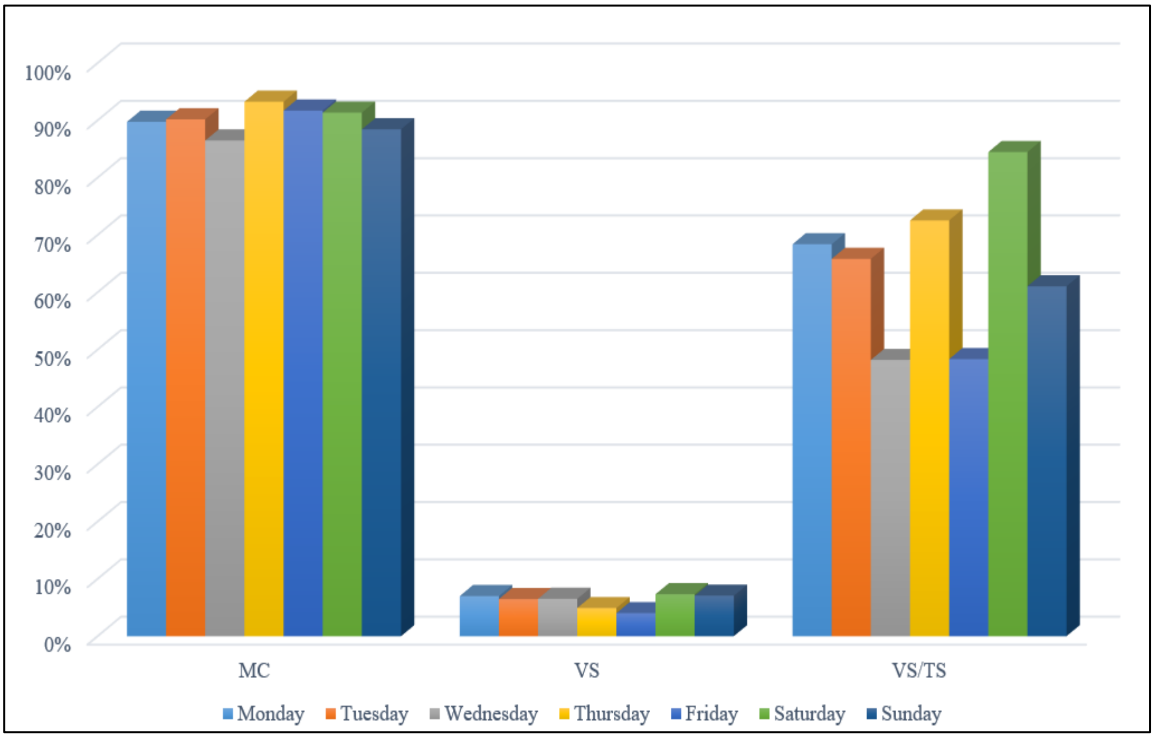


Figure 3.3. The weekly values of MC, VS and VS/TS for the first conditioning unit.

Table 3.3. Characteristics of waste sample from the second conditioning unit.

Sample From the Second Unit	**Moisture Content (%)**	**TS (%)**	**VS (%)**	**TKN (%)**
Monday	85.9	14.00	96.73	0.43
Tuesday	91.13	8.88	96.91	0.41
Wednesday	89.60	10.4	96.24	0.42
Thursday	87.5	12.5	96.87	0.415
Friday	85.13	14.88	97.21	0.436
Saturday	85.9	14.14	96.40	0.44
Sunday	81.3	18.75	96.92	0.445
Average	86.64	13.38	96.75	0.43

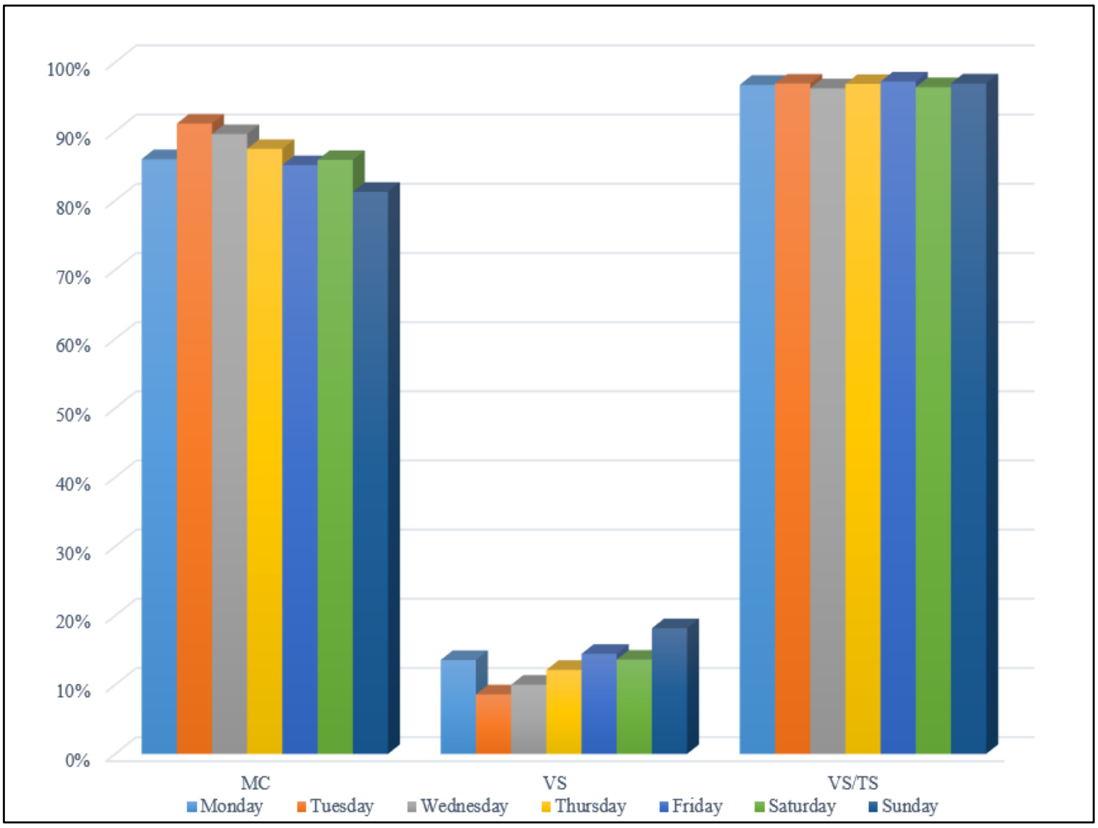


Figure 3.4. The weekly values of MC, VS and VS/TS for the second conditioning unit.

The tables indicate the values of moisture content, volatile solid content and VS/TS ratio for these two conditioning tanks. The moisture content of the waste sample taken from the first tank ranged from 86% to 93%. In addition, volatile solid content ranged from 4% to 7% and VS/TS content ranged from 48% to 84%. The average values of the first conditioning unit were measured as 90% for moisture content, 6% for volatile solids, and 64% for VS/TS. According to the results of the second tank, the MC ranged from 81% to 91%, the VS content ranged from 9% to 14% and VS/TS content ranged from 96% to 97%. The average values were also calculated as 87% for moisture content, 10% for volatile solids, and 97% for VS/TS. The moisture and volatile solid content of the first conditioning unit stayed almost stable but VS/TS contents of Wednesday and Friday's sample displayed 48% content. There are no major variations for the moisture, volatile solid content and the other samples of VS/TS ratio. When it comes to the second tank, VS/TS content was the nearly steady state. The variations of the moisture content were not too much. On the other hand, VS contents of Tuesday and Sunday's sample showed the lowest and the highest value of the second conditioning unit. According to Table 2.2, it is clearly seen that the measured moisture content and VS/TS content for these two conditioning tanks are close to the values of various feedstocks in the literature.

In addition to moisture content and total solids, the results for conductivity, pH and FOS/TAC ratio are indicated in Table 3.4. Furthermore, it is important to know that the results of three digesters are calculated by averaging the values of waste samples coming from the digesters.

Table 3.4. Characteristics of waste sample taken from all three digesters.

Sample for Three Digesters With Average Values	**Moisture Content (%)**	**TS (%)**	**pH**	**Conductivity (µS)**	**FOS/TAC**
Monday	95.6	4.40	7.8	13.2	0.39
Tuesday	95.4	4.6	7.8	13.4	0.42
Wednesday	95.5	4.59	8.00	13.5	0.4
Thursday	95.5	4.5	7.9	13.1	0.4
Friday	95.5	4.5	7.9	12.9	0.39
Saturday	95.2	4.86	7.9	13.2	0.4
Sunday	95.4	4.6	7.95	13.35	0.39
Average	95.4	4.6	7.9	13.24	0.4

Various substrates can be utilized in the specified biogas plant. However, some considerations were taken into account beforehand. First, it is important to determine the appropriateness of any waste sample for the anaerobic digestion process via waste characterization analysis. Second, biomethane potential or biogas potential is another parameter that should be considered because it enables to measure anaerobic digestibility of each feedstock before the anaerobic digestion process.

Trace elements have important roles in the anaerobic digestion process because trace elements especially iron (Fe), nickel (Ni), cobalt (Co), molybdenum (Mo) and zinc (Zn) are major elements for microbial activities and enzymatic reactions. In Table 3.5, heavy metal concentrations of every particular waste types used in the specified biogas plant are indicated.

Table 3.5. Heavy metal concentrations of different types of wastes.

Type of Feedstock	**Ni (ppb)**	**Zn (ppb)**	**Cu (ppb)**	**Cd (ppb)**	**Fe (ppb)**	**Cr (ppb)**
Confectionery	4000	16000	2000	1000	15000	3500
Mix Meat	2000	51000	2000	-	43000	7000
Yeast	3000	64000	2000	1000	41000	9000
Juice	5000	-	2000	1000	38000	3000
Coffee	2000	12000	1000	-	10000	2000
Vegetable waste	3500	20000	3000	1000	32000	6000
Wastewater sludge	7000	58000	7000	1000	504000	13000
Poultry manure	5700	118000	13000	1050	302000	5500
Food waste	4000	22000	3000	1000	78000	6000
Milk	2500	13000	3000	1000	11000	4000
Yoghurt	4000	19000	3000	1000	12800	5000
Ice Cream	2000	23000	3000	1000	22000	5000

3.3.2. Biochemical Methane Potential Analysis (BMP)

The BMP test is widely utilized to assess the methane potential and the digestibility of various organic feedstocks (Valenti and colleagues, 2018). The test consists of two main elements: anaerobic inoculum and organic substrate. Initially, each organic substrate is chemically characterized and mixed with active anaerobic inoculum taken from the anaerobic digester in the plant. The mixture comprising of organic substrates and inoculum is placed in air-tight glass bottles where biogas production occurs (Ohemeng-Ntiamoah and colleagues, 2019). During the test, the temperature of BMP bottles is kept in a constant temperature approximately 38 ^{o}C (Valenti and colleagues, 2018). Besides, the whole duration of BMP test is generally between 30 and 60 days (Filer and colleagues, 2019).

3.4. Anaerobic Digesters

In the specified biogas plant, three anaerobic digesters have been used in order to increase waste treatment and methane production. The mixture of several substrates is pumped into the first and the second digester. In the following step, feedstocks are directly transferred to the last digester which is referred as F3 digester. It is obvious that non-digestible wastes remaining from the first and second digester can be evaluated into the third digester. Thanks to the re-evaluation of remaining wastes, higher methane yield can be obtained. The capacities of three digesters in this specified biogas plant are detailed in Table 3.6. Figure 3.5 also demonstrates the feedstock flow between these three digesters.

Table 3.6. The capacity of every digester in the specified biogas plant.

Digester	**Capacity of Digester (m^3)**
F1 Digester	5000 m^3
F2 Digester	2000 m^3
F3 Digester	2000 m^3

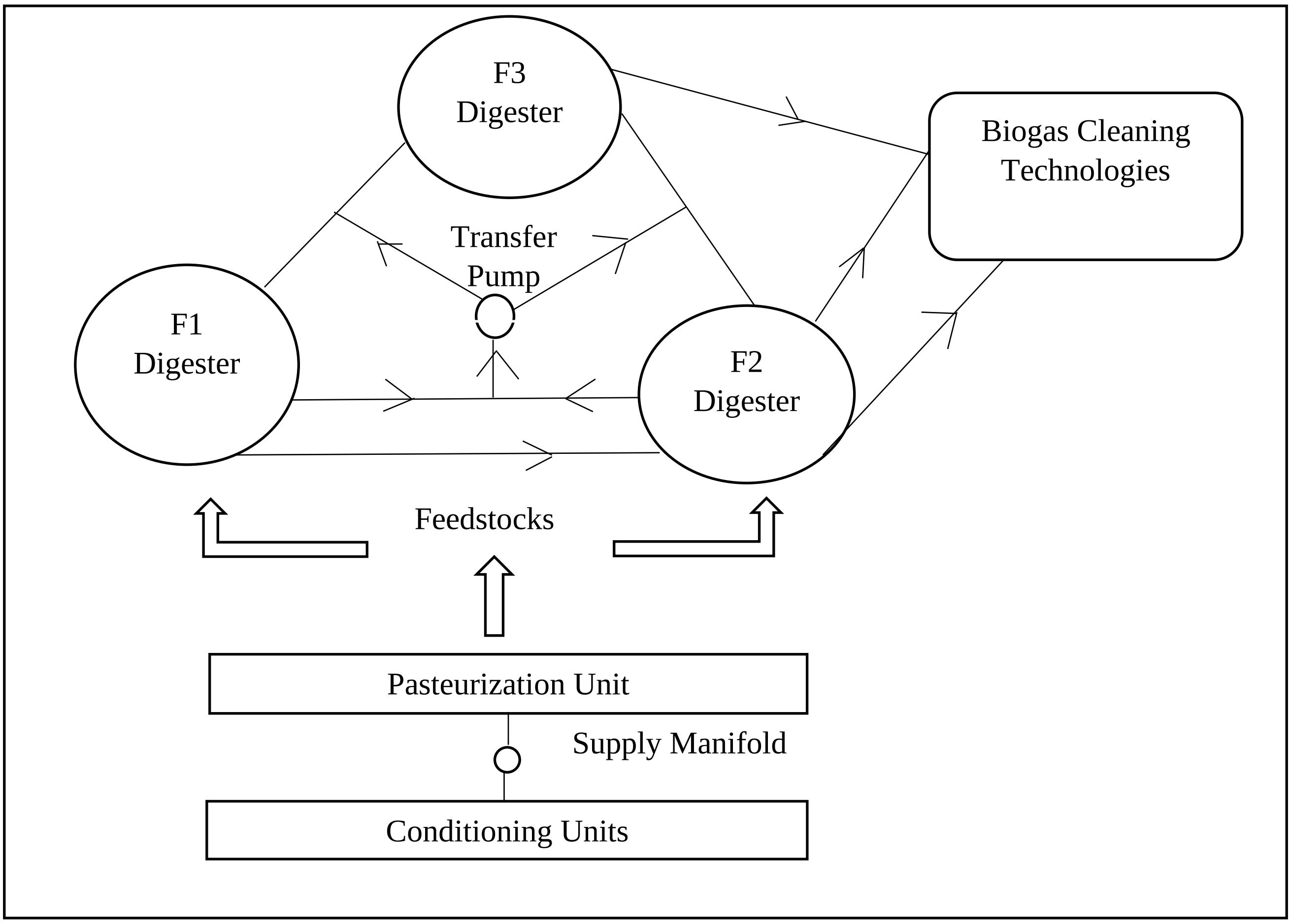


Figure 3.5. Feedstock flow between F1, F2, F3 digesters.

Digesters are performed within mesophilic range (20-45 °C) and the required temperature range is maintained by using of serpentine systems in the digesters. The retention time (RT) is described as the time needed for complete degradation of organic matter or the time substrate remains in the anaerobic digester while methane production has been occurring (Kothari et al., 2014). The retention time for anaerobic digestion depends on waste composition and temperature in the digester (Kwietniewska et al., 2014). The retention time varies from 10 to 40 days in mesophilic conditions, whereas it is shorter in the plant which is operated thermophilic conditions (Kothari et al., 2014). The retention time is generally between 10 and 30 days within the digesters of the specified anaerobic digestion plant. 8 tons and 4 tons of wastes are respectively pumped to the F1 and the F2 digesters in every hour. In the following step, the total amount of waste approximately 12 tons is directly transferred into the last digester which is referred as F3.

In each digester, the accumulation of biogas is occurred by membrane gas holders that are utilized for the storage of biogas coming directly from anaerobic digestion of waste. These membrane gas holding units are mounted on the roof of each digester.

After the anaerobic digestion process, the accumulated biogas is upgraded by applying some biogas cleaning technologies. In the specified biogas plant, the chiller unit and the activated carbon technology are specifically utilized in order to decrease the moisture content of the produced biogas and to remove H_2S from biogas, respectively.

3.5. Combined Heat and Power Unit

The biogas obtained from the plant is converted to electricity and heat in the combined heat and power unit. Before the CHP unit, biogas is firstly purified to eliminate some components especially for hydrogen sulfide (H_2S). In this sense, activated carbon has been considered as a suitable technology for biogas upgrading in the plant. In addition to these technologies, there is a necessary process for separating water from produced biogas before the usage of biogas in gas motors. That's why it is important to apply biogas drying equipment such as a chiller unit to reduce the moisture content of biogas. In the specified plant, the average methane content of the biogas is 60.9%, while carbon dioxide content is approximately 28.9%. In addition, the produced biogas generally contains a low concentration of hydrogen sulfide as 89 ppm. The rest of the biogas consists of other gases such as oxygen, ammonia, nitrogen, water vapours.

