Lappeenranta University of Technology
School of Energy Systems
Degree Program in Sustainable Technology and Business
Sustainable Science
Master’s Thesis

Deniz Caglayan

EFFECTIVE LFG MANAGEMENT- A CASE STUDY IN ISTANBUL, TURKEY

Examiner: Professor Mika Horttanainen
Supervisors: Professor Mika Horttanainen
DSc. Jouni Havukainen

ABSTRACT

Lappeenranta University of Technology

School of Energy Systems

Degree Program in Sustainable Technology and Business

Sustainable Science

Deniz Caglayan

Effective LFG Management – A Case Study in Istanbul

Master's Thesis

2017

75 Pages, 11 Figures, 20 Tables and 13 Equations.

Examiners: Professor Mika Horttanainen

DSc. Jouni Havukainen

Keywords: Life cycle assessment, landfill gas, municipal solid waste, anaerobic digestion, biogas, combustion, upgrading, cost-benefit analysis.

Waste management has become a growing trend in Turkey and policies are being developed to ameliorate the environmental standards. Besides, MSW management is a critical factor for Turkey while being a candidate country for EU accession.

The mitigating of the environmental impacts caused by MSW, particularly to the landfill gas have been gained a significant importance globally. Even though there are plenty of the researches and regulations have been carried out regarding the landfilling, the specific importance of LFG in conjunction with the environmental impacts are still largely unknown in Turkey, and the measurements on the LFG performance are rarely estimated, although the

environmental impacts are directly affected by LFG. Therefore, the main desire of this thesis is to assess the environmental performances of the created LFG utilization scenarios in a sanitary landfill in Istanbul, Turkey. Furthermore, every scenario is economically evaluated by cost-benefit analysis to illustrate the optimal scenarios in terms of economic feasibility.

The environmental impacts caused by LFG are measured using a LCA modelling for a case landfill at Odayeri, Turkey. The results show that the major contributor to the environmental impact potentials is the LFG leaking in the landfill, and each alternative LFG utilization scenario created has lower environmental impacts than the current system. Particularly, Scenario 2, where the biogas upgrading system is activated to the facility is the best environmentally-friendly scenario in terms mitigating of GW impacts because the amount of avoided emissions is more than that of other scenarios. Furthermore, this system seems economically feasible and all the investment needed can be repaid in a short-time period.

The LCA modelling demonstrates that LCA can be used as a useful tool for the planning LCA management options by directly comparing the actual environmental impacts of different technologies and planning options.

ACKNOWLEDGEMENT

First of all, I would like to thank my supervisors, Professor Mika Horttanainen for his guidance and enthusiasm towards my work; and Mr. Jouni Havukainen for all his special support, inspiration and the discussions during the thesis work.

I would also like to thank Mr. Ivan Deviatkin for his help in using GaBi Software.

Similarly, a thank you goes to all Lappeenranta University of Technology's staffs for providing thesis students convenient working places in the university.

Thanks are also extended to all my friends and my family who supported me throughout the thesis process.

Finally, I feel gratitude to M. Kemal Atatürk for being an inspirational figure in every period of my life.

"Our true mentor in life is science." – M. Kemal Atatürk

September 12, 2017

Deniz Caglayan

Table of Contents

LIST OF SYMBOLS AND ABBREVIATIONS

AP	acidification potential
CHP	combined heat and power
CNG	Compressed Natural Gas
$CO2_{eq}$	carbon dioxide equivalent
EP	eutrophication potential
EU	European Union
FU	functional unit
g	gram
GHG	greenhouse gas
GW	global warming
GWP	global warming potential
h	hour
H_2S	hydrogen sulfide
IPCC	Intergovernmental Panel on Climate Change
kt	kilo ton
LCA	life cycle assessment
LCIA	life cycle impact assessment
LFG	landfill gas
LPG	Liquefied Petroleum Gas
Mm^3	million cubic meters
MSW	municipal solid waste
N	normal
NH_3	ammonia
NO_X	nitrogen oxide
OMTS	octamethyltrisiloxane
PE	person equivalent
PO_4-eq	Phosphate equivalent
S	scenario
SO_{2eq}	Sulfur dioxide equivalent

t	ton
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound
W	watt

CH_4: Methane

CO_2: Carbon dioxide

$\sum_{k=i}^{n}$: Sum over *k* from *i* to *n*

1 INTRODUCTION

1.1 Background

Landfilling is the most preferred waste disposal method throughout the world because it can be considered as very cheap and simple solution. From an environmental point of view, landfills cause negative environmental impacts to air, land, and water such as Greenhouse Gas (GHG) emissions. Since a great amount of solid waste is vacated in landfills all over the world, a proper environmental management in landfills is a crucial element to pay attention to reduce the harmful environmental impacts of landfilling (Manfredi et al., 2009; Niskanen et al., 2013).

Landfills should be carefully filled, monitored and operated while they are active and for up to 30 years after they are closed. After closing landfills, methane (CH_4) generation degressively continues where cumulative GHG emissions are observed in the long term. However, the low CH_4 generation makes the utilization difficult because engines in the gas utilization process have a specific capacity of treating LFG. The challenging after-care periods can be shortened and ameliorated by the utilization of the organic material for energy production. Thus, there will be emission savings due to the substituted fossil fuels. In addition to emission savings and energy production, there are also environmental benefits can be obtained, such as the risk of groundwater pollution or surrounding soil is avoided with a shorter after-care period in landfills. Besides, economic advantages can be achieved as all the operational costs decrease when the after-care period is shortened, and several economic conditions can support the extraction and utilization processes (Niskanen et al., 2013).

Landfill gas (LFG) is generated when organic waste decomposes anaerobically in landfills. And main components of LFG are methane and carbon dioxide (roughly contains 50 to 55 percent methane and 40 to 45 percent carbon dioxide). In addition to the main components, approximately 1% other components are found in LFG, such as nitrogen and oxygen (Goossens, 1996). Methane is a major emission from landfills and 23 times more powerful as a greenhouse gas than is carbon dioxide. Without any methane treatment, a substantial amount of GHG emissions would occur. Globally, more than 70% of the GHG emissions released in the waste management operations are contributed by LFG emissions. According to the Intergovernmental Panel on Climate Change (IPCC), methane recovery from landfills is a bottleneck in terms of mitigating GHG emissions (Matthews and Themelis, 2007; IPCC, 2007). As a growing trend, methane can be recovered and used for energy generation, and thereby GHG emissions caused by fossil fuel for the energy generation can be avoided with the utilization of LFG (Manfredi et al., 2009).

1.2 MSW Management in Turkey

There is a growing trend on waste to energy initiatives at Turkey. The first step of the solid waste management in Turkey is the by-law on Solid Waste Control. According to the Turkish Ministry of Environment and Urbanization, the MSW management systems have been developed significantly, even though there have been some deficiencies in its implementation. 25 million tonnes MSW were collected in 2010, equivalent to 84% of the total generated MSW. The amount of MSW going to landfill increased by 5% between the years of 2001 and 2010. The number of engineered landfills increased from 15 to 88 between 2003-2012. According to data shown by European Environment Agency, 54% of the MSW is sent to sanitary landfills, other 44% of the MSW is dumped into municipal dumpsites, the rest 2% is treated by composting or other methods. MSW management is obviously increasing its popularity in Turkey that the number of licensed sanitary landfills has boomed. In 2004, there were only 46 recycling and recovery facilities for several types of recyclable waste in Turkey, whereas this number of licensed facilities in Turkey has increased to 956 by 2012 (European Environment Agency, 2013).

Ministry of Environment and Urbanization of Turkey (MoE&U) estimated that GHG emissions were 401.9 million tonnes CO_2 equivalent in the year 2010. 71% of GHG emissions was contributed by energy generation activities while only 9 % the emissions caused by waste (Ministerie van Buitenlandse Zaken, 2013). In 2005, Turkey has adopted a legislation called “Renewables Law” that identifies the scope and size of the facilities for renewable energy production. 2 years later, an incentive was initiated to encourage electricity production through renewable energy sources. The incentive allows renewable electricity producers to sell their produced electricity with a price of 5- 5.5 $cents/kWh for 10 years. In 2010, the guaranteed incentive has been ameliorated to 13.3 $cents/kWh for electricity production generated from biogas that means the electricity producers in Turkey can sell the electricity via the electricity grids with a fixed price. The law also provides renewable producers to benefit 85% discount on transmission cost in a period of 10 years. In 2012, Turkey has implemented a new control mechanism on “Mandatory monitoring, reporting and verification emission data (MRV)”. In addition, Turkey is also a candidate to EU accession and thereby aims to comply with the environmental obligations of EU including EU-ETS directive (Ministerie van Buitenlandse Zaken, 2013; Icapcarbonaction.com, 2017). In the lights of EU directives and IPCC guidelines on waste management, utilization of waste and restricting the emissions released from landfills are considerably recommended (EU 99/31/EC; IPCC, 2007). In addition to that, according to the planned reduction in the amount of biodegradable waste, the implementation of EU Landfill Directive will be implemented by 2025 in Turkey (European Environment Agency, 2013).

Unfortunately, there are not enough numbers of reliable data regarding the future trends of the MSW in Turkey. However, there are some important developments of legislation mentioned above that can be considered as the sign of potential future trends in MSW practices. Accordingly, most of the EU waste management directives related to MSW have been implemented into Turkey’s national legislation.

1.3 Objectives and Research Questions

The main objective of this thesis is to compare environmental impacts of different utilization possibilities for the landfill gas. The methods planned to achieve these objectives is to assess the environmental and economic potential of different approaches for the effective LFG management. The assessment will be done as a case study. Therefore, the following research questions are considered as suitable with the aim of this thesis;

- What are the environmental and economic consequences of applying different technical approaches for the LFG recovery and utilization in “Odayeri Landfill”?
- What are the critical factors of the feasibility and performance for the “Odayeri Landfill”?
- How and why carrying out LCA is important for sanitary landfills?
- What are the prominent environmental impact categories in LFG management?

2 LITERATURE REVIEW

2.1 Landfill Gas Generation

2.1.1 Characteristics of Landfill Gas

Landfill gas is produced from waste by a chemical decomposition or degradation process taking place in anaerobic conditions. Several factors affect this process such as temperature, moisture content, waste combination, type of substances for microbial degradation (Bove and Lunghi, 2006).

After municipal solid wastes landfilled, organic compounds start to decompose with biochemical reactions. Waste decomposition consists of four separate phases:

1. Aerobic decomposition: The organic compounds in this phase are oxidized aerobically at near the surface of landfill in the presence of oxygen. This stage also resembles a combustion reaction because of the oxygen consumed, and the heat (water vapor) and carbon dioxide produced (Themelis and Ulloa, 2007).
2. Acidogenic: In this phase, anaerobic reactions start after the conditions are established. Expectedly, CO_2, water, H_2 and organic acids are produced. Energy release rate is low due to the anaerobic circumstances. Ph level decreases below 5 and acidic formation occurs (Bove and Lunghi, 2006).
3. Acetogenesis: In this phase, acids and alcohols are oxidized to acetic acid, propionic acid, butyric acid and ethanol. Additionally, CO_2 and H_2 are produced. The reaction in this phase according to Themelis and Ulloa (2007) is represented in Equation 1 below;

$$C_6H_{12}O_6 \text{-} \; 2C_2H_5OH + 2CO_2 \qquad \text{(Eq.1)}$$

4. Methanogenesis: Product of acetogenesis phase is converted by methanogenesis bacteria to produce methane and CO_2. According to Themelis and Uloa, 2007, this is carried out two different reactions: decomposing the acids to methane and CO_2, or reacting H_2 with CO_2. Two different equations are shown below;

$$CH_3COOH \text{-} CH_4 + CO \qquad \text{(Eq.2)}$$

$$CO_2 + 4H_2 \text{-} CH_4 + 2H_2O \qquad \text{(Eq.3)}$$

Some researchers have assumed that there are five phases including Maturation Phase as the last one (Harper and Pohland, 1986; Bove and Lunghi, 2006).

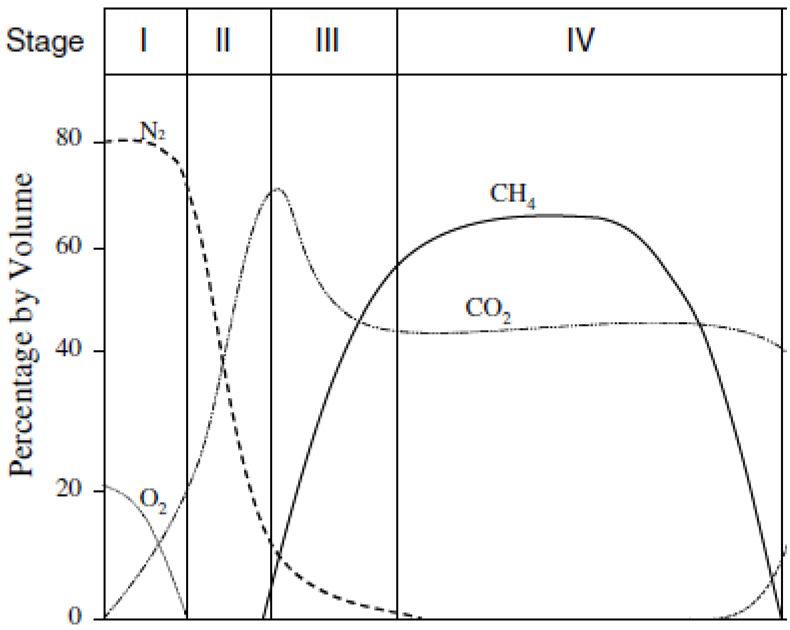


Figure 1. Landfill gas composition during 4 phases (Source: Themelis and Uloa (2007))

According to Themelis and Uloa, 2007, average concentrations of compounds in landfill gas are illustrated in Table 1 below;

Table 1.*Composition of Landfill Gas (Source: Themelis and Uloa (2007))*

Compound	Average Concentration
Methane (CH_4)	50
Carbon dioxide (CO_2)	45
Nitrogen (N_2)	5
Hydrogen sulphide (H_2S)	<1
Non-methane organic compounds (NMOC)	270ppmw

LFG or biogas contains water vapor when it is near to the saturation point that represents the cell temperature. In addition to H_2S, very few amounts of ammonia and other minor compounds are contained in LFG. At this point, the presence of water is important nuance in terms of maintaining the anaerobic reaction. According to Equation 4 shown below, CH_4 and CO_2 has 54% and 46%, respectively. The composite organic compound's molecular weight is 146 and water is 18 g/mol. This equation also specifies that 5.4. kg of Organics gets reacted by each kg of water. As general, MSW contains at least 20% of moisture which is enough to cause the reaction with the biomass. However, the performance of the anaerobic bacteria is stimulated with a higher percentage of moisture content in MSW, thus consistency on water addition is essential (Themelis and Ulloa, 2007).

$$C_6H_{10} + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2 \qquad \text{(Eq.4)}$$

2.1.2 Factors Affecting Generation

Waste degradation for landfill gas can last for decades but this duration depends on several factors, such as Ph, temperature, moisture content, the density of the waste and nutrient content. As mentioned earlier, the moisture content in the waste is an essential factor highly affecting LFG generation performance. Nutrient content is the second essential parameter because the nutrient is necessary for the methanogenic bacteria in its reaction. The length of gas production is dependent on the quantities of available nutrients. The optimal range of pH and temperature provides bacteria more effective performances. Particle size and density of waste also affect the gas production rates (Gowing, 2001). El-Fadel, Findikakis and Leckie show the influence of the factors and represent an overview of evaluation in the studies examined in their literature study, which is presented in Table 2 (El-Fadel, Findikakis and Leckie, 1997).

