MODELLING AND ASSESSMENT OF LANDFILL GAS GENERATION AT AFYONKARAHİSAR LANDFILL SITE

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ABSTRACT

MODELLING AND ASSESSMENT OF LANDFILL GAS GENERATION AT AFYONKARAHİSAR LANDFILL SITE

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Management of municipal solid wastes is one of the important environmental problems because of increasing population and developing industrialization in our country. Besides, there is a need to seek alternative energy sources due to rapid consumption of conventional energy sources. Landfilling is still the most common solid waste disposal method in the world and generated landfill gas consists of significant amount of methane that could be used for energy generation. In this study, it is aimed to model the landfill gas generation at different waste composition scenarios at Afyonkarahisar Sanitary Landfill Site. LandGEM and IPCC 2006 models were used for estimating the landfill gas amounts and determining energy content of the gas in the site. According to model results, methane generation rate (k) and methane generation potential (L_0) were 1.56 1/year and 44.12 m^3/Mg, respectively. When organic wastes are stored in the site separately, 40% higher methane gas generation could be obtained. With separation of ash, 24% increase could be obtained. In addition, service life of the lots increased. On the other hand, if recyclable wastes were separated from the waste for storage, methane gas generation was approximately the same as the base case due to small percentage of recyclables in the waste. Greenhouse gas (GHG) emission evaluations showed that only organic waste storage scenario provides 0.6% reduction in GHG emissions in Turkey.

Keywords: LandGEM, IPCC 2006, Municipal solid waste, GHG emission, Methane gas generation

ÖZ

AFYONKARAHİSAR DEPONİ SAHASINDAKİ DEPO GAZI ÜRETİMİNİN MODELLENMESİ VE DEĞERLENDİRİLMESİ

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Belediye katı atıklarının yönetimi, nüfus artışı ve endüstrileşmenin gelişmesinden dolayı ülkemizdeki önemli çevresel problemlerden biridir. Bunun yanında, enerji kaynaklarının hızlı tüketiminden dolayı alternatif enerji kaynaklarının araştırılması gerekmektedir. Düzenli katı atık depolama dünyada halen en yaygın katı atık bertaraf yöntemlerinden biridir ve üretilen depo gazı önemli miktarda enerji üretimi için kullanılabilinecek metan gazı miktarı içermektedir. Bu çalışmada, Afyonkarahisar Düzenli Katı Atık Depolama Sahası için depo gazı üretiminin farklı atık kompozisyon senaryolarına göre modellenmesi amaçlanmıştır. Depo gazı üretiminin ve enerji içeriğinin tahmininde LandGEM ve IPCC 2006 modelleri bu depolama sahası için kullanılmıştır. Sonuçlara göre, metan üretim hızı (k) ve metan üretim potansiyeli (L_0) değerleri 1,56 1/yıl ve 44,12 m^3/Mg dır. Organik atıklar depolama alanında ayrı depolandığı zaman depolama alanından yaklaşık olarak %40 daha fazla metan gazı üretimi elde edilmiştir. Külün ayrılması ile %24 artış elde edilmiştir. Buna ek olarak, depolama alanlarının hizmet süresi artmıştır. Diğer taraftan az oranda geri dönüştürülebilir atık miktarı bulunduğu için eğer geri dönüştürülebilir atıklar ayrılıp, kalan atıklar depolama alanında depolanmış olsaydı metan gazı üretimi mevcut durumla yaklaşık olarak aynı olurdu. Sera gazı emisyon azalımı değerlendirmesi, sadece organik atık depolama senaryosunun uygulanmasının Türkiye’de sera gazı emisyonunda %0,6 azalım sağladığını göstermiştir.

Anahtar Kelimeler: LandGEM, IPCC 2006, Belediye atıkları, Sera gazı emisyonu, Metan gazı üretimi

To my family

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ABBREVIATIONS

TÜİK	Turkish Statistical Institute
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
GMI	Global Methane Initiative
UNECE	United Nations Economic Commission for Europe
CCAC	Climate and Clean Air Coalition
EPA	Environmental Protection Agency
OECD	Organization for Economic Cooperation and Development
UNFCCC	United Nations Framework Convention on Climate Change
EEA	European Environment Agency
DOC	Degradable Organic Content
$DDOC_m$	Decomposable Degradable Organic Content
L_0	Methane Generation Potential
MCF	Methane Correction Factor
k	Methane generation rate
CAA	Clean Air Act
NTP	Normal Temperature Pressure
STP	Standard Temperature Pressure
IPCC	Intergovernmental Panel on Climate Change
LMOP	Landfill Methane Outreach Program
LHV	Lower Heating Value
RMSE	Root Mean Square Error
LFG	Landfill Gas

CHAPTER 1

INTRODUCTION

Waste generation rate is increasing year by year in the world. 1.3 billion tons of solid waste was generated in 2012 worldwide. It is estimated that 2.2 billion tons of solid waste will be produced in 2025 (The World Bank, 2017). In Turkey, 27.1 million tons municipal solid wastes were collected in 2014. This amount accounts for 87% of the total solid waste amount. It can be said that major part of the total solid waste is municipal solid waste in Turkey. According to the TÜİK statistics, daily municipal solid waste amount produced per person is 1.08 kg. Municipal solid waste generation is affected by population and economic growth. Data through 2008 to 2014 indicated that population and waste generation increased proportionally in Turkey. It is estimated that municipal solid waste amount will be 33 million tons in 2023 according to the National Waste Management and Action Plan of Turkey (Ministry of Environment and Urbanization, 2016).

While waste generation amounts are increasing, management of the waste amounts become a problem. Sanitary landfilling is the most dominant solid waste handling method in Turkey compared to other waste handling methods (Ministry of Environment and Urbanization, 2016). It is stated that landfilling is still a common solid waste management method in the world as well. Yet, management strategies have been started for recycling of solid waste and measures are taken to decrease the solid waste generation (Amini, Reinhart, & Mackie, 2012). In Turkey, 82 sanitary landfill sites were in operation in 2016. In addition to this, there are more than 800 unsanitary landfill sites (Ministry of Environment and Urbanization, 2016).

Unmanaged methane gas emissions from landfill sites is an important problem as methane is a greenhouse gas (GHG) (Melikoglu, 2012). All around the world, landfills are the third anthropogenic methane emission sources (Amini et al., 2012).

Collection and use of methane are important since this gas constitutes an energy source. With this usage, greenhouse gas (GHG) emissions would be decreased as well by obtaining energy from a non-fossil fuel. In Turkey, there are 33 landfill sites converting landfill gas to the energy (Ministry of Environment and Urbanization, 2016). Quality and quantity of gas are affected by operation conditions of landfill and waste types (Worrell & Vesilind, 2012). Therefore, better operation of the sites is required to meet the optimum conditions for gas production in landfills.

Landfill gas generation estimation can be important for determining the efficiency of the site in energy production. Potential problems and solutions can be evaluated to obtain high quality and quantity of landfill gas for energy generation. In literature, there are modeling and laboratory scale studies on landfill gas production. In estimation of landfill gas generation from landfill sites, zero and first order decay models have been used. In zero order models, it is considered that waste age and type do not affect the rate of waste decay and landfill gas generation (Heimann, Muthu, & Karthikeyan, 2016). In addition to this, it is assumed that biogas generation is steady in time (Kamalan, Sabour, & Shariatmadari, 2011). In first order decay models, time-dependent carbon depletion is calculated for wastes. EPER Germany and SWANA-zero order and IPCC 1996 models are examples to zero order decay models. On the other hand, LandGEM, TNO, Gassim, Afyalzorg, IPCC 2006 and LFGEEN are example models that assume first order decay for gas production (Kamalan et al., 2011). Intergovernmental Panel on Climate Change recommends the first order decay models for landfill and methane gas generation evaluations at landfill sites. Researches show that higher order models give more accurate results (Govindan & Agamuthu, 2014). Therefore, first order decay models are generally used for determining gas generation in the landfill sites.

There have been applications for investigating landfill gas generation for different waste compositions in the laboratory scale (Alibardi & Cossu, 2015; Kobayashi et al., 2012; Gunaseelan, 2004). In addition to these studies, laboratory and field measurements have been used together to specify gas generation using IPCC 2006 and LandGEM models (Wangyao et al., 2010; Chakraborty et al., 2013; Govindan &

Agamuthu, 2014). LandGEM and IPCC 2006 models are commonly preferred first order decay models in the world. They are public and run in Excel as add-ins. Taşkan (2001), Işın (2012), Cakir et al. (2016) and Mou et al. (2015) applied LandGEM and IPCC 2006 models to estimate gas generation amounts in selected landfills using default model values. The LandGEM model has been used in several countries for gas generation specification (Faour et al., 2007; Fei et al., 2016). These studies showed common usage and reliability of LandGEM and IPCC 2006 models for examining landfill gas generation at landfill sites.

In this study, LandGEM and IPCC 2006 models were applied to predict and evaluate the gas generation profile at Afyonkarahisar Sanitary Landfill Site. Landfill gas generation and its amount are also important due to emissions to the atmosphere as GHG. In the landfill site, energy has been generated from landfill gas since 2012. However, projections of gas generation for future and current operating conditions were not made. In other words, gas generation potential had not been evaluated for the site. Moreover, impact of energy production at the site on GHG emissions was not studied. In order to address these issues, LandGEM and IPCC 2006 models were calibrated with the help of historical data. Four different management scenarios were considered. These scenarios were compared to the current practice. With this comparison, advantages that may be brought by different management alternatives were evaluated. In addition to this, GHG emission reduction and energy production potential were evaluated using modelling results for the site. In conclusion, the results of the study can contribute to landfill gas management of Afyonkarahisar Sanitary Landfill Site.

CHAPTER 2

LITERATURE REVIEW

2.1. Municipal Solid Wastes

Throughout the world waste generation rates are increasing year by year. According to the data in 2012, 1.3 billion tons of solid waste was generated in the world. In other words, 1.2 kilogram waste was generated by a person per day. It is estimated that 2.2 billion tons of municipal solid wastes will be generated by 2025 in the world (The World Bank, 2017). Solid waste management is important for cities since livable and sustainable cities can be formed by providing good management strategies. However, many developing countries and cities face with management problem for wastes. Costs for good waste management forms 20-50% of municipal budgets. Therefore, waste management is considered as expensive. Good waste management includes integrated waste management systems (The World Bank, 2017).

Municipal solid wastes are defined as non-hazardous and domestic wastes or wastes that have similar content and structure in Waste Management Regulation of Turkey. Municipal solid wastes do not include medical, hazardous, construction, excavation soil and special wastes (Ministry of Environment and Urbanization, 2016). According to the TÜİK municipal waste statistics, 28 million tons of municipal solid wastes were collected in our country in 2014. Actually the exact amount of municipal solid wastes was 27,126,138 tons in 2014 (Ministry of Environment and Urbanization, 2016). On the other hand, according to the action plan of Ministry of Environment and Urbanization, total waste amount was 31,115,327 tons in 2014 (Ministry of Environment and Urbanization, 2016). According to the statistics of TÜİK, daily municipal solid waste generation per person was calculated as 1.08 kg.

This unit waste generation amount is given as 0.96 kg/capita/day in the action plan (Ministry of Environment and Urbanization, 2016). Types of solid wastes produced in Turkey are given Figure 1. Municipal solid wastes comprise main part of the total wastes with 87.18%.

Ministry of Environment and Urbanization declared the National Waste Management and Action Plan for 2023 in 2016. This report was formed for 7 geographical regions and 15 sub-zones in Turkey. According to this report, municipal solid waste amount was 27.1 million tons in 2014 in Turkey. It was estimated that municipal solid waste amount would be approximately 29.6 million tons in 2018 and 33 million tons in 2023. When data from 2012 to 2014 was considered, it was seen that although the municipal solid waste amount increased, waste amount per person decreased. Population and economic growth affected municipal solid waste generation. Moreover, reduction and recovery from these wastes became important in the period from 2008 to 2014. It was seen that population and waste generation increased proportionally (Ministry of Environment and Urbanization, 2016).

For specifying waste management plans, waste amount and characteristic are important parameters. Three management methods were identified for management of municipal solid wastes in 2014 in Turkey. Application percentages of these are given in the Figure 2 for 2014 (Ministry of Environment and Urbanization, 2016). As mentioned before, municipal solid waste amount increased from 2012 to 2014, but waste amount per person decreased. The reason of this is related with recording and data evaluation. The waste amounts were recorded with the help of inputs from sanitary landfill sites. On the other hand, in 2014, 63.5% of these wastes were sent to sanitary landfill sites, 35.5% to municipal disposal sites, 0.5% to compost facilities and remaining 0.5% was handled through other methods.

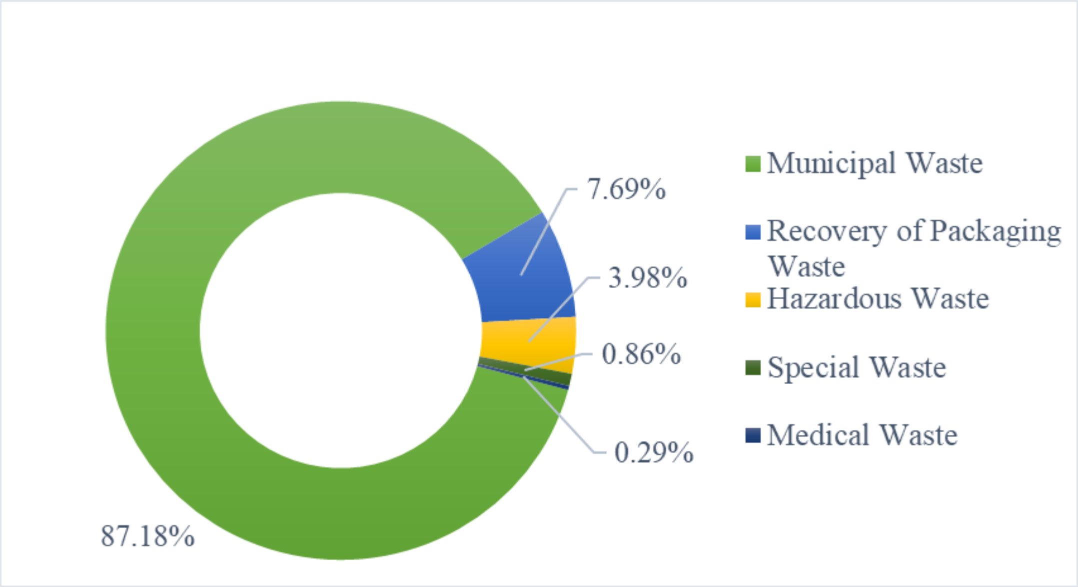

Figure 1.Solid waste types in Turkey in mass basis (Ministry of Environment and Urbanization, 2016)

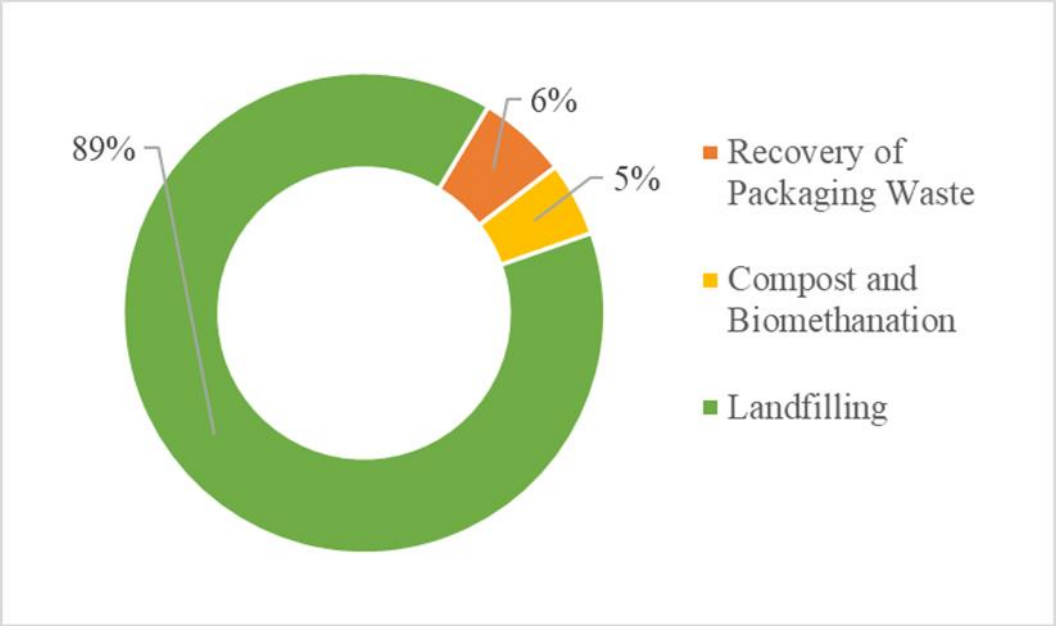

Figure 2.Management methods for municipal solid wastes in Turkey (Ministry of Environment and Urbanization, 2016)

In our country, although separate collection of packaging wastes is required, the major portion of these wastes is sent to landfill sites. When packaging waste was ignored, municipal solid wastes were collected and sent to recovery facilities, sanitary landfill and unsanitary disposal sites in 2014. The percentage of these three methods in municipal solid waste management is depicted in Figure 5. It can be seen that sanitary landfilling is the most common method for municipal solid waste handling in Turkey (Ministry of Environment and Urbanization, 2016).