In the cogeneration unit, two gas engines are utilized to generate energy from produced biogas in the specified plant. A gas sensor is also placed into the CHP unit in order to observe any gas leaks.

3.6. Separator and Storage Units for Digestate

After the whole digestion processes, digestate is transmitted to the separator unit. In this unit, decanter centrifuges separate the solid phases from the liquid fraction. The solid and liquid fractions are stored in two different tanks having 20 m^3 and 1000 m^3.

Liquid digestate is used as soil conditioners that provide to improve soil structure. Pasteurization of the digestate is a suitable treatment method for anaerobic digestion plants based on food wastes and animal by-products (Banks and colleagues, 2018). In the specified plant, the liquid digestate is always efficiently pasteurized for a total of 4 hours at 70 ^{o}C before land application.

4. THE IMPACT ASSESSMENT OF THE SPECIFIED BIOGAS PLANT

4.1. Introduction

In the study, it is aimed to environmentally assess different expired wastes transferring specifically from industries, supermarkets, animal farms, wastewater treatment plants and oil factories, to handle waste accumulation problem, to provide expired waste utilization and to actualize energy recovery by utilizing anaerobic digestion technology. Within the scope of the life cycle impact assessment of this study, four main steps were carried out the CML Methodology was implemented in order to group the life cycle impact results into the midpoint categories, for instance, climate change, human toxicity, marine aquatic ecotoxicity or eutrophication.

The study is conducted in a specified biogas plant located in the Marmara Region of Turkey. Besides, there are two important units that should not be considered independently from each other. Laboratory unit is the one of these important parts of a biogas plant because the characterization of various expired wastes is carried out in this unit. Thanks to waste characterization, it is easily determined which type of waste is applicable for the anaerobic digestion process. At the same time, methane potential and biodegradability of feedstocks are measured by testing of expired wastes, and the test results give an insight into anaerobic digestion performance of various biomass. Apart from laboratory, digester unit is the other crucial part of the biogas plant. After all laboratory tests are concluded, some expired wastes are accepted to be operated in anaerobic digestion process. However different pretreatment technologies are implemented before the usage of these expired wastes for anaerobic digestion process.

Biogas can be evaluated for energy production such as electricity and heat, while also it can be utilized as a substitute for natural gas by upgrading or as vehicle fuel in transportation. In Table 4.1, the amount of electricity and heat generation during the measurements can be found. It is also seen that the total amount of digestate is approximately 390 tons before the separation of solid and liquid parts.

Table 4.1. The products of the specified biogas plant.

Period	**Waste Transferred**	**Biogas Generation**	**Digestate Generation**	**Electricity Generation**	**Heat Generation**
During 3 days	450 ton	49680 m^3 per 3 days	390 ton	108 MWh per 3 days	25.5 MWh per 3 days

Furthermore, biogas plants need internal energy for many reasons like feeding systems, feedstock pre-treatment, combined heat and power units, heating systems and other operational energy demands. In this case, energy requirements of the plant, namely as on-site heat and electricity demand, may be supplied by biogas. The following electricity consumption data of the specified biogas plant which are used for its internal energy demands are demonstrated in Table 4.2. Besides, the amount of heat consumption in the plant is showed in Table 4.3.

Table 4.2. Electricity consumption of the plant.

The Unit of the Specified Biogas Plant	**Working Duration (hour)**	**Electricity Consumption (kWh)**
Motor in grinder unit	22.5 hours	337.5 kWh
Motor in centrifuge unit	22.5 hours	3240 kWh
Motor in star screen unit	7.5 hours	225 kWh
Mixer in conditioning unit	72 hours	1080 kWh
Mixer in pasteurization process	12 hours	96 kWh
Supply manifold in conditioning unit	36 hours	540 kWh
Transfer pump in digester tank	12 hours	180 kWh
Mixers in digester tanks	36 hours	1620 kWh
Motor in chiller process	-	225 kWh
Biogas Compressors	102 hours	765 kWh
Pumps in CHP unit	-	792 kWh
Gas Motors in CHP unit	-	2160 kWh
Motor in separator process	21 hours	105 kWh
Mixer in digestate pasteurization process	12 hours	96 kWh
Pumps for the digestate storage tanks	10 hours	74 kWh

Table 4.3. Heat consumption of the plant.

The Unit of the Specified Biogas Plant	**Heat Consumption (kWh)**
Pasteurization process	17000 kWh
Anaerobic digestion process	8500 kWh

In the following table, each scenario for this study is clearly indicated. All scenarios of the study are based upon how to evaluate the energy performance of this specified biogas plant. In the study, there are two scenarios related to energy utilization and these scenarios are compared in terms of environmental assessment. It is worth mentioning that not only the energy output from biogas can be evaluated to meet on-site energy demand, but also it can be possible to inject into grids.

Table 4.4. The scenario types for the study.

Scenario	**Name**
On-site Energy Utilization	Scenario A
Energy Utilization from Electricity Grid and Natural Gas	Scenario B

In the study, the specified biogas plant is discussed by means of life cycle assessment methodology. The life cycle assessment of the study contains the measurement results derived from air emissions of the biogas plant, water and energy consumption during biogas production, the comparison environmental impacts of energy utilization options with on-site and electricity grid.

In this study, the specified biogas plant is analyzed during three days and all measurement results are recorded to the GaBi software based on these three days’ period. The study is mainly based on how to utilize the produced energy and to measure all environmental impacts of the specified biogas plant if energy utilization options change. In this LCA study, two assessments are evaluated. The first assessment is based on the production of energy in the specified biogas plant and the utilization of produced energy to meet internal energy requirements of the biogas plant. The second assessment mainly focuses on supplying energy demand of the plant from grid. In this case, produced energy in the specified biogas plant is directly injected into electricity grid without feeding some units of the plant that need heat and electricity to operate regularly.

4.2. Goal and Scope Definition

Environmental impact assessment of a specified biogas plant during energy production by using several wastes and the evaluation of energy utilization options are aimed in the life cycle assessment for this study. In this sense, the functional unit, the extended allocation and the system boundaries were taken into account within the scope of the study.

Since the change in end-use of energy generated by the anaerobic digestion process can affect the whole environmental impacts derived from the biogas plant, energy is a crucial parameter for this study. Apart from the benefits of energy utilization options, energy production by anaerobic digestion technology has been making a big contribution to overcome waste accumulation and energy problem.

The specified biogas plant always requires electricity and heat for the operational energy demands of all processes. In this specified biogas plant, energy requirements have been supplied by energy produced from the CHP unit of the plant. It means that there is not any energy supply from the grid for the purpose of internal usage if the energy demand of the plant is provided by biogas which was produced by waste utilization. In addition to the supply of on-site electricity demand by generated biogas, electricity produced in the plant has also transferred into the electricity grid and met the electricity demands of some consumers and buildings. In the scope of Scenario A, on-site energy utilization which is one of the energy utilization options is evaluated.

According to Scenario B, the energy requirements for the specified biogas plant can be directly supplied from the electricity grid without using produced energy in the cogeneration unit. In this scenario, the specified biogas plant has more negative effects on the environment because all energy demands in the plant are met by the electricity grid. This situation causes more greenhouse gas emissions derived from the power plant and the life cycle assessment of the biogas plant has experienced firsthand.

The utilization of different types of wastes especially for expired wastes to produce energy, the meeting of electricity and heat requirements of the specified biogas plant from the produced energy in the biogas plant, obtaining appreciable effect on waste reduction in the Marmara Region, the decrease in electricity consumption from the electricity grid for the biogas plant by transferring produced electricity into the plant and achieving significant reductions in global warming potentials are expected as main goals of this study.

4.3. Functional Unit

The functional unit is expressed as a quantified description of the service or the product performance; that is, the functional unit is utilized as a reference unit of a life cycle study. In this study, the functional unit is expressed as “generating 108 MWh of electricity through the use of 450 tons of food wastes during the three-days period”. Thanks to the functional unit, it is easy to compare different energy utilization options.

4.4. System Boundaries

System boundaries express unit processes to be included and excluded in the LCA of this study. In accordance with the International Organization for Standardization, it determines unit processes that are part of a product system. System boundaries of the study contain the transportation of various wastes to the biogas production site, waste storage in the waste acceptance area of the plant, manufacture of the main products of the anaerobic digestion process, biogas utilization and upgrading in the CHP unit, energy utilization options, solid and liquid digestate storage.

In this LCA study, Scenario B was separated 3 subsystems: subsystem 1 (S1) including waste transportation and management, waste preparation for anaerobic digestion and biogas production stages, subsystem 2 (S2) including biogas cleaning technologies and energy production units, subsystem 3 (S3) including digestate preparation before digestate use for other purposes. In Table 4.5, the main processes of these three subsystems are shown.

Table 4.5. The processes of the subsystems in Scenario B.

Subsystem 1 (S1)	**Subsystem 2 (S2)**	**Subsystem 3 (S3)**
-Waste Transportation -Waste Shredder -Spiral Helezon System -Star Screen Unit -Centrifuge -Conditioning Unit -Pasteurization -Anaerobic Digesters	-Biogas Chiller Unit -Biogas Compressor Application -Combined Heat and Power	-Separator -Digestate Pasteurization

In Scenario A, it should be known that the transportation of liquid digestate generated in the plant to local farmers is eliminated. In addition, solid digestate is utilized as refuse-derived fuel in the plant but this step is excluded. It is clear to understand that almost all processes except for application methods of produced digestate are considered in Scenario A.

The system boundaries of Scenario A are listed below:

- The specified biogas plant is continuously operated 365 days a year, so the plant has been active all year round, along with 24/7 maintenance and support. 450 tons of wastes are totally transported and operated in the system in order to assess potential environmental impacts of the specified biogas plant. On the other hand, the operation of this LCA study is based on 3 days' period because the related wastes are periodically transported to the specified biogas plant every 3 days.
- The loading capacity of truck-trailers for waste transportation is 27 tons, while lorries have 17.3 tons of capacity. The carrying capacity of an oil tanker is generally 23 tons.
- The total distance for waste transportations from different locations is 246.1 km. A total of 10 truck-trailers, 10 big lorries and 1 small lorry are utilized to transfer whole wastes from supermarkets, industries, manufactures and animal farms to the specified biogas plant.
- The plant is working as three digesters with 5000 m^3, 2000 m^3 and 2000 m^3 loading capacity.
- Heat and electricity requirements of the specified biogas plant are provided by produced energy in the CHP unit of the plant.
- The produced electricity in the specified plant is 108 MWh for 3 days. The total amount of internal electricity consumption in the plant is approximately 9.81 MWh during these three days' period. After some small fractions of the generated electricity are used for on-site energy consumptions, the rest of the produced electricity is fed into the grid.
- After controlling some important parameters such as heavy metals, pH value and moisture content, liquid digestate is transferred to local farmers in the Marmara Region.
- In the context of the LCA study of the specified biogas plant, internal electricity requirements of the waste shredder unit, the centrifuge unit, transfer pumps and supply manifolds in the conditioning unit and digesters, mixers to homogenize the feedstock, the separator and chiller unit, pumps used in the CHP unit, and heat requirements of pasteurization units and digesters to satisfy their heat demand are taken into consideration.

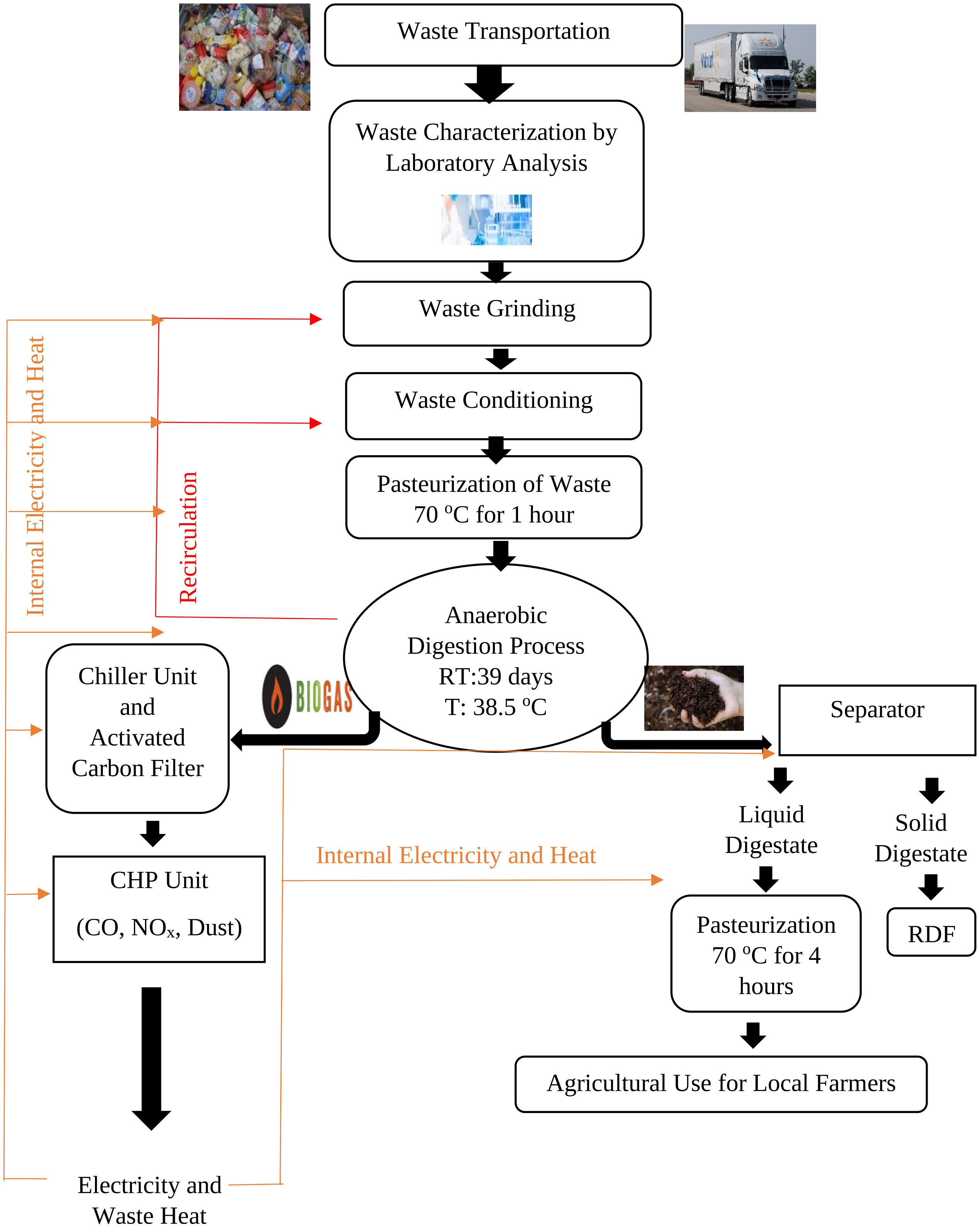


Figure 4.1. System boundary of on-site energy utilization.

In Scenario B, digestate transportation is also excluded from the system boundary. In addition, the produced energy in the specified plant is directly injected into the electricity grid. For this reason, it is clear that electricity requirements for the plant operation is only supplied by grid mix. Apart from electricity, internal heat demand specifically for pasteurization units and anaerobic digesters is met through natural gas. In Scenario B, current energy supply methods are applied for making all results comparable.

The system boundaries of Scenario B are listed below:

- The specified biogas plant is continuously operated 365 days a year, so the plant has been active all year round, along with 24/7 maintenance and support. 450 tons of wastes are totally transported and operated in the system in order to assess potential environmental impacts of the specified biogas plant. On the other hand, the operation of this LCA study is based on 3 days' period because the related wastes are periodically transported to the specified biogas plant every 3 days.
- The loading capacity of truck-trailers for waste transportation is 27 tons, while lorries have 17.3 tons of capacity. The carrying capacity of an oil tanker is generally 23 tons.
- The total distance for waste transportations from different locations is 246.1 km. A total of 10 truck-trailers, 10 big lorries and 1 small lorry are utilized to transfer whole wastes from supermarkets, industries, manufactures and animal farms to the specified biogas plant.
- The plant is working as three digesters with 5000 m^3, 2000 m^3 and 2000 m^3 loading capacity.
- The overall heat and electricity requirements of the specified biogas plant are supplied from the grid mix.
- The total amount of internal electricity consumption in the plant is approximately 9.81 MWh during three days' period. The overall electricity requirement of the specified biogas plant is assumed to be supplied by the electricity grid in this scenario.
- The overall heat requirement of the plant is approximately 25500 kWh for three days' period. The amount of heat consumption in the plant is normally supplied in the CHP unit. In Scenario B, natural gas is considered instead of waste heat recovery and the natural gas process of GaBi 9.2 software is utilized for internal heat requirements. This process is adjusted like providing the same amount of heat with the produced heat in the plant.
- After controlling of some important parameters such as heavy metals, pH value and moisture content, liquid digestate is transferred to local farmers in the Marmara Region.
- In the context of Scenario B, internal electricity requirements of the waste shredder unit, the centrifuge unit, transfer pumps and supply manifolds in the conditioning unit and digesters, mixers to homogenize the feedstock, the separator and chiller unit, pumps used in the CHP unit, and heat

requirements of pasteurization units and digesters to satisfy their heat demand are taken into consideration.