Table 2.*Effect of variables influencing gas generation (Source: El-Fadel, Findikakis and Leckie, 1997).*

Variable	Gas Enhancement Potential			Gas Inhibition Potential		
	Low	Medium	High	Low	Medium	High
Composition		+		–		
Density	+					
Particle size	+					
Temperature		+			–	
pH		+		–		
Nutrients	+			–		
Microbes	+			–		
Moisture			+			
Oxygen						–
Hydrogen	+			–		
Sulfate				–		
Toxics					–	
Metals				–		

2.1.3 Landfill Gas Generation and Emission

Gas generation estimation is an essential part in applying LCA to assess environmental impacts caused by LFG. The CH_4 generation estimations can be carried out by using different methods and measurements for an individual landfill. LandGEM, EPER, GasSim, Waste Model, TNO, LFGGEN, and IPCC First Order are the well know LFG or CH_4 generation estimation methods that have been developed over the years (Spokas et al., 2006; Niskanen et al., 2013). These methods and measurements are mostly focused on the relationship between landfilled waste data, decomposition studies in laboratory or test cell projects. During the study of Spokas et al. (2006), the predicted amount of CH_4 gas generations in the three landfills were successfully validated by using an estimation model based on first-order degradation model. The generated CH_4 was estimated by following equation (Spokas et al., 2006):

$$V = G \sum_{n=1}^{Z} A_n\, C_{org,n} k_n e^{-k_n t} \qquad \text{(Eq.5)}$$

$V = CH_4$ production (m^3)

$G = 0.94\ m^3\ CH_4\ kg^{-1}$ organic carbon, which is the formation constant

A_n = the total amount of waste stream n present in refuse (kg)

$C_{org,n}$ = the amount of organic carbon presence in waste stream n

K_n = the half-life of waste stream n (yr^{-1})

t = how many years have been since the start from filling

Z = number of waste categories

After the measurement outcomes, the study was found favorably in multiple landfill sites (Spokas et al., 2006). More general, the CH_4 estimation method is typically defined by using similar form of Equation 6 (Niskanen et al., 2013):

$$G = W_a L_0 k e^{-kt} \quad \text{(Eq.6)}$$

$G = CH_4$ production rate from a single year's refuse ($m^3\ CH_4$/year)

W_a = annual waste acceptance rate (tonne/year)

L_o = maximum methane yield ($m^3\ CH_4$/tonne)

K = decay rate (per year)

t = the elapsed years from start of filling

According to Themelis and Uloa (2007), due to the fact that sulfur and nitrogen are minor components and occur fundamentally in mixed and food wastes. Additionally, if nitrogen and sulfur are excluded, the molecular structure of mixed paper is very similar to cellulose, $(C_6H_{10}O_5)_x$. If the minor elements are excluded, the approximate molecular structures in MSW can be associated with the molecular composition $C_6H_{10}O_4$ (Themelis and Ulloa, 2007).

Typical MSW contains 69.5% biomass materials in a landfill and rest of them are petrochemical materials, such as plastics, rubber and nylon. Biomass materials also include moisture and some inorganic particles. It is assumed that the amount of dry material in the biomass corresponds to 60% and results in the approximate of 2.86 kmol (417 kg) of

$C_6H_{10}O_4$ /tonne of total MSW. According to equation 4, 208 m^3 of CH_4 gas or 0.149 tonnes of CH_4 is generated by one tonne of MSW (Themelis and Ulloa, 2007). Then, this inference found in the Themelis' study was compared with the other reported data of anaerobic digestion in the literature and found quite similar to each other (Themelis and Ulloa, 2007).

$$C_6H_{10}O_4 + 1.5H_20 \rightarrow 3.25CH_4 + 2.75CO_2 \qquad \text{(Eq. 7)}$$

Estimation of released LFG emission is another essential part of LCA modelling. There have been several studies conducted researches on this subject and different measurement methods have been used for gas emission evaluations. Estimation of the gas emissions was carried out through a micrometeorological method by Lohila et al. (2007); tracer methods were used by Spokas et al. (2006), Börjesson et al. (2007); and with flux chambers by Spokas et al. (2006).

2.1.4 CH_4 oxidation in landfill top cover

CH_4 oxidation is an aerobic process where CH_4 emissions are oxidized by O_2 in the biosphere. It may appear the emission of CH_4 from waste and fluctuating O_2 from the ambient air, which enables the necessary environment for the activation of methanotrophic bacteria (Scheutz et al., 2009)

Aerobic CH_4 oxidation proceeds with the following reactions in Eq. 8 below:

$$CH_4 + 2O_2 \text{ --- } CO_2 + 2H_2O + \text{heat} \qquad \text{(Eq. 8)}$$

$$\Delta G° = -780 \text{ kJ mol}^{-1} \text{ CH}_4$$

(Source: Scheutz et al., 2009)

Understanding the affecting factors on CH_4 mass balance are necessary to effectively manage the CH4 oxidation processes displayed in Figure 2 (Scheutz et al., 2009). The relationship of CH4 mass balance is characterized below:

CH_4 production = CH_4 recovered + CH_4 emitted + Lateral CH_4 migration + CH_4 oxidized + Δ CH_4 storage (all units = mass t^{-1}; from Bogner and Spokas 1993)

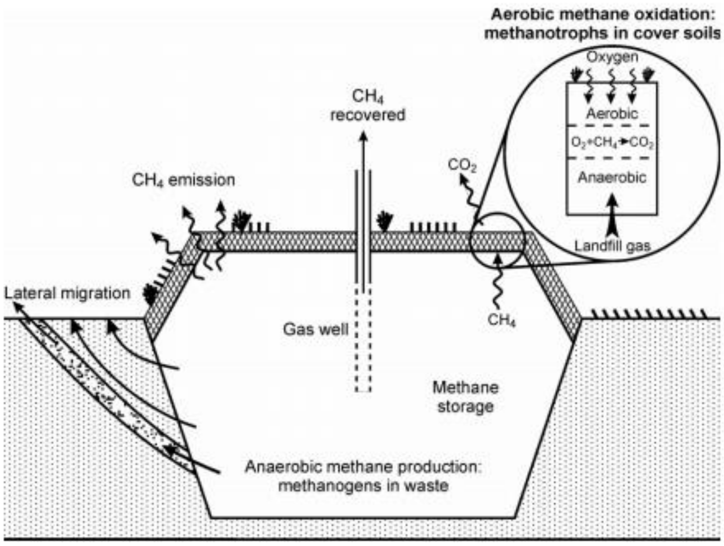


Figure 2. Landfill methane mass balance (Source: Scheutz et al., (2009)).

There are numbers of environmental factors influencing CH_4 oxidation in landfills, thus the CH_4 oxidation rate depends on the factors; such as soil structure, soil cover temperature and moisture, the presence of CH_4 and O_2, pH, nutrients, etc. In the literature review studied by Scheutz et al., (2009), CH_4 oxidation rates obtained for soils vary from 10% to 100% in column and batch experiments. With a suitable soil cover, in optimum conditions, the maximum oxidation rate can be obtained up to 100 % (Scheutz et al., 2009).

All the countries in the United Nations Framework Convention on Climate Change (UNFCC) are required to collect GHG inventories including oxidation. These estimations are based on national level estimates for landfilled waste, the estimated amount of LFG generation, the CH_4 content of LFG, LFG recovery and CH_4 oxidation. GHG estimations at the national level, especially for developing countries are highly unpredictable because the about solid waste data might not be available and quantified. CH_4 oxidation rate is specifically applied as default values from 0 to 10% by the IPCC based on greenhouse gas inventories (IPCC, 2006). These values specifically determined in Scheutz et al., (2009)'study: 0% for developing countries and 10% for developed countries. (Scheutz et al., 2009).

2.1.5 Gas Collection

Gas collection efficiency is a landfill specific factor defined as the average amount of LFG collected and it depends on landfill conditions, such as; top cover types and thickness, landfill cell configurations and gas collection systems (Spokas et al., 2006; Niskanen et al., 2012). According to the guidelines made by Ministry of Environment of British Columbia, there are details needed to be considered for gas collection efficiency in landfills. In case of downtime in LFG management system and below 50% CH_4 content in LFG will result in a decrease in the average flow rate of LFG that is collected (Ministry of Environment, 2010). The United States Environmental Protection Agency, USEPA and Ministry of Environment of British Columbia, are treated the 75% collection efficiency as both a design standard and a performance objective for engineered landfills (Ministry of Environment, 2010; USEPA, 2008). In addition to that, collection rate values vary by different top cover types. Another guideline prepared by French Environmental Agency identified default values for the collection rate in active LFG recovery systems: 35% for an operating cell, 65% for a temporary covered cell, 85% for a clay covered cell with clay final cover, and 90% for a cell with geomembrane final cover (Spokas et al., 2006).

2.2 LFG Flares

The collected LFG is typically flared or utilized. Flaring the LFG in high temperature converts the methane component of the gas to carbon dioxide and water, and GHG emissions are primarily aimed to reduce by decreasing the CH_4 gas through flares. Flares are generally used in the events of the utilization system is down for maintenance or repair, or a surplus of LFG is burnt (Ministry of Environment, 2010). According to the Landfill Directive of European Environmental Agency, landfill gas must be collected and treated from all landfills receiving biodegradable waste. If the collected gas cannot be utilized, then it must be burnt by flares (European Environmental Agency, 1999).

The treatment efficiency of organic compounds in the combustion is generally indicated between 95% and 100% by the US Environmental Protection Agency. (USEPA, 2008). Besides, UNFCCC identifies the default value for flare efficiency as 90% for enclosed flare (UNFCCC, 2006).

2.3 Energy Utilization

LFG is considered as a valuable source of energy that consists of approximately 50% of CH_4 gas, which means that it equals to half of the energy content of natural gas. Utilizing LFG also reduces GHG emissions caused by methane in LFG and produces renewable energy. In addition to that, LFG is sort of a CO_2-neutral fuel that can substitute fossil fuel and thereby reduce CO_2 emissions in the atmosphere. Therefore, LFG should be utilized to produce energy if LFG utilization is economically feasible (Terraza and Willumsen, 2009).

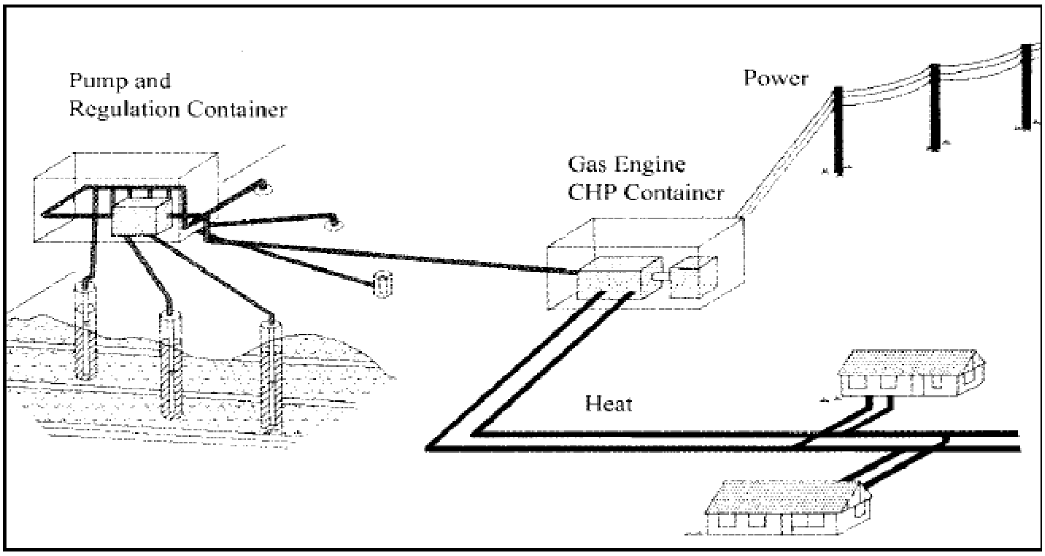


Figure 3. System for a landfill gas plant. (Source: Willumsen (2001))

There are several methods for energy recovery from landfill gas. The most common method of utilizing LFG is to produce electricity in a gas engine/generator unit. Another common method is to use LFG in a combined heat and power (CHP) plant for generating electricity, heating and producing hot water in a gas boiler or steam. Additionally, LFG can be utilized for heat only purposes (buildings, district heating or industrial steam). There are also other possibilities to use LFG for energy purposes, such as upgraded to natural gas quality as fuel for vehicles, leachate evaporation, direct use, etc. The numbers of utilization options are schematized in Table 3 below. The different use of LFG is described in the following sub-sections (Terraza and Willumsen, 2009; Willumsen 2001).

Table 3*.Utilization Options of LFG (Source:Themelis and Ulloa (2007))*

Direct heating applications	Use for industrial boilers Space heating and cooling (e.g. for greenhouses) Industrial heating/cofiring
Electricity generation applications	Processing and use in reciprocating internal combustion (RIC) engines (stoichiometric or lean combustion) Processing and use in micro-turbines, gas or gas and steam turbines combined cycle Processing and use in steam turbines Processing and use in fuel cells
Feedstock in chemical manufacturing processes	Conversion to methanol (industrial or vehicular use) Conversion to diesel fuel (vehicular fuel)
Purification to pipeline quality gas	Utilization as vehicular fuel Incorporation into local natural gas network
Soil remediation	Leachate evaporation system
Heat recovery from landfill flares	Using organic Rankine cycle Using Stirling cycle engines

2.3.1 Electricity Generation

The use of LFG for electricity generation is a promising method both in terms of utilizing energy and its benefits to reduce air pollution. High-grade LFG is typically preferred to be used for electricity generation. LFG contains plenty of trace components as well as CO_2, CH_4 and a smaller amount of O_2 and N_2. (Qin, Egolfopoulos and Tsotsis, 2001).

As the most used technology for electricity generation from LFG, a RIC (reciprocating internal combustion) engine is used primarily to produce electricity and to provide the waste heat source for heat recovery (Hao et al., 2008). Reciprocating type of engine is a trusted technology in terms of a range of size and lowest first capital costs for CHP systems. In addition to good operating capability and practical use, there is a high efficiency at partial load operations, which provides users to have a flexible power source, and coming with a different range of energy utilization applications. However, reciprocating engines generally have high vibrations that need shock absorption and shielding measurements to minimize acoustic noise. Considerable numbers of moving parts, regular maintenance times, and increased maintenance costs significantly decrease fuel efficiency advantages in this system. In addition, high emissions from this technology – especially nitrous oxide- is a fundamental drawback that needs improvement. Big manufacturers around the world try to produce engines with lower emissions. Besides, there is an emission control option that reduces emissions during the operations named as selective catalytic reduction (SCR) (Wu and Wang, 2006).

According to Hao et al., (2008), the range of the efficiency of RIC in electricity production is between 25-45 %, which means that more than half of the fuel energy not used. In order to make LFG utilization environmentally and economically feasible, more efficient energy recovery technologies should be implemented. Cogeneration (combined heat and power, CHP) and trigeneration (combined cooling, heating and power, CCHP) are efficient ways for energy recovery in LFG applications (Hao et al., 2008).

2.3.2 Combined heat and power production (Co-generation systems)

Heating applications of LFG provide more energy conversion efficiency than that for only electricity generation. Due to the low-grade LFG is generally used, the equipment should be designed to process on this fuel and withstand the various trace components that cause corrosion in the combustion engines (Ministry of Environment, 2010).