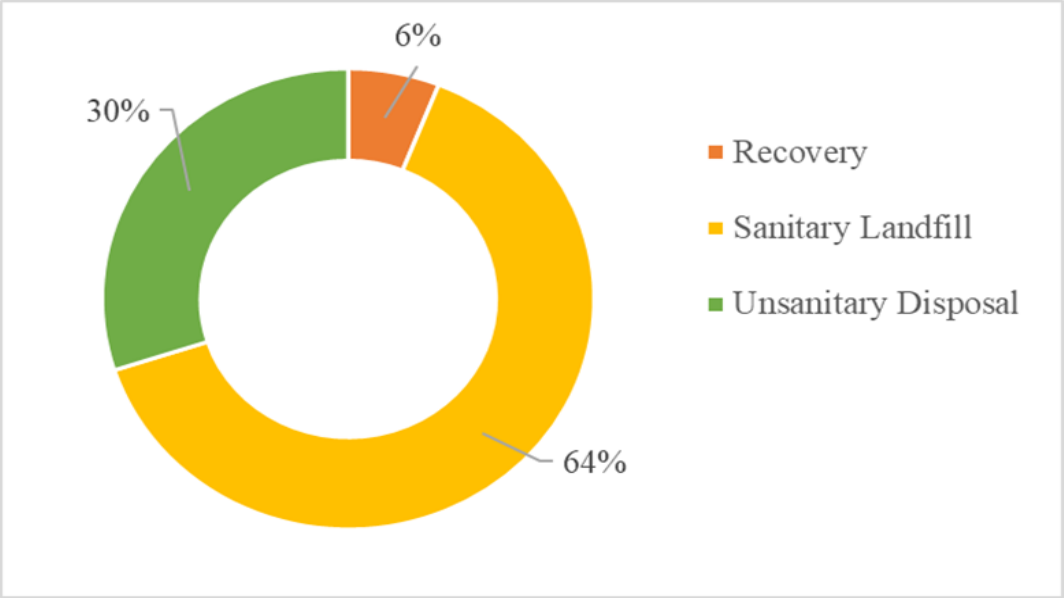

Figure 3.Municipal solid waste processing methods (Ministry of Environment and Urbanization, 2016)

Although management strategies have started to aim at decreasing solid waste production and increasing recycling, disposal of the wastes to the landfill sites and sanitary landfills is still one of the common solid waste management methods. There were 79 sanitary landfill sites in Turkey in 2014. These landfill sites provided service for 47.4 million population in 1073 municipalities. The number of sanitary landfill sites reached to 81 and they provided service for 48.9 million population in 1091 municipalities by the end of 2015. In 2016, the number of sites reached to 82. These sites were founded in 59 provinces. In addition to these, there are more than 800 unsanitary landfill sites in Turkey. The municipal solid waste amount sent to the unsanitary landfill sites decreased by 44% from 2008 to 2014. On the other hand, incoming municipal solid waste amount to the sanitary landfill sites increased by 42% from 2008 to 2014 (Ministry of Environment and Urbanization, 2016).

Across Turkey waste production continues to increase compared to past years and this increase in the waste generation enhances the need for sustainable management of waste. Sustainable solid waste management includes reduction, reuse, recycling and recovery of wastes. There are 30 metropolitans, 51 provincial, 919 district and 397 town municipalities in Turkey. In addition to these, some municipalities other than metropolitans are forming unions for efficient and economical management of collection and disposal of waste jointly. There are 59 such unions in Turkey. The Ministry is planning to construct landfill in Mediterranean and Aegean Regions in addition to the sanitary landfill sites in Marmara, Aegean and Central Anatolia (Ministry of Environment and Urbanization, 2016).

The highest municipal solid waste amount is in the Marmara Region. Aegean Region has 15% share in the total municipal solid waste amounts in Turkey. In other words, the second highest municipal solid waste amount is in the Aegean Region. Afyonkarahisar is found in this region. For Turkey and Aegean Region, municipal solid waste characterizations are given in Figure 4 and Figure 5, respectively, based on 2014 data. In addition to this, for Aegean Region which includes Afyonkarahisar, estimated solid waste amount is 489,352 tons in 2023 (Ministry of Environment and Urbanization, 2016).

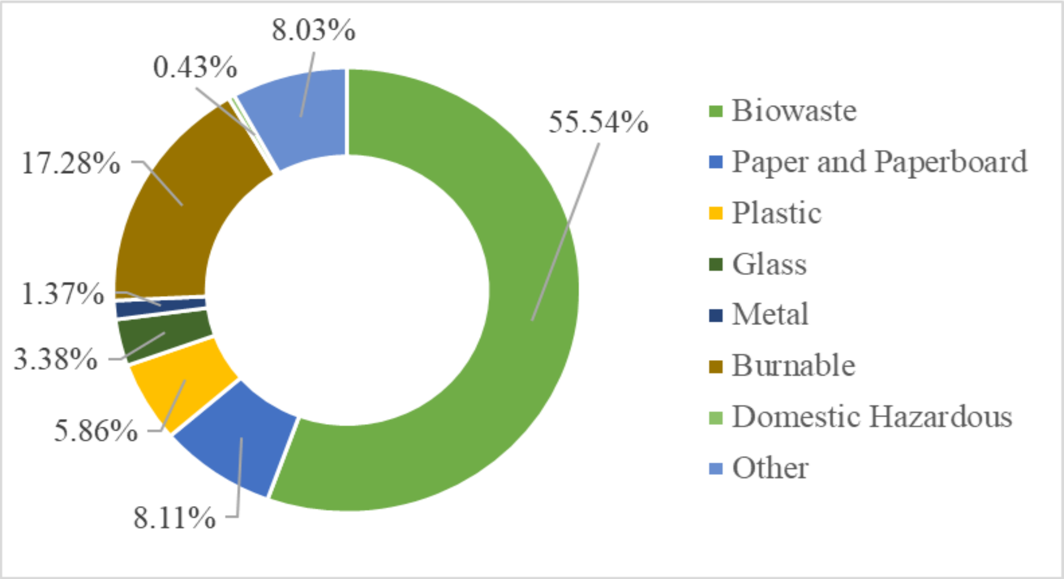

Figure 4.Municipal solid waste characterization for Turkey (Ministry of Environment and Urbanization, 2016)

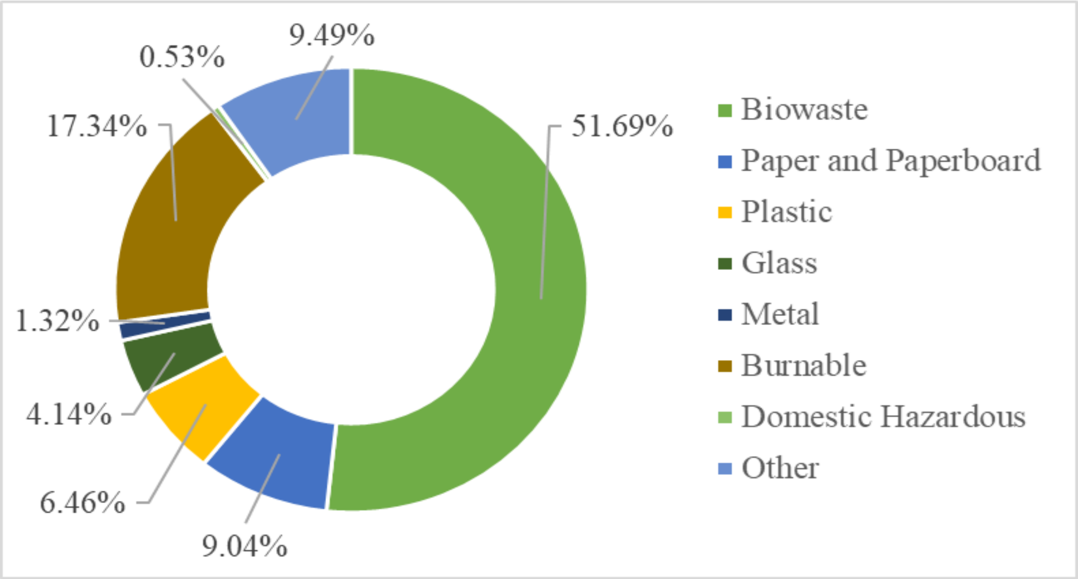

Figure 5. Municipal solid waste characterization for Aegean Region (Ministry of Environment and Urbanization, 2016)

2.2. Energy Generation from Wastes

Traditional energy production systems consume natural resources rapidly (Dolgen, Sarptas, Alpaslan, & Kucukgul, 2005). Oil sources are decreasing and fossil fuel usage damages the environment. Considering these situations, renewable energy sources have become important (Amini et al., 2012). In our country, search for alternative energy sources has been promoted to meet increasing energy demand. For obtaining energy from renewable sources, solid waste is one of the important sources (Dolgen et al., 2005; Tercan, Cabalar, & Yaman, 2015).

Landfill gas from sanitary landfills is formed by anaerobic degradation of organic content of municipal solid wastes. In this gas, the amounts of methane and carbon dioxide are higher than other components (Dolgen et al., 2005). There are five stages which contribute to landfill gas generation during biodegradation of organic waste. These stages are aerobic, acidogenic, acetogenic, methanogenic and aerobic. In the first stage, hydrolysis and aerobic degradation occur. In completion of this aerobic period, readily degradable carbohydrates are converted to carbon dioxide, water and simple sugars. In the second stage, simple sugar fermentation to volatile acids and hydrolysis happen. In the acetogenic stage, hydrogen and carbon dioxide are formed by conversion of soluble acids to acetic acids. Then, with methanogenic stage, methane and carbon dioxide gases are formed by methanogenic generation organisms. In the last stage, methane is oxidized with re-establishment of aerobic conditions (Govindan & Agamuthu, 2014).

If gas emission is controlled and managed, methane gas which is emitted from landfill sites can be used as a renewable energy source (Amini et al., 2012). Methane gas is an important greenhouse gas as well. When methane gas is not managed well, it causes environmental problems (Melikoglu, 2012). Usage of landfill gas for producing energy helps in solution of climate change and global warming problems (Melikoglu, 2012). In Turkey, the most common method which is used in disposal of solid wastes is sanitary landfilling. In Turkey, there are 33 landfill sites which convert landfill gas to energy (Ministry of Environment and Urbanization, 2016).

According to literature, 1 ton of municipal solid waste (as dry weight) in landfills forms approximately 120-150 m^3 landfill gas. The calorific value of the gas is approximately 5-6 kWh/m^3 (Dolgen et al., 2005).

Operation conditions of landfill and waste types can significantly affect quality and quantity of gas in integrated solid waste management systems (Worrell & Vesilind, 2012). Because of this, operation of landfill sites and deposition conditions of waste types constitute engineering problems. For solving these problems, modeling approach is important in terms of investigating different scenarios. In this study, change in landfill gas generation according to different waste compositions and waste placement alternatives in landfill sites are evaluated through modeling. For this purpose, Afyonkarahisar Sanitary Landfill Site was investigated

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2.3. Greenhouse Gases

Greenhouse gases are expressed as gases trapping heat in the atmosphere (EPA, 2016b). According to the Kyoto Protocol, there are six greenhouse gases. These are carbon dioxide, methane, nitrous oxide and three fluorinated gases (Eurostat, 2014). These gases enter the atmosphere through several situations. These are given as following (EPA, 2016b).

- Carbon dioxide (CO_2) is emitted to atmosphere through burning fossil fuels which are coal, natural gas and oil, trees and wood products and solid waste. In addition to this, some chemical reactions as in manufacturing of cement contribute to emission of carbon dioxide.
- Methane (CH_4) enters the atmosphere through production and transport of coal, oil and natural gas. Also, decay of organic waste in municipal solid waste landfills, livestock and other agricultural practices contribute to the emission of this gas to the atmosphere.
- Nitrous oxide (N_2O) enters to the atmosphere through combustion of fossil fuels and solid waste, agricultural and industrial activities.

- Fluorinated gases are hydrofluorocarbons, sulfur hexafluoride, nitrogen trifluoride and perfluorocarbons. These gases are synthetic and powerful greenhouse gases. Industrial processes cause to emission of these gases to the atmosphere.

Carbon dioxide is a major greenhouse gas emitted from human activities. According to the 2015 data, 82.2% of all U.S. anthropogenic greenhouse gas emissions was due to carbon dioxide. Anthropogenic emissions of this gas have increased carbon dioxide in the atmosphere since industrial revolution (EPA, 2016b). On the other hand, 10% of all U.S. anthropogenic greenhouse gas emissions were due to methane gas. Impact of methane gas to global warming was more than 25 times greater than carbon dioxide over 100-year period. More than 60% of total methane emissions result from human activities (EPA, 2016b).

According to the 2015 U.S. data, landfills had 18% of total methane gas emissions (EPA, 2016b). It is also stated that the third largest anthropogenic source of methane emissions is landfills containing municipal solid wastes in the United States (EPA, n.d.). Contribution of landfills in greenhouse gas generation in the world is shown in Figure 6. As shown in the figure, the largest source of greenhouse gas emission is landfill sites in comparison to other waste handling operations (Eurostat, 2014).

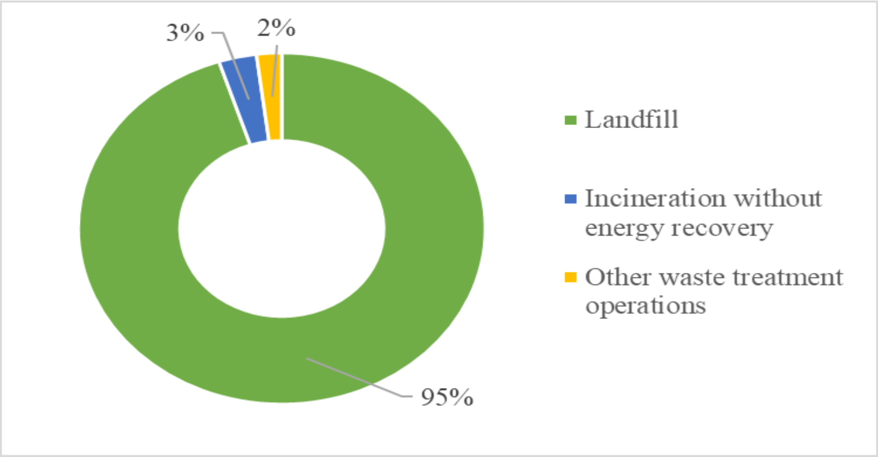


Figure 6.Estimated greenhouse gas emissions from different waste disposal handling operations in 2011 (Eurostat, 2014)

According to the EPA's Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions Report for 1990-2030, when total non-CO_2 emissions are considered, the waste sector had 13% of the total emissions in 2005. It is estimated that the waste sector will contribute to 11% of the total emissions by 2030. Emissions from different sources are as given in Figure 7. As shown in this figure, landfilling of solid wastes has huge contribution to the emissions within the waste sector. Emissions from landfilling and wastewater were 92% throughout 1990 to 2030. In addition to this information, landfilling was the 4th largest individual emission source of non-CO_2 greenhouse gas emissions in 2005 with 794 $MtCO_2e$ (EPA, 2012).