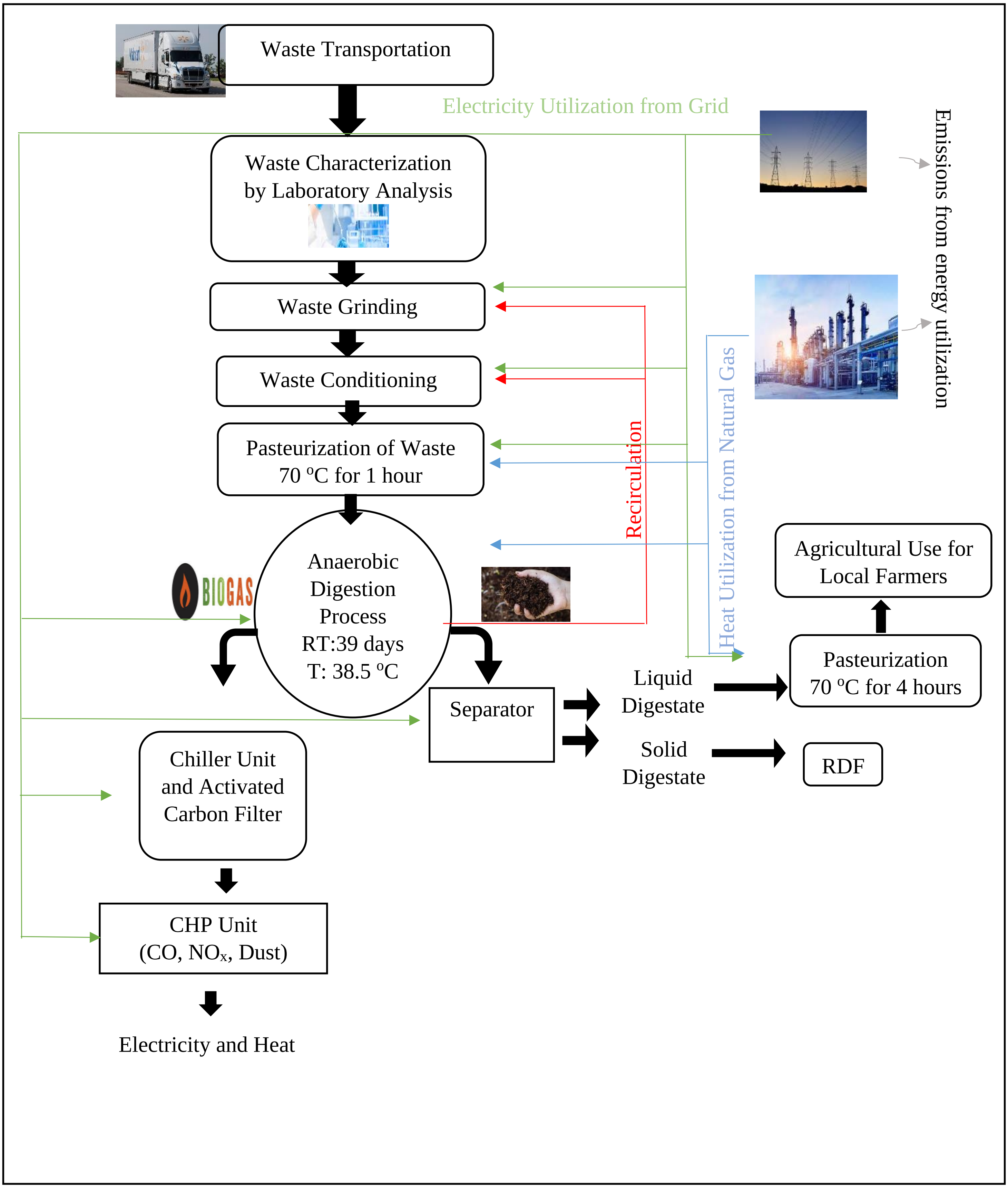


Figure 4.2. System boundary of energy utilization from electricity grid and natural gas.

4.5. Life Cycle Inventory Analysis

Life Cycle Inventory, abbreviated LCI, is a stage that includes resources, the collection and the calculation of relevant inputs and outputs. Inventory analysis enables to determine of the relevant inputs and outputs of the plant in the system. Detailed information for on-site energy utilization and energy utilization from the electricity grid and natural gas was collected from the specified biogas plant. LCI also comprises a flow diagram for every scenario and the flow diagram indicates all processes that will be evaluated. Besides, the inventories for these two scenarios are computed compatible with the functional unit.

In Table 4.6 and Table 4.7, the collected data and key assumptions for the specified biogas plant's input data within the system are indicated. Regarding Scenario A, approximately 450 tons of wastes, which were mostly food and supermarket wastes, were transported from different factories and supermarkets in the specified locations to the dumping area of the specified plant. It should be considered that these transportation processes were done with different types of vehicles because these vehicles had different loading capacities, for instance, 17.3 tons or 27 tons. In the transportation process, diesel was used as fuel and the total travelled distance were also measured by determining the distance between the supermarkets and the specified biogas plant. The more distance and upload capacity the specified plant is exposed to; the more gas emissions are observed. Besides, the specified supermarkets' locations can be seen in Figure 4.3 and Figure 4.4.

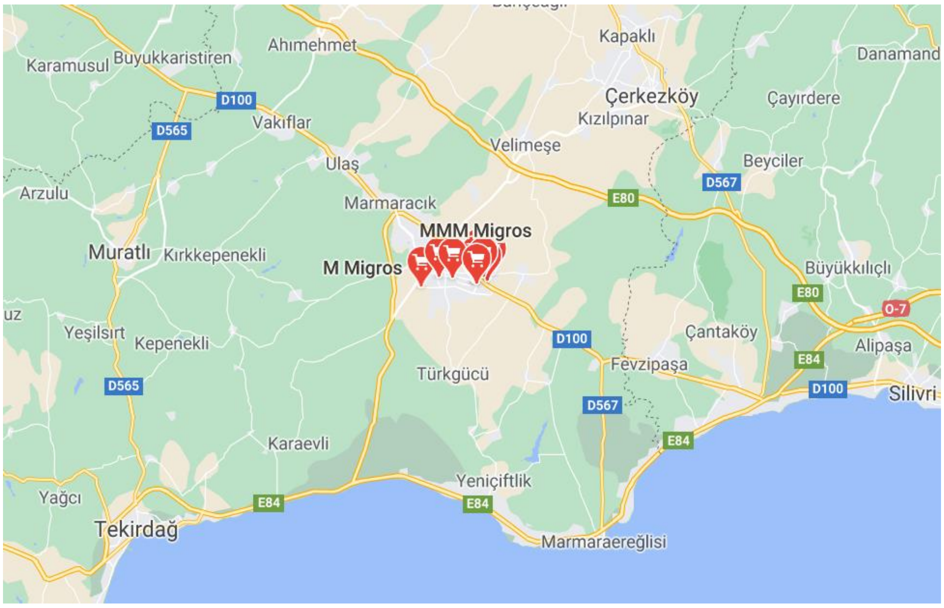


Figure 4.3. The selected supermarkets in the Çorlu Region.

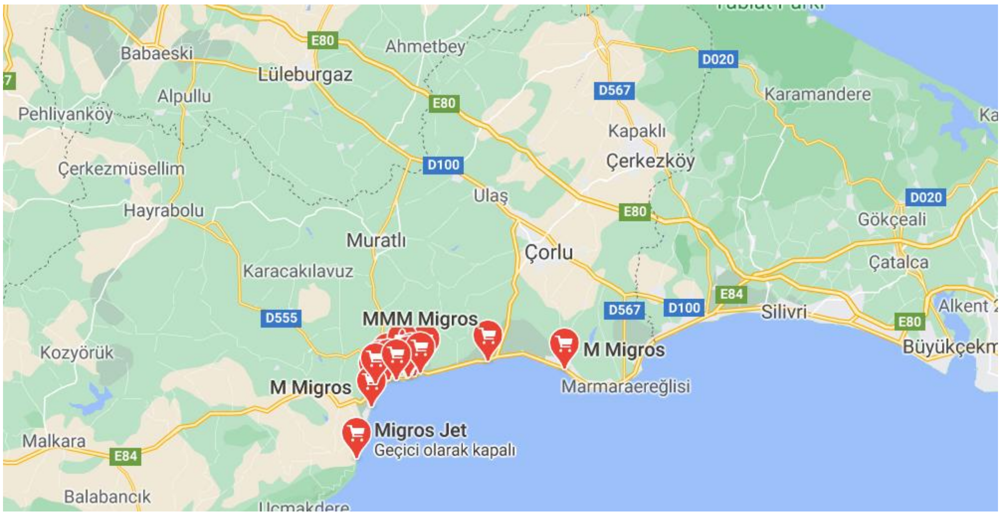


Figure 4.4. The selected supermarkets in the Tekirdağ Region.

The 41603.8 MJ of the produced electricity was consumed for the total electricity demands of the operation units. In addition, the produced electricity from biogas was 388800 MJ and approximately 10.70 percent of the produced electricity was directly recirculated to the processes of the plant. Furthermore, it is a fact that most of the produced waste heat, 91800 MJ, were specifically return to pasteurization and anaerobic digestion processes. In addition, the non-utilizable waste part was directly discharged to the RDF process and the RDF process was excluded in this LCA study. The produced liquid digestate was handled for the agricultural activities of the local farmers in the Marmara Region. The transportation of liquid digestate was also excluded.

Table 4.6. The inventory data sources for Scenario A.

Process	**Required Data**	**Value**	**Input Data**	**Data Sources**	**Selected Flow from GaBi 9.2**
Waste transportation with truck-trailer	Loading capacity	27 ton	Transport	GaBi 9.2 Software, The specified plant	EU-28:Transport, truck-trailer (40 t total capacity, 24.7 t paylod), Biowaste [waste for recovery]
	Biowaste	270 ton			
	Distance	135.1 km			
Waste transportation with lorry	Loading capacity	17.3 ton	Transport	GaBi 9.2 Software, The specified plant	EU-28:Lorry transport, including fuel (Euro 0-6 mix, 22 t total weight, 17.3 t maximum payload), Biowaste [waste for recovery]
	Biowaste	173 ton			
	Distance	100.3 km			
Waste transportation with small lorry	Loading capacity	7.5 ton	Transport	GaBi 9.2 Software, The specified plant	RER: Small lorry (7.5 t including fuel ELCD), Biowaste [waste for recovery]
	Biowaste	7.5 ton			
	Distance	10.7 km			
Dumping area	Biowaste	450 ton	Storage	The specified plant	Biowaste [waste for recovery]
Waste Shredder	Biowaste	450 ton	Material Recovery	The specified plant	Biowaste [waste for recovery], Electricity from biogas [System-dependent]
	Electricity	1215 MJ			
Spiral Helezon System	Biowaste	440 ton	Transport	The specified plant	Biowaste [waste for recovery], Electricity from biogas [System-dependent]
	Electricity	972 MJ			
Star Screen Unit	Solid Waste	50 ton	Separation	The specified plant	Waste (solid) [Waste for disposal], Electricity from biogas [System-dependent]
	Electricity	810 MJ			

Table 4.6. The inventory data sources for Scenario A cont.

Refused Derived Fuel	Solid Waste	89 ton	Fuel production	The specified plant	Waste (solid) [Waste for disposal]
Centrifuge	Biowaste	440 ton	Separation	The specified plant	Biowaste [Waste for recovery], Circuit water [Waste for recovery], Electricity from biogas [System-dependent]
	Circuit water	390 ton			
	Electricity	10692 MJ			
Conditioning Unit	Biowaste	390 ton	Storage	The specified plant	Biowaste [Waste for recovery], Circuit water [Waste for recovery], Electricity from biogas [System-dependent]
	Circuit water	450 ton			
	Electricity	3888 MJ			
Pasteurization	Biowaste	390 ton	Thermal Treatment	The specified plant	Waste heat [Waste for recovery], Biowaste [Waste for recovery], Circuit water [Waste for recovery], Electricity from biogas [System-dependent]
	Circuit water	450 ton			
	Electricity	2289.6 MJ			
	Waste heat	32209.2 MJ			
F1 and F2 anaerobic digesters	Biowaste	390 ton	Ecoinvent	The specified plant	Waste heat [Waste for recovery], Biowaste [Waste for recovery], Circuit water [Waste for recovery], Electricity from biogas [System-dependent]
	Circuit water	450 ton			
	Electricity	4536 MJ			
	Waste heat	20397.6 MJ			

Table 4.6. The inventory data sources for Scenario A cont.

F3 anaerobic digester	Biowaste	390 ton	Ecoinvent	The specified plant	Waste heat [Waste for recovery], Biowaste [Waste for recovery], Circuit water [Waste for recovery], Electricity from biogas [System-dependent]
	Circuit water	450 ton			
	Electricity	1944 MJ			
	Waste heat	10198.8 MJ			
Biogas chiller unit	Biogas	49680 m^3	Recovery	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity from biogas [System-dependent]
	Electricity	810 MJ			
Activated Carbon Technology	Biogas	49680 m^3	Recovery	The specified plant	CH: biogas, from biowaste, at storage [fuels]
Biogas compressor application	Biogas	49680 m^3	Compressed air equipment	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity from biogas [System-dependent]
	Electricity	2754 MJ			
Combined heat and power	Biogas	49680 m^3	Energy conversion	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity from biogas [System-dependent]
	Electricity	10627.2 MJ			
Thermal energy from biogas	Waste heat	91800 MJ	Thermal energy from biogas	The specified plant	Waste heat [Waste for recovery]
Electricity from biogas	Electricity	388800 MJ	Electricity distribution	The specified plant	Electricity from biogas [System-dependent]

Table 4.6. The inventory data sources for Scenario A cont.

Separator	Digested matter	390 ton	Separation	The specified plant	CH: digested matter, application in agriculture [fuels], Electricity from biogas [System-dependent]
	Electricity	587 MJ			
Pasteurization	Digested matter	351 ton	Thermal treatment	The specified plant	CH: digested matter, application in agriculture [fuels], Electricity from biogas [System-dependent], Waste heat [Waste for recovery]
	Electricity	479 MJ			
	Waste heat	28994.4 MJ			
Liquid digestate storage	Digested matter	351 ton	Storage	The specified plant	CH: digested matter, application in agriculture [fuels]
Liquid Digestate Usage for Local Farmers	Digested matter	351 ton	Consumption	The specified plant	CH: digested matter, application in agriculture [fuels]
Solid waste storage	Solid waste	39 ton	Storage	The specified plant	Waste (solid) [Waste for disposal]

Similar to Scenario A, the distance and upload capacities were taken into consideration in Scenario B. In the transportation process, diesel was used as fuel and the total travelled distance were also measured by determining the distance between the supermarkets and the specified biogas plant. The total electricity and heat requirements of the specified plant were supplied from the electricity grid and natural gas sources. The produced electricity from biogas, approximately 388800 MJ, was directly transmitted into the electricity grid. Furthermore, the produced waste heat, 91800 MJ, was discharged to the atmosphere after the cooling. The small amount of energy was consumed in order to circulate the produced waste heat into the plant and this situation was excluded in Scenario B; the reason was that there was not any energy recirculation in this Scenario. In addition, the non-utilizable waste part was directly discharged to the RDF process and the RDF process was excluded in this

LCA study. The produced liquid digestate was handled for the agricultural activities of the local farmers in the Marmara Region. The transportation of liquid digestate was also excluded.

Table 4.7. The inventory data sources for Scenario B.

Process	**Required Data**	**Value**	**Input Data**	**Data Sources**	**Selected Flow from GaBi 9.2**
Waste transportation with truck-trailer	Loading capacity	27 ton	Transport	GaBi 9.2 Software, The specified plant	EU-28:Transport, truck-trailer (40 t total capacity, 24.7 t paylod), Biowaste [waste for recovery]
	Biowaste	270 ton			
	Distance	135.1 km			
Waste transportation with lorry	Loading capacity	17.3 ton	Transport	GaBi 9.2 Software, The specified plant	EU-28:Lorry transport, including fuel (Euro 0-6 mix, 22 t total weight, 17.3 t maximum payload), Biowaste [waste for recovery]
	Biowaste	173 ton			
	Distance	100.3 km			
Waste transportation with small lorry	Loading capacity	7.5 ton	Transport	GaBi 9.2 Software, The specified plant	RER: Small lorry (7.5 t including fuel ELCD), Biowaste [waste for recovery]
	Biowaste	7.5 ton			
	Distance	10.7 km			
Dumping area	Biowaste	450 ton	Storage	The specified plant	Biowaste [waste for recovery]
Waste Shredder	Biowaste	450 ton	Material Recovery	The specified plant	Biowaste [waste for recovery], Electricity [Electric power]
	Electricity	1215 MJ			

Table 4.7. The inventory data sources for Scenario B cont.

Spiral Helezon System	Biowaste	440 ton	Transport	The specified plant	Biowaste [waste for recovery], Electricity [Electric power]
	Electricity	972 MJ			
Star Screen Unit	Solid waste	50 ton	Separation	The specified plant	Waste (solid) [Waste for disposal], Electricity [Electric power]
	Electricity	810 MJ			
Refused Derived Fuel	Solid waste	89 ton	Fuel production	The specified plant	Waste (solid) [Waste for disposal]
Centrifuge	Biowaste	440 ton	Separation	The specified plant	Biowaste [waste for recovery], Circuit water [Waste for recovery], Electricity [Electric power]
	Circuit water	390 ton			
	Electricity	10692 MJ			
Conditioning Unit	Biowaste	390 ton	Storage	The specified plant	Biowaste [waste for recovery], Circuit water [Waste for recovery], Electricity [Electric power]
	Circuit water	450 ton			
	Electricity	3888 MJ			
Pasteurization	Biowaste	390 ton	Thermal Treatment	The specified plant	Thermal energy (MJ) [Thermal energy from natural gas], Biowaste [waste for recovery], Circuit water [Waste for recovery], Electricity [Electric power]
	Circuit water	450 ton			
	Electricity	2289.6 MJ			
	Thermal energy	32209.2 MJ			

Table 4.7. The inventory data sources for Scenario B cont.