This section explains the co-generation systems that are suitably used for LFG utilization applications. CHP is typically defined as a combined production of electrical and useable thermal energy from the same energy source, while combined cooling, heating and power (CCHP) technologies come from combined heat and power (CHP) that is a proven and reliable application over a period of 100 years, which is mainly used in large-scale centralized power plants. The slight difference between CCHP and CHP is that thermal or electrical energy is also utilized for space or process cooling purposes in a CCHP implementation (Wu and Wang, 2006).

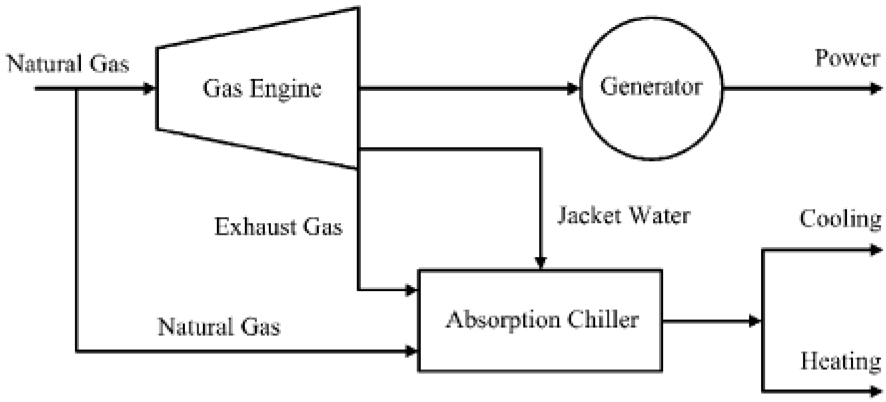


Figure 4.Typical CCHP System (Source:Wu and Wang, 2006)

RICs (reciprocating internal engines) operate in Otto Cycle Principle, which converts linear movement of the piston to the circular movement of the crankshaft connecting with a rod linked between the piston and the crankshaft. The rotating shaft runs the generator to produce electricity. During the power generation, the other forms of heat generations at different grades are simultaneously produced by the RIC engine. These different forms reveal in the hot temperature exhaust gas, the jacket hot water, the thermal energy from the lube oil cooler, the thermal energy from the inter-cooler, and the radiation and balance heat. Generally, these thermal energies are dispersed into ambient air or water directly or indirectly by heat exchangers. The typical efficiencies of CHP systems are estimated as 45% for electricity and 40% for heat + cooling, while heat and electrical line losses are 13% and 2% respectively (Hao et al., 2008). Typical CCHP system is illustrated in Figure 4.

2.3.3 Organic Rankine Cycle

Rankine cycle is a closed loop system where working fluid repetitively circulates through four steps to convert the waste heat into mechanical or electrical power. (Sprouse and Depcik, 2013).

Water as working fluid is mostly suitable for high-temperature applications and large-scale systems. The problems occurred with using water in medium and small centralized applications can be amended by selecting another suitable working fluid. Organic compounds have a relatively higher molecular mass that leads to several advantages over the conventional steam power plant. The main reason of being preferred organic cycle is that organic fluids provide higher efficiencies at low temperatures as Organic Rankine Cycle is used for biomass applications. Another main reason of ORC is the economic and legal advantage that water performs good efficiency at high pressure requiring measures of safety that are not considered economically feasible for small plants (Drescher and Brüggemann, 2007).

Iso-butane or propane is typically used in ORC as the water is not preferred. According to Drescher and Brüggemann (2007), in most of the biomass ORC applications, octamethyltrisiloxane (OMTS) is chosen as a working fluid. OMTS performs relatively low thermal and heat recovery efficiency for high temperature ORC (Sprouse and Depcik, 2013; Drescher and Brüggemann, 2007).

The ORC is continuously used for geothermal energy conversion. Since it is known that the ORC is an external combustion engine and if the energy source of ORC process is LFG, no technical and operational differences happen. Since it is understandable to expect that the performance depends on the input energy content and not on the fuel type, these data in Table 4 considered as a reference for an ORC system working on LFG. However, it should be noted that some deviations might occur during the calculations on the emissions when the ORC is operated with LFG (Bove, R. and Lunghi, P. 2006).

__Table 4__.Emissions depending on the LFG combustion system (Source:Bove and Lunghi (2006)).

Electric efficiency	18%
Fuel consumption (kJ/kWh)	19202
Emissions (µg/kJ)	-
NO_x	16
CO	18.9

The numbers of ORC-installed plants are increasing dramatically as the ORC technology is becoming trusted and cost-effective. Although, there are at least 100 plants that implemented ORC technology in their systems, finding the available data on existing plants are quite challenging. Tchanche et al., (2011) reached the evaluation performance of two plants in Austria: Admond CHP Plant (400 kWe) and Lienz (1000 kWe). The plant in Lienz produces 60,000 MWh/year for district heating and feeds 7200 MWh/year of electricity into the grid. The overall plant efficiency performs up to 82%, while the plant is fully automatic with a proper part load operation with the electrical efficiency of 18% (Tchanche et al., 2011).

2.3.4 Upgrading the Methane

LFG can be upgraded to the quality of natural gas feeding into natural gas distribution network to be refueled in gas refueling stations. This method is economically more profitable when the gas is suitable for that, but big investments in gas purification are necessary. Before it can be commercialized as natural gas, some compounds such as liquid, CO_2, N_2, and trace components such as H_2S should be removed from LFG. Thereby, the methane concentration increases and becomes the form of biomethane Therefore, the purity of LFG can be accomplished as natural gas in most cases is almost 100 percent CH_4. In addition to the purification process, the gas must be odorized (Terraza, H. and Willumsen, H. 2009; Willumsen, H. 2001).

The upgrading methane process has gained a significant popularity due to decreasing fossil fuel use and increasing attention on renewable energy activities in many countries. However, upgrading methane adds costs on the biogas production. It is thus important to have an optimized upgrading system in terms of low energy consumption and high methane content in the upgraded gas (Wellinger and Petersson, 2009).

Many places in the world, for example, the US, Europe, Brazil, etc., there are plants in which LFG is compressed and used in either for transmitting to natural gas grids or types of vehicles, buses or ordinary cars. The gas quality requirements are the same as those for being upgraded to natural gas quality. The feasibility of using LFG in vehicles depends on the factors such as chosen system, tax system, landfill generation/capture rate (Terraza, H. and Willumsen, H. 2009).

There is a number of technologies available on the market such as water scrubbing (WS), pressure swing adsorption (PSA), membrane separation (MS) (Starr et al., 2012). CH4 content of biomethane is typically assumed to be 97% for feeding biogas into the natural gas grid. CH_4 losses during the upgrading process contribute to GHG emissions besides to power supply (upstream process). The desulfurization process is applied in PSA method to allocate the entire energy consumption. The upgrading process with PSA generally reaches a methane content of 95%. In this case, propane is required to be dosed into the PSA-upgraded biogas. CH_4 loss that corresponds to 1.5% of the overall amount of collected CH_4 (Pertl et al., 2010). Apart from that, according to another report carried out by SGC, the CH_4 loss during the PSA upgrading process is measured as 1,8% (Svenskt Gastekniskt Center AB, SGC, 2013 (Pertl et al., 2010).

Two different measurement of the $CH_{4,}$ the amount of energy and chemicals needed during the upgrading processes are presented in Table 5.

If there is no grid available, the biomethane should be transported in liquid or compressed form by truck, ship or rail. Distributing the biomethane via natural gas grid leads to lower GHG emissions than does compressed biomethane handling by trucks. In terms of distance, the nearness between the natural gas grid and refueling stations is important to emit lower emissions (Uusitalo et al., 2014).

Table 5. Energy and chemicals consumptions associated with upgrading technologies

Upgrading Technologies	Methane Loss (%)		Electricity Consumption [MJ/m^3]	Propane Consumption [Nm^3/m^3]
	Pertl et al (2010)	SGC (2013)		
PSA	1,5	1,8	1,87	0,013
WS	1,5		1,14	0
MS	6		1,8	0

2.4 Legislative framework for LFG management

Energy demand in Turkey is increasing every year. To decrease the dependency on petroleum and natural gas, the country encourages the energy recovery activities from renewable resources that contain biogas. Besides, the accession process to the EU plays a vital role in shaping the environmental road map of Turkey. Since the country has adopted its targets and aims for EU harmonization, investments have started by establishing of sanitary landfills over a period of years. Therefore, the laws and regulations for energy generation from LFG aim to leverage renewable energy usage and ensure that the country maintains its environmental targets and goals both for EU accession and the country's own progress.

Landfill gas generation is regulated by following laws and regulations:

I. Electricity Market Law (Law No. 4628): The aim of this law is to make sure that the development of a financially sound and transparent electricity market operates under the provisions of civil law; the delivery of sufficient, low cost, a good quality, environmentally friendly electricity to customers in proper conditions and to comply with the autonomous regulation of this market. This law only covers electricity generation (Ministerie van Buitenlandse Zaken, 2013; Icapcarbonaction.com, 2017).

II. Law on Utilization of Renewable Energy Resources based on Electrical Energy Production (Law No. 5346): it is also named as "renewable law" approved in 2005. The scope of this law covers the renewable energy sources, such as wind, solar, geothermal, biomass, biogas, wave, current and tidal energy resources, and hydro plants with a less than 15 km^2 area. An incentive was released in 2007 stating that there will be a guaranteed tariff of 5-5.5 $ cents per kWh for electricity generation through renewable resources. In 2010, the incentive has been improved to 13.3 US$ cent/kWh for electricity generation based on biogas. Renewable energy producers also benefit from having an 85% discount over transmission cost for a period of 10 years (Ministerie van Buitenlandse Zaken, 2013; Icapcarbonaction.com, 2017).

III. Regulation on Production of Electricity Without a License (Official Newspaper No. 27774): According to this law, for those who produce electricity through renewable resources at facilities less than 500 kW of installed capacity and less than 50 kW of installed capacity at micro-cogeneration facilities. The producers are able to sell their excess electricity production to the national grid. The price is determined as the feed-in tariff in the case the electricity is produced by renewable resources, while the price is set as the average wholesale price for electricity production at micro-cogeneration facilities. In addition, there are additional incentives for those who prefer using local (Turkish) equipment that may add 0.4 cents to 2.4 cents per kWh to the price for five years (Ministerie van Buitenlandse Zaken, 2013). These incentives can be seen in Table 6.

Table 6*.Additional Incentives for local components (Source: Ministry of Energy and Natural Resources)*

Source	**Locally produced parts**	**Additional Incentives (US$ cents/kWh)**
Biomass	Fluid based steam boiler	0.8
	Fluid or gas fired steam boiler	0.4
	Gassing and gas cleaning group	0.6
	Steam or gas turbine	2.0
	Engine	0.9

2.5 Environmental Impacts of LFG

The number of studies in last 2-3 decades has identified that landfilling remains as a threat to the human health and the environment with the existence of LFG and liquid leachate. Both contain several hazardous chemical compounds by generating various type of waste decomposition processes. LFG consists of 50-60% CH_4 and 30-40% CO_2 with some sort of compounds such as aromatics, chlorinated organic compounds, and sulfur compounds.

CH_4 and CO_2 are both considered within GHGs as both contribute to global warming. Global warming is undoubtedly one of the most important environmental issues of the world. It is illustrated in IPCC's report that the release of greenhouse gasses (GHG) can cause increases in the global average temperature as well as climate change at a regional level (IPCC, 2007). Global warming potential (GWP) is the most emphasized environmental impact category in this study as it evaluated carefully for all the landfill gas utilization scenarios that have been created. The most significant GHGs in these scenarios and their comparable GWP over 100 years are Carbon dioxide (CO_2= 1 GWP100), Methane (CH_4=23 GWP100), Nitrous Oxide (NO_x= 310 GWP100). Landfills are the main contributors of anthropogenic CH_4 emissions and accounted for 3 to 4% of anthropogenic GHG emissions globally (Han et al., 2009).

The gas engines that are mostly used for LFG utilization, and particularly the gas engines cause more air pollutant particles than gas and steam turbines. Due to the imperfect combustion, the gas engine exhausts substantial quantities of nonmethane organic compounds and carbon monoxide (CO) as far as a lot of nitrogen oxide compounds (NO_x). It is well known that nitrogen in the air is oxidized by the operation conditions at high temperature, and thus forms a thermal NO_x. Therefore, it is challenging to install a gas engine in a facility if there are strict regulations on air pollution (Shin et al, 2005).

The amount of the avoided GHG emissions depends on the emission factor (emission value) for the substituted electricity production in the modelling, and thus which varies substantially based on the selected GHG emission value (Niskanen, 2012).

Waste disposal and pollution are inseparably related. All solid wastes are complex mixtures resulting in deterioration before any collection and treatment, which is usually occurred due to storage conditions. Particularly processed solid wastes and some indicated materials contain significant origins of several pathogens. Undoubtedly, those pathogens have a potential to pose catching diseases, and this potential remains not necessarily solved. Thus, no current treatment technologies can totally remove such risks. Wastewater and waste sewage sludge treatments are effective methods to mitigate of the diseases such as epidemics and waterborne. Besides, LFG collection and treatment reduce the risk of pathogen-related diseases. However, the mechanisms that are in charge to inactivate pathogen in such processes are still needed to have further studies. Nevertheless, those treatment processes minimize the pathogens to spread during treatment (Hamer, 2003).

Landfill fire precautions require attention in LFG management system. Fires can pose for several reasons in many areas, including operations of a LFG management system and chemical reactions occurred in the landfill itself. Landfill fire possibilities can be prevented by an effective strategy addressing fires if they happen. Therefore, having a fire management plan is strongly recommended, and that plan is directly included in the operation of the LFG management system.

LFG collection and treatment reduces the risk of landfill fires as the combustion and leachate treatment processes are managed well. On the other hand, landfill fires cause serious health problems to human and the LFG management system itself because of the insecure conditions occurred. Toxic gases can be emitted by the burning waste. If the landfill fire reveals in conjunction with LFG management system equipment, site workers may be harmed by any interaction with the equipment. In addition to that, landfill fires have a great environmental risk on the landfill and the surrounding area. Uncontrolled combustion of halogenated compounds generally causes the emissions of dioxins and furans; as the emitted toxic gases are previously stated (Ministry of Environment, 2010).

2.6 Economic Evaluation of LFG Recovery

Apart from environmental assessment, the economy is an important determinant on municipal waste management, it is crucial to analyze this aspect systematically as the environmental aspect. Economic evaluation of LFG depends on the numbers of factors, including energy marketability, energy prices, equipment selections, landfill gas quantity and transportation cost. More specifically, there is a number of main cost and revenue factors for economic assessment of landfill management. Main cost factors can be considered as investment cost and O&M cost, while revenue factors are mostly about production (tonnes/year) and selling price (€/kWh) (Aye and Widjaya, 2006). The core aim of doing an economic evaluation for waste - energy projects is to make the selling price of the production (e.g. electricity, thermal energy, biomethane, etc) profitable. Jaramillo and Matthews (2005) found out that 0.04$/kWh electricity price is profitable to make the waste-energy projects profitable. Larger landfills would require lower electricity prices because there is larger LFG generation potential (Jaramillo and Matthews, 2005).

Shin et al., (2005) indicated in his study that economic criterion of LFG is carried out by cost and profit analysis. Cost analysis includes capital cost, annual operation and maintenance cost, and in the meantime, carbon and energy tax will be added according to the climate agreement principles for a region/country in which the procedures of climate change and carbon taxes have been already implemented (Carlsson Reich, 2005; Shin et al., 2005). In addition to this analysis method, another economic method called Cost-Benefit Analysis (CBA) represented in Perkin's study. CBA basically aims to evaluate all the negative and positive impacts over monetary terms (Perkins, 1994).