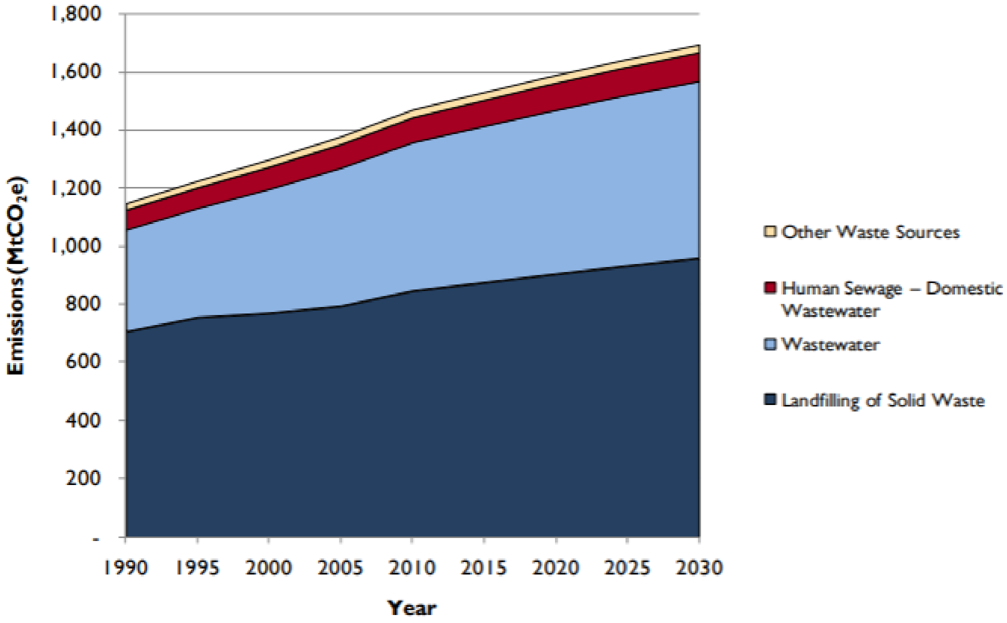


Figure 7.Total non-CO_2 emissions from the waste sector by source ($MtCO_2e$) (EPA, 2012)

Global methane emissions from landfilling of solid waste increased by 12% from 1990 to 2005. In addition to this, it is estimated that emissions will increase by 21% from 2005 to 2030. The yearly emission values are as given Table 1 (EPA, 2012).

Table 1.Total methane emissions from landfilling of solid waste ($MtCO_2e$) (EPA, 2012)

	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	706.1	755.4	769.8	794.0	846.7	875.6	905.0	933.3	959.4

Global Methane Initiative (GMI) was established in 2004. This initiative internationally aims to decrease, recover and use of methane gas arising from biogas which involves agriculture, municipal solid waste and wastewaters, coal mines and oil and gas systems. The initiative works together with other international organizations. For reducing global methane emissions, the initiative has established key alliances with partners such as the United Nations Economic Commission for Europe (UNECE) and the Climate and Clean Air Coalition (CCAC). Turkey became a partner in GMI on 30 September 2010 in Coal Mines, Municipal Solid Waste, and Oil and Gas Subcommittees. According to the EPA's Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases report in 2010, 12th estimated highest anthropogenic methane emission was in Turkey in the world. 26% of Turkey's anthropogenic methane emission was due to agriculture (manure management), coal mining, municipal solid waste and wastewater (Global Methane Initiative, n.d.). In addition to GMI, Turkey is also a member of the Organization for Economic Cooperation and Development (OECD) countries as mentioned in the global emission report. 45% of the global methane due to landfilling of solid wastes was emitted by OECD countries. However, U.S. had the largest part of these emissions from landfilling of solid wastes within the OECD countries (EPA, 2012).

Turkey's ratification to Climate Change Convention was on 24 May 2004. Also, Turkey's ratification to Kyoto Protocol was on 28 May 2009 (United Nations Framework Convention on Climate Change, n.d.). According to the United Nations Framework Convention on Climate Change report for Turkey, greenhouse gas emissions from 1990 and 2015 were declared for Turkey (United Nations Framework Convention on Climate Change, 2016). Moreover, data specified by UNFCCC for

Turkey's greenhouse gas emissions is given in Table 2 from 1990 to 2015 (United Nations / Framework Convention on Climate Change, 2016).

Table 2. GHG emissions of Turkey in kton CO_2 equivalent (United Nations / Framework Convention on Climate Change, 2016)

Year	**GHG emissions (kton CO_2 equivalent)**
Base year	213,971.94
1990	213,971.94
1995	246,553.35
2000	296,473.41
2005	337,152.78
2010	406,805.31
2014	455,614.99
Last Inventory Year	475,056.40
Change from base year to latest reported year	122.02%

According to results in the Table 2, GHG emissions increased by 122% from 1990 to 2015 in Turkey. For Turkey, it is stated that total target reduction in GHG emission will be 21% from 1,175 to 929 million tons CO_2 equivalent by the end of 2030 (UNFCCC, n.d.). Total emissions in Turkey were specified as 440 million tons CO_2 equivalent in 2012. According to the 2012 data, the highest emissions occurred in energy sector with 70.2%. The waste sector had effects on emissions with a share of 8.2%. Detailed emissions for different sources are as given in Figure 8 (UNFCCC, n.d.). GHG emissions distributions in the waste sector are as given in Figure 9 for Turkey (United Nations Framework Convention on Climate Change, 2016).

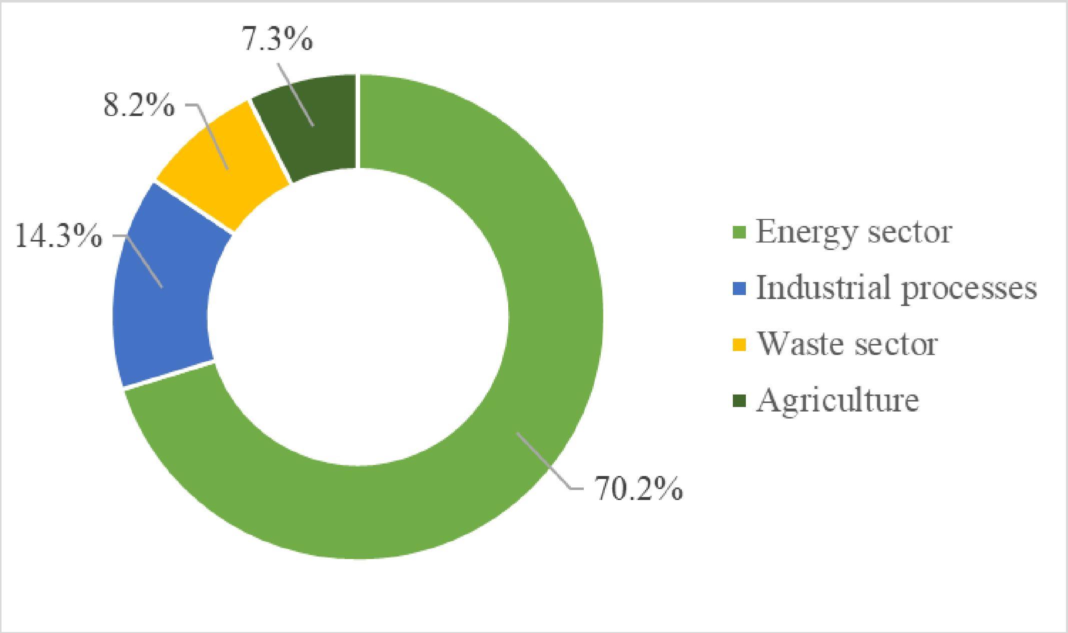


Figure 8.Greenhouse gas emission contributions from different sectors in Turkey in 2012 (UNFCCC, n.d.)

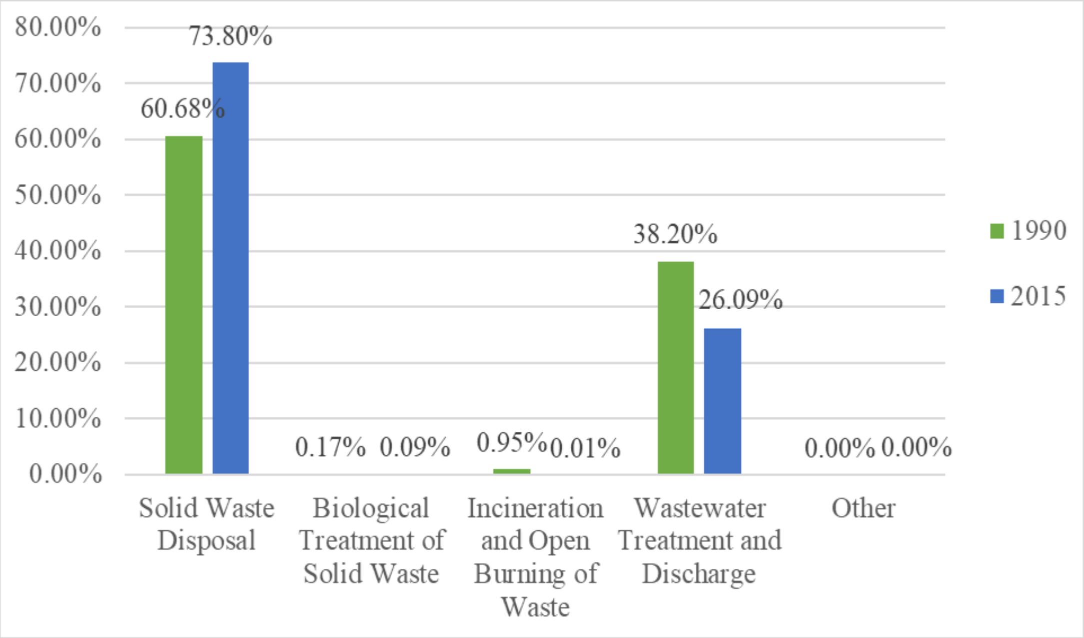


Figure 9. Contributions to GHG emissions in the waste sectors from 1990 to 2015 (United Nations Framework Convention on Climate Change, 2016)

As shown in Figure 9, the main GHG emissions in the waste sector in Turkey were due to solid waste disposal sites. In addition to this, the contribution of solid waste disposal for GHG emissions within the waste sector increased from 1990 to 2015, from 60.68% to 73.80%, respectively. This shows that solid waste disposal sites have importance for greenhouse gas emissions in Turkey. In addition to this information, according to data of UNFCCC (2016) for Turkey, aggregate greenhouse gas emissions due to solid waste disposal in Mtons CO_2 equivalent are given in Table 3.

Table 3.Aggregate GHGs in Turkey due to solid waste disposal, Mtons CO_2 equivalent (UNFCCC, 2016)

Category	**Base Year (1990) (Mtons CO_2 equivalent)**	**Last Inventory Year (2015) (Mtons CO_2 equivalent)**
Solid waste disposal sites	6.73	12.46
Managed waste disposal sites	No info	3.44
Unmanaged waste disposal sites	6.73	9.02
Uncategorized waste disposal sites	No info	No info

On the other hand, data by the European Environment Agency (EEA) on methane emissions in Turkey and EU28 countries from 1990 to 2015 are provided in below figures (EEA, 2017). Also, share of methane emissions in Turkey due to solid waste disposal with respect to total methane emissions are depicted in Figure 12 (EEA, 2017).

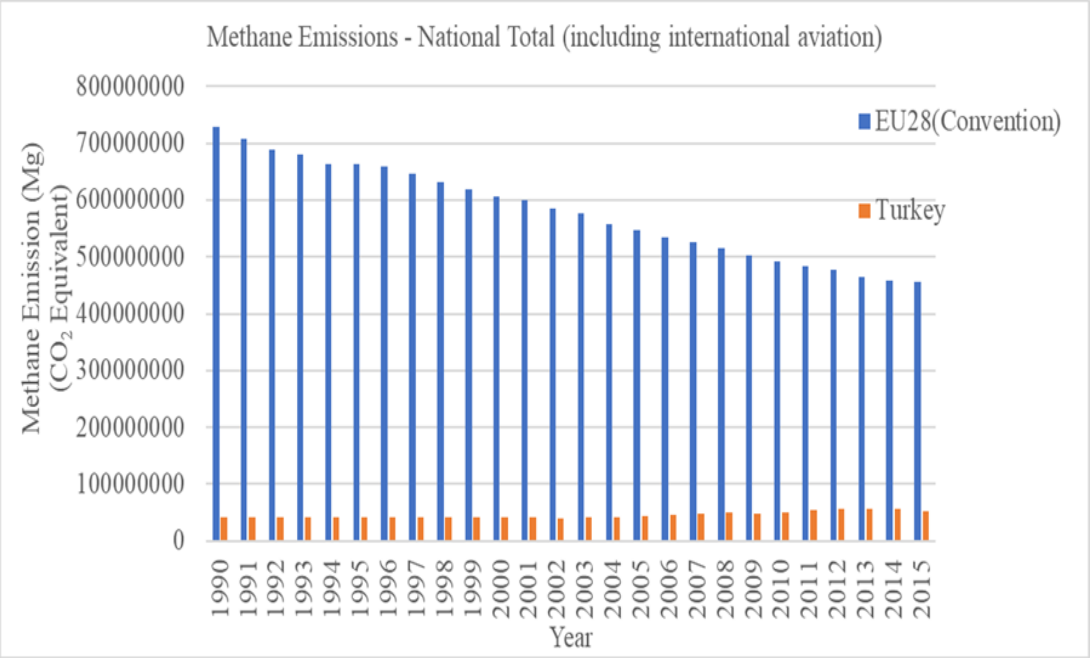


Figure 10.Total national methane emission in the World and Turkey (EEA, 2017)

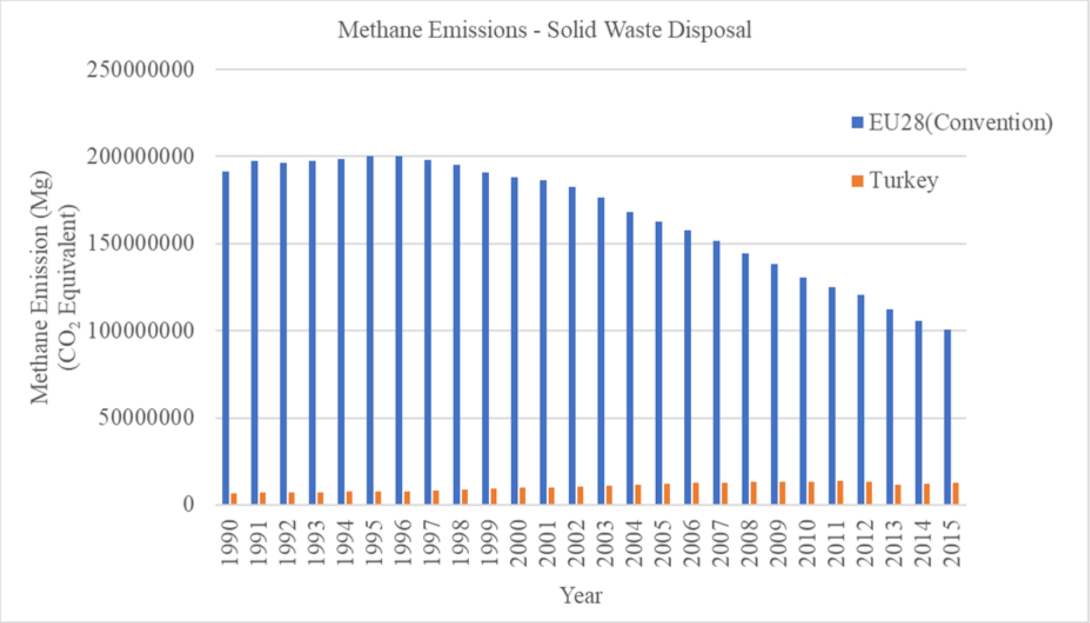


Figure 11. Total national methane emission in the World and Turkey due to solid waste disposal (EEA, 2017)