F1 and F2 anaerobic digesters	Biowaste	390 ton	Ecoinvent	The specified plant	Thermal energy (MJ) [Thermal energy from natural gas], Biowaste [waste for recovery], Circuit water [Waste for recovery], Electricity [Electric power]
	Circuit water	450 ton			
	Electricity	4536 MJ			
	Thermal energy	20397.6 MJ			
F3 anaerobic digester	Biowaste	390 ton	Ecoinvent	The specified plant	Thermal energy (MJ) [Thermal energy from natural gas], Biowaste [waste for recovery], Circuit water [Waste for recovery], Electricity [Electric power]
	Circuit water	450 ton			
	Electricity	1944 MJ			
	Thermal energy	10198.8 MJ			
Biogas chiller unit	Biogas	49680 m^3	Recovery	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity [Electric power]
	Electricity	810 MJ			
Activated Carbon Technology	Biogas	49680 m^3	Recovery	The specified plant	CH: biogas, from biowaste, at storage [fuels]
Biogas compressor application	Biogas	49680 m^3	Compressed air equipment	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity [Electric power]
	Electricity	2754 MJ			
Combined heat and power	Biogas	49680 m^3	Energy conversion	The specified plant	CH: biogas, from biowaste, at storage [fuels], Electricity [Electric power]
	Electricity	7776 MJ			

Table 4.7. The inventory data sources for Scenario B cont.

Waste heat	Waste heat	91800 MJ	Thermal energy from biogas	The specified plant	Waste heat [Waste for recovery]
Electricity distribution to grid	Electricity from biogas	388800 MJ	Electricity distribution	The specified plant	Electricity from biogas [System-dependent]
Separator	Digested matter	390 ton	Separation	The specified plant	CH: digested matter, application in agriculture [fuels], Electricity [Electric power]
	Electricity	587 MJ			
Digestate Pasteurization	Digested matter	351 ton	Thermal treatment	The specified plant	CH: digested matter, application in agriculture [fuels], Electricity [Electric power], Thermal energy (MJ) [Thermal energy from natural gas]
	Electricity	479 MJ			
	Waste heat	28994.4 MJ			
Liquid digestate storage	Digested matter	351 ton	Storage	The specified plant	CH: digested matter, application in agriculture [fuels]
Liquid Digestate Usage for Local Farmers	Digested matter	351 ton	Consumption	The specified plant	CH: digested matter, application in agriculture [fuels]
Solid waste storage	Solid waste	39 ton	Storage	The specified plant	Waste (solid) [Waste for disposal]

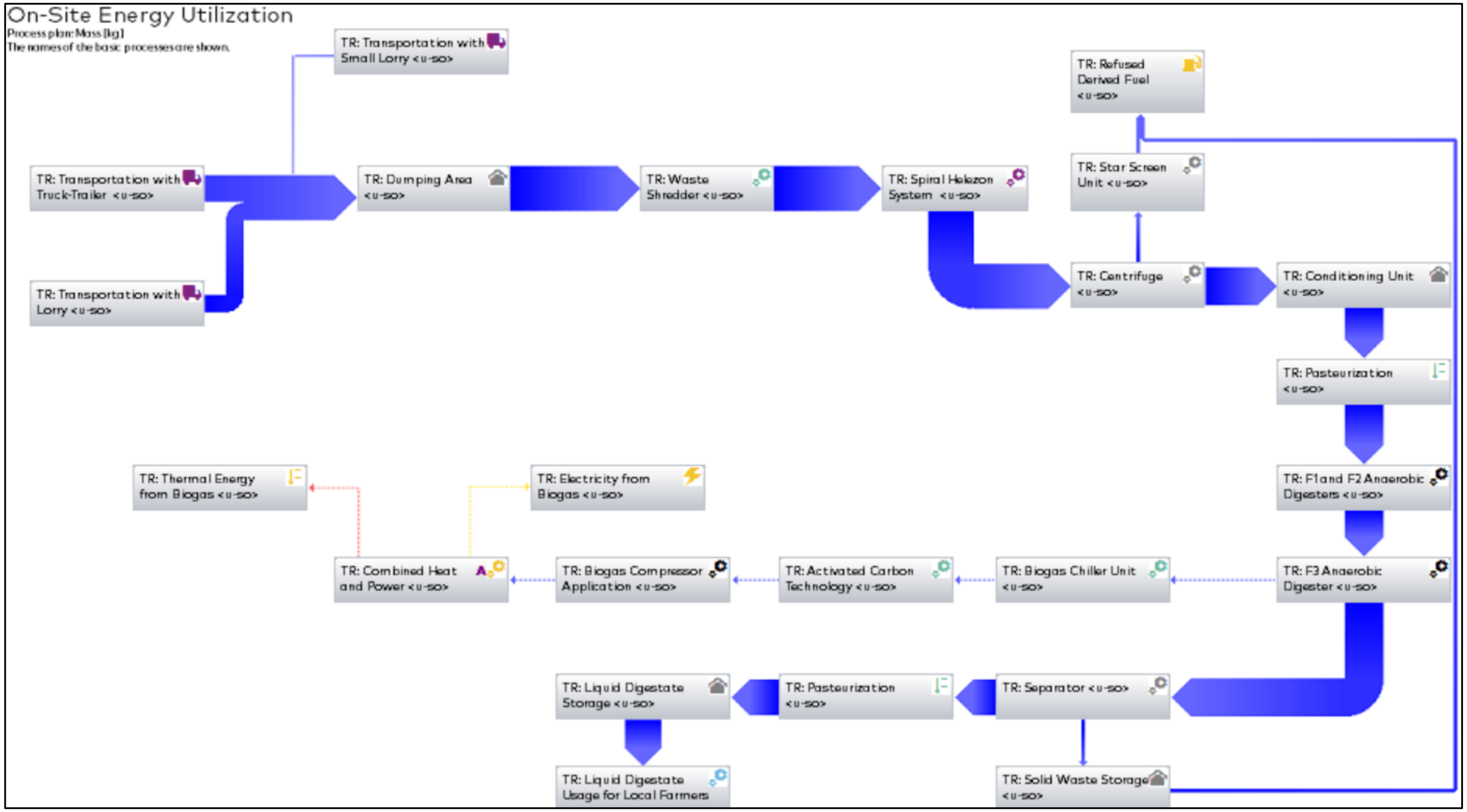


Figure 4.5..GaBi plan of Scenario A.

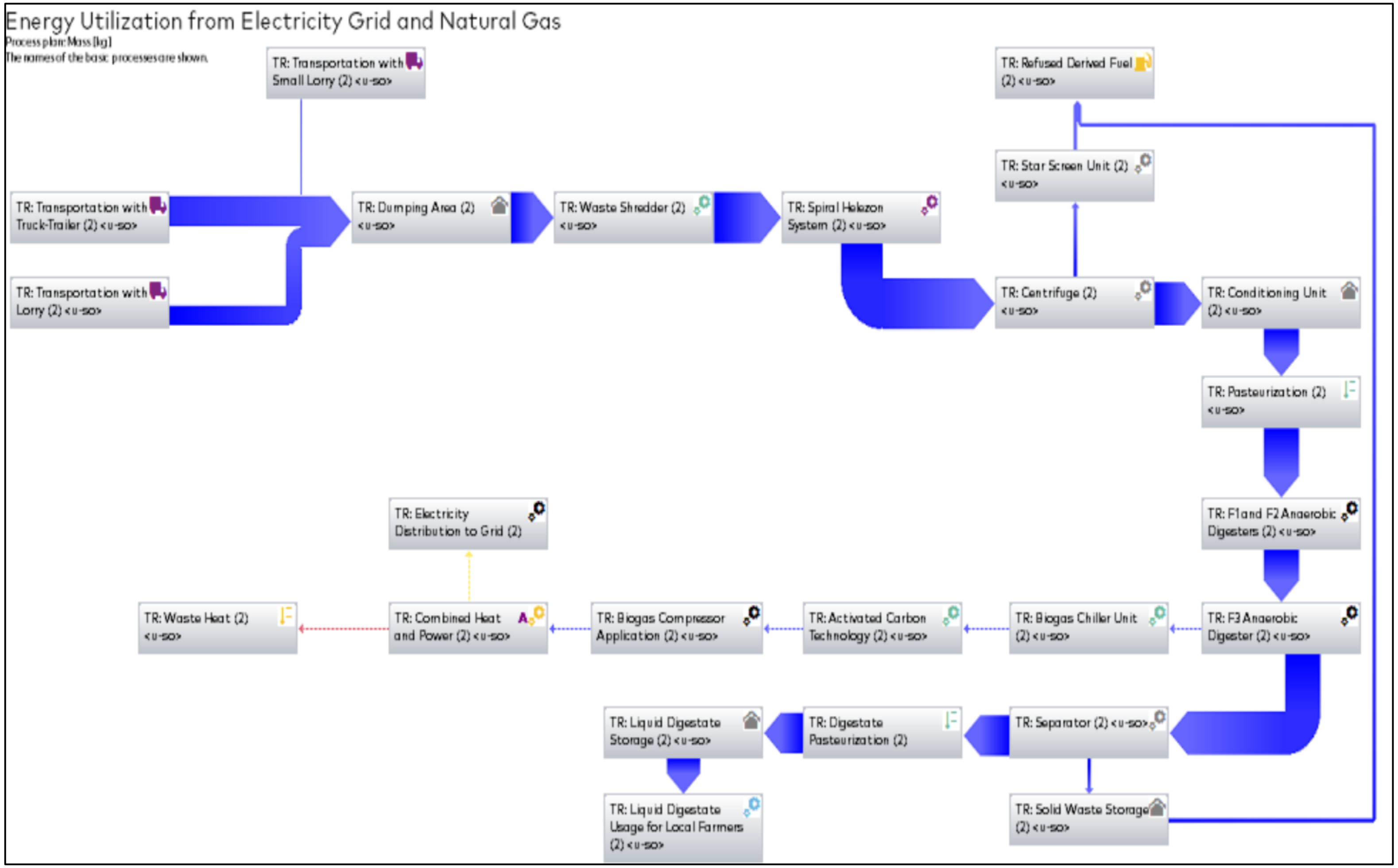


Figure 4.6. GaBi plan of Scenario B.

4.6. Life Cycle Impact Assessment

In the scope of the life cycle impact assessment, GaBi 9.2 Software and the EcoInvent Database have been utilized. Based on the life cycle impact assessment of the study, some flow diagrams have been generated in the software. These diagrams include both waste transportation to the specified plant and the utilization of mixed wastes within energy production. In addition to EcoInvent Database, CML Methodology has been implemented in order to group the life cycle impact results into midpoint categories. In the Life Cycle Impact Assessment, the 4 main stages, classification, characterization, normalization and weighting, have been carried out. Regarding the LCIA for this study, five main categories were conducted to determine the environmental impact of Scenario A and Scenario B. In this sense, global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential and human toxicity potential were examined.

4.6.1. Classification

Within the scope of the classification procedure, the results of the life cycle inventory analysis are attributed to various impact categories. The impact categories and the selected life cycle inventory data are indicated in Table 4.8.

Table 4.8. The selected life cycle inventory data and impact categories for the study.

Impact Categories	**The Selected Life Cycle Inventory Data**	**Unit**
Global Warming Potential (GWP)	CO_2, N_2O, SF_6, CH_4	kg CO_2-eq.
Acidification Potential (AP)	NH_3, NO_x, SO_2, H_2SO_4	kg SO_2-eq.
Eutrophication Potential (EP)	NH_3, NO_x, N_2O, PO_4^{3-}, P	kg Phosphate-eq.
Photochemical Ozone Creation Potential (POCP)	CO, NO_x, SO_2, NMVOC (unspecified), Hydrocarbons, CH_4	kg Ethene-eq.
Human Toxicity Potential (HTP)	NO_x, NH_3, SO_2, NMVOC (unspecified), Hydrocarbons, Dust (PM 2.5)	kg DCB-eq.

4.6.2. Characterization

In this step, it is clear to measure the environmental impacts of each emission type to the related impact categories. After the implementation of the functional unit in this study, the allocation stage was applied. The allocation means that the distribution of all input and output flows' quantities of a process between the tracked outputs (GaBi Manual). In this study, the apportioned output flows were energy, emissions from electricity and natural gas consumption and CHP emissions, while the tracked outputs were electricity and waste heat. Besides, the extended allocation between two important outputs of the final process in this study, electricity and waste heat, was carried out in the software. Based on the extended allocation procedure, the LCA characterization results for each impact category were portioned out amongst electricity and waste heat. In Table 4.9, the quantified LCA characterization results for Scenario B are shown for electricity and waste heat.

Table 4.9. The extended allocation results between the produced energy.

Impact Category	**Unit**	**Electricity (388800 MJ)**	**Waste Heat (91800 MJ)**
Global Warming Potential (GWP)	kg CO_2-eq.	13429.4	3170.6
Acidification Potential (AP)	kg SO_2-eq.	62.5357	14.7643
Eutrophication Potential (EP)	kg Phosphate-eq.	2.8315	0.6685
Photochemical Ozone Creation Potential (POCP)	kg Ethene-eq.	3.22791	0.76209
Human Toxicity Potential (HTP)	kg DCB-eq.	29.5285	6.9715

The LCA characterization results were divided between two products. It is clearly seen that a great majority of the quantified LCA characterization results stems from electricity production and the contribution of the electricity to the total amount of the quantified LCA characterization results is approximately 80.9%. On the other hand, the waste heat has 19.1% of the quantified results. In fact, the proportional results of the extended allocation procedure are the same for both scenarios; that is, on-site energy utilization and energy utilization from electricity and natural gas. Nevertheless, in Scenario A, the total amount of the quantified LCA characterization results are less and waste transportation and CHP emissions are the main contributors to the impact categories. In the scope of Scenario A, the produced energy in the CHP unit is directly transferred into the plant. In this case, the system does not need any external energy source like a grid or natural gas for its operational units;

that is, the internal energy demand is supplied by the produced electricity and heat. For this reason, it would be seen the remarkable results for scenario B within the extended allocation procedure.

In Table 4.10, the total amounts of the detailed impact categories were calculated for one day and an annual period. It can be concluded that yearly electricity production leads to more emissions and contributes to every environmental impact category negatively.

Table 4.10. The results of each LCA impact category for one day and annual scale.

Impact Category	**Unit**	**The Produced Electricity in one day (129600 MJ)**	**The Produced Electricity in a year (47304000 MJ)**
Global Warming Potential (GWP)	kg CO_2-eq.	4476.47	1633910.45
Acidification Potential (AP)	kg SO_2-eq.	20.85	7608.42
Eutrophication Potential (EP)	kg Phosphate-eq.	0.944	344.48
Photochemical Ozone Creation Potential (POCP)	kg Ethene-eq.	1.076	392.73
Human Toxicity Potential (HTP)	kg DCB-eq.	9.843	3592.62

In Table 4.11, the comparison of the two scenarios based on the total amounts of each LCA impact categories can be seen. It is obviously concluded that Scenario B has the majority of the LCA characterization results; this is because the internal electricity and heat requirements of the specified biogas plant were supplied by natural gas and electricity grid; that is, the environmental impacts of Scenario B are more dominant.

Table 4.11. The total results of each LCA impact category for Scenario A and Scenario B.

Impact Category	**Unit**	**Scenario A (total)**	**Scenario B (total)**
Global Warming Potential (GWP)	kg CO_2-eq.	4060	16600
Acidification Potential (AP)	kg SO_2-eq.	2.5	77.3
Eutrophication Potential (EP)	kg Phosphate-eq.	0.3	3.5
Photochemical Ozone Creation Potential (POCP)	kg Ethene-eq.	0.37	3.9
Human Toxicity Potential (HTP)	kg DCB-eq.	2.2	36.5

4.6.2.1. Global Warming Potential (GWP)

The global warming potential impact category specifies a measure of the total contribution to global warming with the unit of carbon dioxide equivalent. In this study, the specified plant consists of a lot of processes including transportation, waste utilization, separation, biogas generation and electricity and heat distribution. In order to see the detailed impact results and to easily compare the scenarios, all processes in Scenario B were separated into three subsystems.

The result of the GWP impact category for subsystem 1 (S1) is indicated in Figure 4.7. To begin with, subsystem 1 includes transportation, waste utilization and gas generation processes. In Figure 4.7, only Scenario B is evaluated because Scenario A, on-site energy utilization, has the same amount of emissions as Scenario B. Besides, the waste transportation process is the only one contributor to the GWP impact category in Scenario A. Nonetheless, in Scenario B, there are some dominant GHG emission contributors other than transportation process; that is, electricity utilization from the grid and thermal energy from natural gas have an important effect on the GWP impact category. In Scenario B, internal energy has been supplied by some external sources and it means that the total amount of GHG emissions are higher than Scenario A.

For the purpose of waste transportation from mainly supermarkets to the specified biogas plant, diesel was utilized as fuel and three different vehicle types were selected from the GaBi program. In addition, these vehicle types have various payload capacities as 7.5, 17.3 and 27 tons. It is obviously seen that waste transportation with the truck-trailer process is the main source in the GWP impact category and the second contributor is the pasteurization unit. Approximately 270 tons of wastes were transported and the total distance travelled by truck-trailers was 135.1 km in order to reach the specified biogas plant. In the pasteurization unit, the total amount of electricity consumption was 2289,6 MJ and the internal energy demand was due to the waste mixing and supply manifold parts. The other crucial GHG emission sources for the pasteurization unit was natural gas. It is a well-known fact that pasteurization operation is conducted at 70 ^{o}C for 4 hours and the thermal energy requirement for this process is supplied by natural gas in Scenario B. The main source for the GWP impact category is also carbon dioxide in the pasteurization unit.