In addition, there would be a remarkable advantage if the system studied for the economic analysis and the LCA have the same system boundaries, and thereby the two analyses supplement each other in the decision process. Accordingly, life cycle costing (LCC) as an economic analysis method is sometimes used in a combination with an LCA over the same system boundaries. LCC is often used for analyzing of all costs of a product with a long-life span or with a high running cost, and this type of analysis views the waste management system as a single economic actor and estimates the annual life cycle economic costs of waste treatment facilities (Carlsson Reich, 2005). The cost is inclined to focus solely on the treatment of municipal solid waste, and excluded from indirect costs such as indirect property values of constructing a landfill (Cleary, 2009).

3 METHODOLOGY

This chapter generally presents the methods used for this study. LCA is used for environmental impact assessment, while CBA is preferred to be used for economic assessment of the case landfill in Istanbul.

3.1 Life Cycle Assessment

Life cycle assessment is a method that can be used to assess the environmental impacts of a product, material, process or activity. An LCA is a comprehensive and an internationally standardized method for evaluating potential environmental impacts with the full life cycle of a product system (ISO, 2006a and 2006b). According to the ISO standard, a LCA should consist of four distinct phases, as presented in Figure 7.

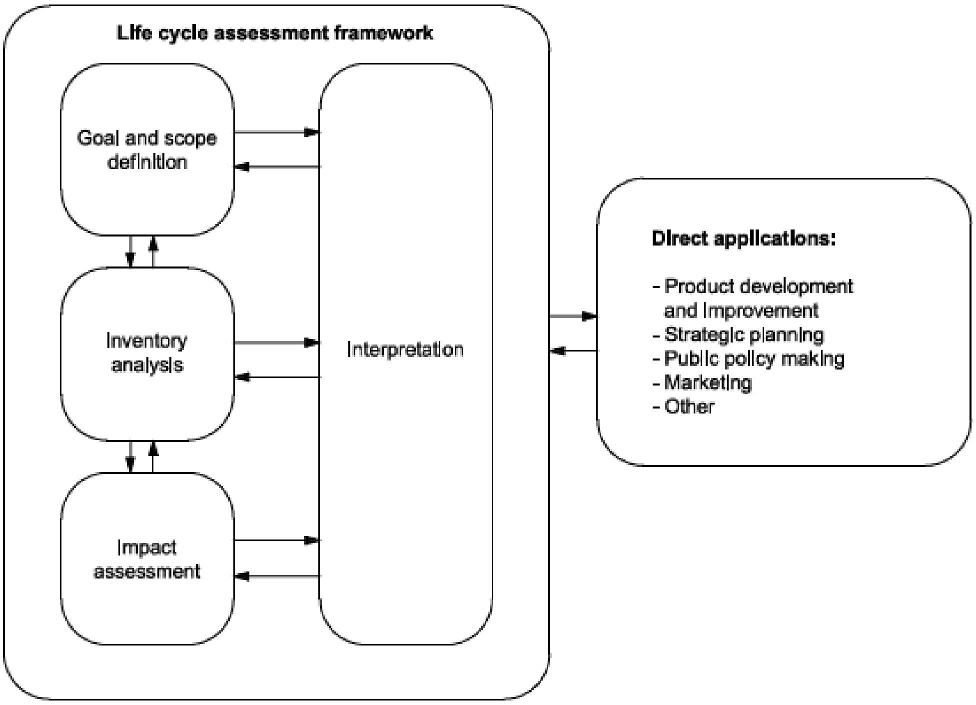


Figure 7. Stages of an LCA (Source: ISO 2006a).

3.1.1 Goal and Scope Definition

In this phase, the LCA practitioner should define the goal and scope of a study as related to a planned LCA model. Functional unit (FU) is an important basis to be specified that enables to find alternative goods, or services, to be compared and analyzed (Rebitzer et al., 2004). In other words, the FU makes sure that comparison among the different alternatives gives a clear understanding when relating to the same unit. With regards to waste management system, the FU can be indicated, for instance, the treatment of one tonne of waste, the treatment of all waste in a year for a facility, the amount of waste received or converted to biogas in one year for a facility, etc. When defining the FU, defining the time horizon of a study is important, how long the emissions and biogas will be examined for, what will be the condition of the substances after the utilization period, etc. Likewise, system boundaries should be specified, which parts will be included and excluded from the study. Generally, LCA studies refer to be performed in “cradle to grave approach”, which accounts all the emissions of a product or a system from extracting the raw material of the product until the disposal of the product. However, it is almost impossible to implement the cradle to grave approach into a waste management study as life cycle of the product before dispatching to the disposal is largely unknown or it is hard to control this part in the chain for a waste handler. Therefore, the collection, the transport to waste treatment facility, treatment and disposal processes are accounted during a waste LCA. This approach also refers as zero burden, which means any contribution before the dumped waste is excluded from the study.

The case study is based on Turkish conditions, but the issue is not restricted to Turkey only since alternative energy utilization systems can be found in many countries especially in Europe, Northern America. In addition to that, any related issues to leachate are excluded from the study.

As it mentioned earlier, this thesis aims to create 4 alternative LFG utilization scenarios and to make a comparative environmental and economic assessment based on the landfill in Istanbul, Turkey. Due to the FU is set to be the amount of collected gas in the Odayeri Landfill in 2014, all the scenario settings are based on this amount and the possible fluctuations within the following years in the collection rate, the oxidation rate, the methane generation, vs. excluded from the study.

3.1.2 Life Cycle Inventory Analysis

In the inventory analysis phase, all the quantities of emissions and waste flow caused by a product's life cycle are estimated and accounted. The processes and the related material and energy flows are formed to demonstrate the product system, and to gather its overall inputs and outputs to or from the environment (Rebitzer et al., 2004). This creates the production system model and an inventory of a LCA, which requires being used in Impact Assessment. The models used for calculating the inventory data are described in detail in this chapter.

LFG content and the amount of LFG collected in the landfill for this study are based on the data provided by Ortadogu Energy (2017) that is illustrated in Table 7 and Table 8 respectively (Ortadogu Energy, 2017). Air emissions from gas engines and upgrading process are carried out by Fruergaard's study in which waste to energy principles are widely studied (Fruergaard and Astrup, 2011). Emissions associated with combustion of biogas in the gas engine is presented in Table 9, and the gas collection efficiency is assumed to be 90%.

According to the data, concentrations of primary gases in the landfill are as follows;

Table 7*.Compounds in the LFG (Source: (Ortadogu Energy, 2017)).*

Compound	**Approximate Value**
CH_4(%)	48-57
CO_2(%)	35-47
O_2(%)	0,2-1,5

__Table 8__.Estimated yearly amount of generated LFG (Source: (Ortadogu Energy, 2017))

Year	**Collected gas from the landfill (Nm^3)**	**CH_4(%)**
2009	27.033.360	50,3
2010	42.696.240	50,2
2011	39.533.880	52,5
2012	70.588.080	55,1
2013	104.892.240	53,8
2014	123.886.568	57,4
2015	102.445.629	52,4
2016	145.883.560	53,2

__Table 9__.Emissions associated with combustion of biogas in gas engine (Source: Fruergaard and Astrup, 2011)).

Unit	**g/MJ biogas**
CO	0,0115
NO_X	0,148
CH_4	0,465
NMVOC	0,105

According to the data given by the landfill operator, approximate electricity recovery efficiency of the engine is measured as 42 %. However, the net electrical efficiency of the engine is calculated 39,6 % after the downtime of the engines during the operations in 2014, and this number is used in the modelling in order to be more accurate. Therefore, 39,6% as electricity efficiency of the engines is used for the current LFG modelling. Besides, the engines being used in the facility are German brand named as GE JENBACHER JGS 420 GS-L.L. The technical data about the engine as follows in Table 10;

Table 10.*Technical data about the combustion engine (Source: (cogeneration.com.ua, n.d.)).*

Jenbacher Type 4: J420	
Electrical Output (kW)	1487
Energy Input (kW)	3508
NOX	500 mg/m^3N
Thermal Efficiency	42,8
Electrical Efficiency	42,4
Total Efficiency	85,2

All the assumptions, the data and measurements used in this study are aimed to reach the actual situation in the landfill facility as well as possible.

3.1.3 Life Cycle Impact Assessment

Impact assessment is the third phase of LCA that assess the data obtained in inventory phase with characterization factors, which is carried out to ask the magnitude of the impact. The results of impact assessment can be given in unit processes either in reference unit for each process (e.g. kg CO_2 equivalents for Global Warming) or as a normalized one in PE (person equivalents) that is the impact of all generated activities for an average person for one year.

Relevant studies and researches about LFG management systems show that GWP, AP and EP are important environmental impact categories that the magnitudes of them are strongly affected by the emissions released along with the waste to energy processing. Accordingly, these three impact categories are decided to be evaluated for this study. The background information and impact of GWP, AP and EP are presented in this chapter.

3.1.3.1 Global Warming Potential

GW is undoubtedly one of the most important environmental issues of the world. It is illustrated in IPCC's report that the release of GHG can cause increases in the global average temperature as well as climate change at a regional level (IPCC, 2007). Global warming potential is the most emphasized environmental impact category in this study as it evaluated carefully for all the LFG utilization scenarios that have been created. The most significant GHGs in these scenarios and their comparable global warming potential over 100 years are carbon dioxide (CO_2= 1 GWP100), methane (CH_4=21 GWP100), nitrous Oxide (NO_2= 310 GWP100).

3.1.3.2 Acidification Potential

Acidification occurs mainly because of the interaction of nitrogen oxide (NO_X) and Sulphur dioxide (SO_2) gases with other atmospheric components. Anthropogenically derived pollutant deposition increases the rates of acidification.

Acidification potential (AP) as an environmental impact category is one of the major environmental problems globally. It can be basically explained that when acids are emitted, the pH factor falls and thereby acidity increases, which results in inevitable consequences such as the acidification of lakes and water courses that lead to somber problems for the ecosystem (SeppaÌa, J., et al, 2006).

3.1.3.3 Eutrophication Potential

Eutrophication refers the overabundance of nutrients causing immoderate biomass growth and decay in soil or water, ending up in oxygen depletion. Ammonia, nitrogen oxides, nitrates and phosphorus contribute eutrophication. Eutrophication potential is expressed by using kg PO_4 eq. unit process.

3.1.4 Life Cycle Interpretation

This is the last step of LCA, where the results from impact assessment and interpretation are interpreted and evaluated against goal and scope for the study.

Life cycle interpretation takes place at every stage in LCA as it is an iterative process. Based on the results of the interpretation phase, it is sometimes required to go back and revise parts of goal and scope, inventory and the impact assessment. The final and amended version can be found after the number of iterations.

3.1.5 GaBi Software

The GaBi software is used in this study to perform a comparative LCA of the different LFG utilization methods in a landfill. Gabi is a tool that can be used for estimating the output of a particular process (in terms of landfill gas generated and/or energy/emission generated, in this particular module). In addition to that GaBi has an extensive database that makes the inventory process easier for the users. Accordingly, sub-processes such as EU-27 Natural Gas Mix, Thermal Energy from natural gas and Electricity grid mix are used as ready data from the GaBi's database.

3.2 Sensitivity Analysis

The objective of the sensitivity analysis is to understand and assess the importance of impacts and considerations that uncertainty of the model can have effects into the modelled system if certain parameters are suddenly changed (Kellens et al., 2011). The parameters used in the LFG management model such as gas generation (CH_4 potential), collection efficiency and oxidation rate, as well as the efficiency of biogas combustion might have a significant effect on the intensity of the measured impacts. Therefore, a sensitivity analysis is carried out in this thesis that the key parameters are presented transparently. For the variation of the parameters for this sensitivity analysis the key assumptions (system boundaries) established in the section 3.4.1. in this thesis, are followed, and the sensitivity analysis is carried out for GW, AP and EP impact categories.

LFG collection efficiency is the ratio of the collected LFG and uncollected LFG amounts; thus, it directly affects the LFG treatment performance. Collection efficiency varies among the studies carried out LFG management such as Börjesson et al. (2007) and Spokas et al. (2006). As the LFG collection efficiency in this thesis is chosen from the study carried out by Spokas et al. (2006) as 90% (due to geomembrane top cover), and the alternative gas collection efficiencies for the sensitivity analysis are 75% for the low rate; 95% for the high rate in the sensitivity analysis (Spokas et al., 2006; Manfredi et al., 2009).

Likewise, the oxidation rate can be varied significantly among the studies carried out regarding the LFG management. The oxidation rate is taken 10% in many LFG operators as it recommended by IPCC (IPCC,2006). According to the study made by Chanton et al. (2009), the oxidation rate averagely was 36% in the studies landfills, and the rate alters from 22% to 55% with soil covers. The oxidation rates are set to be 20% and 0% for the sensitivity analysis in this thesis.

Any change in the gas engine efficiency directly affects the amount of emissions released in the landfill and accordingly the magnitudes of environmental impacts. The variations used in this analysis are obtained from literature as follows:

- 39% as electricity; 42% as heat from actual performance of the engines in the facility.
- 29% as electricity; 27% as heat from the study made by Yingjian et al (2014).
- 42% as electricity; 45% as heat from Yingjian’s study and technical specification of GE JENBACHER engine (Yingjian et al., 2014; cogeneration.com.ua. n.d.).

Lastly, the CH_4 content of LFG is carried out as the last sensitivity determinant. The measured CH_4 content in the facility in 2014 is 57,6 % in the LFG. Like collection efficiency, the CH_4 content of the gas is also an important determinant that can entirely change the measurements in the LFG management. The sensitivity analysis is aimed to get comparative results among the varied parameters in illustrating the importance of the determinants in the LFG management system. According to Themelis and Ulloa (2007), LFG typically contains 45-65% CH_4, and the CH4 content of LFG in the Odayeri facility is between 50-57,5% from 2009 to 2016 (Themelis and Ulloa, 2007). Therefore, the other two sensitivity parameters of CH_4 content in the LFG are decided to be 60% and 50%.

3.3 General Principles and Flow Chart of LCA Modelling

The number of elements is included in the LFG management of the study: collection, oxidation, fugitively released LFG in the landfill regarded as uncollected gas. Besides, the collected gas treatment including flares, the gas upgrading system, the gas combustion processes, the utilization with energy production, and the energy substitution. On the other hand, waste-water treatment and generation, on-site operations (activities in the soil such as bulldozers and compactors, etc.) are not regarded as the essential elements in this study because they have different aspects of LFG management. The LCA modelling of LFG management in the facility is shown in Figure 6.

Due to the FU of this study is already decided to be the collected amount of LFG in the landfill facility in 2014, the modelling starts from gas collection system (zero burden approach). GWP, AP and EP are the environmental impact categories are considered as GWP is the primary impact category in LFG management because of the magnitude of the CH_4 emissions on GW impact. Accordingly, AP and EP are also important impact categories in terms of energy recovery from MSW.