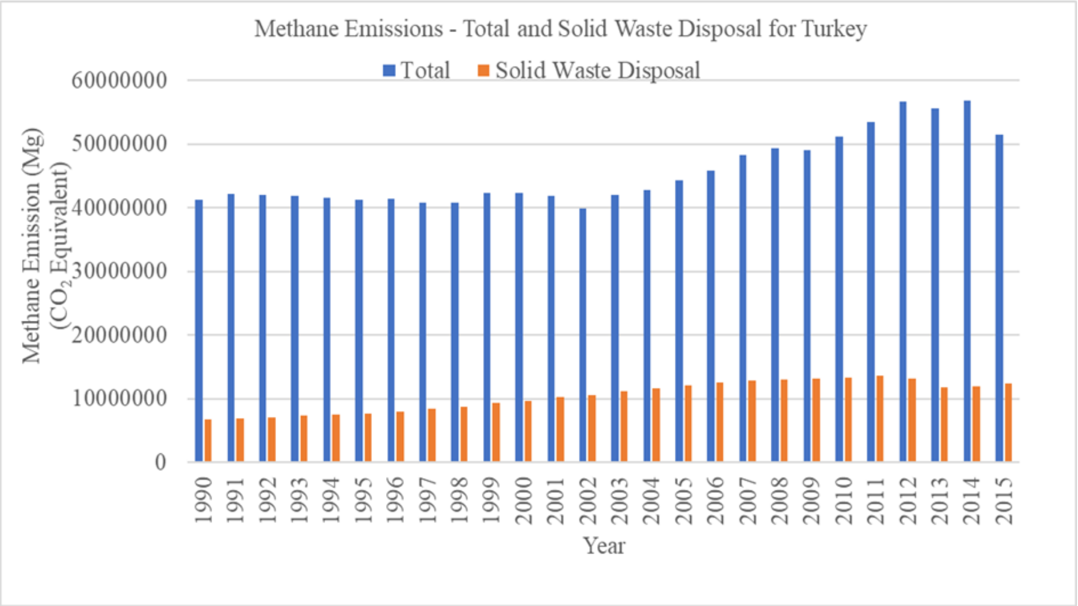


Figure 12.Total methane emissions and methane emissions due to solid waste disposal for Turkey (EEA, 2017)

2.4. Models

There are several models that simulate landfill gas generation. These are zero and first order decay models. In the zero order decay models, biogas generation in a landfill site is steady in time (Kamalan et al., 2011). In this type of models, it is assumed that rate of waste decay and landfill gas generation are not affected from waste age and waste type. Therefore, this type of models is preferred when global and national emissions are estimated with the assumption of no major change in waste composition and amount (Heimann, Muthu, & Karthikeyan, 2016). EPER Germany, SWANA-zero order and IPCC 1996 are examples for zero order decay models. On the other hand, in first order decay models, depletion of carbon in waste is calculated as a function of time. TNO, LandGEM, Gassim, Afvalzorg, IPCC and LFGEEN are examples to first order decay models (Kamalan et al., 2011).

2.4.1. Afvalzorg

The Afvalzorg model is a first order and multi-phase model. Typical waste composition can be used in this model. There are eight waste categories and three fractions. Landfill gas generation is calculated for each fraction. The mathematical description of the model is expressed as given in below equation (Rajaram et al., 2011).

$$\alpha_t = \varsigma * \sum_{i=1}^{3} c * A * C_0 * k_{1,j} * e^{-k_{1,j}t} \qquad (1)$$

where

α_t = Landfill gas production at a given time (m^3 LFG/year)

ς = Dissimilation factor

i = Waste fraction with degradation rate $k_{1,j}$ (kg_i / kg waste)

c = Conversion factor (m^3 LFG/ kg OM degraded)

A = Amount of waste in place (Mg)

C_0 = Amount of organic matter in waste (kg OM/ Mg waste)

$k_{1,j}$ = Degradation rate constant of fraction I (1/year)

t = Time elapsed since deposition (year)

2.4.2. GasSim

Standard risk assessment methodology is supplied for operators and consultants in the last version GasSim2.5. The model contributes to landfill gas risk assessment by simulating landfill gas generation, emissions, migration and impacts. The model is a probabilistic model and includes Monte Carlo simulation for selecting random pre-defined possible input values and inclusion in model calculations (Golder Associates, 2012). Waste amount is entered into the model in Mg. In addition to this, specific breakdown during a particular year of disposal is required for the model. Calculation modules of the model are protected (Heimann et al., 2016).

2.4.3. Swana Zero Order

The Solid Waste Association of North America (SWANA) is one of the zero order models. The governing equation of the model is as given below (Heimann et al., 2016).

$$Q = (M*L_0) / (t_0 - t_1) \quad \text{for } t_0 < t < t_1 \tag{2}$$

where

Q = Methane generation rate (m^3/year)

M = Waste amount in the disposal site (mg)

L_0 = Methane generation potential (m^3/mg waste)

t_0 = Lag time (year)

t_1= Time to endpoint of generation (year)

2.4.4. Eper Germany

EPER Germany model is another zero-order model. The model is mathematically expressed by the equation given below (Heimann et al., 2016).

$$M_e = M*BDC*BDC_f*F*D*C \tag{3}$$

where

M_e = Amount of diffuse methane emission (mg CH_4 / year)

M = Annual amount of landfilled waste (mg)

BDC = Proportion of biodegradable carbon (mg C in waste / mg waste)

BDC_f = Proportion of biodegradable carbon converted into landfill gas (%)

F = Fraction of methane in landfill gas (-)

D = Collection efficiency factor (-)

2.4.5. IPCC

IPCC model which is developed by the support of UNEP and WMO aims at examination of climate change and global warming. There are two main IPCC models in the literature. These are IPCC 1996 which is used for determining landfill gas amount with default values and IPCC 2006 which has a first order decay reaction equation. The models are running as Excel add-ins.

In IPCC 1996, GHG emission (Gg/year) and generated volume of methane (m^3/year) amounts can be calculated. The equation used in emission calculation is given as below (Kamalan et al., 2011):

$$E = (MSW_T*MSW_f*MCF*DOC*DOC_f*F*16/12)-R)*(1- OX) \quad (4)$$

where

E = Gas generation amount (Gg/year)

MSW_T = Total generated municipal solid waste amount (Gg/year)

MSW_f = Ratio of disposed solid waste amount to total municipal solid waste (-)

MCF = Methane correction factor (-)

DOC = Degradable organic carbon (-)

DOC_f = Fraction of difference from DOC (-)

F = Methane faction in landfill gas (-)

R = Recovered methane (Gg/year)

OX = Oxidation factor (-)

Weight percent in terms of DOC values for different waste types is calculated as in below equation (IPCC, 1996):

$$\text{DOC} = 0{,}4\ A + 0{,}17\ B + 0{,}15\ C + 0{,}3D \qquad (5)$$

where

A= Weight-based percent of paper and textile wastes in total municipal wastes.

B= Percent of garden wastes, park wastes and organic degradable wastes other than food wastes in municipal solid waste.

C= Percent of food wastes in municipal solid wastes.

D=Percent of wood wastes in municipal solid wastes.

IPCC 2006 calculates emissions by using a first order decay reaction. In this model, the degradable organic carbon content (DOC) is assumed to degrade slowly. For calculating first order decay rate, historical waste disposal information is needed. Methane emission is calculated as given below (Pipatti & Svardal, 2006):

$$ECH_4 = [\textstyle\sum_x CH_{4_{x,T}} - R_T] * (1 - OX_T) \qquad (6)$$

where

E_{CH4} = Methane emission (Gg/year)

T = Inventory year (year)

x = Waste type (-)

$CH4_{x,t}$ = Methane amount from x type of waste in T year (Gg/year)

R_T = Recovered methane (Gg/year)

OX_T = Oxidation factor (-)

L_0 value is calculated as given below (Pipatti & Svardal, 2006):

$$L_0 = DDOC_m * F * 16/12 \tag{7}$$

where

L_0 = Methane generation potential (Gg CH_4)

$DDOC_m$ = Decomposable DOC amount (organic carbon that will degrade under anaerobic conditions in landfill site) (Gg)

F = Methane fraction of landfill gas (-)

16/12 = Molecular weight ratio (CH_4/C)

$DDOC_m$ is calculated as in given equation:

$$DDOC_m = W * DOC * DOC_f * MCF \tag{8}$$

where

W = Deposited waste (Gg)

DOC = Degradable organic carbon (Gg C/Gg)

DOC_f = Degradable organic carbon fraction (-)

MCF = Methane correction factor (-)

There are two options for specifying landfill gas emission of municipal solid waste in IPCC model. The first one is a multi-phase model. This model depends on waste composition data. Every degradable waste amount is entered into the model. The second option is a single-phase model. This model is based on bulk waste amount. The single-phase model is also used for industrial wastes and sludge. DOC and half decay rate values can be entered into the model separately. If waste composition is not varying, similar results can be obtained with these two models. According to climatic conditions of the solid waste disposal sites, different degradation ratios could be selected. Suggested (default) k values are given in IPCC for slow, medium and fast degradation of wastes and climate conditions (Pipatti & Svardal, 2006).

For running IPCC 2006 model, information as listed below is required (Pipatti & Svardal, 2006):

- Type of wastes in a landfill site
- Geographical location of a landfill site, size and waste age
- Measurements of landfill gas at the given landfill site and methane ratio in the landfill gas
- Amounts of yearly waste acceptance and the beginning year of acceptance of wastes in the landfill site
- Recovered gas percentage
- Average annual rainfall amount

2.4.6. TNO

TNO model is one of the first order decay models. Landfill gas generation is calculated by taking the waste amount in the disposal site, degradation of organic carbon in the waste and degradation rate into consideration. Mathematical description of the model is as given below (Heimann et al., 2016).

$$\alpha_t = \varsigma * 1.87 * A * C_0 * k_1 * e^{-k_1 t} \tag{9}$$

where,

α_t = Landfill gas production at a given time (m^3/year)

ς = Dissimilation factor (0.58)

A = Amount of waste in disposal site (m^3/kg C degraded)

C_0 = Amount of organic carbon in waste (kg C in waste/mg waste)

k_1 = Degradation rate constant (0.094)

2.4.7. LandGEM

This model is developed by USEPA. It can be used for specifying emissions of landfill gas, methane gas and carbon dioxide gas from organic compounds and municipal solid wastes. The model can be run by using not only data specific to the landfill sites but also default values of the model. There are two types of specified parameter values. These are CAA (Clean Air Act) and Inventory (AP-42) parameters. In the model, default values are specified based on the solid waste disposal sites in the United States (EPA USA, 2005).

Model is run under Microsoft Excel. Inputs and outputs are stated in worksheets including introduction, user inputs, pollutants, input review, methane, results, graphs, inventory and report (EPA USA, 2005). First order decay reaction is used in the model. According to version 3.02, the governing equation is:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 (M_i/10)\, e^{-k t_{ij}} \tag{10}$$

where

Q_{CH4} = Annual methane production (m^3/year)

i = Time increment (1 year)

n = Difference between the year of gas production calculation and the beginning year of waste acceptance (year)

j = Time increment (0.1 year)

k = Methane generation rate (1/year)

L_0 = Methane generation potential (m^3/Mg)

M_i = Accepted waste amount in the i^{th} year (Mg)

t_{ij} = Age of accepted waste in the i^{th} year (year)

Methane generation rate changes according to moisture content, pH of wastes, temperature of wastes and whether there are active microorganisms or not. In CAA and Inventory, default values of k are as given in Table 4 (EPA USA, 2005).

Table 4. Default values for methane generation rate (EPA USA, 2005)

Sources of Default Value	**Landfill Type**	**k ($year^{-1}$)**
CAA	Conventional	0.05
CAA	Arid area	0.02
Inventory	Conventional	0.04
Inventory	Arid area	0.02
Inventory	Wet area	0.7

On the other hand, L_0 changes according to the type of wastes in landfill sites and composition of wastes. When cellulose content increases, L_0 value also increases. In this model, default L_0 values are as given in Table 5.

Table 5. Default values for methane generation potential (EPA USA, 2005)

Sources of Default Value	**Landfill Type**	**L_0 (m^3/Mg)**
CAA	Conventional	170
CAA	Arid area	170
Inventory	Conventional	100
Inventory	Arid area	100
Inventory	Wet area	96

If k value is not selected among default values, it can be calculated for a given landfill site according to the "Method-2E-Determination of Landfill Gas Production Flow Rate" guide (EPA USA, 1989). The value of k is calculated using the equation below through iteration.

$$k_e^{-k} * A_{avg} - \frac{Q_f}{2L_0{}'M_r} = 0 \qquad (11)$$

where

M_r = Mass of decomposable refuse affected by the test well (Mg)

Q_f = Final stabilized flow rate (m^3/minute)

A_{avg} = Average age of refuse tested (year)

k = Landfill gas generation constant (1/year)

$L_0{}'$ = Revised methane generation potential to account for the amount of non-decomposable material in the landfill (m^3/Mg)

Information required to run the model is as follows:

- Capacity of solid waste disposal site
- Annual waste acceptance amount
- Methane generation rate
- Methane generation potential
- Total concentration of organic carbon which does not include methane
- Opening year of the site
- Whether landfill site is used for hazardous wastes or not

2.5. Example Modeling and Laboratory Scale Studies On Landfill Gas Production

In studies focusing on modeling of gas generation in landfill sites, the first order decay models are widely used. The first order decay models are recommended by

IPCC as well for determining landfill gas generation at landfill sites. As mentioned before, LandGEM and IPCC models use first order decay for specifying methane emissions. In the LandGEM model, the important input parameters are k and L_0. On the other hand, in the IPCC model, decomposable degradable organic carbon ($DDOC_m$) is the major parameter in the estimation of methane generation, instead of L_0 (Wangyao, Towprayoon, Chiemchaisri, Gheewala, & Nopharatana, 2010). According to researchers, higher order models provide better accuracies with respect to measured data (Govindan & Agamuthu, 2014).

For determining methane generation potential, different aspects with different methods were studied in the world. In general, solid waste models were used in order to specify methane gas generation amounts. However, there are several laboratory scale studies about the gas generation rate and potential as well which helps to determine the parameter values used in modeling.

Alibardi and Cossu (2015) investigated the composition variability of the organic fraction of municipal solid waste and its effect on hydrogen and methane production potentials. According to this research in Italy, bread, pasta, vegetables, fruits, and meat-fish-cheese were taken into consideration as organic wastes. These waste groups were evaluated by separating them into fractions as protein, carbohydrate and fat. In the result of the study, it is indicated that more methane is produced by meat-fish-cheese waste group. On the other hand, the least amount of methane gas is produced by bread and pasta groups. It was said that wastes with compositions of protein and lipid have high methane generation potential (Alibardi & Cossu, 2015). Likewise, methane gas amount was evaluated by considering four waste types which were fat, protein, carbohydrate and cellulose in the study which was carried out in Kyoto city (Kobayashi, Xu, Li, & Inamori, 2012). In the thermophilic conditions, there were 20 municipal solid waste components tested. According to the results of the study, it was seen that in the order of high to low methane gas generation, the waste types were fat, protein and carbohydrates. In addition to these results, the highest methane generation amount was obtained from cooking oil wastes (Kobayashi et al., 2012).

Another experimental research for determining methane generation potential was carried out in India for fruit and vegetable wastes. In the study, 54 different fruit and vegetable wastes were investigated in terms of their methane generation potentials. In the result of the study, it was seen that methane gas formation amount from mango shell, citrus and pomegranate seed wastes were more than the gas formation from cellulose wastes. In the overall results, it was stated that fruits and vegetable wastes constitute important methane potential parts within the organic fraction of municipal solid wastes (Gunaseelan, 2004).

Composition, carbon sequestration and methane yield of municipal solid wastes of United States were investigated by using and compiling literature data for methane yields and existing data of waste compositions from landfills. In the study, eleven statewide waste characterization studies were considered for evaluation of variation in composition of waste. Discarded or disposed waste data was taken into consideration after separation of recyclable and compostable materials. The waste data included landfilled and treated material in waste to energy facilities for 11 states in US. It is stated that only organics and paper wastes contributed to methane gas generation in the landfill sites. The highest methane gas generation amounts were obtained from composite paper, paperboard, paper bag and food wastes (Staley & Barlaz, 2009).