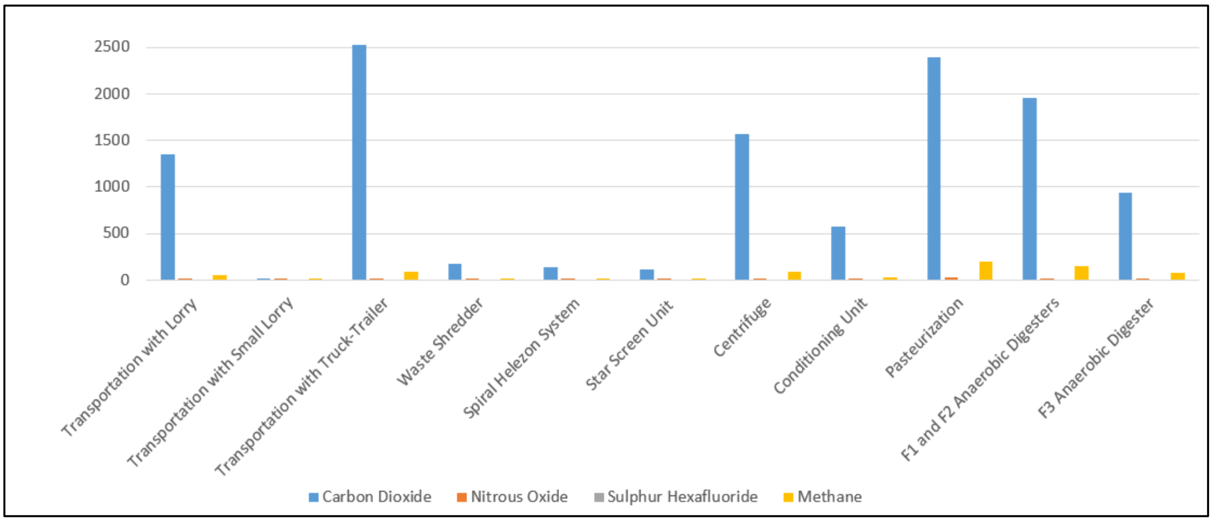


Figure 4.7. Global warming potential of the subsystem 1 in Scenario B (kg CO_2-eq.).

In Figure 4.8, the quantified GWP impact category of subsystem 2 is shown. The subsystem 2 consists of biogas cleaning technologies and the energy utilization process. In subsystem 2, gas motors in the CHP unit, the blower used for biogas compressing and the chiller unit ran on electric power and the required electric power was withdrawn from the grid. The main sources of GWP in Scenario B are carbon dioxide, followed by nitrous oxide. It can be stated that the majority of nitrous oxide emissions is produced in the combined heat and power unit. Normally, the required energy for heat transfer pumps in the CHP unit is considered within the scope of Scenario A. However, the required energy to transfer waste heat into the plant was excluded in Scenario B and this amount was approximately 792 kWh. The reason for that is to observe the environmental impacts if the produced waste heat is not used for internal purpose. In this sense, the produced waste heat is directly discharged into the atmosphere after cooling.

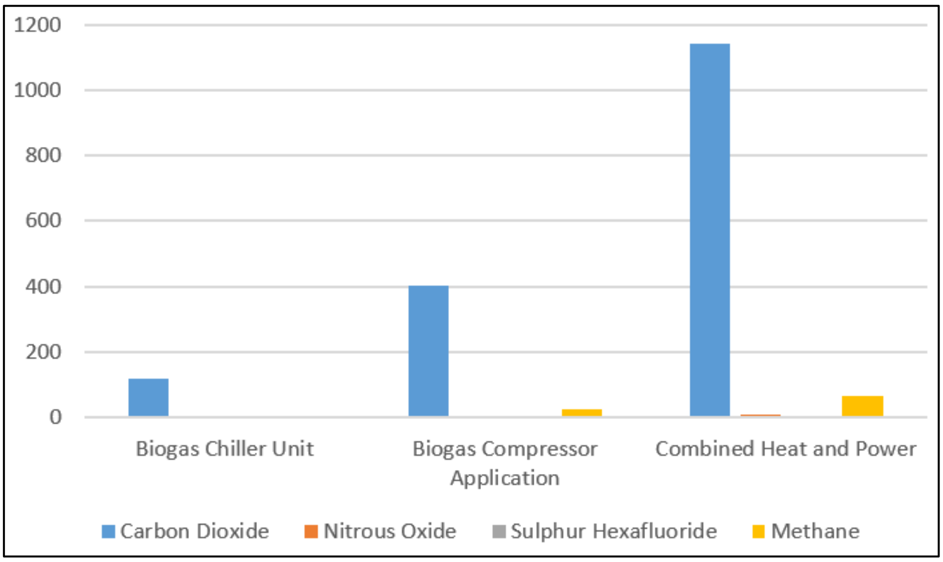


Figure 4.8. Global warming potential of the subsystem 2 in Scenario B (kg CO_2-eq.).

The result of the GWP impact category for subsystem 3 is indicated in Figure 4.9. Subsystem 3 includes the separation of liquid and solid digestate, and the pasteurization of liquid digestate before the usage for local farmers. The GHG emissions were derived from the use of electricity from the grid and thermal energy from natural gas in the digestate pasteurization unit. It can be concluded that the pasteurization of the produced digestate has the biggest impact on the global warming potential due to having more emissions derived from natural gas consumption.

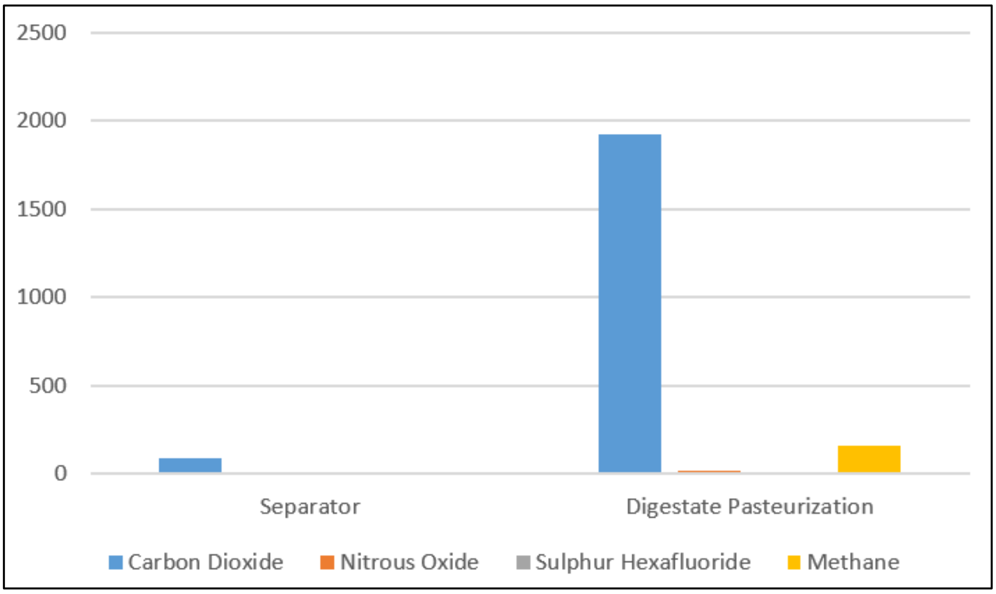


Figure 4.9. Global warming potential of the subsystem 3 in Scenario B (kg CO_2-eq.).

4.6.2.2. Acidification Potential (AP)

Because of the potential impacts of the related contaminants especially SO_2 and NO_x to the atmosphere, soil and water, acidification potential is originated. The acidification potential is expressed as SO_2 equivalent.

The result of the acidification potential impact category for Scenario A is indicated in Figure 4.10. Based on Scenario A, transportation processes of waste to the plant, and the CHP unit are the main sources of the environmental impact in this category and the reason is that there are only two main processes causing some gas emissions by diesel consumption and CHP emissions. It can be seen that the most dominant process in this category is waste transportation by truck-trailer. It is expected that truck-trailer transportation has an important role in acidification potential results because approximately 270 tons of the wastes was utilized; that is, the majority of the delivered waste was transferred by truck-trailers. Besides, the total distance for transportation by truck-trailer was 135.1 km and this is the process that travelled the long-distance and consumed the most of diesel.

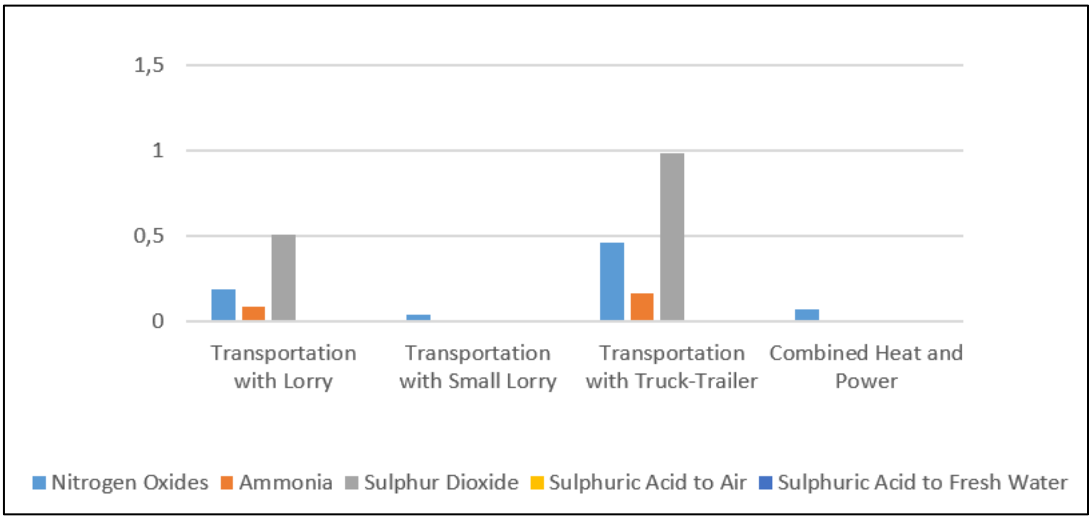


Figure 4.10. Acidification potential for Scenario A (kg SO_2-eq.).

The quantified AP impact categories of subsystem 1, subsystem 2 and subsystem 3 are shown in Figure 4.11, Figure 4.12 and Figure 4.13, respectively. Regarding the life cycle impact results of Scenario B, the centrifuge process is the main contributor to the acidification impact category. The combined heat and power unit contributes to acidification potential, after the centrifuge process. Besides, the dominant gas is sulphur dioxide in subsystem 1 and 2 of Scenario B, while nitrogen oxides is the main contributor to the category in the subsystem 3 including separator and digestate pasteurization processes. It is clear to see that NO_x has a noticeable effect on the AP impact category in some stages that consumed natural gas in order to be required thermal energy for anaerobic digestion and pasteurization activities.

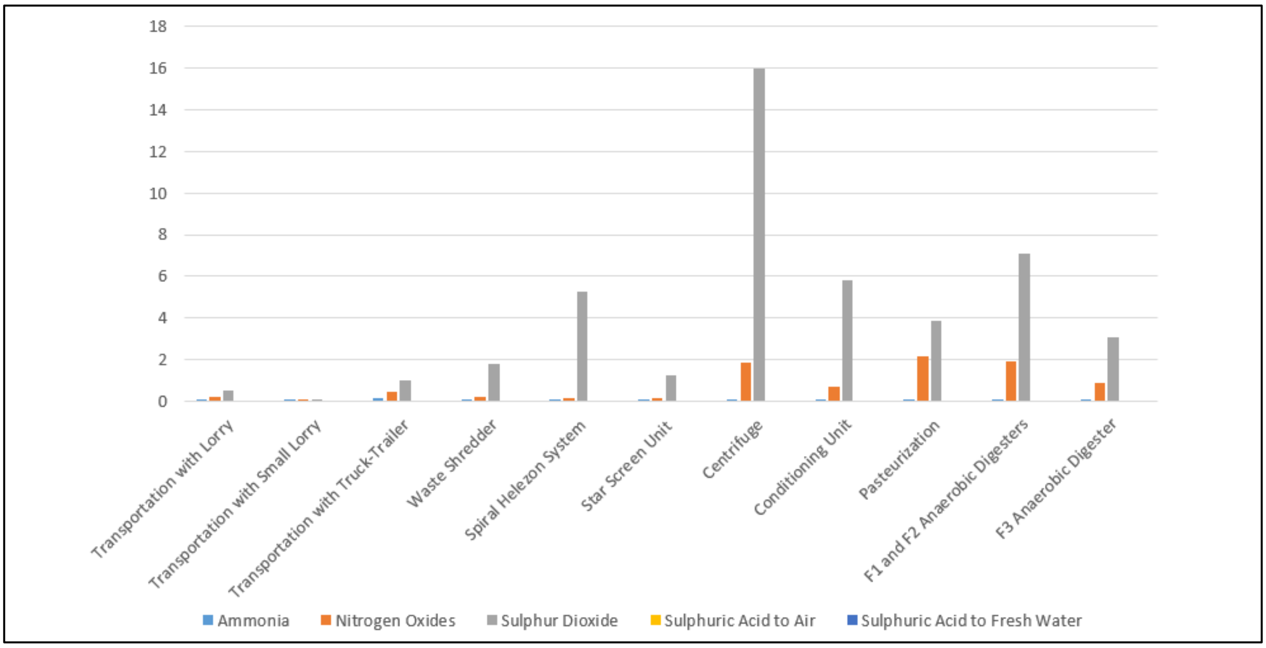


Figure 4.11. Acidification potential of the subsystem 1 in Scenario B (kg SO_2-eq.).

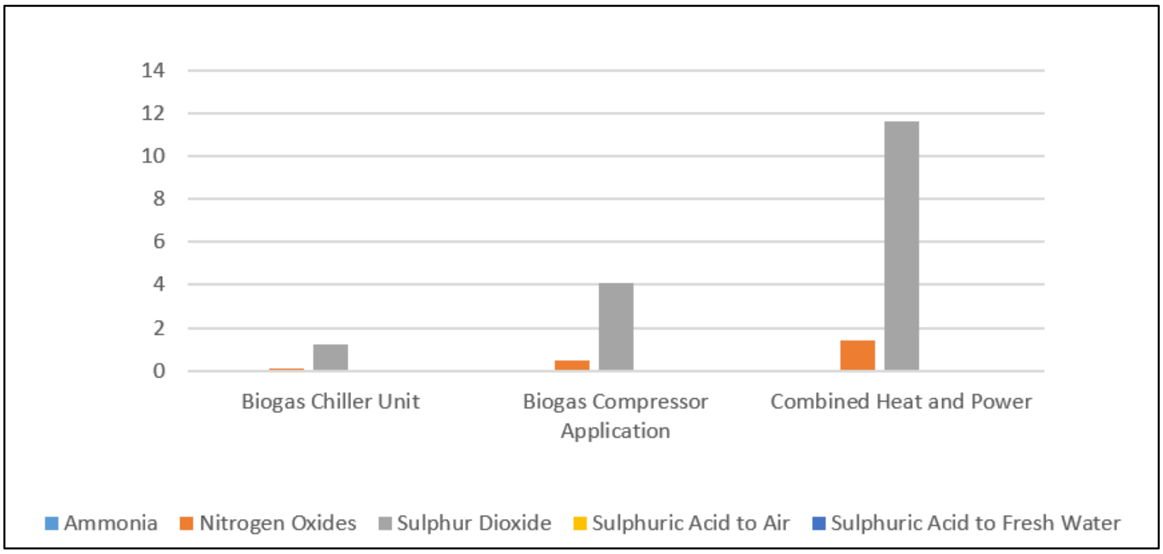


Figure 4.12. Acidification potential of the subsystem 2 in Scenario B (kg SO_2-eq.).

It can be seen that the main sources of this impact category are NO_x and SO_2 in subsystem 3. The digestate pasteurization is more dominant than the separator process due to having more emissions derived from natural gas consumption. On the other hand, there was only one emission source for the digestate separation unit: electricity consumption from the grid. In the digestate separation unit, the supply manifold used before the digestate pasteurization unit, the liquid-solid separator machine and the pump used to transfer the solid fraction of the digestate into the storage tank needs electric power.

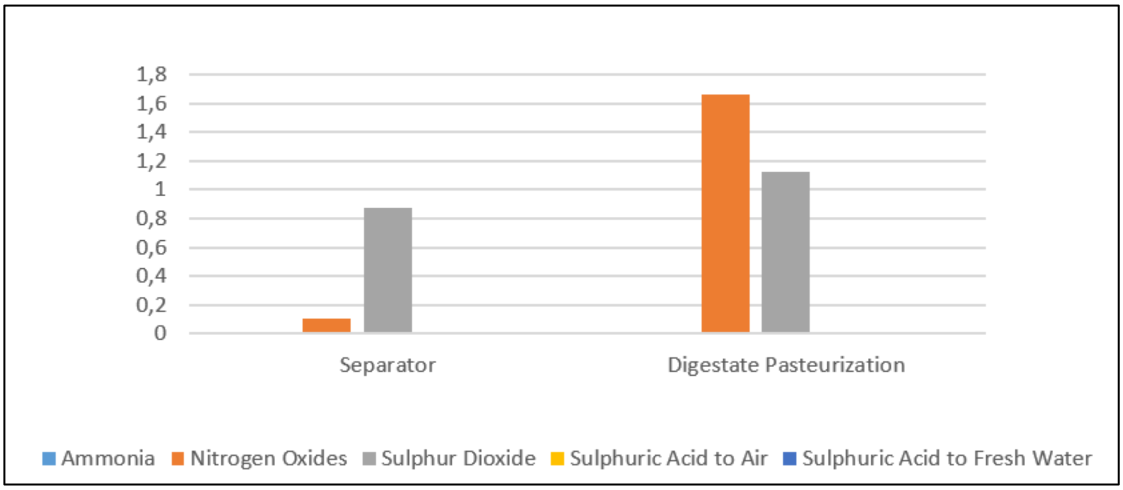


Figure 4.13. Acidification potential of the subsystem 3 in Scenario B (kg SO_2-eq.).