In addition to that, any items before the collection process are excluded in this study such as transportation, the amount of MSW. Apart from that, CH_4 generation is very important in terms of calculating the amount of LFG emitted, and accordingly CH_4 generation is estimated by using the following equations 9 and 10:

Total LFG = collected LFG (m^3) / collection rate (90%) (Eq. 9)

Emitted LFG = total LFG – collected LFG (Eq. 10)

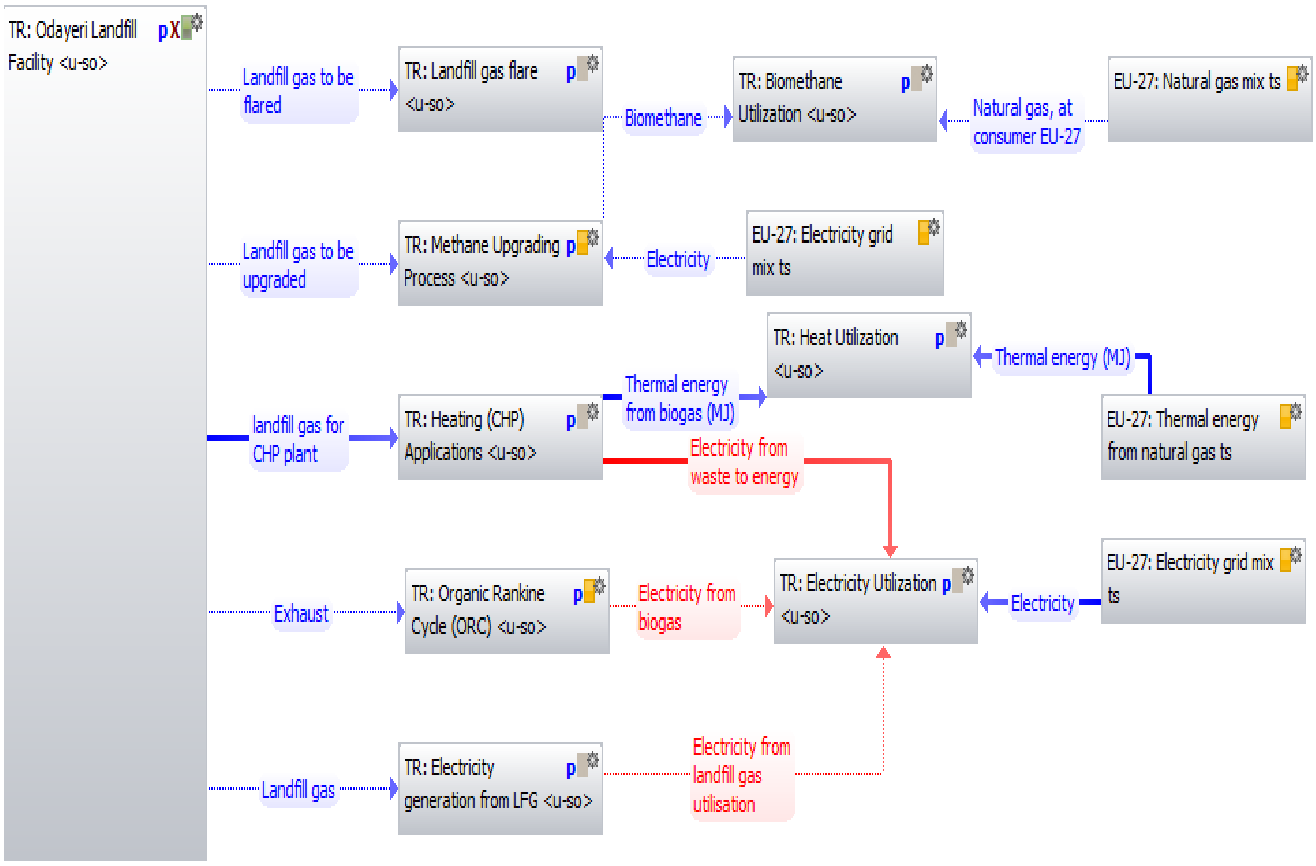


Figure 6. Main Process of LCA modelling in the LFG management

3.4 Cost Benefit Analysis

In order to estimate the economic evaluation of waste management scenarios for the landfill facility, cost benefit analysis approach is preferred to be carried out in this thesis. CBA is an established economics approach to estimate and compares the total costs and benefits in alternative scenarios and schemes (Jamasb and Nepal, 2010).

Hellweg et al. (2005) developed a measurement method called environmental cost efficiency (ECE) that measures the quantified environmental benefits of technology A compared to B per additional cost (shown in eq.11). The ECE is carried out with separate financial and environmental assessments. It is assumed that the discounted net cost is carried out by the annuity method. The annuity method allows distributing the net present value of the life-time of the investment. Since the annuity method is more suitable than net present value in terms of comparing different technologies with different life-times, using the annuity method for economic assessment is recommended. Equations of the net present value and annuity method are illustrated in Eq, 12 and 13 respectively (Hellweg et al., 2005).

$$ECE_{A,B} = \frac{NEB_{AB}}{AC_{AB}} = \frac{NEB_A - NEB_B}{NC_A - NC_B} = \frac{(-IP_A)-(IP_B)}{NC_A - NC_B} \left[\frac{points}{Euro}\right] \qquad \text{(Eq.11)}$$

$$NPV_x = \sum_{t=0}^{T}\left((B_{x,t} - C_{x,t}) \times \frac{1}{(1+r)^t}\right) \qquad \text{(Eq.12)}$$

$$A_x = \frac{NPVx \times (1+r)^T \times r}{(1+r)^T - 1} \; [Euros] \qquad \text{(Eq.13)}$$

In equations 11-13, A, B and C are the different kind of technologies. NEB_{AB} is the environmental benefit of technology A compared to B, AC_{AB} is the financial cost required to implement technology A instead of B, IP_x is the environmental impact of potential technology X used in the assessment, NC_x is the net cost (to be decided with Eq.13) $B_{x,t}$ and $C_{x,t}$ illustrate the benefits and costs of the technology X at time t, r is the discount rate, t is a time index, and T is the life-time of the technology X. If the net cost of technology A is less than that of technology B ($NC_A < NC_B$), then the technology A is better from the economic point of view. After knowing the environmental superiority of the technologies compared to each other, there can be a trade-off between environmental and economic targets (Hellweg et al., 2005).

3.4.1 Internal Combustion Engines and Flares

As it stated earlier in this study, Internal Combustion Engines are used in the Odayeri Landfill to produce energy from LFG and besides, more than two-thirds of the sanitary landfills where electricity produced use this sort of technology. Table 11 made by U.S. EPA provides the information about performance and costs of five different gas-powered IC engines that are commercially available. The estimated life-time of IC engines is between 25-50 years if they are properly used (Jaramillo and Matthews, 2005).

__Table 11__.Typical IC Engine Performance and Costs (Source: Jaramillo and Matthews, (2005)).

	system 1	**system 2**	**system 3**	**system 4**	**system 5**
nominal capacity (kW)	100	300	800	3000	5000
electric efficiency (%)	30.6	31.1	33.3	36.0	39.0
heat rate (MJ/kWh)	11,76	11,57	10,81	10,02	9,24
typical capital costs (€/kW)	1292	1020	853	783	783
typical O&M costs (€/kWh)	0,0156	0,010	0,0082	0,0079	0,0079

Please note that due to the functional unit of this study is already decided to be the amount of collected gas in the landfill in 2014, and, expectedly, the economic evaluation of gas collection efficiency, oxidation rate, gas combustion efficiency and CH_4 content of the gas are not included in CB analysis.

The gross power generation potential (GPGP) in a given year is calculated by Eq.14 below;

$$GPGP_T = \frac{LFG_T \mu_{col} E_c}{(365)(24)H_r} \qquad \text{(Eq.14)}$$

Where LFG_T is the LFG generated in year T, μ_{col} is the collection efficiency, E_c is the methane content of LFG; and H_r is the heat rate of the equipment of the technology, as given in Table 5.

The net power generation potential (NPGP) is then calculated by subtracting the parasitic loads, which is energy lost coming from auxiliary equipment and is usually around 2% of the gross power generation potential for IC engines. After the calculation of NPGP, the annual electricity generated (AEG) kWh is calculated by Equation 15 below:

$$AEG = NPGP\ (24)\ (365)\ 90\% \qquad \text{(Eq.15)}$$

Where 24 is hours per day, 365 is days per year, and 90% is the average percentage of the working time of engines in a year after considering the maintenance, downtime, etc. (Jaramillo and Matthews, 2005).

To decide how many engines are required and the associated capital cost, the potential net power generation during the lifetime of IC engine is divided by the nominal capacity of each system type as it is illustrated in Table 10. The lowest capital cost is preferred for the analysis of the system in the equipment (IC engine). Please note that O&M costs are not compared because there are not many differences among the O&M costs and they are comparably smaller than capital costs.

After the system planning to be used is decided based on lowest capital cost, the total O&M cost can be calculated by multiplying electricity generation (in kWh) by the average O&M cost of the chosen system as given in Table 10. If the LFG produces more electricity than the actual capacity of the equipment, production at equipment capacity is used to calculate the costs. This is carried out by replacing the NPGP in Eq.14 with the equipment nominal capacity, as given in Table 11. Besides, this method is used to calculate the revenues from selling the electricity at any given price and the benefits from a tax credit, if available (Jaramillo and Matthews, 2005).

3.4.2 Biogas Upgrading Process

The overall cost of cleaning and upgrading biogas comes from investment cost, the operation of the plant and maintenance of the equipment. The removal of CO_2 is the most expensive process when biogas is upgraded to be used as vehicle fuel (IEA Bioenergy, 2006).

The investment required for full treatment to upgrade methane for vehicle use depends on several factors. Expectedly, one major factor is the size of the facility. More investment means more installed capacity. According to the report prepared by IEA Bioenergy, the standard investment needed for treatment 300 nm^3 per hour of raw gas in a facility is 1 million Euro. It should be noted that this investment for a plant was assessed between 1998 and 2006. The significant operation costs for full treatment to vehicle fuel quality are electricity, labour, and depending on the technique, consumption costs (water, chemicals, etc.).

Economic assessment of upgrading technologies is also considered in this paper. Table 12 demonstrates that the availability of membrane separation, water scrubbing and physical absorption are the highest. Water scrubbing and membrane separation are associated with the lowest maintenance costs. Patterson et al., (2011) combined data regarding the cost estimates of upgrading biogas to biomethane from various studies as it seen in Table 13. This data relating to plants with an output of between 200 and 300 m3/h biomethane (Patterson et al., 2011).

Table 12*.Technical availability and maintenance costs of upgrading technologies (Source: Patterson et al., (2011)).*

	Technical availability per year (%)	Maintenance cost (€/yr)
PSA	94	56,000
Water scrubbing	96	15,000
Chemical (amine) scrubbing	91	59,000
Physical absorption	96	39,000
Membrane separation	98	25,000

Table 13.*Cost estimates of upgrading biogas to biomethane from studies undertaken 2007-2009 (cost per m3 of upgraded biogas (€/m3)).*

Upgrading Technologies	**De Hullu et al. (2008)**	**Persson, Wellinger et al. (2007)**	**Jönsson (2009)**	**Hammer, Petterson et al. (2007)**
PSA	0.26	0.11-0.16	0.11-0.22	-
Water scrubbing	0.15			0.11[a]
Chemical (amine) scrubbing	-			-
Physical absorption	-	-	-	-
Membrane (low pres.)	0.22	-	-	-
Cryogenic	0.40	-	-	-

In order to assess the economic potential of biogas upgrading system in the Turkey, it is necessary to associate these costs with those of producing biogas as well as the marketability of biomethane. Unfortunately, there is no biogas upgrading system in Turkey up to now. The produced biogas is only separated from condensate and hydrogen sulphur to be used in gas engines. Therefore, data is taken from literature. According to Rehlund & Rahm (2007), biogas upgrading cost for a large plant between 200-300 Nm3/hour-1 is between 0,01 – 0,16 € kWh-1 (Rehlund & Rahm, 2007).

According to the current Turkey market conditions, consideration of the facility with a capacity of 123 Mm^3/a collected gas shows that biogas upgrading cost should be averagely 0,085 € kWh-1.

As PSA (Pressure Swing Absorption) is chosen as an upgrading technology in the facility, the investment cost is estimated around 680.000 €, and service and maintenance costs are 56.000 € annually, while operation cost is 187.250 € (De Hullu et al, 2008).

To make a comparison the acquisition costs between biomethane and diesel, there is one report published by Turkish Petroleum and LPG Tariffing Association. According to the report, the average cost of low Sulphur diesel fuel in the Turkey is currently 1.1 €/l. Excluding overall tax (62% of the average cost) and another kind of costs (15.2% of the average cost), a normal price of low Sulphur diesel fuel is around €0,195/l. As 1 l of diesel is energetically equivalent to 1m3 of upgraded biogas it is likely that upgraded gas is not able to compete with petroleum based product such an undistorted market in Turkey (Petrol ve LPG Piyasası Fiyatlandırma Raporu, 2016). However, initiatives on those systems are considered as promising for Turkey in terms of reducing the energy dependency and, more importantly, to achieve emission savings through utilizing municipal solid waste.

3.5 Case Study

3.5.1 Description of the landfill

The case landfill is one of the biggest landfills in the Europe: Odayeri Landfill in Istanbul, Turkey. The landfill site covers an area of approximately 100 hectares with a total amount of waste of more than 61 million tonnes landfilled during the 17 years of operation, from 1995 to 2012. Due to the high content of organic fractions in the landfilled waste, the Odayeri Landfill generates a significant amount of LFG rich in methane (CH_4).

The landfill has started to utilize LFG for electricity generation since December 2008. There are leachate collection and treatment systems in the landfill. The gas collection system at the landfill site consists of 239 gas wells, 125 km of pipes have been used for water, compressed air and gas lines. In addition to that, 2 flares with 2500 m^3/h capacity for each, 2 membrane gas balloons each has 16.000 m^3 capacity, 7 vacuum pumps with 2500 m^3/h capacity for each are the other technical information considered prominent. Top cover consists of 60-70 cm clay + 50 cm soil.

3.5.2 LFG Generation at Odayeri Landfill Facility

Firstly, residential waste aerobically decomposes in the solid waste storage areas. Then this field is covered with soil to cut oxygen presence inside and thus methane gas generation anaerobically starts with decomposition. Vertical wells with an average depth of 30m or, horizontal wells with a depth of 5m are drilled and the LFG is collected by vacuums and vacated to manifolds (gas collectors). Collected landfill gas in manifolds are connected to the main gas unit, which is established near the field, and thereby the landfill gas collected from the field is discharged to the energy production unit. On average 8-12 wells are connected to each manifold. Leachate is collected in condensate tanks then transferred to the biological waste water treatment plant.

Collected landfill gas has a moist structure and its calorific value and combustion efficiency are considerably low. Therefore, first, vacuumed landfill gas is sent to the heat exchanger (charge cooler) then to condenser units. The temperature of the landfill gas is cooled up to 5° C in heat exchanger units so that the moisture is removed. In condenser units, sort of gas contaminations and particles are collected and removed from the condensing water and gas. After the removing moisture content, landfill gas is transferred to gas engines by passing through vacuum pumps (boosters).

Firstly, the gas is supplied in internal combustion engines where it is burned and chemical energy is converted to mechanical energy and in generator to electricity. The excessive amount of LFG in the case of maintenance/breakdown is burnt by a flare with the 2.000 m3/hour capacity. So that harmful methane is not released to the atmosphere and it contributes to the reduction of emission, even the plant is out of work. The gas storage balloons are installed to keep a stable vacuum in the system and are also used as temporary storage units. The energy generated in the plant is delivered to the national electrical grid for the usage of consumers.

Process flows of the landfill facility are illustrated in Figure 8.