In some studies, laboratory and field measurements were made as well as modeling. An example study was conducted in Thailand. In the study, optimization of gas emission inventory parameters, methane correction and oxidation factors was performed to represent tropical conditions. Methane generation rate was measured using a chamber experiment in the field. Measurements were made during drought and wet seasons. For optimization, IPCC model was used. When the results of the study are evaluated, it was seen that methane emissions changed spatially. In addition to this, higher methane gas amount could be obtained with the help of effective management of the landfill site. When IPCC and field data were compared, more reliable outputs were obtained with IPCC model (Wangyao et al., 2010). Likewise, in a research in Malaysia, IPCC model was used for comparing model predictions and real values at Jeram Engineered Sanitary Landfill Site. LandGEM model was used for calculation of some parameters required in the IPCC model. In this study, different from previous studies, two approaches were applied during methane generation estimation. The first was bulk waste approach. With this approach, methane gas which was obtained from the bulk waste was specified. In the second approach, parameter values were specified for every degradable waste types and methane generation potential of these were determined. According to the obtained results, it was stated that methane generation rate found by the first approach (0.08 1/year) was less than the second approach (0.09 1/year) (Govindan & Agamuthu, 2014). A similar approach was applied in the research by Chakraborty et al. (2013). In the research, like in the Malaysia case, impact of applying pre-division of bulk waste which is reusable and has high carbon content on energy potential at the site was evaluated with respect to the case of no pre-division using LandGEM model. With random sampling at two different days, waste composition analysis was performed. In addition to this, calorific values of the municipal solid wastes were obtained using a calorimeter. In modeling, default degradable organic carbon values were used. Also, methane generation rate (k) was selected as 0.09 1/year according to the default value of IPCC 2006 (Chakraborty, Sharma, Pandey, & Gupta, 2013). This selected rate value is the same as in the Govindan & Agamuthu's study. According to the composition, methane generation potentials (L_0) for no pre-division wastes of three landfill sites were evaluated as 79, 77 and 82 m^3/tons. On the other hand, for pre-division wastes, L_0 values were found as 47, 48 and 51 m^3/ton. The methane volume was found as %50 (Chakraborty et al., 2013). On the other hand, Govindan & Agamuthu (2014) specified the methane volume 50-67% in their case.

As mentioned before, IPCC 1996 uses default values. Therefore, when there is a lack of historical data, the IPCC 1996 model can be selected. Abushammala et al. (2015) selected this model for determining methane generation potentials of sanitary landfill and dump sites of Malaysia. In addition to this, Jigar et al. (2016) used this model for determining methane gas generation in Ethiopia where data was lacking. In Abushammala et al.'s study (2015), not only surface gas emissions but also soil gas concentrations were specified as well. The L_0 values for sanitary landfills and dumps sites were evaluated as 151.7 m^3/ton and 75.9 m^3/ton, respectively. On the other hands, the k values of sanitary landfills were found as 0.136 1/year during wet seasons and 0.072 1/year during drought seasons. The k values of dump sites were found as 0.08 1/year during wet seasons and 0.0049 1/year during drought seasons. In the light of these information, it is stated that k value in wet seasons are 1.8 times higher than k value of drought seasons. In addition to this, k value of sanitary landfills is 17 times higher than dump sites. It can be seen that sanitary landfills, in other words managed landfills, have higher methane generation rate and potential than dump sites (Abushammala, Ahmad Basri, & Younes, 2015).

LandGEM, IPCC 2006 and other models were used for landfill and methane gas generation studies in Turkey as well. One of them was done for İzmir, Harmandalı Landfill Site. Methane generation was predicted using models with literature and field data as inputs. In the study, LandGEM, IPCC 2006, Multiphase, Tabasaran Rettenberger and Scholl Canyon models were selected and used. L_0 was calculated as 57.22 and 32.55 m^3CH_4/Mg using US EPA 1998 and IPCC 2006, respectively. On the other hand, k values were selected from literature. According to rapid, medium and slow degradation, k values were selected as 0.175, 0.1 and 0.056 1/year, respectively. These L_0 and k values were used as inputs in the models. L_0 values obtained with US EPA 1998 and IPCC 2006 were used for finding methane generation by LandGEM model. The k was used as 0.142 1/year in two different models. With these inputs, landfill gas generation data was obtained for different years (Işın, 2012). Another study at the Harmandalı Landfill Site utilized LandGEM, Multi-Phase and IPCC 2006 models. Measurements were performed at 77 chimneys at the site using a gas analyzer. Three k values were selected from literature as inputs to the models as 0.35, 0.1 and 0.05 1/year. When the results of the study are considered, it was seen that predictions by LandGEM model were higher than other models (Cakir, Gunerhan, & Hepbasli, 2016). On the other hand, in a study in Erzurum (Taskan, 2001), it was stated that Tabasaran&Rettenberger model provided better results than LandGEM. In the study, management of landfills and methane generation potentials were evaluated using Tabasaran&Rettenberger and LandGEM. For Tabasaran&Rettenberger model, input values were selected from literature. On the other hand, for LandGEM case, default values of L_0 and k were selected and used as 100 m^3CH_4/Mg and 0.04-0.02 1/year, respectively (Taşkan, 2001). In a study in Denmark, it was stated that IPCC and Afvalzorg models provided more appropriate results than LandGEM. In the Denmark case, L_0 and k as model inputs were selected from default values of the models (Mou, Scheutz, & Kjeldsen, 2015).

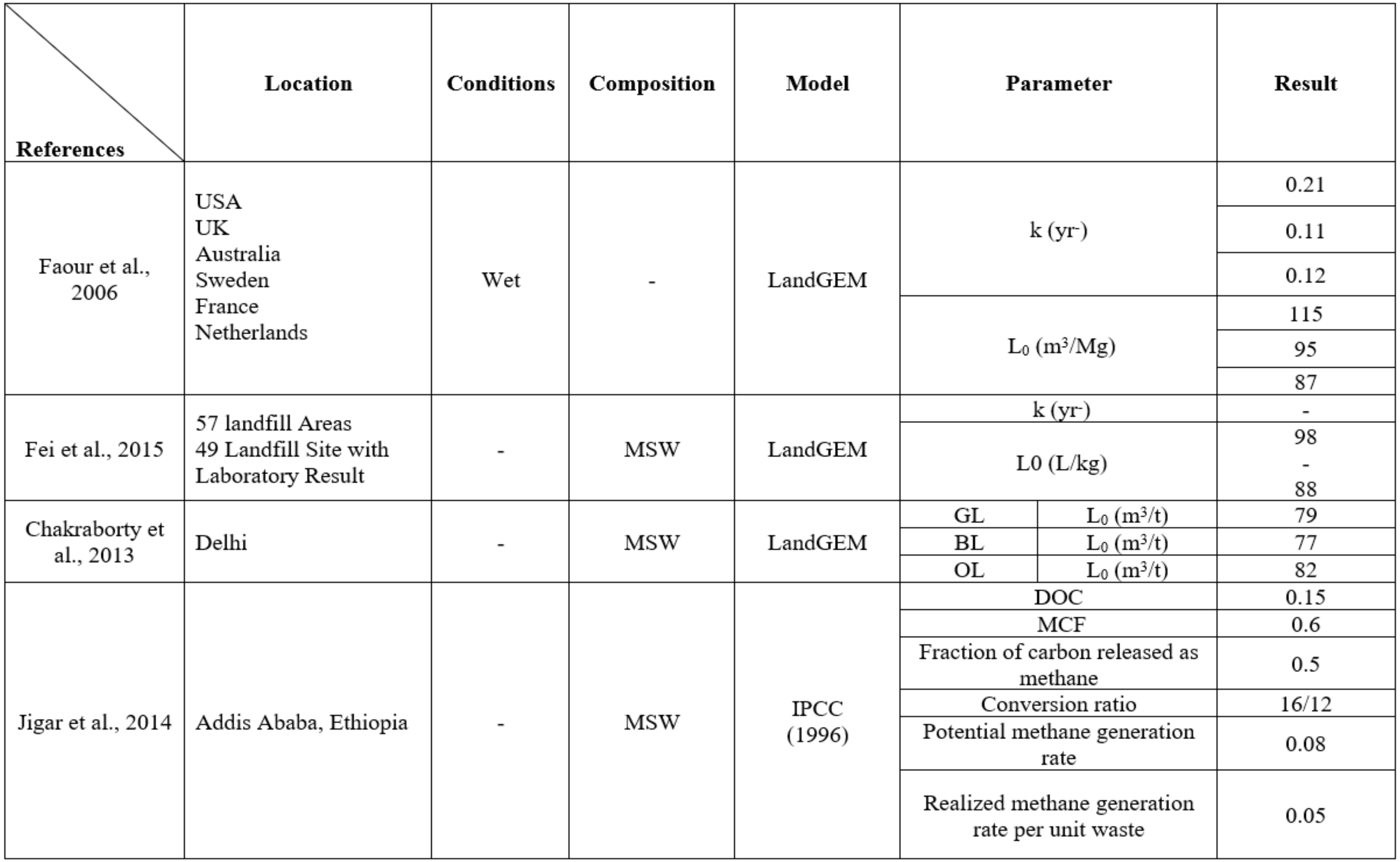
In some researches, landfill sites of several countries were investigated in terms of landfill and methane gas generation and potential. One of them was conducted by Faour et al., (2007). The research was applied for landfill sites in United States, Holland, Australia, France and Sweden. Likewise, as in previous mentioned studies, field data and model predictions by LandGEM model were compared. However, field data could not be efficiently collected for every field. In three landfill sites, L_0 values were found as 115, 95 and 87 m^3/Mg. On the other hand, k values were 0.21, 0.11 and 0.12 1/year (Faour, Reinhart, & You, 2007). The second study of the same researchers was carried out by 49 laboratory experiments and 57 landfill monitoring studies which supplied inputs to LandGEM model. Maximum methane generation rate, L_0 and k values for the model were calculated for each dataset. In the result of the research, moisture control, nutrients, temperature and microorganisms contributed in increasing k and reducing maximum methane generation rate. In addition to this, it was stated that higher k and L_0 values could be achieved by optimizing closure plans of landfills, design and operation of biogas collection system through taking site specific waste compositions and biodegradation conditions into consideration (Fei, Zekkos, & Raskin, 2016).

There is a new LandGEM model version for modelling of gas generation which is called as Central Eastern Europe Landfill Gas model. The model is developed by EPA which is similar to the LandGEM model. This model was used for Turkey for determining the effects of decreasing biodegradable wastes on methane generation potential. For this study, default values were used in the model. Three scenarios were formed. In the first one, the case of no change in waste composition was investigated. In the second, impact of meeting the target waste composition according to the regulations was researched. In the third one, the situation of 5 years delay in meeting the target was considered (Altan, 2015).

As mentioned above, wastes with different characteristics in terms of waste compositions and decomposition, the way and conditions of waste deposition can affect landfill gas generation amount and characteristics of landfill gas. The importance of these effects can be evaluated with the help of modeling approach. In this study, LandGEM and IPCC 2006 models were used and L_0 and k values were calculated for Afyonkarahisar Sanitary Landfill. For calculating the L_0, the equation in the IPCC guide was used. The k values were used in LandGEM model as input. On the other hand, in the IPCC 2006 model, instead of L_0, DDOC values were used which were selected from default values ranges.

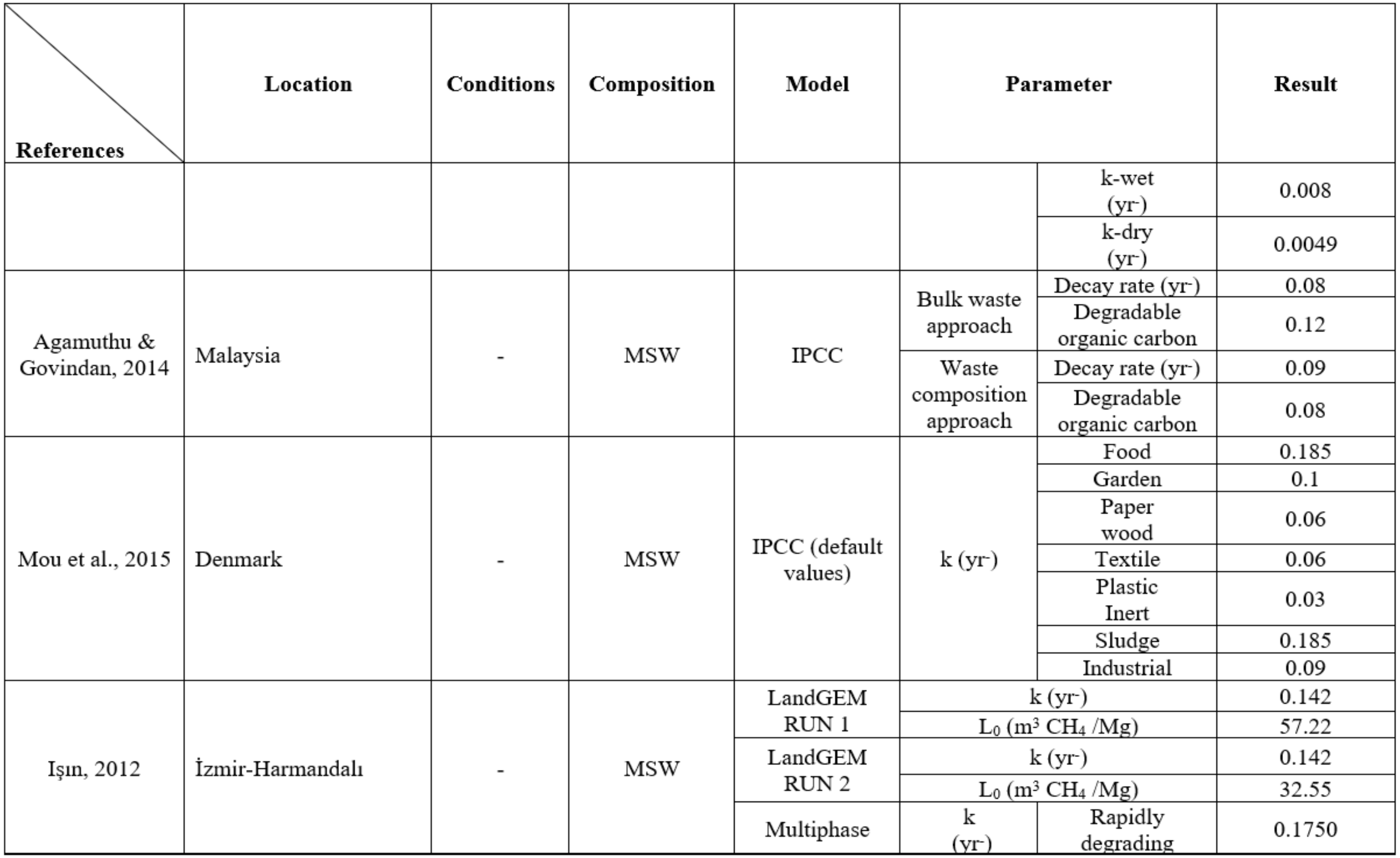
The summary of studies which are mentioned above and parameter values stated in these studies are summarized in Table 6. This table is used as a reference in this study for modeling and comparisons. In the literature, k and L_0 values ranged as 0.035-0.35 1/year and 32.55-170 m^3 CH_4/Mg, respectively.