4.6.2.3. Eutrophication Potential (EP)

Because of the potential impacts on terrestrial and aquatic environments by the accumulated nitrogen and phosphorus containing compounds, eutrophication potential is originated. The eutrophication potential is expressed as kg of phosphate equivalent.

In Figure 4.14, the quantified EP impact category of Scenario A is shown. Waste transportation with truck-trailers is the main contributor to the eutrophication impact category. After the transportation with the truck-trailers process, the waste transportation with lorries and the CHP unit contribute to eutrophication potential, respectively. In addition to truck-trailers, lorry vehicles play an important role in this impact category because the maximum loading capacity of each lorry was 17.3 ton, and 450 tons of wastes were transported from the related supermarkets or factories to the specified biogas plant along with the total travel distance, approximately 100,3 km. It is easy to observe that nitrogen oxides, NO_x, is the most dominant gas in this category for each process and ammonia is the second contributor especially for waste transportation with lorries and with truck-trailers.

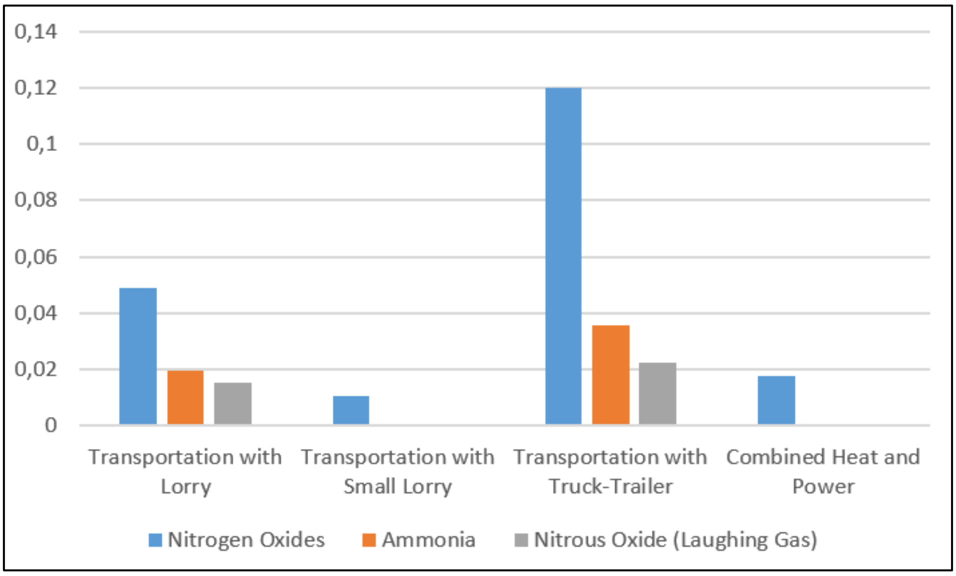


Figure 4.14. Eutrophication potential for Scenario A (kg Phosphate-eq.).

The result of the EP impact category for subsystem 1 of Scenario B is indicated in Figure 4.15. It can be seen that nitrogen oxides, NO_x, is also the most dominant gas for subsystem 1. The main contributors of this impact category are the pasteurization, anaerobic digestion and centrifuge processes and the reason is the usage of thermal and electric power for the internal requirement of these processes and the generated emissions derived from energy use through external sources like natural gas and electricity grid.

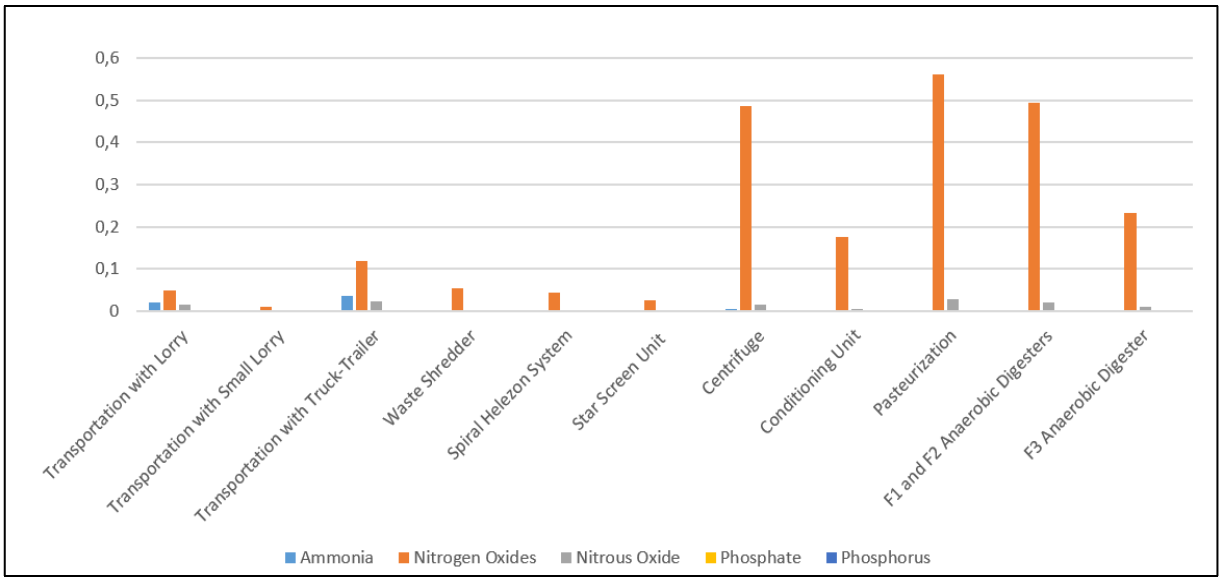


Figure 4.15. Eutrophication potential of the subsystem 1 in Scenario B (kg Phosphate-eq.).

In Figure 4.16, the quantified EP impact category of subsystem 2 is shown. It can be observed that the main source of this impact category is the gas emissions coming from the CHP unit. The fact is that the required energy, which is utilized to transfer the produced waste heat to the other processes of the specified plant, was excluded from the scope of Scenario B; therefore, there were no emissions arising from the heat transfer pumps. Nevertheless, electricity consumption by gas engines in the CHP unit and emissions occurred while biogas was burned are the main contributors to the eutrophication impact category.

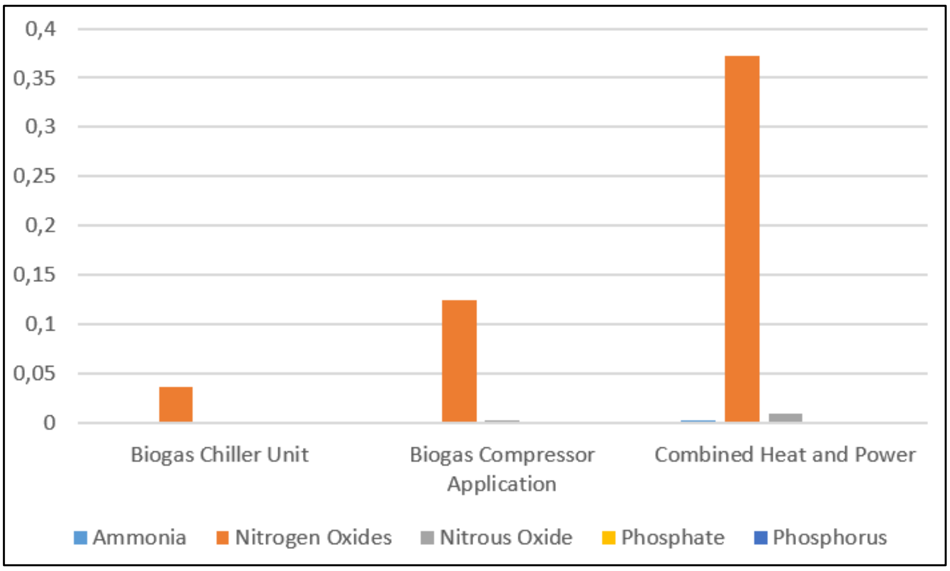


Figure 4.16. Eutrophication potential of the subsystem 2 in Scenario B (kg Phosphate-eq.).

The result of the EP impact category for subsystem 3 of Scenario B is indicated in Figure 4.17. Regarding subsystem 3, the digestate pasteurization contributes to this impact category and the main emission source is nitrogen oxides resulted from natural gas and electricity use.

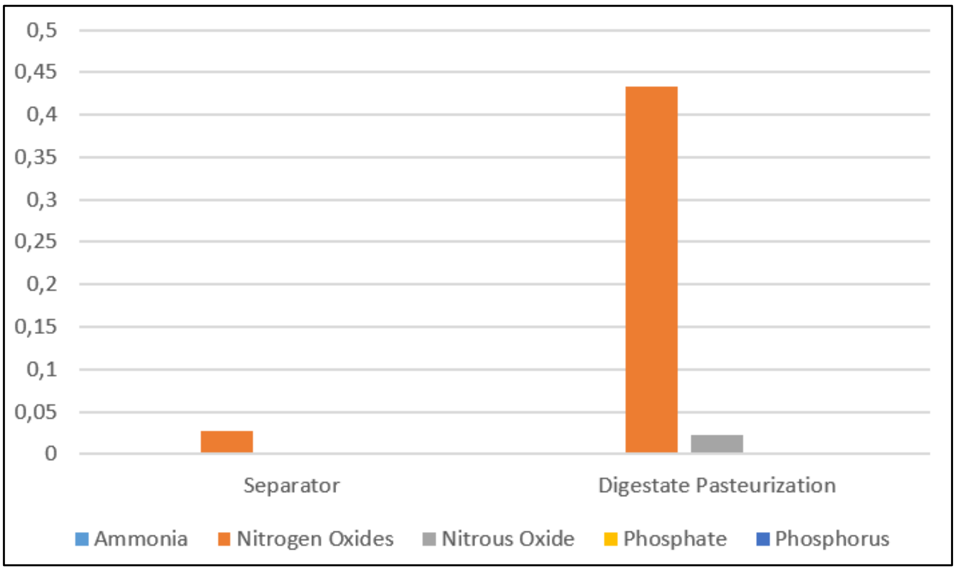


Figure 4.17. Eutrophication potential of the subsystem 3 in Scenario B (kg Phosphate-eq.).

4.6.2.4. Photochemical Ozone Creation Potential (POCP)

As a consequence of the photochemical reactions between volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx) in the condition of high temperature or under the impact of sunlight in order to generate ozone, photochemical ozone creation is originated. The eutrophication potential is expressed as kg of ethene equivalent.

The result of the POCP impact category for Scenario A is indicated in Figure 4.18. Transportation with truck-trailer is the main contributor to this impact category followed by the transportation with lorry process. Besides, the main sources of environmental impact in the POCP impact category are carbon monoxide, group NMVOC, sulphur dioxide and nitrogen oxides, respectively. The effect of the small lorry on this impact category seems to be unnoticeable, the reason is that the total amount of waste transported by a small lorry was 7.5 ton. On the other hand, 173 tons of waste was carried by 10 lorries, while 270 tons of waste transported by 10 truck-trailers.

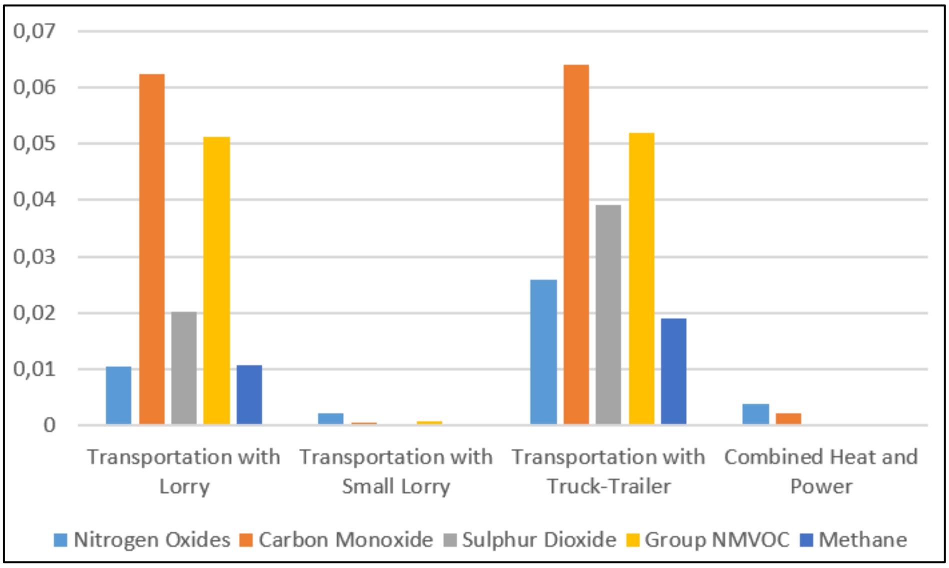


Figure 4.18. Photochemical ozone creation potential for Scenario A (kg Ethene-eq.).

In Figure 4.19, the quantified POCP impact category of subsystem 1 is shown. It is obviously seen that the majority of the environmental impact in this impact category is stemmed from the centrifuge stage and sulphur dioxide is the most dominant gas in the photochemical ozone creation potential category. The centrifuge process is the main contributor in this category due to the fact that the centrifuge was operated for 7.5 hours a day. In addition to the centrifuge process, the first and the second digesters, the pasteurization and the conditioning units are the other important contributors to this impact category.

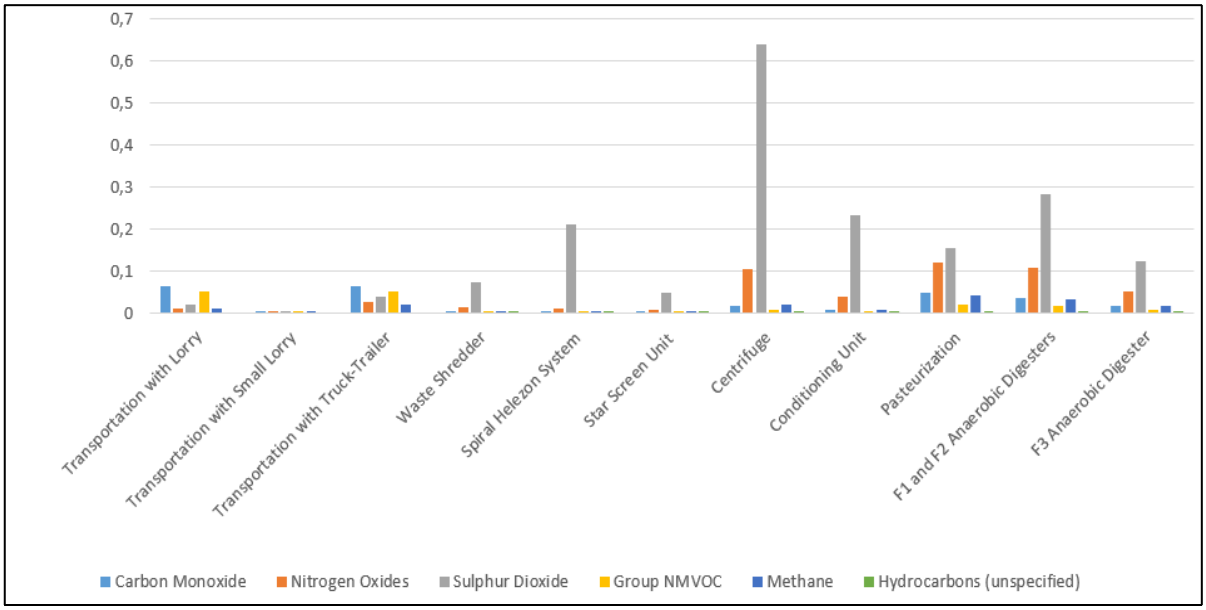


Figure 4.19. Photochemical ozone creation potential of the subsystem 1 in Scenario B (kg Ethene-eq.).

The result of the POCP impact category for subsystem 1 of Scenario B is indicated in Figure 4.20. The main contributor in this category is the combined heat and power process; the reason is that this process was the most electricity consuming stage in subsystem 2. It is clearly understood that the generated gas emission is directly interrelated to electricity consumption.

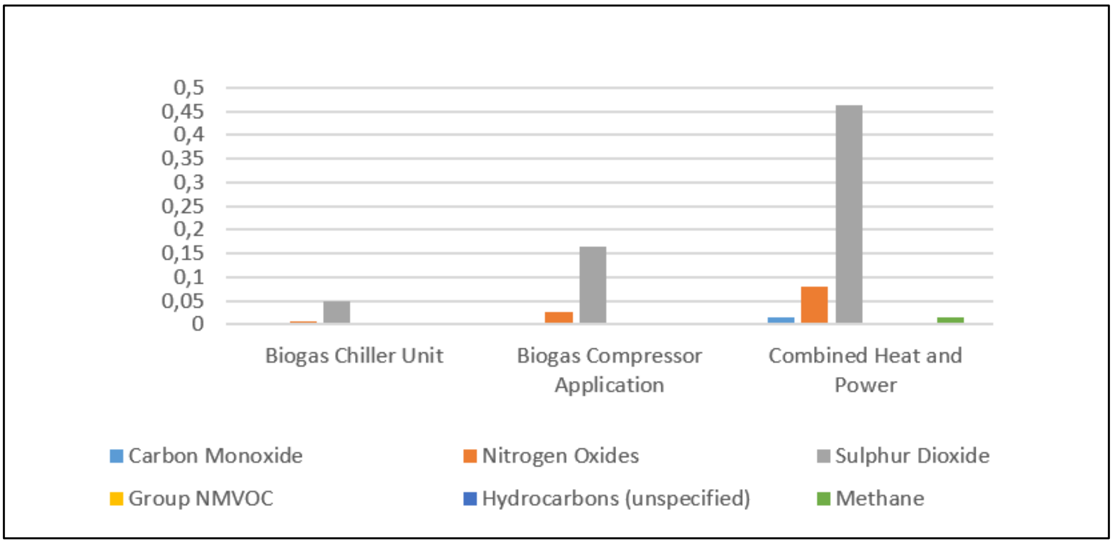


Figure 4.20. Photochemical ozone creation potential of the subsystem 2 in Scenario B (kg Ethene-eq.).