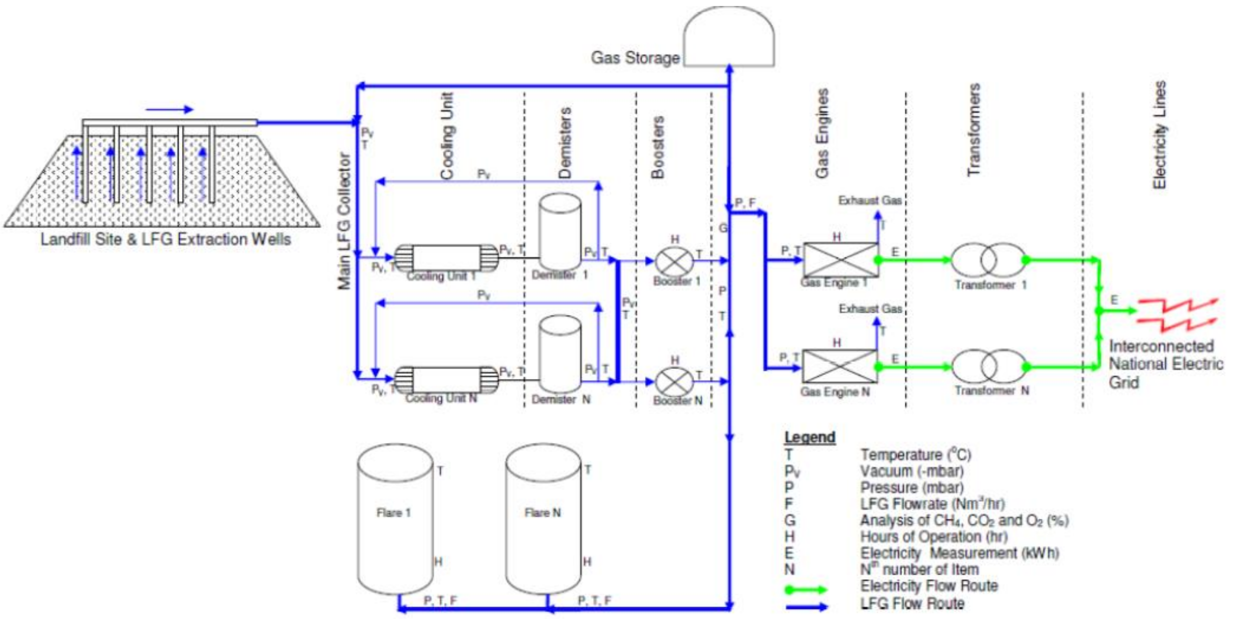


Figure 8. Flow Process of Odayeri Landfill

3.5.3 Scenario Settings and Modelling Assumptions

The fraction of C, H, N, O and S are assumed as the MSW fundamental composition for the study. The scenarios studied in this thesis are based on the following assumptions: since every scenario has energy outputs, it is assumed that internal energy consumption of the landfilling facility is provided by those energy outputs except in Scenario 2 where the biogas upgrading system is implemented. According to the information given by the landfill operator company, internal electricity consumption of the facility corresponds to roughly 3-5% of the total gross electricity produced in the plant. In addition, if a scenario has an energy output that brings environmental benefits, both gross and net environmental impact indicators (GWP, AP and EP) are illustrated; environmental benefits gained from recycled material (e.g. ferrous metal and compostable matter) are not accounted for, due to unavailable data; since the membrane top cover is currently being used in the landfill, the collection efficiency is assumed to be 90% for all scenarios as indicated in Niskanen et al., (2013)'s study and the issues related to leachate are excluded from the study.

3.5.3.1 Baseline Scenario

The current gas utilization technology in the facility is chosen as the baseline scenario. Wastes are buried in a monitored landfill. The organic fraction of wastes decomposes in anaerobic reactions and releasing the LFG. This largely consists of CH_4 (57%) and CO_2 (42%), but it might also contain traces like H_2S, HCl, HF and other chemical compounds. In the facility, there are 20 internal combustion engines (17 out of 20 has each 1415 kW capacity; rest of them has each 1364 kW capacity) producing only electricity. The energy conversion efficiency of each engine is approximately 42%. It is assumed that around 3.7% of collected LFG is flared to convert CH_4 to the less harmful CO_2 (mainly). This sort of CO_2 emissions from LFG flaring is quantified but it is not accounted in GWP because it is not derived from fossil fuels (it is obtained from organic fraction).

Other assumptions regarding the landfill facility for the Baseline Scenario are the following: the main emissions released from flare are CO, NO_2, HCl, HF (emission factors: 800, 100, 12 and 0,02 mg/m3 respectively) and the main emissions fugitively released from landfill with biogas (i.e. CO_2 and CH_4) are CO, HCl and HF (emission factors: 13, 65 and 13 mg/m3 respectively); heavy metals released to the atmosphere are only Mercury (Hg) and Cadmium (Cd) (White et al., 1999).

3.5.3.2 Scenario 1

It is indicated in the baseline scenario that around 3.7% of the collected LFG in the landfill goes to the flares. Scenario 1 aims to close the flares and to increase the methane treatment capacity of internal combustion engines, and thereby the desired environmental and economic savings can be achieved.

3.5.3.3 Scenario 2

In addition to the closing flares as it is carried out for the all scenario settings, scenario 2 is based on the LFG upgrading to biomethane, which corresponds to reaching the quality of natural gas. Since there are supporting infrastructure and developments regarding the use and distribution of biomethane, the upgrading process is considered an innovative option in biogas utilization systems. Based on the data by NTV media corporation, there are more than 20.000 vehicles in Istanbul using fuel as compressed natural gas, which can be replaced with biomethane. In addition to the number of vehicles, there are 27 refueling stations specifically for the compressed natural gas-powered vehicles in Istanbul (NTV, 2017). In addition to that, the vehicles running on CNG have 7% of lesser carbon emissions than the diesel cars.

3.5.3.4 Scenario 3

The electricity conversion efficiency of the engines in the facility is approximately 42%. As known from the Section 3.4.2., electricity is only produced in the energy utilization system. In addition to the electricity generation, the operator company thinks to obtain the heat energy from engine jacket water and waste heat from gas engines to be utilized in the heating facility and potential greenhouse farming.

In this Scenario, flares are closed and the use of engines (CHP) are planned to be elaborated and improved for heat and power purposes. The overall energy conversion efficiencies of the engines are anticipated to be increased up to 81% with the configuration of the engines (39% as electricity treatment efficiency and 42% as heat recovery efficiency). The produced heat is also planned to be used in a new large greenhouse facility placed near the main facility, and thereby, the most valued vegetables such as tomato, pepper, cucumber and eggplant can grow in there.

Canakci and Akinci (2006) have made an extensive research about energy requirements for the greenhouses at the south part of Turkey. According to the study, the total annual energy requirements for producing tomato, pepper, cucumber and eggplant are measured as 47, 45,49 and 49.5 GJ/1000 m^2, respectively. In the end of the study, it was revealed that the tomato production in the greenhouse is the most profitable one in terms of energy and economic values. Since the Odayeri Landfill facility has 100 ha area and the produced heat in this scenario is 1,1 PJ/a, one massive greenhouse that covers an area 5 ha is planned to be installed to produce tomatoes (Canakci and Akinci, 2006).

On the other hand, only very few amounts of the produced heat are used for greenhouse farming that corresponds 0,0002% of the produced heat in the facility. In this case, most of the recovered heat energy is released to the atmosphere after few of it is utilized to heat the facility.

3.5.3.5 Scenario 4

All the scenario settings are the same as they are in Scenario 1. Additionally, in Scenario 4, the Organic Rankine Cycle is planned to be implemented in the electricity conversion system. As it described widely in Section 2.3.4., since the Organic Rankine Cycle System generates electricity with the utilizing waste heat of the internal combustion engines, 480 °C of waste heat from the flue gas of combustion engines in the facility are benefited to generate electricity. The general descriptions of the scenarios are represented in Table 15.

3.5.3.6 *Other Modelling Assumptions*

The yearly utilization period is set to be averagely 7500 h for each utilization option. If the collected gas is unable to be treated, it is burnt by the flares. The LFG treatment efficiency of a flare is assumed to be 98% (Niskanen et al., 2013). The gas engine efficiency is desired to be 42% for electricity and 38% for heat in Scenario 3 as it is indicated in the information catalogue of the gas engine. The total internal energy consumption of the upgrading process in Scenario 2 is adjusted to be 9.1% including the CH_4 loss that corresponds to 1.5% of the overall amount of collected CH_4 (Pertl et al., 2010). It is assumed that the lost CH_4 is not released to the atmosphere without treatment. General outlook of the scenarios is represented in Table 14 and other inventory information of the scenarios are seen in Table 15.

Table 14.*General description of the scenarios*

Scenarios	**LFG management options**	**Flares**	**Energy Utilization**
Baseline Scenario	Current LFG management	On	Electricity generation
Scenario 1	Power generation	Off	With an increased methane treatment capacity of ICEs, power generation
Scenario 2	LFG upgrading to biomethane	Off	Biomethane generation (feasible to be used replacing compressed natural gas)
Scenario 3	Combined heat and power generation	Off	Electricity generation and large scale of heat generation
Scenario 4	Power Generation	Off	Increased capacity of power generation with ORC (higher electrical efficiency)

***Table 15**. Inventory of energy flow of the system and efficiency values of treatment technologies in LFG utilization options*

Scenarios	**LFG Management Options**	**Produced LFG (Mm^3)**	**Flared LFG (Mm^3)**	**LFG used for CHP (Mm^3)**	**Only electricity Production (TJ)**	**Heat Production (TJ)**	**Biomethane Production (kt)**	**Electricity Efficiency (%)**	**Heat Efficiency (%)**
Baseline Scenario	Current LFG management	123	4.5	0	1060	0	0	0,39	0
Scenario 1	Power generation	123	0	0	1100	0	0	0,39	0
Scenario 2	LFG upgrading to biomethane	123	0	0	0	0	147	0	0
Scenario 3	Combined heat and power generation	123	0	123	1100	1180	0	0,39	0,42
Scenario 4	Power Generation	123	0	0	1350	0	0	0,42	0

4 RESULTS AND DISCUSSION

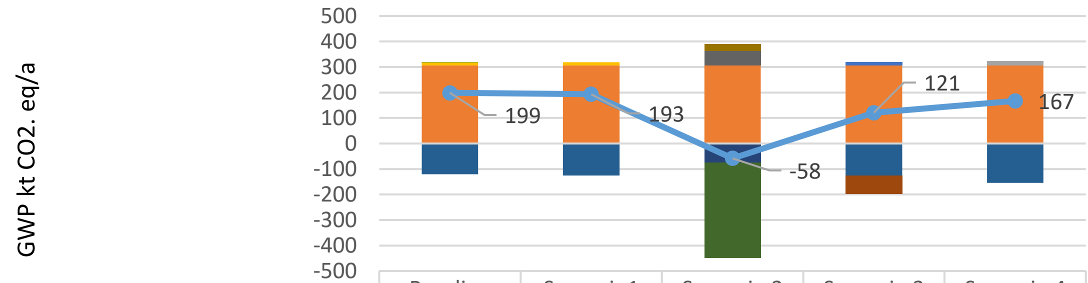
4.1 Life Cycle Impact Assessment

Environmental impact potentials caused by solid waste landfilling activities show that landfill gas has a substantial effect on GWP, AP and EP impact categories. These three categories are carefully evaluated in this section. There is the number of significant factors that change the magnitude of the impact categories are presented in Figure 9-10-11.

4.1.1 Global Warming Potential

The main contributors to GW impact in all scenarios are presented in Figure 9. According to the figure, the current landfill gas utilization scenario (Baseline Scenario) has the biggest impact on GWP, while closing the flare in Scenario 1 brings 6 kt CO_2 eq. avoided emissions. Apparently, the most remarkable environmental benefit can be seen in Scenario 2 as implementing the biogas upgrading systems that can avoid a vast amount of the emissions caused by the natural gas used in the vehicles. The magnitude of GW impact for Scenario 2 is negative, which means that the environmental savings of the system are greater than the caused environmental impacts. In addition, the LFG processing system in Scenario 3 has considerably lesser GW impact than the current scenario as the gas engines are intended to be used for combined heat and power processing. From the current scenario to scenario 4, the magnitude of GW impact is decreased to 167 kt CO_2 eq. from 199 kt CO_2 eq. by just implementing Organic Rankine Cycle system and closing the flare. Therefore, as expected, more energy recovery brings benefits to avoid more GHG emissions.

In addition to that, as can be seen from the Figure 9, the biggest contributor to GWP is identified as the process named “Emissions of the landfill” referring the main operations in the landfill field, and the processes called “electricity substitution “, “heat energy substitution for CHP” and “Emissions of the biomethane utilization” are the compensators to mitigate the emissions.



	Baseline	Scenario1	Scenario 2	Scenario 3	Scenario 4
Emissions of the biomethane utilization	0	0	-374	0	0
Avoided production of natural gas	0	0	-75	0	0
Electricity demand from upgrading	0	0	26	0	0
Upgrading	0	0	59	0	0
Heat energy substitution for CHP	0	0	0	-72	0
Electricity Substitution	-121	-126	0	-126	-155
Flare	2	0	0	0	0
Chp	0	0	0	13	0
Combustion	13	13	0	0	0
Organic Rankine Cycle	0	0	0	0	16
Emissions of the landfill	306	306	306	306	306
Total	199	193	-58	121	167

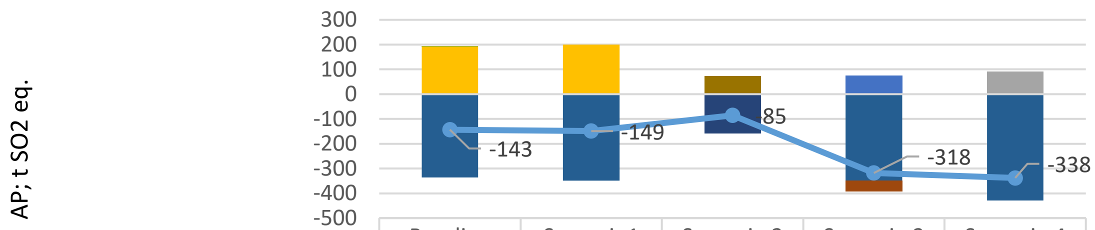
Figure 9. GWP 100 years (kt CO2.eq/a)

4.1.2 Acidification Potential

As it mentioned earlier in the methodology chapter, AP is affected of mainly the interaction of NO_x and SO_2 gases with other chemical components in the atmosphere.

Figure 10 represents the magnitude of AP that varies by the different LFG utilization scenarios. It can be clearly seen that the LFG utilization system in Scenario 2 strongly triggers the magnitude of AP due to the reason that substituted electricity in other scenarios have a substantial mitigating effect on this impact category. In other meanings, there are a number of chemical compounds in electricity from fossil fuels that they significantly contribute to AP impacts (due to the high characterization factors), and in the case of avoiding the electricity utilization from unrenewable resources, the system gains significant emission savings in AP. Apart from that, ORC system in Scenario 4 has the least impact on

AP because of the substantial amount of substituted electricity and the lesser amount of the emitted gas in ORC process.