Table 6. Summary of literature survey and parameters of them



References	Location	Conditions	Composition	Model	Parameter	Result
Faour et al., 2006	USA UK Australia Sweden France Netherlands	Wet	-	LandGEM	k (yr^{-})	0.21
						0.11
						0.12
					L_0 (m^3/Mg)	115
						95
						87
Fei et al., 2015	57 landfill Areas 49 Landfill Site with Laboratory Result	-	MSW	LandGEM	k (yr^{-})	-
					L0 (L/kg)	98 - 88
Chakraborty et al., 2013	Delhi	-	MSW	LandGEM	GL L_0 (m^3/t)	79
					BL L_0 (m^3/t)	77
					OL L_0 (m^3/t)	82
Jigar et al., 2014	Addis Ababa, Ethiopia	-	MSW	IPCC (1996)	DOC	0.15
					MCF	0.6
					Fraction of carbon released as methane	0.5
					Conversion ratio	16/12
					Potential methane generation rate	0.08
					Realized methane generation rate per unit waste	0.05

Table 6. Summary of literature survey and parameters of them (continued)



References	Location	Conditions	Composition	Model	Parameter		Result
						k-wet (yr^{-})	0.008
						k-dry (yr^{-})	0.0049
Agamuthu & Govindan, 2014	Malaysia	-	MSW	IPCC	Bulk waste approach	Decay rate (yr^{-})	0.08
						Degradable organic carbon	0.12
					Waste composition approach	Decay rate (yr^{-})	0.09
						Degradable organic carbon	0.08
Mou et al., 2015	Denmark	-	MSW	IPCC (default values)	k (yr^{-})	Food	0.185
						Garden	0.1
						Paper wood	0.06
						Textile	0.06
						Plastic Inert	0.03
						Sludge	0.185
						Industrial	0.09
Işın, 2012	İzmir-Harmandalı	-	MSW	LandGEM RUN 1	k (yr^{-})		0.142
					L_0 (m^3 CH_4 /Mg)		57.22
				LandGEM RUN 2	k (yr^{-})		0.142
					L_0 (m^3 CH_4 /Mg)		32.55
				Multiphase	k (yr^{-})	Rapidly degrading	0.1750

Table 6. Summary of literature survey and parameters of them (continued)

References	Location	Conditions	Composition	Model	Parameter		Result
Wangyao et al., 2010	Thailand	Wet and dry	MSW	IPCC	Half life value for food, paper, wood and textile wastes		2, 10, 20 and 10 years
					MCF for deep, shallow landfills, deep and shallow dumpsites		0.65, 0.2, 0.15, 0.1
					DOC of food waste, papers, wood and textiles		0.15, 0.4, 0.43, 0.24
					DOC_f		0.5
					k for food waste, papers, wood and textiles (yr^{-})		0.347, 0.069, 0.035, 0.069
Younes et al., 2015	Malaysia	Wet and dry	MSW	IPCC (1996)	Air Hitam Landfill	L_0 (m^3/t)	151.7
						k-wet (y^{-})	0.136
						k-dry (yr^{-})	-
					Jeram Landfill	L_0 (m^3/t)	151.7
						k-wet (yr^{-})	0.136
						k-dry (yr^{-})	0.072
					Sungai Sedu Landfill	L_0 (m^3/t)	75.9

Table 6. Summary of literature survey and parameters of them (continued)

References	Location	Conditions	Composition	Model	Parameter		Result
						Modera. degrading	0.1000
						Slowly degrading	0.0560
				Tabasaran Rettenberger	k (yr^{-})		0.142
				Scholl Canyon RUN1	k (yr^{-})		0.142
					L_0 (m^3 CH$_4$ /Mg)		29.99
				Scholl Canyon RUN2	k (yr^{-})		0.142
					L_0 (m^3 CH$_4$ /Mg)		32.55
Cakir et al., 2016	İzmir-Harmandalı	-	MSW	Multiphase	k (yr^{-})	Fast degrading	0.076-0.694
						Medium degrading	0.046-0.116
						Slow degrading	0.013-0.076
				LandGEM	k (yr^{-})		0.35
							0.1
							0.05
				IPCC 2006	-		-
Taşkan, 2001	Erzurum	-	MSW	LandGEM	k (yr^{-})	CAA	0.05-0.02
						AP-42	0.04-0.02
					L_0 (m^3 CH$_4$ /Mg)	CAA	170
						AP-42	100
				Tabasaran Rettenberger	k (yr^{-})		0.035-0.04

Table 6. Summary of literature survey and parameters of them (continued)

References	Location	Conditions	Composition	Model	Parameter		Result
						Decomposable	160
Altan, 2015	Turkey	-	MSW	Central Eastern Europe Landfill Gas Model Version 0.1	L_0 (m^3 CH_4 /ton)	Fast decay	70
						Medium fast decay	93
						Medium slow decay	182
						Slow decay	200

CHAPTER 3

METHODOLOGY

In this study, the methodology which is given as a flowchart in Figure 13 was used. Firstly, the study area was determined and a field study was performed at the site. Measurements were made during the field work as will be described in following sections. Gas measurements were conducted. Historical data was gathered about the landfill site. Finally, models were run for determining gas generation from the landfill site. Collected data was used for calibration of the models. With the calibrated models, scenarios were evaluated to investigate potential changes in landfill gas generation at the landfill site. In addition, electrical energy generation amount and GHG emission reduction were evaluated according to the model gas generation results.

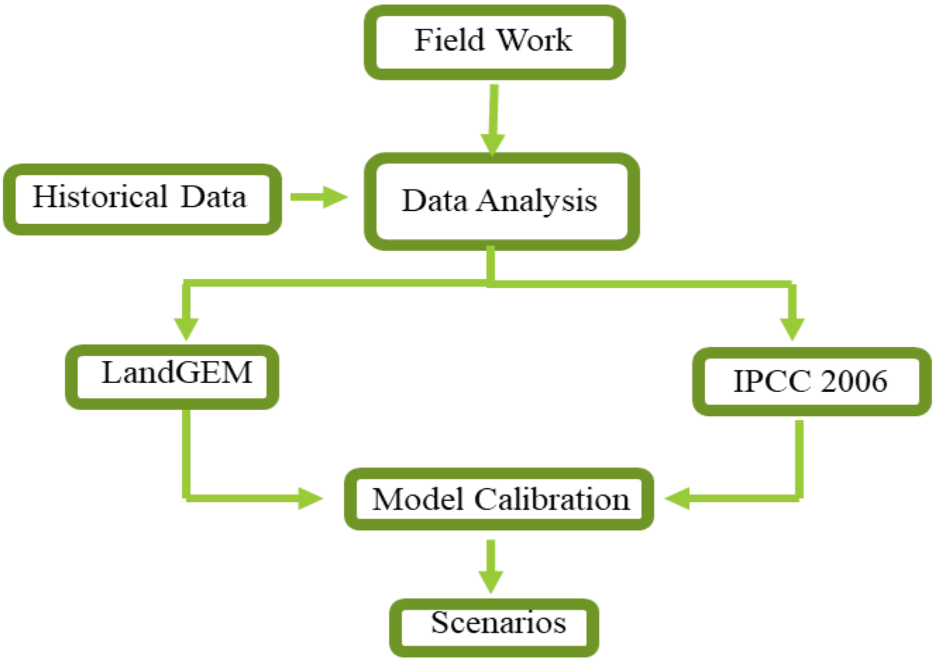


Figure 13.Flowchart of the methodology

3.1. Study Area

Afyonkarahisar Province has a 14,570 km^2 surface area. Majority of this area is located in the Aegean Region. The east part of the province has similar properties with Central Anatolia Region. The province, extending from north to south, constitutes the southern part of the highland which connects West Anatolia and Central Anatolia Regions. There are 16 districts, 19 towns and 490 villages in the province (Municipality of Afyonkarahisar, 2015a). According to data, population of Afyonkarahisar province was determined as 701,452 in 2016 (TÜİK, 2017). In this province, one of the important growing sources of income is manufacturing industry. Marble mining, dairy (cream) and meat processing are important industries (Municipality of Afyonkarahisar, 2015b).

3.2. Landfill Site and Field Studies

Afyonkarahisar Landfill Site is operated by the Afyonkarahisar Environment Service Union. This union was established in 2005 and serves 50 municipalities and 143 villages in the region. The disposal, recovery and energy generation of solid wastes are provided. Afyonkarahisar Environment Service Union started its activities in 2006. On the other hand, solid waste disposal site started to serve in 2009. There are two lots in this site. The site accepts approximately 450-500 ton municipal solid wastes per day. The total deposited amount of municipal solid waste exceeded 1 million tons in between 2009 and 2016. Moreover, the total electric generation amount was 53,386.09 MW in between 2012 and 2016. Integrated solid waste site includes solid waste pre-treatment and compost facilities. In addition, there are 70 chimneys, in which only 35 of them are active. This field was chosen to further study based on the aforementioned data.

During the field study, measurements were obtained from 10 different locations on 7 June 2017. The locations are shown in Figure 14. A-9 and A-10 are main collectors.

A-9 and A-10 include gas generation from past and new lots, respectively. An MRU Optima 7 biogas analyzer was used for analyzing biogas in the field. Before the device was used, accuracy of the device was tested at ITC Ankara Mamak Integrated Solid Waste Recovery and Disposal Site against the devices they use at the site. Agreement was achieved in all measurements. Results of the measurements at the study site were given in Chapter 4. Site measurements were conducted once as there were problems with incompatible well mouth for connection to the gas analyzer and water intrusion into gas wells which created problems in measurements.

Figure 14.Afyonkarahisar Landfill Site and measurement points

3.3. Model Application for Afyonkarahisar Sanitary Landfill Site

3.3.1. Gas Generation in Afyonkarahisar Landfill Site

The amounts of deposited solid waste in Afyonkarahisar Landfill Site between 2009 and 2017 (Afyonkarahisar Environmental Service Union, 2017) are given in Figure 15. The given data shows that the amount of wastes is almost stable within a year while it increases over the years. The reason of that is related to increasing the accepted wastes by adding new villages and municipalities in the Union. The characterization of deposited wastes was determined in 2016 (Afyonkarahisar Environmental Service Union, 2017). The results of this characterization are given in Table 7. In addition, from 2014 to 2017, amounts of landfill gas and methane gas are given in Figure 16 and Figure 17, respectively (Afyonkarahisar Environmental Service Union, 2017).

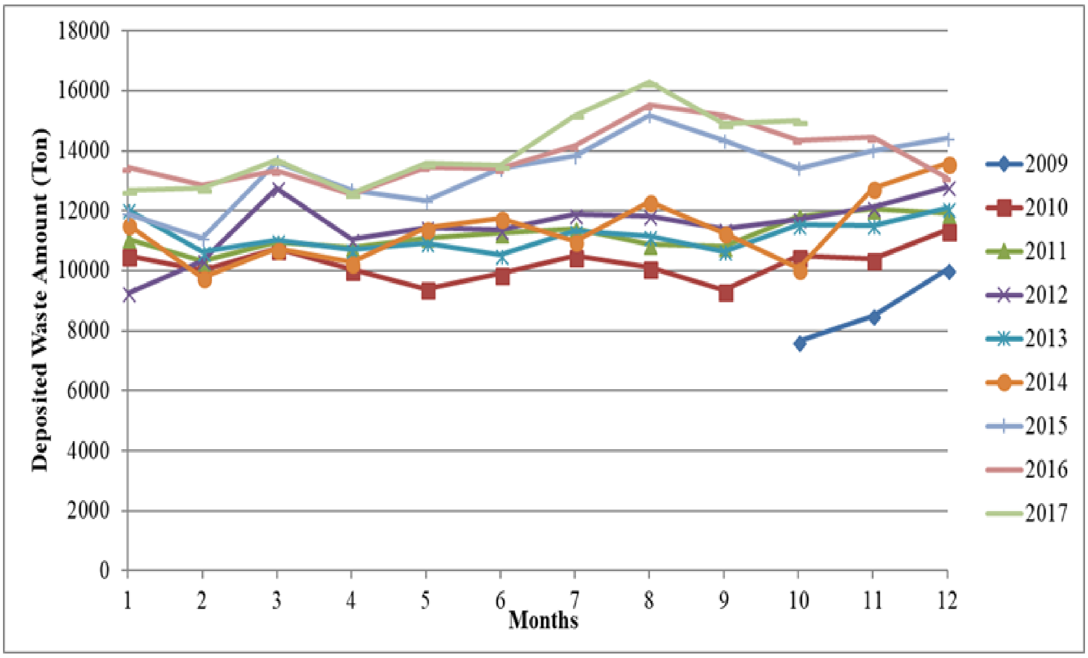


Figure 15.The amount of deposited municipal solid waste in Afyonkarahisar Landfill Site

Table 7.Characterization of solid wastes deposited in Afyonkarahisar Landfill Site in mass basis

Waste Types	Ratio in MSW (%)
Organic	50.00
Inorganic	46.61
Paper and paperboard	0.02
Nylon	0.90
Plastic	0.68
Glass	0.55
Metal	0.34
Aluminum	0.05
Pet	0.82
Sack	0.03
Other non-burnable	0
Other burnable bulk wastes	0
Other non-combustible bulky wastes	0
Waste electrical and electronic equipment	0
Hazardous waste	0

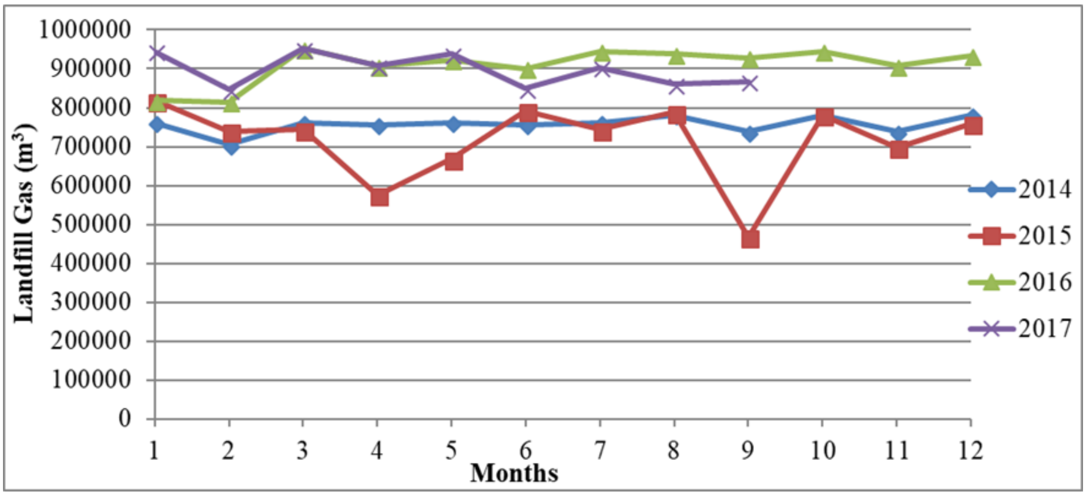


Figure 16.Monthly landfill gas generation in Afyonkarahisar Landfill Site

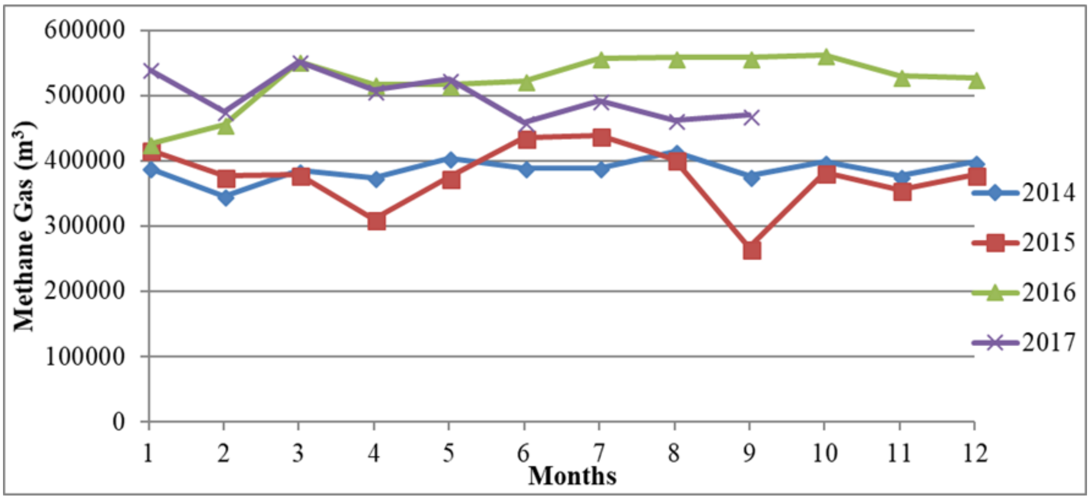


Figure 17.Monthly methane gas generation in Afyonkarahisar Landfill Site

3.3.2. Calculation of Potential Methane Generation Capacity (L_0)

As mentioned before, methane generation potential (L_0) is important parameter for LandGEM model. According to the data given in above sections, IPCC 2006 and LandGEM models were chosen for the calculation of gas generation amount. In the IPCC 2006 model, degradable organic compound amount ($DDOC_m$) is an important parameter for the calculation of L_0 (equations 7 and 8 in Chapter 2). $DDOC_m$ value changes according to different waste types (IPCC, 2006). In this first order decay model, equation 8 can be written in another form for each waste type (i), as given below (Thomazoni, Schneider, & Saffer, 2013).

$$(DDOC_m)_i = W * FR_i * DOC_i * DOC_f * MCF \qquad (12)$$

The FR_i is the ratio of each waste type to total waste amount (Gg of waste type/Gg total waste). IPCC 2006 is a model working under Excel, as mentioned before. For the calculation of methane generation and methane generation potential, 8 waste types are used as inputs. These waste types are food, garden, wood and straw, textile, disposable nappies, sludge and industrial wastes. Each type of wastes has different DOC and FR values. For Afyonkarahisar Landfill Site, waste characterization was obtained for 15 waste types in 2016 (Table 7). However, these waste types are different from IPCC 2006 waste types. For this reason, Afyonkarahisar data was adapted to the model as will be given below.