In Figure 4.21, the quantified POCP impact category of subsystem 3 is shown. The digestate pasteurization unit leads to more emissions than the separation unit; the reason is that both electricity and thermal energy were consumed at the same time. Additionally, in the digestate pasteurization unit, the main source is nitrogen oxide due to the excessive amount of heat consumption. On the other hand, in the separation unit, the main contributor is sulphur dioxide, as in the other processes in the subsystem 1 and 2 of Scenario B.

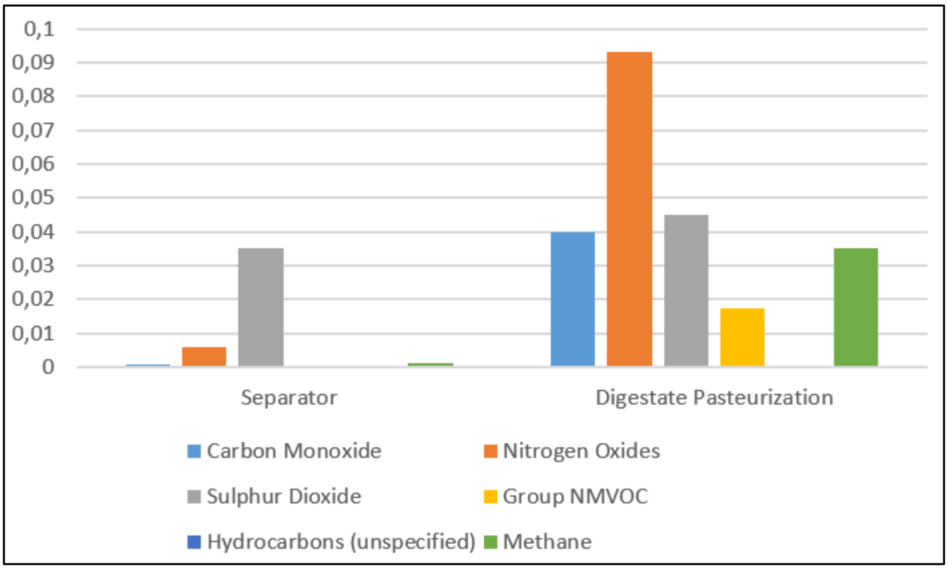


Figure 4.21. Photochemical ozone creation potential of the subsystem 3 in Scenario B (kg Ethene-eq.).

4.6.2.5.Human Toxicity Potential (HTP)

Human toxicity potential is a measure of the potential damage of chemical components to the environment and this impact category is expressed as kg of dichlorobenzene (DCB) equivalent.

In Figure 4.22, the quantified HTP impact category of Scenario A is shown. Waste transportation with truck-trailers is the main contributor to the human toxicity impact category. The transportation with lorries and the CHP unit contribute to this category, after the truck-trailer process. It can be seen that the dominant gas is nitrogen oxides in Scenario A. It is a well-known fact that nitrogen oxide emissions are associated with some respiratory diseases.

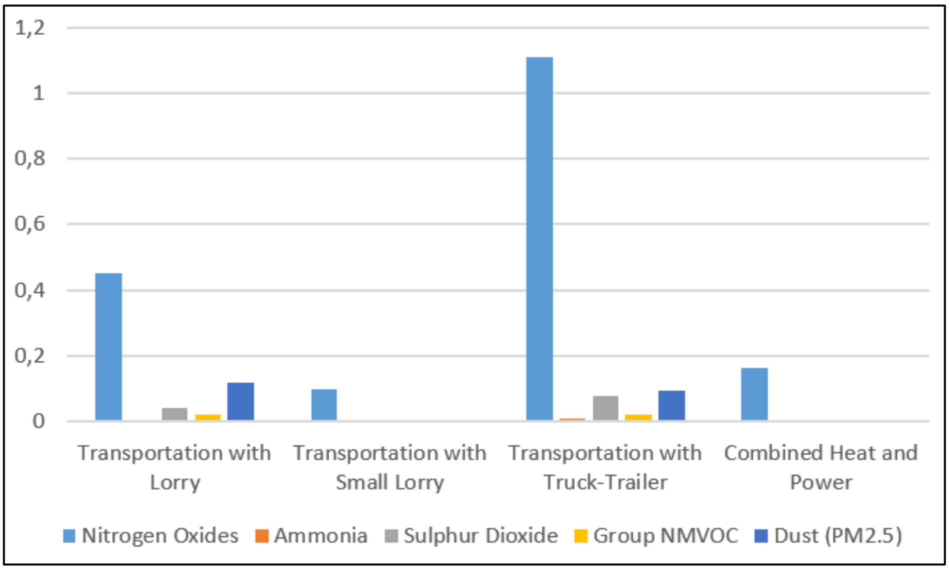


Figure 4.22. Human toxicity potential for Scenario A (kg DCB-eq.).

The result of the HTP impact category for subsystem 1 of Scenario B is indicated in Figure 4.23. The centrifuge unit is the main contributor to the human toxicity impact category if the total amount of environmental impacts is taken into consideration. After the centrifuge process, the pasteurization and the anaerobic digestion stages contribute to human toxicity potential, respectively. Besides, the main source of environmental impact in the HTP impact category is nitrogen oxides. Regarding the toxic effects of nitrogen oxides, respiratory problems and tissue damage in the throat are some of the adverse impacts of this gas emission on human beings.

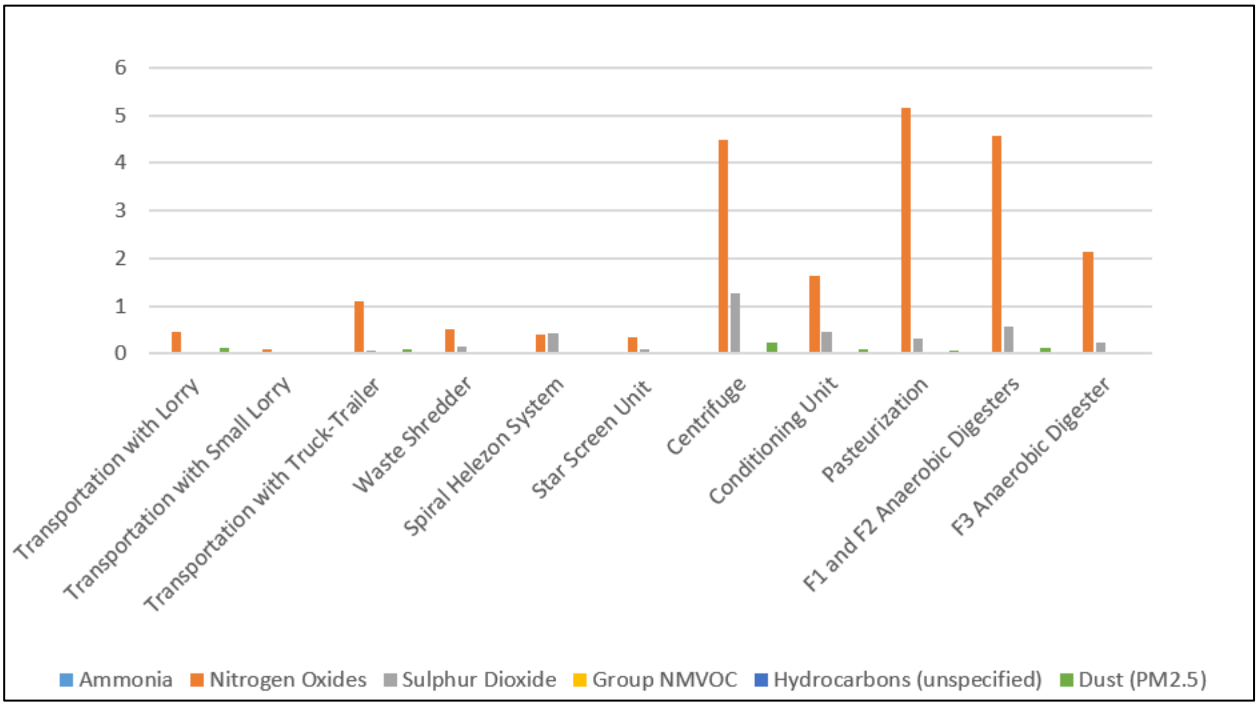


Figure 4.23. Human toxicity potential of the subsystem 1 in Scenario B (kg DCB-eq.).

In Figure 4.24, the quantified HTP impact category for subsystem 2 is shown. The main contributor in this category is the combined heat and power process and the majority of the environmental impacts in the CHP unit is derived from nitrogen oxides.

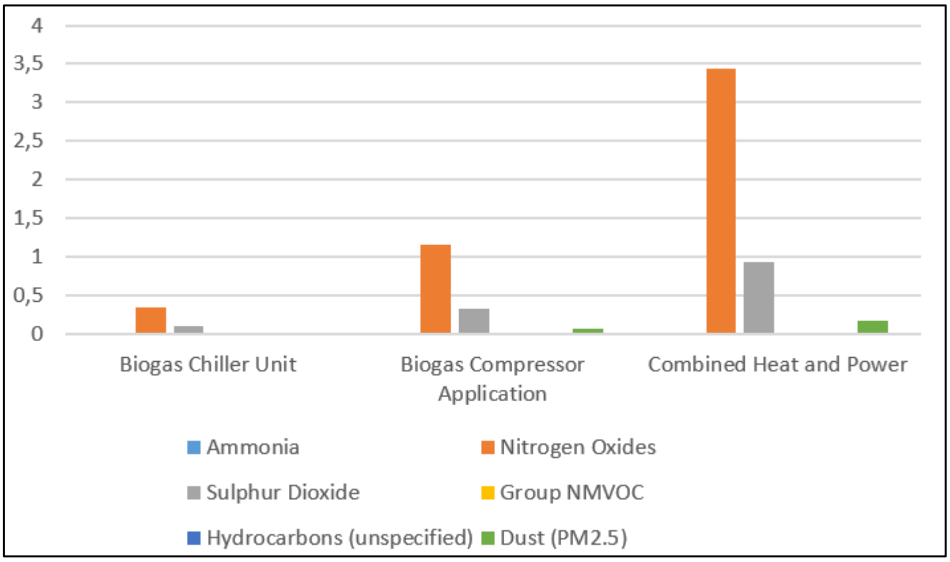


Figure 4.24. Human toxicity potential of the subsystem 2 in Scenario B (kg DCB-eq.).

The result of the HTP impact category for subsystem 3 of Scenario B is indicated in Figure 4.25. Concerning subsystem 3, the digestate pasteurization contributes to this impact category and the main emission source is nitrogen oxides resulted from the use of thermal energy and electricity withdrawn from natural gas and the electricity grid, respectively.

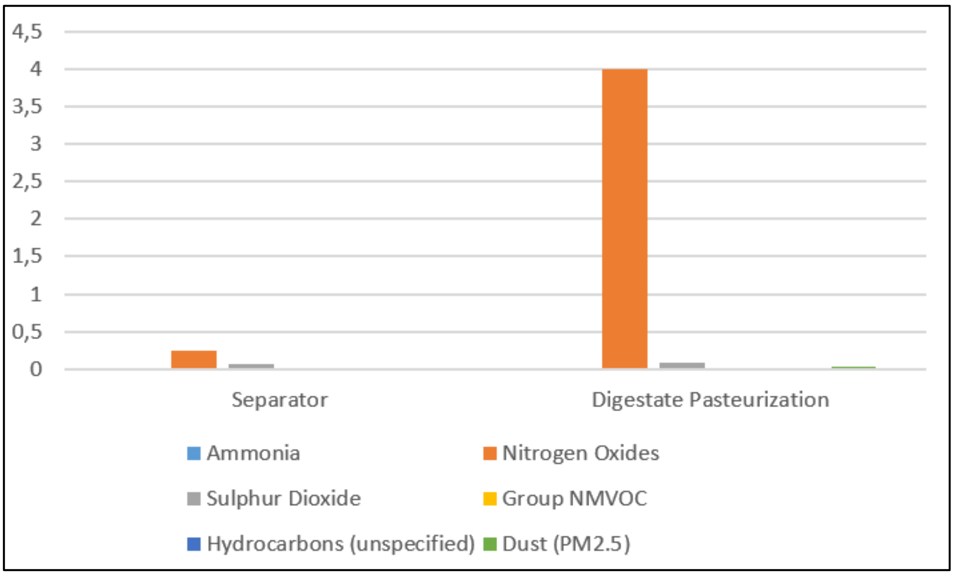


Figure 4.25. Human toxicity potential of the subsystem 3 in Scenario B (kg DCB-eq.).

4.6.3. Normalization

In the normalization step, the magnitude of the impact indicator results is measured based on reference values. Normalization is an optional step, however, this element of an LCA study helps to analyze life cycle impact results and compare various impact categories by giving the non-dimensional results.

The normalization results for Scenario A and Scenario B is indicated in Figure 4.26. Within the scope of the normalization step, the CML 2001-January 2016 method was utilized in the study. Regarding Scenario A, it can be seen that the global warming potential has the highest effect on the normalization step; the reason of that the majority of the generated emissions was stemmed from the transportation processes and the CHP unit and there were no emission sources other than these two main processes. In addition, in Scenario A, the internal energy demand in the specified biogas plant was totally met from the produced waste heat and electricity by biogas. For this reason, the main contributors to the GWP of Scenario A were CHP emissions and diesel. On the other hand, Scenario B has the highest results in every impact category. It is a fact that electric power and thermal energy were obtained from the electricity grid and natural gas respectively. The supplied energy was consumed to operate all transfer pumps, gas engines, waste mixers or to maintain essential temperature conditions for the pasteurization and digestion processes. Thus, Scenario B constitutes a major share of the total impact, especially in the GWP and AP impact category.

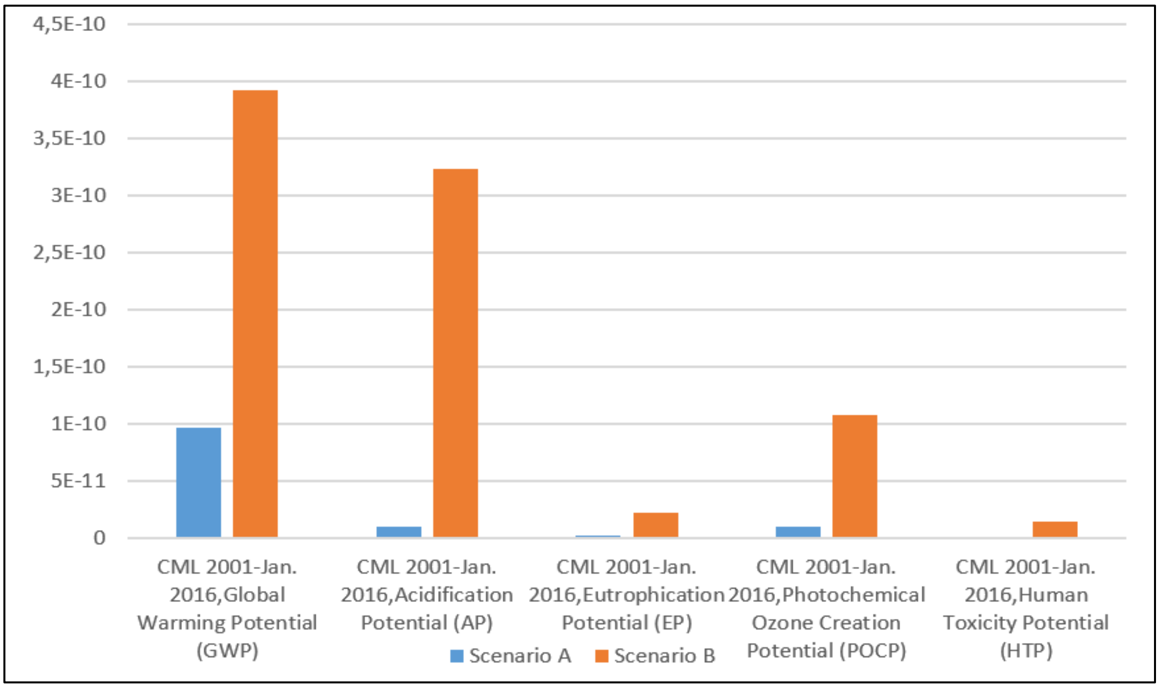


Figure 4.26. Normalization results for Scenario A and Scenario B.

4.6.4. Weighting

Weighting is an optional step that aggregates the normalized impact category results by multiplying them with a weighting factor. This step provides to compare the impact indicator categories based on their importance.

The weighting results for Scenario A and Scenario B is indicated in Figure 4.27. Regarding the weighting step, the thinkstep LCIA Survey 2012, CML 2016 (global) option was utilized in the study. According to the impact indicator results, the weighted results also indicates similarity with the normalized results and it can be seen that the global warming impact category has the relative importance in Scenario A. The relative importance of Scenario B is mostly coming from the global warming potential and acidification potential.