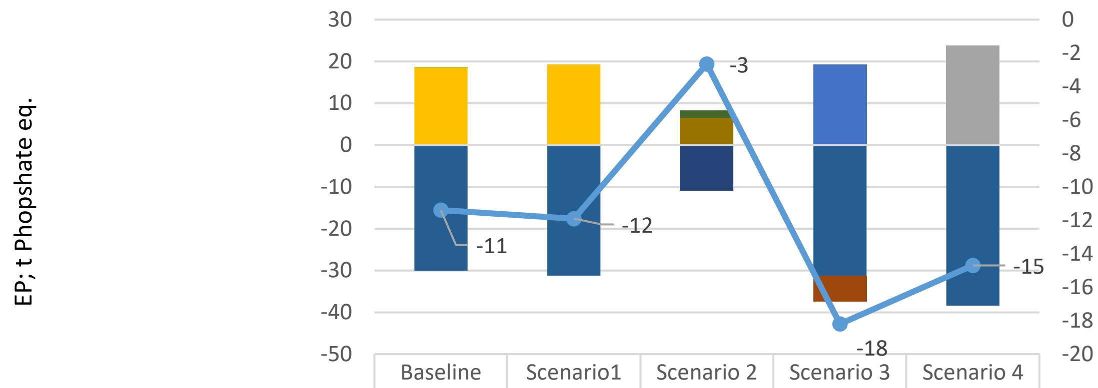


	Baseline	Scenario1	Scenario 2	Scenario 3	Scenario 4
Emissions of the biomethane utilization	0	0	0	0	0
Avoided production of natural gas	0	0	-158	0	0
Electricity demand from upgrading	0	0	73	0	0
Upgrading	0	0	0	0	0
Heat energy substitution for CHP	0	0	0	-43	0
Electricity Substitution	-336	-349	0	-349	-429
Flare	0	0	0	0	0
Chp	0	0	0	74	0
Combustion	193	200	0	0	0
Organic Rankine Cycle	0	0	0	0	91
Emissions of the landfill	0	0	0	0	0
Total	-143	-149	-85	-318	-338

Figure 10. AP (t SO_2 eq./a)

4.1.3 Eutrophication Potential

Figure 11 represents the EP in all the scenarios in this study. Among the scenarios, the lowest AP impact is seen in Scenario 3 as the combined heat and power systems are implemented and thus, the electricity and heat substitution are lowered the EP impacts. Besides, there is not a momentous change between the current scenario, Scenario 1 and Scenario 4, while the largest EP impact occurs in Scenario 2 where the biogas is upgraded because the avoided production of natural gas is not as effective as the impact of the substituted amount of electricity on the magnitude of EP. The most effective contributor and compensator to EP are combustion and substitution processes respectively.



	Baseline	Scenario1	Scenario 2	Scenario 3	Scenario 4
Emissions of the biomethane utilization	0	0	2	0	0
Avoided production of natural gas	0	0	-11	0	0
Electricity demand from upgrading	0	0	7	0	0
Upgrading	0	0	0	0	0
Heat energy substitution for CHP	0	0	0	-6	0
Electricity Substitution	-30	-31	0	-31	-38
Flare	0	0	0	0	0
Chp	0	0	0	19	0
Combustion	19	19	0	0	0
Organic Rankine Cycle	0	0	0	0	24
Emissions of the landfill	0	0	0	0	0
Total	-11	-12	-3	-18	-15

Figure 11. EP (t Phosphate eq./a)

4.2 Sensitivity Analysis

GWP, AP and EP impact categories are carried out for the all LFG utilization scenarios. The tables represent result of the sensitivity analysis in the entire system. The changes in GWP, AP and EP impact categories are illustrated in percentages in order to give a clear understanding of the effects on the whole system.

The sensitivity analysis for each scenario is represented separately in sub-chapters.

4.2.1 Sensitivity Analysis 1- Collection Efficiency

Collection efficiency is one of the important parameters that alter the amount of emissions released in the landfill. As it is known, collection efficiency refers the ratio between collected and uncollected gas. Due to the cover type is currently used in Odayeri Landfill, the collection efficiency is set to be 90%; other two parameters are determined based on the study carried out by Manfredi et al., (2009). According to the study, gas collection efficiency is considered as 75 ±20%. Therefore, the other two sensitivity parameters are set to be as follows: 75% and 95% (Manfredi et al., 2009). Sensitivity analysis carried out for collection efficiency in each scenario is illustrated in Table 16 below.

Table 16*.Performance of collection efficiency in sensitivity analysis*

	Collection efficiency (%)									
	Baseline Scenario		**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Original parameter	90%		90%		90%		90%		90%	
Sensitivity parameters	75%	95%	75%	95%	75%	95%	75%	95%	75%	95%
Change of GWP	+307%	-80%	+317%	-83%	+1053%	-277%	+506%	-132%	+366 %	-96%
Change of AP	0	0	0	0	0	0	0	0	0	0
Change of EP	0	0	0	0	0	0	0	0	0	0

According to the results of sensitivity analysis, collection efficiency has a strong effect on GW impact balance for the whole scenarios. 95% as collection efficiency leads to lower

GWP while another one with 75% as collection efficiency comes with much higher GW impacts. The differences in GWP with the collection efficiency parameters are represented in percentages in Table 17. As it is seen, the highest collection efficiency (95%) lead to a numerally negative GWP which refers that environmental benefits are higher than the environmental effects of the facility. The whole LFG management system is affected drastically after the collection efficiency is set to be 75%. The high GW emissions cannot be compensated due to it happens early phase of the operation. Hence, rest of the operations are restricted to process only the amount of collected gas in any case. The increase in collection efficiency has a double effect when the collected gas is used for energy recovery because avoided GHG emissions are gained after the renewable energy production and accounted as negative impacts. As it is shown, when the collection efficiency is set to be 75%, the magnitude of GW impact is affected dramatically in scenario 2 due to the 1,5% of CH_4 loss during the upgrading process. Therefore, the lesser amount of collected LFG affects the system in scenario 2 more than the others. In addition, the performance of collection efficiency has no impact on AP and EP.

4.2.2 Sensitivity Analysis 2 – Oxidation Rate

As collection efficiency, oxidation rate can be taken otherwise among different landfills. The oxidation rate used in this study is 10% as it recommended by IPCC. Other oxidation rates are taken from relevant studies (20% and 0%).

Table 17*.Performance of collection efficiency in sensitivity analysis*

	Oxidation Rate (%)									
	Baseline Scenario		**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Original parameter	10%		10%		10%		10%		10%	
Sensitivity parameters	0%	20%	0%	20%	0%	20%	0%	20%	0%	20%
Change of GWP	+17%	-17%	+17%	-17%	+55%	-55%	+27%	-27%	+20%	-20%
Change of AP	0	0	0	0	0	0	0	0	0	0
Change of EP	0	0	0	0	0	0	0	0	0	0

As it is shown in Table 17, increasing the oxidation rate can lower the GWP as it increased the amount of CH_4 gas that oxidized. On the other hand, GW impact increases when there is no oxidation on the top cover. Normally, any change in oxidation rate has a significant impact on GWP if the collection rate is low. Although the changes are in the same magnitude as the differences between the scenarios, the impact of oxidation rate is not as strong as that of collection efficiency on GWP, because the collection rate is already 90% in this analysis that means fugitively released gas is very low, thus less amount of oxidized CH_4. The magnitude of AP and EP are not affected by the oxidation rate.

4.2.3 Sensitivity Analysis 3 – CH_4 content of LFG

CH_4 content in landfill gas is one of the important determinants in sensitivity analysis, which is measured as 57,6% of LFG at Odayeri Landfill. Since LFG generally contains 45% to 60% CH_4, and thus, the other two sensitivity parameters are set to be 50% and 60% respectively (Themelis and Ulloa, 2007). Thereby the current parameter can be between the two sensitivity parameters and observed more clearly. As it is for collection efficiency, any change in the CH_4 content of LFG can affect the rest of the phases in LFG management.

As it is illustrated in Table 18, when the CH_4 content of LFG is increased to be 60%, the magnitude of GW impact is slightly increased because the LFG contains more CH4 and accordingly fugitively released LFG will includes more CH4 emissions.

***Table 18**.Performance of CH_4 content of LFG in sensitivity analysis*

	CH₄ content of LFG (%)									
	Baseline Scenario		**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Original parameter	57,6%		57,6%		57,6%		57,6%		57,6%	
Sensitivity parameters	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%
Change of GWP	-13%	+4%	-13%	+4%	-44%	+13%	-13%	+4%	-13%	+4%
Change of AP	+13%	-4%	+13%	-4%	+4%	-2%	+13%	-4%	+13%	-4%
Change of EP	+10%	-8%	+13%	-3%	+5%	-1%	+12%	-5%	+14%	-2%

On the other hand, if the CH_4 content in landfill gas is set to be 50%, then there will be less amount of fugitively released CH_4 emissions that increases the magnitude of GW impacts. As other sensitivity analyses in this study, Scenario 2 is the most affected one for varied CH_4 contents on GW impact because of the CH_4 loss in the upgrading process.

Table 19 also demonstrates the changes of AP and EP due to the sensitivity analysis for CH_4 content in LFG. According to the table, the magnitude of AP and EP are affected by CH_4 content with a different way than GWP is affected. Lowering the CH_4 content of LFG comes with higher magnitudes of AP and EP impacts because there will be more emissions released by combustion process in Scenario Baseline-1-3 and 4. The most contributed process to AP and EP impact in Scenario 2 is the process named "Avoided production of natural gas" meaning that if there is less biomethane recovery due to lower CH4 content in LFG, then there will be less amount of substituted natural gas. Hence, higher CH_4 content leads to numerically negative AP and EP impacts in all the scenarios as there will be more energy recovery that means less emissions related to AP and EP emitted.

4.2.4 Sensitivity Analysis 4 – Gas Engine Efficiency

As it stated in Chapter 3.2., the varied parameters used for gas engine efficiency are picked from the literature:

1. 39% as electricity; 42% as heat are the original parameters of the engines used in the facility
2. 29% as electricity; 27 as heat from the study carried out by Yingjian et al (2014)
3. 42% as electricity; 45% as heat from Yingjian's study and technical catalogue of GE JENBACHER engine (Yingjian et al., 2014; cogeneration.com.ua. n.d.).

As expected, gas engine efficiency affects electricity and heat production efficiency, therefore the amount of the avoided GW impact is affected. Due to high collection efficiency, the total fugitively released LFG is low, as it is shown in Table 20. There is no change for any environmental impact categories for Scenario 2 in which the upgrading process is operated in a different technology than that of gas combustion engines.

Unlikely the two sensitivity analyses based on the varied parameters of collection efficiency and oxidation rate, this analysis has impacts on AP and EP as efficiency improvement affects so that more other electricity generation is substituted and thereby more emissions are avoided.

In Table 19, gas engine efficiency affects the magnitudes of the AP and EP relatively lower than that of GWP. Besides, GWP values are represented with kt CO_2 eq., while AP and EP are analyzed with t SO_2 and t PO_4 unit processes.

Table 19.*Performance of gas engine efficiency in sensitivity analysis*

	Gas Engine Efficiency (%)									
	Baseline Scenario		**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Original parameter	39% E; 42%H		39% E; 42%H		39% E; 42%H		39% E; 42%H		39% E; 42%H	
Sensitivity parameters	29% E 27% H	42% E 45% H	29% E 27% H	42% E 45% H	29% E 27% H	42% E 45% H	29% E 27% H	42% E 45% H	29% E 27% H	42% E 45% H
Change of GWP	+14%	-4%	15%	-5%	0	0	45,4%	-11%	17%	-5%
Change of AP	+26%	-8%	+26,2%	-7%	0	0	+27%	-7%	+21%	-6%
Change of EP	+23%	-12%	+27%	-8%	0	0	+28%	-9%	+23%	-4%

E: electricity efficiency of the gas engine; H: heat recovery efficiency of the gas engine

The result of the sensitivity analysis approved the importance of collection rate as it known in other relevant references. Especially GWP is strongly dependent on the gas collection efficiency. In addition to that, oxidation rate and collection efficiency are dependent on each other. If collection rate is low, the oxidation rate becomes more important, which means that oxidation rate is a crucial parameter for an efficient LFG management.

Sensitivity analysis results also showed that the effect of gas engine efficiency and CH_4 content of LFG have significant impacts on GWP, AP and EP.

Please note that the avoided GWP, AP and EP are heavily dependent on the assumptions related to the substituted energy recovery processes they are selected from the studies discussed in Methodology Chapter. Therefore, the selections for the assumptions should be carried out carefully.

4.3 Economic assessment through gas management scenarios

This section covers the cost-benefit analysis for the created scenarios for the Odayeri Landfill over specific waste management targets and compares them with fossil fuel based energy. In order to make an overall assessment for gas management options, it is important to measure and sum the costs and benefits linked with the different possibilities. However, there are some unattainable economic data that lead to uncertainties in economic analysis. Thereof, the considerable number of data are taken from some relevant studies. In the end, this analysis is aimed to get the best results from the gas management scenarios.

The general descriptions of the scenarios are represented in Table 15.

4.3.1 Scenario 1

By closing the flares in the facility, there is a need of processing the excessive amount of LFG by a gas engine. As it is currently used in the facility, GE JENBACHER JGS 420 GS-L.L gas engine is decided to be installed to generate electricity from the excessive amount of LFG after the calculated treatment capacity needed to process the excessive amount of gas (cogeneration.com.ua, n.d.). According to the data are given by Ortadogu Energy (2017), 4.5 Mm^3 of LFG was burnt through the flare in 2014 (Ortadogu Energy, 2017). At this point, GE JENBACHER engine with 5.3 Mm^3/year treatment capacity is decided to be purchased. Repayment time for gas utilization system is carried out by following assumptions: the total investment cost of one engine is 0,46 M€, the electricity selling price is 11,3 € cents/kWh and loan interest is 5,1%.

4.3.2 Scenario 2

In Scenario 2, the biogas upgrading system is carried out in LFG utilization system. A big shift is planned since constructing a renewable energy source as an alternative to the fossil fuels consumption that allows Turkish market to minimize its energy dependency, especially against that of natural gas. The produced biomethane energy in one year is calculated as 1,6

TWh. According to the study carried out by Patterson et al, (2011), the biomethane upgrading cost is set to be 0,25 €/m^3, while the biomethane selling price is assumed to be 30 €/MWh (Patterson et al., 2011). Accordingly, the total biogas upgrading cost in one year is 30,9 M€ and the total revenue is 47,7 M€. In addition to that, investment cost (including plant, gas treatment and building costs) is 680.000 € for a PSA system, and the total service, maintenance and operation cost is 237.250 € annually. More than that, installing the gas pipeline connection to the grid is excluded from the study. However, due to the overuse of natural gas in Turkey, the infrastructure for natural gas is highly developed in industrial zone.

The optimistic possibilities are assumed when calculating the repayment ending period because there is limited information about the procurement process, business interrelations and current market situations. Therefore, more profound researches related to those topics are required. According to the calculation, the upgrading system can make more than 1,5 M€ of profit monthly, and the repayment is supposed to be ended in a few months.

4.3.3 Scenario 3

Economically, there would be some investments needed for constructing a greenhouse facility and purchasing one more engine.

According to Canakci and Akinci (2006), the total investment cost for construction of 840 m^2 greenhouse is around 14.3 k€ (Canakci and Akinci, 2006). Accordingly, the planned greenhouse facility is around 5 ha that needs to be provided 0,85 M€ of investment cost. Moreover, net return of tomato production in the greenhouses is measured approximately 117 000 €/a.

Hence, the overall investment cost including one more gas engine and installing greenhouse facility corresponds to 1,31 M€ for implementing the system in Scenario 3. Yet, there are some uncertainties and restricted resources related to economic analysis of greenhouse farming. More clearness is needed in literature and Turkish market.