One parameter used in the calculation of $DDOC_m$ is the ratio of waste types amounts to the total amounts (Table 7). The aforementioned adaptation is taken place for several waste types. Firstly, organic waste amount which is given in Table 7 includes not only food wastes but also garden wastes. On the other hand, in the IPCC model, these waste types are categorized as different types. These types are food, garden, paper, wood and straw, textile, disposable nappies, sludge and industrial wastes. According to the study on solid wastes carried in İstanbul, food waste was specified as 99% of organic waste amounts. The remaining 1% was found as garden wastes (Karakaya, 2008). In addition, another study in İzmir suggests that 98% and 2% of organic wastes was determined as food wastes and garden wastes, respectively (Işın, 2012). In agreement with these studies, 99% and 1% of organic wastes were accepted as food waste and garden waste, respectively. Paper waste fraction was obtained as 0.02% according to the characterization in the site in 2016. However, sludge is not accepted as waste in the landfill. Therefore, the fraction of this waste type was taken as zero. Likewise, since wood and straw wastes are not accepted to the landfill site, fractions of these types were also taken as zero. Thus, final fractions of waste types are as shown in Table 9. These fractions were used in the calculation of L_0 values. (Dry content of waste types was taken as default values in the guide of IPCC 2006 model.)

One of the parameters required for the calculation of L_0, namely $DDOC_{m,}$ was separately calculated for each waste type. Total $DDOC_m$ value was obtained by summing up all $DDOC_m$ values of each waste type. In the calculation of $DDOC_m$ value, DOC (Gg C/Gg waste) information is needed. These DOC values are given in the guide of IPCC model. For Afyonkarahisar Landfill Site, default DOC values were used since DOC values were not specifically found for the site. The default values are given in Table 8 according to the guide of the model. As the values are given as a range, highest, middle and lowest values were taken into consideration.

Therefore, three L_0 values were obtained and tested while using the models. The purpose of these calculations is to find methane generation potential ranges for Afyonkarahisar Landfill Site and determine the L_0 value that fits the historical field data.

Table 8.Default DOC values for each waste type

Waste Types	Wet DOC Content (%)
Food waste	8-20
Garden waste	18-22
Paper	36-45
Wood and straw	39-46
Textile	20-40
Disposable nappies	18-32
Sludge	4-5
Industrial waste	0-54

Table 9.Fraction of waste types used in the calculation of L_0 and modeling

Waste Types	Weight Fraction
Food waste	0.495
Garden waste	0.005
Paper	0.0002
Wood and straw	0
Textile	0.02
Disposable nappies	0.04
Sludge	0
Industrial waste	0

Table 10.Default dry matter contents of waste types

Waste Types	Dry Matter Content (%)
Food waste	40
Garden waste	40
Paper	90
Wood and straw	85
Textile	80
Disposable nappies	40
Sludge	0
Industrial waste	90

Another parameter that is used for the calculation of $DDOC_m$ is DOC_f. According to the IPCC 2006 guide, DOC_f is calculated as:

$$DOC_f = 0.014 * T + 0.28 \tag{13}$$

where T denotes temperature (˚C). According to the IPCC guide, temperature is taken as 35 ˚C for anaerobic regions of landfill sites. In the measurements of Afyonkarahisar Landfill Site by using the gas analyzer, average temperature was obtained as 37˚C from 10 different measurement points. However, since this field study was taken place during one day, temperature was accepted as 35 ˚C. Thus, DOC_f value was calculated as 0.77.

For the calculation of $DDOC_m$, another necessary data was MCF. In the IPCC model, it is stated that MCF value changes with respect to municipal solid waste management and landfill site structure. Default MCF values given in the model guide are given in Table 11. Afyonkarahisar Landfill Site is a sanitary landfill site. According to the TÜİK, all sanitary landfill sites are accepted as “well managed anaerobic site” since there is no semi-aerobic solid waste disposal sites in Turkey (Demirok, 2016). Because of this, MCF value was accepted as 1.0 in this study. As a result of these, $DDOC_m$ values were calculated for different DOC contents. L_0 values were calculated by using Equation 7 (in Chapter 2) and $DDOC_m$ values for DOC contents. In this equation, F denotes the methane content in the landfill gas. For Afyonkarahisar Landfill Site, F was calculated as 55.5% on average according to the yearly data of landfill gas and methane gas. Calculated $DDOC_m$ values for high, medium, and low DOC contents are provided in Table 12, Table 13 and Table 14, respectively. Calculations are provided in Appendix. Weight fractions were taken from site specific waste characterization. Dry DOC contents were taken from IPCC guide.

Table 11.Classification of solid waste disposal sites and default MCF values

Site Type	**MCF**
Managed anaerobic	1.0
Managed semi-aerobic	0.5
Unmanaged-deep(>5 m waste) and/or high water table	0.8
Unmanaged-shallow	0.4
Uncategorized solid waste disposal site	0.6

Table 12. Calculated $DDOC_m$ values according to the highest DOC content value

Waste Types	**Dry DOC Content**	**DOC_f**	**Weight Fraction**	**$DDOC_m$**
Food waste	0.08	0.77	0.495	0.031
Garden waste	0.088	0.77	0.005	$3.38*10^{-4}$
Paper	0.405	0.77	0.0002	$6.341*10^{-5}$
Wood and straw	0.391	0.77	0	0
Textile	0.32	0.77	0.02	0.005
Disposable nappies	0.128	0.77	0.04	0.004
Sludge	0	0.77	0	0
Industrial waste	0.486	0.77	0	0

Table 13. Calculated $DDOC_m$ values according to the medium DOC content value

Waste Types	**Dry DOC Content**	**DOC_f**	**Weight Fraction**	**MCF**	**$DDOC_m$**
Food waste	0.056	0.77	0.495	1	0.021
Garden waste	0.08	0.77	0.005	1	$3.08*10^{-4}$
Paper	0.365	0.77	0.0002	1	$5.7065*10^{-5}$
Wood and straw	0.361	0.77	0	1	0
Textile	0.24	0.77	0.02	1	0.004
Disposable nappies	0.1	0.77	0.04	1	0.003
Sludge	0	0.77	0	1	0
Industrial waste	0.243	0.77	0	1	0

Table 14. Calculated $DDOC_m$ values according to the lowest DOC content value

Waste Types	**Dry DOC Content**	**DOC_f**	**Weight Fraction**	**MCF**	**$DDOC_m$**
Food waste	0.032	0.77	0.495	1	0.0122
Garden waste	0.072	0.77	0.005	1	$2.8*10^{-4}$
Paper	0.324	0.77	0.0002	1	$5.073*10^{-5}$
Wood and straw	0.332	0.77	0	1	0
Textile	0.16	0.77	0.02	1	0.003
Disposable nappies	0.072	0.77	0.04	1	0.002
Sludge	0	0.77	0	1	0
Industrial waste	0	0.77	0	1	0

According to the highest, medium and lowest DOC content values, L_0 values were obtained as 44.12 m^3/Mg, 31.60 m^3/Mg and 19.09 m^3/Mg, respectively.

In the L_0 calculation, density of methane was used. There are two densities for methane gas. These are based on normal temperature pressure (20 ˚C and 1 atm) and standard temperature pressure (0 ˚C and 1 atm). For NTP and STP, the densities are 0.667 kg/m^3 and 0.72 kg/m^3, respectively. In the LandGEM model, the results of methane gas are calculated by using the density at NTP conditions. When L_0 values for the density in STP and NTP conditions were entered to the model, the difference in yearly methane gas generation amounts changed between 2% and 97%. Therefore, for calculation of L_0, which is an input of the model, 0.667 kg/m^3 value was used which aided in obtaining consistent result with the output of model. In literature, there is generally inconsistency between input and output in terms of density. With this conversion, this problem was solved.

3.3.3. Closure Year Calculation of Afyonkarahisar Landfill Site

In the landfill site, there are two lots as mentioned before. Each lot has 1,620,000 m^3 capacity. When 8 years data which are from 2009 to 2017 are considered, it is seen that total municipal solid waste amount is 1,186,316.97 tons. According to the information from the site, density of compacted solid waste is 0.82 ton/m^3. Storable total solid waste amount is calculated as 1,328,400 tons when density and total amount of waste are taken into consideration. This implies that each lot provides service for 9 years. It is found that the first lot will reach the total capacity in 2018 since the landfill site started the service in 2009 and accepted the waste in the last three months in 2009. In addition, it was observed that the remaining capacity of the lot was low during the field study.

3.3.4. Population Estimation for IPCC 2006

In the IPCC 2006 model, solid waste amount per capita is needed as model input. For Afyonkarahisar Province, population data was given in Table 15 (TÜİK, 2017). The model requires the population projection for 80 years. The equation that is necessary for the estimation of future population is obtained by regression based on the historical population values. For this determination, it was assumed that population change trend in the past years will be valid until 2089 and there is a linear increase in the population. As mentioned before, the landfill site accepts solid waste from not only Afyonkarahisar but also neighborhood villages and municipalities. Because of this, closure of the site does not only depend on population growth rate and waste generation of this population in Afyonkarahisar. Population increase during the service life of the site was considered.

Table 15.Population information of Afyonkarahisar in between 2009 and 2017

Year	**Population**
2009	701,326
2010	697,559
2011	698,626
2012	703,948
2013	707,123
2014	706,371
2015	709,015
2016	714,523
2017	715,693

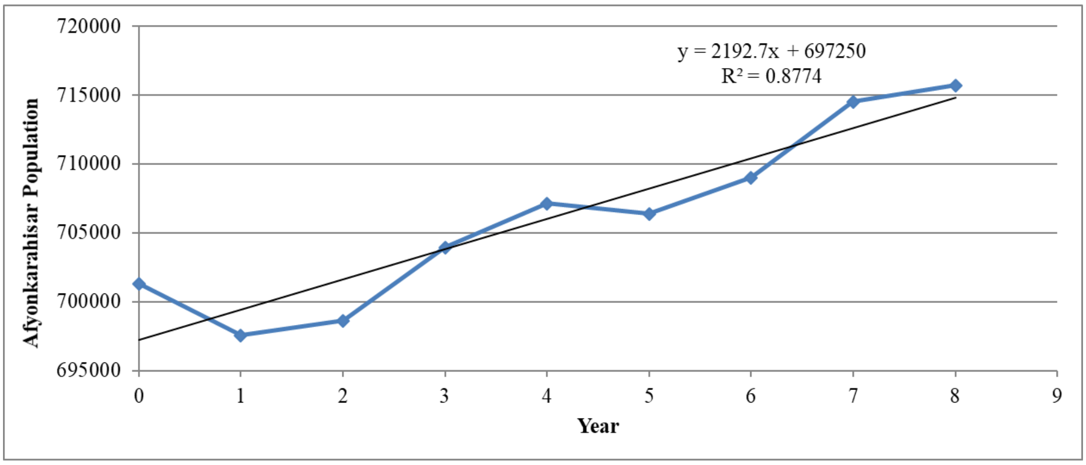


Figure 18.Population distribution of Afyonkarahisar over 2009 -2017

Table 16. Specified and projected population of Afyonkarahisar

Year	Population	Year	Population
2009	701,326	2022	725,755
2010	697,559	2023	727,948
2011	698,626	2024	730,141
2012	703,948	2025	732,333
2013	707,123	2026	734,526
2014	706,371	2027	736,719
2015	709,015	2028	738,911
2016	714,523	2029	741,104
2017	715,693	2030	743,297
2018	716,984	2031	745,489
2019	719,177	2032	747,682
2020	721,370	2033	749,875
2021	723,562	2034	752,068

Table 16. Specified and projected population of Afyonkarahisar (continued)

Year	Population	Year	Population
2035	754,260	2063	815,656
2036	756,453	2064	817,849
2037	758,646	2065	820,041
2038	760,838	2066	822,234
2039	763,031	2067	824,427
2040	765,224	2068	826,619
2041	767,416	2069	828,812
2042	769,609	2070	831,005
2043	771,802	2071	833,197
2044	773,995	2072	835,390
2045	776,187	2073	837,583
2046	778,380	2074	839,776
2047	780,573	2075	841,968
2048	782,765	2076	844,161
2049	784,958	2077	846,354
2050	787,151	2078	848,546
2051	789,343	2079	850,739
2052	791,536	2080	852,932
2053	793,729	2081	855,124
2054	795,922	2082	857,317
2055	798,114	2083	859,510
2056	800,307	2084	861,703
2057	802,500	2085	863,895
2058	804,692	2086	866,088
2059	806,885	2087	868,281
2060	809,078	2088	870,473
2061	811,270	2089	872,666
2062	813,463		

As mentioned above, solid waste amount is entered to the model by using waste amount per capita in the IPCC 2006 model. In the LandGEM model, waste amount is directly entered as the waste amount. In the IPCC 2006 model, used waste amount per capita is given in Table 17.

Another difference between IPCC and LandGEM in terms of necessary inputs is that the fraction of each waste type is entered to the IPCC model. In this model, industrial wastes are also considered as important and model is formed in detail for industrial wastes. However, in Afyonkarahisar Landfill Site, since industrial wastes are not accepted, the industrial waste was not considered in the model.

Table 17.Yearly population and amount of waste per capita changes

Year	**Population (million)**	**Waste Amount per capita (kg/capita)**	**Total Waste (Gg)**
2009	701,326	149.4	26.19*
2010	697,559	176.1	122.81
2011	698,626	192.3	134.37
2012	703,948	196.0	137.97
2013	707,123	189.6	134.10
2014	706,371	193.3	136.55
2015	709,015	226.0	160.26
2016	714,523	232.1	165.87
2017	715,693	234.9	168.18
2018	716,984	200.9	144.08

*Since there were 3 months data for 2009, total waste amount was less than other years.

3.3.5. Methane Generation Rate (k) Calculation for LandGEM

For LandGEM model, methane generation rate (1/year) is an important input. The methane generation ratio from the waste is determined by using methane generation rate. The higher k value indicates that higher methane generation is obtained. Methane generation rate changes depending on 4 factors. These factors are (EPA USA, 2005):

- Moisture content in the waste
- Nutrient availability for microorganisms
- pH of the waste
- Temperature of the waste

According to the LandGEM model guide, EPA Method 2E is used for the calculation of the k value for a given landfill site by using site specific data. In this method, k is calculated by using equation 11 (in Chapter 2). The $L_0^{'}$ used in equation 11 is calculated as:

$$L_0^{'} = L_0 * f \qquad (14)$$

In this equation, f indicates the fraction of decomposable refuse in the landfill. In addition, A_{avg} value in the equation 8 (in Chapter 2) was determined by calculating weighted average according to the monthly waste amount.

Table 18.Average waste age of the lot in Afyonkarahisar Landfill Site

Year	**Waste Amount (Ton)**	**Waste Age**
2009	26,192.37	8
2010	122,814.55	7
2011	134,367.90	6
2012	137,969.37	5

Table 18.Average waste age of the lot in Afyonkarahisar Landfill Site (continued)

Year	**Waste Amount (Ton)**	**Waste Age**
2013	134,101.15	4
2014	136,553.55	3
2015	160,264.65	2
2016	165,868.75	1
2017	168,184.68	0
Total Waste Amount (ton)		**Weighted Average of Waste Age**
1,186,316.97		3.37

For calculating the k values, optimization result was obtained by using Excel-Solver for the iteration over equation 11 (in Chapter 2). The results of L_o and k calculations for LandGEM model is summarized in Table 19.