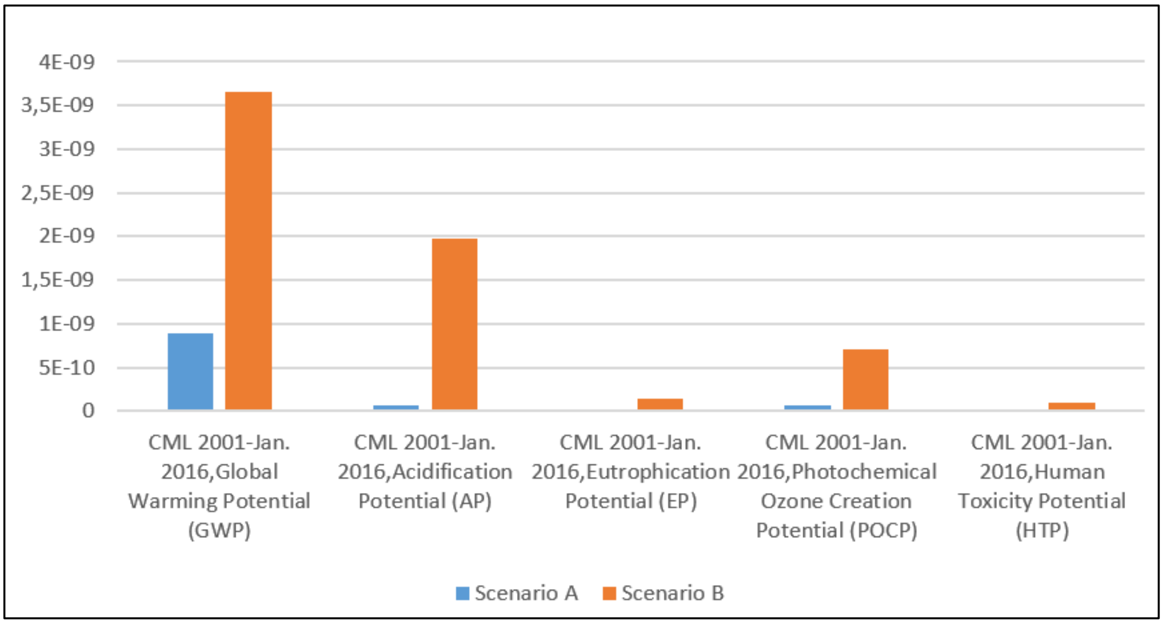


Figure 4.27. Weighting results for Scenario A and Scenario B.

5. CONCLUSIONS

The main idea to be emphasized in this LCA study are to evaluate some expired products via energy production, to handle waste accumulation problem especially in supermarkets, to recover the usable part of the waste compositions by anaerobic digestion technology and to assess environmental impacts of the specified biogas plant based on different energy utilization options.

Regarding electricity production by biogas, 388800 MJ of electricity was generated based on the maximum capacity of the plant which is 450 tons of waste. 41603.8 MJ of the produced electricity was utilized for the internal energy requirements in on-site energy utilization option; that is approximately 10.70% of the produced electricity was directly circulated to the processes of the specified biogas plant. On the other hand, in energy utilization option from the grid, the produced electricity was totally transmitted into the electricity grid. It means that there was no electricity consumption from the produced energy. To meet the energy demand of the biogas plant, electricity was supplied from the grid, and this situation led to more emission production and environmental impacts. According to the Turkish Electricity Transmission Corporation, the net electricity consumption per capita in Turkey is assumed to be 257.84 kWh/month. Within the scope of this net value, compare to the on-site utilization, the electricity consumption of 4841 more people can be achieved; it means that the number of people whose electricity needs were met is higher in Scenario B. In other respects, the summarized characterization results concluded that the total amount of every impact category, global warming, acidification, eutrophication, photochemical ozone creation and human toxicity, are higher in energy utilization from the electricity grid and natural gas; the reason is that most of the emission sources were derived from the electricity production from the grid, other than CHP emissions and diesel consumption. It can be revealed that the on-site energy utilization option is less detrimental and more environmentally-friendly. As regards the specified biogas plant, the on-site energy utilization application has more advantages because it provides the supply of internal energy demand of the specified plant without being dependent on the power grid. This off-to-grid system also enables the effective use of the produced energy. On the other hand, energy utilization from the grid and natural gas option is more profitable for the plant since all produced electricity has directly sold. The primary aim is to put the economic return first by selling the majority of the produced energy.

In this case study, there is another important output in the plant: waste heat. As mentioned before, the on-site energy utilization option enables to utilize of waste heat in several processes of the plant, for instance, pasteurization and anaerobic digestion units. In the pasteurization unit, the waste composition has to be pasteurized, when meat products such as sausage, salami or fermented sausage exist. Besides, the temperature is a critical parameter to sustain microbial activities in anaerobic digesters. In this sense, when it comes to the on-site energy utilization option, the heat consumption by mandatory pasteurization and anaerobic digestion processes were totally supplied from the produced waste heat in the CHP unit. For this reason, on-site energy utilization can be considered an energy-saving option because the internal heat requirements would be met from natural gas, as in the other scenario, if the waste heat was not recirculated to the system. In this case, the application without focusing on waste heat recovery purpose causes more damages to the environment due to the increase in fossil fuel consumption and GHG emissions to the atmosphere. Furthermore, on-site energy utilization with waste heat recovery is an economically feasible option thanks to its saving of fuel bills. On the other hand, the total amount of the produced heat was assumed to be released into the atmosphere in Scenario B. In this case, the capability of waste heat and the heating potential is lost; it means an increase in the dependency on fossil fuel resources.

As regards the other product, the produced liquid digestate can be utilized as a soil conditioner for local farmers. However, some parameters have to be monitored before the use of the produced liquid digestate. According to the heavy metal results of the produced liquid digestate, it is shown that that the heavy metal concentrations of the produced digestate are below the limit value affirmed by the regulation on mechanical separation, bio-drying, bio–methanation plants and fermented products management. In this sense, the produced liquid digestate can be applied as a soil amendment for agricultural activities in the Marmara Region.

Within the scope of three days' period, for the total GWP results, waste transportation was the main contributor to gas emissions. The other important emission sources were the pasteurization and anaerobic digestion processes due to the electricity consumption by the mixers and transfer pumps. The AP results concluded that truck-trailer use has an important role in on-site energy utilization, while the centrifuge process has the biggest share in electricity consumption from the grid. As regards the eutrophication impact category, the majority of the generated gas emissions were derived from waste pasteurization, anaerobic digestion and centrifuge processes, respectively. Centrifuge and CHP units were the main contributors to photochemical ozone creation potential due to the electricity requirements of gas motors and pumps. In the last category named human toxicity potential, natural gas consumption was the biggest share in pasteurization and anaerobic digestion processes.

Regarding the calculated values for impact categories, the total amounts of the detailed impact categories were evaluated for the one-year period. When the annual results of the environmental impact categories were compared, it is concluded that the global warming potential decreases by 75.54%, if the on-site energy utilization option is selected. It means that the observed annual decrease in the GWP impact category is 1525700 kg CO_2-equivalent. Within the scope of the functional unit, the generation of 108 MWh of electricity through the use of 450 tons of food wastes during three-days period, the on-site utilization provides to decrease approximately 12540 kg CO2-equivalent of the emissions in the GWP impact category result. In addition, the acidification potential impact category decreases by 96.76%; that is, the annual decrease is 9100.666 kg SO_2-equivalent. Based on the three-days period, 74.8 kg SO_2-equivalent in the AP impact category totally decreases in the on-site utilization. As regards the third impact potential category, it is observed that the eutrophication potential decreases by 91.71%, when the on-site utilization option is evaluated. Besides, the decreased amount in the three-days period is 3.21 kg Phosphate-equivalent, while the annual decrease in the EP impact category is 390.55 kg Phosphate-equivalent. When it comes to the photochemical ozone creation potential, the annual decrease is 441.0417 kg Ethene-equivalent and the three-days period result based on the functional unit is approximately 3.625 kg Ethene-equivalent. It is resulted that the photochemical ozone creation potential decreases by 90.852% if the produced electricity and waste heat are utilized in the specified biogas plant. In the case of the human toxicity potential, the on-site energy utilization option enables the annual decrease by 93.945% and this value corresponds to 4171.95 kg DCB-equivalent. If the functional unit is taken into account, it is possible to achieve a reduction of 34.29 kg DCB-equivalent in the on-site utilization option. When all impact category results are considered, it is deduced that the on-site energy utilization option is more beneficial than the other scenario because the most detrimental effects of Scenario B are stemmed from the energy consumption by natural gas and the electricity grid.

In conclusion, waste accumulation is a real problem all around the world. To actualize energy recovery and prevent the disposal of expired food wastes to waste mountains, the WTE technologies can be considered. In this case study, the operation of some expired food wastes and energy production were evaluated. As regards the specified biogas plant, the on-site energy utilization is the best option, while electricity and waste heat are continuously producing. In other words, the on-site energy utilization option; that is, being off-to-grid has more positive effects on the environment with the respect to becoming more energy and emission savings.

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APPENDIX A: THE METHODOLOGIES OF EXPERIMENTS

A.1. Total Solid Experiment

The procedure of the total solid experiment consists of two main parts. The first test procedure is related to the preparation of an aluminium dish. The aluminium dish was put in a drying oven at 103 °C to 105 °C for 1 hour. The dish was removed from the oven and transferred to a desiccator for reaching room temperature. Then, the dish was weighed on an analytical balance and the weight of the aluminium dish was recorded before using it for the waste sample. Before the second step of the experiment, the wet sample and dish were weighted together and the weight was recorded. The second step referred to as sample preparation started with drying the wet sample at 103 °C to 105 °C. Then, the dish was transferred to a desiccator until balancing the temperature. Finally, the sample was weighted by using an analytical balance and the weight of the sample was recorded.

The following equation is utilized to measure the total solid amount:

$$\% \text{ Total Solids} = \frac{\text{Wtotal} - \text{Wdish}}{\text{Wsample} - \text{Wdish}} * 100 \qquad \text{(A.1)}$$

Where:

W_{dish} = Weight of dish (mg)

W_{sample} = Weight of wet sample and dish (mg)

W_{total} = Weight of dried sample and dish (mg)

A.2. Volatile Solid Experiment

The aluminium dish containing the dried sample was ignited in a muffle furnace at 550 °C. After reaching a constant temperature, the sample was transferred to a desiccator for cooling. Finally, the sample was weighed on an analytical balance, and the result was recorded.

The following equation is utilized to calculate the volatile solid amount:

$$\% \text{ Volatile Solids} = \frac{\text{Wtotal} - \text{Wvolatile}}{\text{Wsample} - \text{Wdish}} * 100 \qquad \text{(A.2)}$$

Where:

W_{dish} = Weight of dish (mg)

$W_{volatile}$ = Weight of sample and dish after ignition (mg)

W_{total} = Weight of dried sample and dish (mg)

A.3. pH

Before the measurement, the pH meter was properly calibrated by using a buffer test solution with a known the pH value. Afterwards, the pH values of each sample were calculated through ph meter instrument.

A.4. Biochemical Methane Potential Analysis

The determination of total solids and volatile solid of the biomass that will be utilized for the BMP test is a required step before any BMP test is started. After the characterization of the biomass, some required components for the BMP test are prepared. Biochemical methane potential (BMP) test requires substrate and inoculum. In general, the inoculum is the sludge from a full-scale biogas plant. To reduce the generation of methane production by inoculum, the pre-incubation step is commonly suggested. During the pre-incubation step, the inoculum is stored in anaerobic conditions for 1 to 5 days. The pre-incubation is over when methane production finishes. Furthermore, the other important component for the BMP test is a substrate and there are some crucial parameters that should be considered within the context of the substrate. Ph, total solid and volatile solid are compulsory parameters for substrates because the inhibition of the biodegradation process can be occurred if these crucial parameters are not suitable. Thus, chemical properties should be monitored before starting to BMP test.

In addition to inoculum and substrate, the preparation of BMP bottles should be taken into account. Heterogeneous substrates are generally put in large volumes BMP bottles in the range of 500 to 2000 ml, while homogenous substrates are utilized in small volume with 125 to 500 ml. After the preparation of BMP bottles, the same amount of inoculum is put in the bottles. However, it should be considered that three BMP bottles remain as blanks. Then, the substrates are added to the bottles based on the inoculum to substrate ratio, and the bottles and their lids are marked. After placing all bottles, the reactors are closed with a stopper, and the stirring sticks are fastened to the motor. After that, the reactors are put in the water bath, and the connection between CO_2 absorption bottles and the reactors have been achieved. Before starting, the connection between the stirrings, the motors and the gas volume measuring device should be monitored. For flushing the reactors, N_2 is utilized for only 2 minutes. If the anaerobic conditions are provided, the data logging program is started. During the experiments, the water level in the water bath has to be controlled, and the distilled water can be added if the water level decrease. The BMP test generally lasts between 30 and 60 days. The produced methane level is used to understand when the test is terminated. If the methane level is less than 5 ml/day[5], the BMP test is finished. At the end of the BMP test, the produced gas is calculated by the following equation:

$$\mathrm{BMP}= \frac{\mathrm{Vs} - \mathrm{Vb}*(\frac{\mathrm{M\imath s}}{\mathrm{M\imath b}})}{\mathrm{Mvs,sS}} \qquad \text{(A.3)}$$

BMP= The normalized volume of produced methane per gram VS of feedstock added (Nl/g VS)
V_B = The accumulated volume of produced methane through three blanks
V_S = The accumulated volume of produced methane from reactor with sample
$M_{VS,Ss}$ = The value of organic material of substrate contained in sample bottle
M_{IS} = The inoculum value in sample
M_{IB} = The inoculum value in blank

A.5. Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen, abbreviated TKN, is determined by the sum of nitrogen and ammonium. Digestion, distillation and titration are the main steps of this experiment. Firstly, the sample volume is selected based on the standard methods and the digestion reagent is added to the sample. The digester is heated up to more than 380 ^{o}C and the digestion stage starts when H_2SO_4 reaches its boiling point. After, the sample is boiled until the appearance of the solution turns green and transparent; it means that the organic matter is completely removed through the digestion stage. The solution is waited until its cooling and then, the sample is diluted to 300 mL with water. In order to generate an alkaline layer, a sodium hydroxide-thiosulfate reagent is added and the connection between the glass tube and the distillation apparatus are made. After the distillation stage, the distillate is collected and approximately 50 mL boric acid is utilized to determine ammonia by the titration stage.

APPENDIX B: PHOTOGRAPHS TAKEN DURING THE PLANT VISITATION

Figure B.1. Different types of waste compositions.

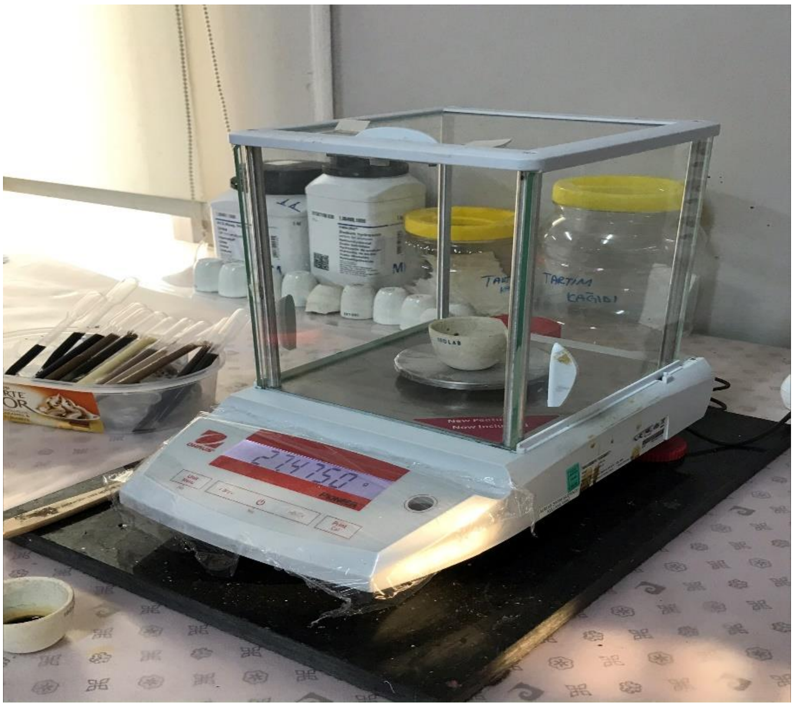

Figure B.2. Analytical balance for the weighing.

Figure B.3. Desiccator equipment.

Figure B.4. Palletized wastes.

Figure B.5. Membrane biogas holder.

Figure B.6. BMP test equipment.

Figure B.7. Bottles in the BMP test.

Figure B.8. Incubator.

Figure B.9. AMPTS in the BMP test.

Figure B.10. The connections between the anaerobic reactors.

APPENDIX C: THE RESULTS OF THE PRODUCED DIGESTATE

Table C.1. The heavy metal concentrations of the produced liquid digestate.

The Average Results of Liquid Digestate Parameters (mg/kg)						
Cd	Cr	Cu	Hg	Zn	Ni	Pb
1	18.8	34.16	0	171.4	16.23	11

Table C.2. The limit value of heavy metal concentrations for liquid digestate (Offical Gazette of Turkey (no: 29498) on 10.10.2015).

The Limit Value by The Regulation (mg/kg)						
Cd	Cr	Cu	Hg	Zn	Ni	Pb
1.5	100	200	1	600	50	120