4.3.4 Scenario 4

In this scenario, Organic Rankine Cycle is planned to be implemented, thereby, waste heat of the engines can increase the electricity generation up to 10%. The installed capacity of the facility will be increased approximately 4 MW. The measured project cost for this technology is 5,08 M€, and other relevant cost estimations are presented in Table 20 below.

Table20.*Economic evaluation for ORC implementation*

Scenarios	**Technology**	**Overall Project Cost (M€)**	**Expected Energy Generation**	**Annually Project Revenue (M€)**	**Repayment Ends**
Scenario 1	One Combustion Engine	0,46	8.862,9 MWh	1,002	7 months later
Scenario 2	Biogas Upgrading	0,91	1.589,9 GWh	47,7	1 month later
Scenario 3	CHP Applications	1,31	8.862,9 MWh	1,002+external greenhouse activities	7 months later
Scenario 4	Organic Rankine Cycle	5,08	30000 MWh	3,39	2 years later

5 CONCLUSION

This study has shown that LCA is a useful tool in waste management systems, particularly with different alternative scenarios to carry out comparative assessments. Among the scenarios, the current LFG utilization system has the biggest impacts on GWP with 193 kt CO_2 eq. as other scenarios are alternatively designed to produce more energy recovery from the LFG. The magnitude of GW impact in Scenario 1-2-3-4 are as follows: 193, -58, 121 and 167 kt CO_2 eq. respectively. Particularly, the LFG management in Scenario 2 that is designed for implementing the biogas upgrading process has numerically negative GW impacts since there is a considerable amount of biomethane production substituted with natural gas. According to the results, the landfill facility has the greatest impact to GWP. The main contributor to GWP is identified as the fugitively released LFG. On the other hand, the LFG system in Scenario 2 has the largest AP impact compared to other scenarios, while LFG utilization through CHP (Scenario 3) and ORC (Scenario 4) have mitigated effects on the magnitude of AP impact. The variations in the scenarios affect the magnitude of EP in a similar way that AP is affected. Implementing biogas upgrading system in Scenario 2 leads to the largest impact on EP with -3 t PO_4 eq, while the lowest EP impact is seen in Scenario 3 and 4 that the LFG utilization systems provide substantial emission savings because of the improved energy treatment systems (CHP and ORC). The major contributors to AP and EP are basically LFG treatment processes including the LFG upgrading and combustion systems. In all the impact categories, the energy substitution processes are the compensators that avoid the emissions from non-renewable energy sources. Therefore, with energy utilization, substantial environmental savings can be succeeded in GWP, AP and EP impact categories.

The results of the sensitivity analysis illustrate that the performance of the gas management system dramatically affects the magnitude of the environmental impacts caused by the gas processing. Especially, it has been observed that collection efficiency is a crucial factor in LFG management. The parameters used in the sensitivity analysis have shown the importance and effects of the parameters in terms of the environmental impact categories and general energy efficiency of the system.

Cost–benefit analysis has been carried out to make a comparative economic assessment of the created LFG utilization scenarios. In the end, the cost–benefit calculation of each scenario has analyzed the balances economically including the cost of investment, service, operation and maintenance costs, and, also the revenues planned to get from the scenarios. According to the economic analysis of the scenarios, upgrading CH_4 has a remarkable potential economically if the uncertainties are handled related to current market situations and infrastructural deficiencies. Additionally, ORC system in Scenario 4 is the most likely to suitably implement with the current LFG management system.

In general, LCA is a valuable tool in terms of developing waste management systems. All the varied LFG utilization scenarios are carried out for obtaining more sustainable alternatives with their financial analyses. Both the economic and environmental feasibility of each selected scenario gives the understanding to make a clear evaluation in the decision process by the stakeholders.

6 REFERENCES

Aye, L. and Widjaya, E. (2006). Environmental and economic analyses of waste disposal options for traditional markets in Indonesia. Waste Management, 26(10), pp.1180-1191.

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., Qingxian Gao, Tianzhu Zhang, Mohammed Abdelrafie Ahmed, Sutamihardja, R. and Gregory, R. (2008). Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). Waste Management & Research, 26(1), pp.11-32.

Börjesson, G., Samuelsson, J. and Chanton, J. (2007). Methane Oxidation in Swedish Landfills Quantified with the Stable Carbon Isotope Technique in Combination with an Optical Method for Emitted Methane. Environmental Science & Technology, 41(19), pp.6684-6690.

Bove, R. and Lunghi, P. (2006). Electric power generation from landfill gas using traditional and innovative technologies. Energy Conversion and Management, 47(11-12), pp.1391-1401.

Canakci, M. and Akinci, I. (2006). Energy use pattern analyses of greenhouse vegetable production. Energy, 31(8-9), pp.1243-1256.

Carlsson Reich, M. (2005). Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). Journal of Cleaner Production, 13(3), pp.253-263.

Chanton, J., Powelson, D. and Green, R. (2009). Methane Oxidation in Landfill Cover Soils, is a 10% Default Value Reasonable? Journal of Environment Quality, 38(2), p.654.

Cherubini, F., Bargigli, S. and Ulgiati, S. (2009). Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy, 34(12), pp.2116-2123.

Cleary, J. (2009). Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. Environment International, 35(8), pp.1256-1266.

cogeneration.com.ua. (n.d.). Jenbacher gas engines- Technical specification. [online] Available at: http://www.cogeneration.com.ua/img/zstored/J420V06_en.pdf [Accessed 13 Oct. 2017].

De Hullu, J. et al., 2008. Comparing different biogas upgrading techniques, Eindhoven: Eindhoven University of Technology

Drescher, U. and Brüggemann, D. (2007). Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. Applied Thermal Engineering, 27(1), pp.223-228.

El-Fadel, M., Findikakis, A. and Leckie, J. (1997). Environmental Impacts of Solid Waste Landfilling. Journal of Environmental Management, (50), pp.1-25.

Enerji Enstitüsü. (2017). Türkiye'nin Çöp Gazı Santralleri | Enerji Enstitüsü. [online] Available at: http://enerjienstitusu.com/santraller/copgazi-santralleri/ [Accessed 21 Apr. 2017] (In Turkish).

European Council (EC) Directive 1999/31/EC. Available from: http://www.epa.ie/pubs/advice/waste/municipalwaste/eulandfilldirective.html

European Environmental Agency (1999). Landfill Gas Control -Guidance on the landfill gas control requirements of the Landfill Directive.

Fruergaard, T. and Astrup, T. (2011). Optimal utilization of waste-to-energy in an LCA perspective. Waste Management, 31(3), pp.572-582.

Goossens, M. (1996). Landfill gas power plants. Renewable Energy, 9(1-4), pp.1015-1018.

Gowing, A. (2001). Measuring and Modelling of Landfill Gas Emissions. Ph.D. University of Waterloo.

Hamer, G. (2003). Solid waste treatment and disposal: effects on public health and environmental safety. Biotechnology Advances, 22(1-2), pp.71-79.

Han, H., Qian, G., Long, J. and Li, S. (2009). Comparision of two different ways of landfill gas utilization through greenhouse gas emission reductions analysis and financial analysis. Waste Management & Research, 27(9), pp.922-927.

Hao, X., Yang, H. and Zhang, G. (2008). Trigeneration: A new way for landfill gas utilization and its feasibility in Hong Kong. Energy Policy, 36(10), pp.3662-3673.

Harper, S. and Pohland, F. (1986). Recent developments in hydrogen management during anaerobic biological wastewater treatment. Biotechnology and Bioengineering, 28(4), pp.585-602.

Hellweg, S., Doka, G., Finnveden, G. and Hungerbühler, K. (2005). Assessing the Eco-efficiency of End-of-Pipe Technologies with the Environmental Cost Efficiency Indicator. Journal of Industrial Ecology, 9(4), pp.189-203.

Icapcarbonaction.com. (2017). International Carbon Action Partnership. [online] Available at: https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=66 [Accessed 24 Apr. 2017].

IPCC, 2006. Guidelines for national greenhouse gas inventories. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html . Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC, 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, p. 104.

IPCC, 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, p. 104.

ISO, (2006a). Environmental management – Life cycle assessment – Principles and framework (ISO 14040: 2006). European Standard EN ISO 14040. The International Organization for Standardization, Geneva, Switzerland.

ISO, (2006b). Environmental management – Life cycle assessment – Requirements and Guidelines (ISO 14044: 2006). European Standard EN ISO 14040. The International Organization for Standardization, Geneva, Switzerland.

Jamasb, T. and Nepal, R. (2010). Issues and options in waste management: A social cost–benefit analysis of waste-to-energy in the UK. Resources, Conservation and Recycling, 54(12), pp.1341-1352.

Jaramillo, P. and Matthews, H. (2005). Landfill-Gas-to-Energy Projects: Analysis of Net Private and Social Benefits. Environmental Science & Technology, 39(19), pp.7365-7373.

Jaramillo, P. and Matthews, H. (2005). Landfill-Gas-to-Energy Projects: Analysis of Net Private and Social Benefits. Environmental Science & Technology, 39(19), pp.7365-7373.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M. and Duflou, J. (2011). Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. The International Journal of Life Cycle Assessment, 17(1), pp.69-78.

Lohila, A., Laurila, T., Tuovinen, J., Aurela, M., Hatakka, J., Thum, T., Pihlatie, M., Rinne, J. and Vesala, T. (2007). Micrometeorological Measurements of Methane and Carbon Dioxide Fluxes at a Municipal Landfill. Environmental Science & Technology, 41(8), pp.2717-2722.

Manfredi, S., Niskanen, A. and Christensen, T. (2009). Environmental assessment of gas management options at the Old Ämmässuo landfill (Finland) by means of LCA-modeling (EASEWASTE). Waste Management, 29(5), pp.1588-1594.

Manfredi, S., Tonini, D., Christensen, T. and Scharff, H. (2009). Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27(8), pp.825-836.

Matthews, E. and Themelis, N. (2007). Potential for Reducing Global Methane Emissions From Landfills, 2000-2030. Eleventh International Waste Management and Landfill Symposium.

methane" United Nations Framework Convention on Climate Change, CDM- Executive Board meeting report Annex 13 https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf

Ministerie van Buitenlandse Zaken (2013). Development of Sanitary Landfills and Waste-to-Energy From Landfill Gas in Turkey. Müge Yazgan.

Ministry of Environment (2010). Lanfill Gas Management Facilities Design Guidelines. British Columbia.

Ministry of Environment and Forestry (2010). National reporting to the eighteenth session of the commission on sustainable development TURKEY. [online] UNCED. Available at: http://www.un.org/esa/dsd/dsd_aofw_ni/ni_pdfs/NationalReports/turkey/Full_text.pdf. [Accessed 21 Apr. 2017].

Niskanen, A. (2012). Landfill Gas Management at Engineered Landfills- Estimation and Mitigation of Environmental Impacts. Ph.D. Lappeenranta University of Technology.

Niskanen, A., Värri, H., Havukainen, J., Uusitalo, V. and Horttanainen, M. (2013). Enhancing landfill gas recovery. Journal of Cleaner Production, 55, pp.67-71.

NTV. (2017). Araçlarda CNG kullanımı yaygınlaşacak. [online] Available at: http://www.ntv.com.tr/ekonomi/araclarda-cng-yakiti-kullanimi-yayginlasacak, [Accessed 11 Sep. 2017].

Patterson, T., Esteves, S., Dinsdale, R. and Guwy, A. (2011). An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK. Energy Policy, 39(3), pp.1806-1816.

Perkins F. Practical cost benefit analysis—basic concepts and applications. Macmillan Education Australia Pty Ltd; 1994.

Pertl, A., Mostbauer, P. and Obersteiner, G. (2010). Climate balance of biogas upgrading systems. Waste Management, 30(1), pp.92-99.

Petrol ve LPG Piyasası Fiyatlandırma Raporu. (2016). [online] EPDK. Available at: https://www.google.fi/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwj0ldO25LrUAhXDZpoKHeajDMAQFggjMAA&url=http%3A%2F

%2Fwww.epdk.org.tr%2FTR%2FDokuman%2F6544&usg=AFQjCNErdyIpbtQ0n_rcdinBVvw6JwQQpQ&sig2=xIauP66ZGssakeVxv8cHmg [Accessed 13 Jun. 2017].

Qin, W., Egolfopoulos, F. and Tsotsis, T. (2001). Fundamental and environmental aspects of landfill gas utilization for power generation. Chemical Engineering Journal, 82(1-3), pp.157-172.

Rebitzer, G., Ekval, T., Frischknecht, R., Hunkeler, D., Norris, G. and Rydberg, T. (2004). Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, 30, pp.701-720.

Rehnlund, B. & Rahm, L. 2007: Report on technological applicability of existing biogas upgrading processes. BiogasMax project. Stockholm, Sweden.

Scheutz, C., Kjeldsen, P., Bogner, J., De Visscher, A., Gebert, J., Hilger, H., Huber-Humer, M. and Spokas, K. (2009). Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. Waste Management & Research, 27(5), pp.409-455.

SeppaÌa, J., et al., Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. International Journal of Life Cycle Assessment, 2006. 11(6): p. 403-416.

Shin, H., Park, J., Kim, H. and , E. (2005). Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. Energy Policy, 33(10), pp.1261-1270.

Spokas, K., Bogner, J., Chanton, J., Morcet, M., Aran, C., Graff, C., Golvan, Y. and Hebe, I. (2006). Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? Waste Management, 26(5), pp.516-525.

Sprouse, C. and Depcik, C. (2013). Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery. Applied Thermal Engineering, 51(1-2), pp.711-722.

Starr, K., Gabarrell, X., Villalba, G., Talens, L. and Lombardi, L. (2012). Life cycle assessment of biogas upgrading technologies. Waste Management, 32(5), pp.991-999.

Tchanche, B., Lambrinos, G., Frangoudakis, A. and Papadakis, G. (2011). Low-grade heat conversion into power using organic Rankine cycles – A review of various applications. Renewable and Sustainable Energy Reviews, 15(8), pp.3963-3979.

Terraza, H. and Willumsen, H. (2009). Guidance Note on Landfill Gas Capture and Utilization. [Technical Notes]. Available at: http://www.resol.com.br/textos/guidance_note_on_landfill_gas_capture-idb.pdf.

Themelis, N. and Ulloa, P. (2007). Methane generation in landfills. Renewable Energy, 32(7), pp.1243-1257.

Turkstat.gov.tr. (2017). Welcome to Turkish Statistical Institute(TurkStat)'s Web Pages: [online] Available at: http://www.turkstat.gov.tr/PreTablo.do?alt_id=1029 [Accessed 30 May 2017].

UNFCCC, 2006. Methodological “Tool to determine project emissions from flaring gases containing

Wanichpongpan, W. and Gheewala, S. (2007). Life cycle assessment as a decision support tool for landfill gas-to energy projects. Journal of Cleaner Production, 15(18), pp.1819-1826.

Wellinger, A. and Petersson, A. (2009). Biogas upgrading technologies – developments and innovations. Task 37. [online] IEA Bioenergy. Available at: https://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/upgrading_rz_low_final.pdf [Accessed 23 May 2017].

White PR, Franke M, Hindle P. Integrated solid waste management – a life cycle inventory. Gaithersburg, MD, USA: Aspen Publishers Inc.; 1999. New York: Chapman & Hall.

Willumsen, H. (2001). Energy Recovery from Landfill Gas in Denmark and Worldwide. [online] lei.lt. Available at: http://www.lei.lt/Opet/pdf/Willumsen.pdf [Accessed 17 May 2017].

Wu, D. and Wang, R. (2006). Combined cooling, heating and power: A review. Progress in Energy and Combustion Science, 32(5-6), pp.459-495.