Table 19.Necessary inputs for the calculation of k and k values for different L_0 values

L_0 (m^3/Mg)	**f**	**L_0' (m^3/Mg)**	**M_r (Mg)**	**Q_f (m^3/year)**	**A_{avg} (year)**	**k (1/year)**
44.12	0.5	22.06	593,159	44,078,030	3.37	1.56
31.60	0.5	15.80	593,159	44,078,030	3.37	1.315
19.09	0.5	9.55	593,159	44,078,030	3.37	0.843

3.3.6. Model Calibration

Calibration of the models was done based on predicted methane gas amounts within 4 years and measured methane gas amounts at the main collector. Calibration was done according to the current situation (base case) which had 50% organic content. Yearly methane gas generation curves and current 4 year-measured data are given in the following figure. There is a good fit between the quantities of measured methane (shown as green) and modeled methane in these gas formation profiles, especially for IPCC 2006. Gas generation profiles obtained using LandGEM and IPCC models are derived using the highest L_0 and associated k values.

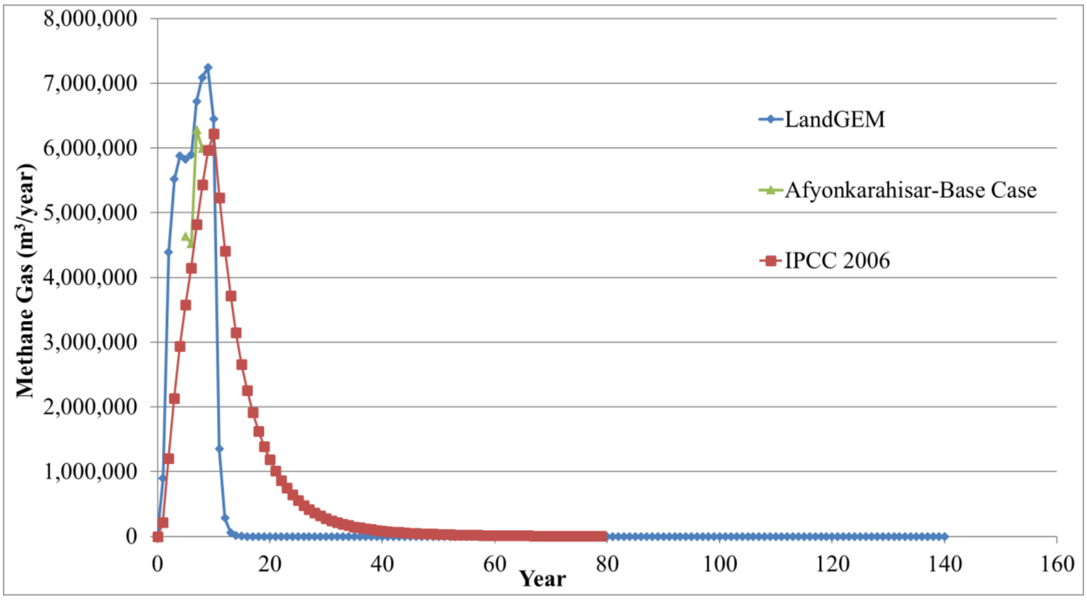


Figure 19.Comparison of yearly modeled and measured methane gas amounts for base case

According to the above results, LandGEM and IPCC 2006 models have exhibited somewhat consistent results compared to other studies in literature. In some studies, gas profiles obtained for LandGEM and IPCC 2006 models were not similar. In this study, the following differences between the gas profiles obtained for the two models are as follows:

- LandGEM model evaluated gas generation for 140 years while IPCC 2006 model for only 80 years.
- In the IPCC model, the methane gas production spreads over the years. However, in the LandGEM model, it can be seen that higher peak was observed with lower overall gas production period.
- In the LandGEM and the IPCC 2006 models, the highest obtained methane gas generation values are 7.244 million m^3 in 2018 and 6.219million m^3 in 2019, respectively.
- When areas under the curves in the Figure 19 are calculated, it is seen that the total methane generation amounts are not significantly different from each other. In the IPCC model, total methane gas amount was calculated as 7.2E+07 m^3 for 80 years. On the other hand, the amount was determined as 5.7E+07 m^3 for 140 years in the LandGEM model. There is approximately 20% difference between the model results

Comparison of predicted and measured methane generation amounts for LandGEM and IPCC 2006 models are shown in Figure 20 and Figure 21, respectively. Since there were only 4 observed annual data, the comparison had to be made on limited data.

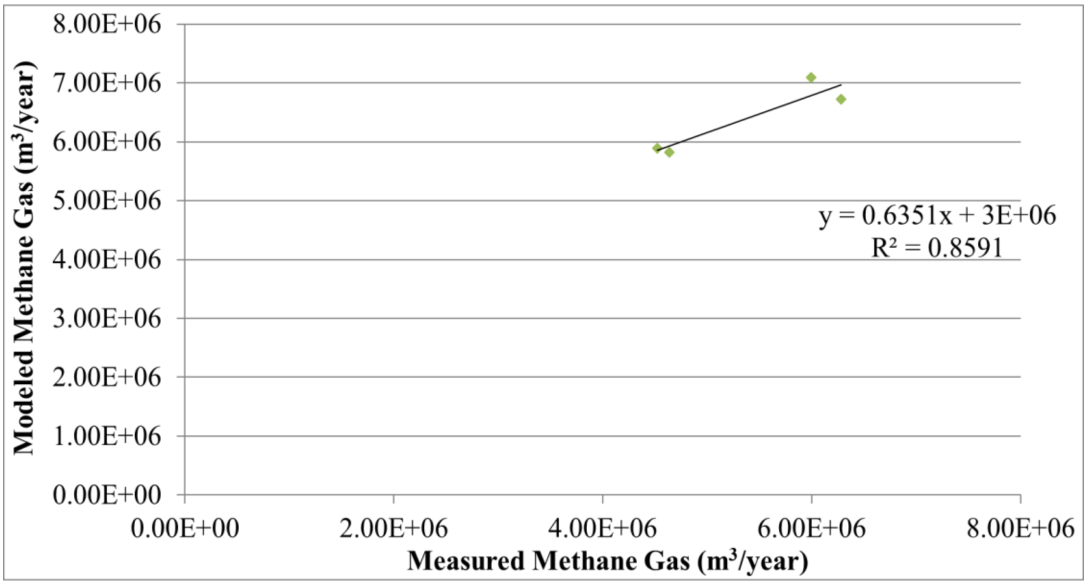


Figure 20.Predicted methane gas amounts by LandGEM versus measured methane gas amounts

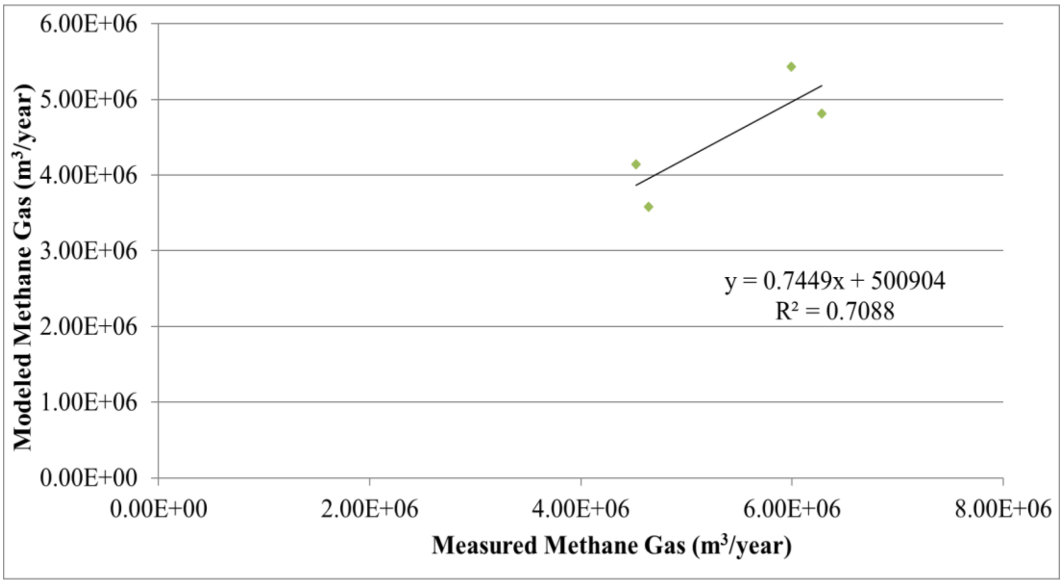


Figure 21. Predicted methane gas amounts by IPCC 2006 versus measured methane gas amounts

When evaluation with respect to measured values is considered, it is seen that LandGEM model had better performance than IPCC 2006 for modeling of gas generation for base case and assumptions used in the study.

The square of correlation coefficient between observed and predicted values is specified by R^2. The formula of R^2 is given as below equation (Alexander et al., 2015).

$$R^2 = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2} \tag{15}$$

Response variable, mean of it and corresponding predicted values are shown as y, $\bar{y}$ and $\hat{y}$, respectively. The size of residuals of model is measured by R^2. The numerator of the equation is expressed as sum of squared residual. This term is important for R^2 since there are small residual in good models. When sum of squared residual is low, high R^2 is obtained. In the perfect models, the value of R^2 is equal to 1 (Alexander et al., 2015).

The root mean square error (RMSE) is another statistical measurement for determining model performance (Chai & Draxler, 2014). Standard deviation of residuals is obtained by RMSE (Alexander et al., 2015). The equation of RMSE is given in the below equation (Holmes, 2000).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \tag{16}$$

According to the study which examines RMSE, model statistics results are not appropriate for only 4 and 10 samples. It is stated that if more samples are used for RMSE calculation, error distribution will be more reliable (Chai & Draxler, 2014). According to LandGEM model results in terms of the highest, medium and lowest L_0 and k, RMSE values were obtained as 1.082E+06, 9.859E+05 and 2.839E+06 m^3/year.

In general, lower RMSE value has better performance for models. In this study, there are only 4-year data for comparison of modelled and measured methane gas generation data. As mentioned above, low number of samples do not give reliable result for RMSE. Therefore, in this study, R^2 was evaluated for determining appropriate model conditions during calibration. According to the LandGEM model calibration results, it was seen that highest situation (highest k and L_0) had highest R^2. The RMSE result difference between highest and medium situation of model results were found as 8%. Although medium situation had lower RMSE value, the model result distribution of it was below compared to measured methane gas generation amounts. However, highest situation had high R^2 value and higher methane gas generation results compared to measured data. Therefore, k values obtained for the highest L_0 values were better inputs for LandGEM model and represented the current situation (base case) better. As mentioned in the methodology section, the highest k and L_0 values were used in further modeling. Since LandGEM model had better performance in matching the measured values, values obtained from LandGEM for the 2014, 2015, 2016 and 2017 were taken as the base case for comparison in evaluation of management scenarios.

Another analysis was made in order to evaluate which default conditions in the LandGEM model was best suited to the conditions in Afyonkarahisar Landfill Site. Inventory wet area and conventional k values were used as an input to the model. These k values were 0.7 and 0.04 1/year, respectively. On the other hand, site specific highest L_0 value was used as it is. The model was run with these default k values for base case (50% organic content). Resultant gas profiles are given in Figure 22.

Total methane gas generation amounts were 5.763E+07 and 5.525E+07 m^3 for specified k and inventory wet default k values, respectively. The difference for these two inputs was calculated as 4%.

The total methane gas generation amounts were 5.763E+07 and 5.322E+07 for specified k and inventory conventional k values, respectively. The difference for these two inputs was calculated as 7%.

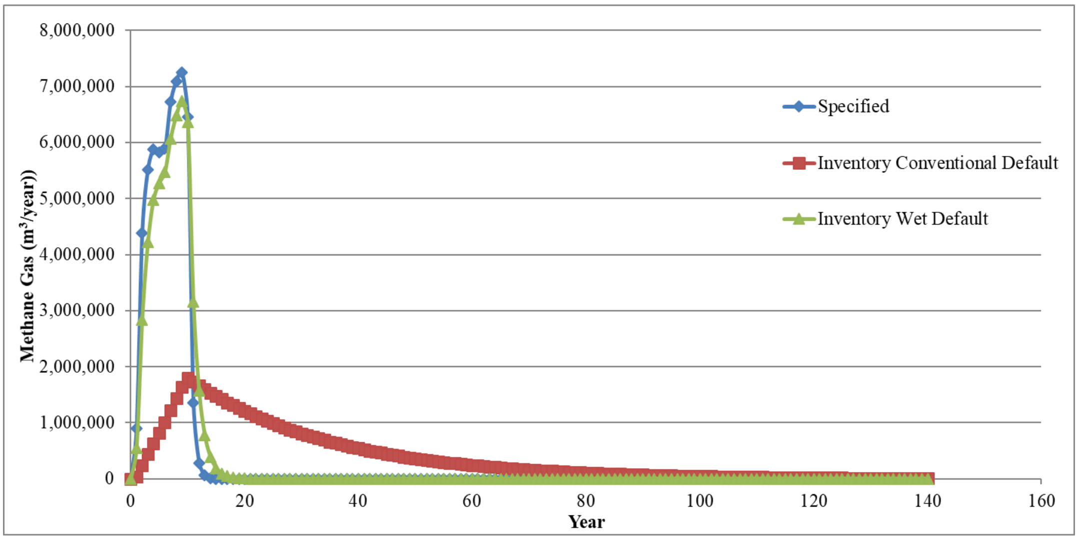


Figure 22.Methane gas generation results for base case according to specified and inventory wet default k values

As shown in the results, it can be interpreted that the studied landfill site can be described using the wet landfill site option in the model. This situation was confirmed at the site as well. During summer period, leachate is recycled in the lot. Therefore, the site is operated as a bioreactor. The calibrated k value was higher compared to the values given in the literature. In one of the studies conducted on methane gas generation from landfills, it was stated that when conventional and bioreactor type landfill sites were compared, the k value was found as 1.72 1/year in terms of readily degrading waste (D. Reinhart & Barlaz, 2010). Similar to this study, the k value was determined as 1.7 1/year for Georgia Tech Wet landfill site while studying gas generation model parameters for wet landfill sites (D. R. Reinhart & Faour, 2005). L_0 value was obtained as 44.12 m^3/Mg. According to the review study about methane generation potential (L_0), this value is within the reported range (Krause, W. Chickering, Townsend, & Reinhart, 2016).

3.3.7. Management Scenarios for the Landfill Site

After calibration of IPCC 2006 and LandGEM model, change in gas generation for different management conditions were investigated as different scenarios. These are:

- Scenario-1 (56% organic content)
- Scenerio-2 (Only organic waste deposited)
- Scenario-3 (Sorting of recyclable wastes)
- Scenario-4 (Sorting of ash)

The detailed explanation of these scenarios is given below.

3.3.7.1. Scenario-1 (56% Organic Content)

In the data obtained from Afyonkarahisar Landfill Site and specified in 2016, the ratio of organic waste content to the total waste was given as 50%. However, since this data is only for one year, it was stated that this ratio could reach 56% by Afyonkarahisar Environment Service Union. In scenario-1, 56% organic content existence was investigated. In this scenario, percentages of solid waste types were taken as given in Table 20. Again, it was assumed that 1% of organic waste was garden waste. The adopted characterization for IPCC 2006 was calculated and given in Table 21. DOC_f and MCF values were taken as 0.77 and 1.0 respectively, as in the case of current situation (base case).

The aforementioned steps used in the calculations of L_0 in the base case (50% organic content) were applied for 56%-scenario. For highest DOC value, $DDOC_m$ was calculated as 0.0435 Gg organic C/Gg waste and L_0 was obtained as 48.22 m^3/Mg. For medium DOC value, $DDOC_m$ was calculated as 0.0311 Gg organic C/Gg waste and L_0 was obtained as 34.49 m^3/Mg. For lowest DOC value, $DDOC_m$ was calculated as 0.0187 Gg organic C/Gg waste and L_0 was obtained as 20.75 m^3/Mg.

Table 20.Percentage of waste types for scenario-1 (Before adaptation)

Waste Type	**The Ratio to Total (%)**
Organic	56.00
Inorganic	40.61
Paper and paperboard	0.02
Nylon	0.90
Plastic	0.68
Glass	0.55
Metal	0.34
Aluminum	0.05
Pet	0.81
Sack	0.03
Other non-burnable	0.00
Other burnable bulk wastes	0.00
Other non-combustible bulky wastes	0.00
Waste electrical and electronic equipment	0.00
Hazardous waste	0.00

Table 21.Adopted weight ratio of waste types for calculations of scenario-1

Waste Type	**Ratio (-)**
Food waste	0.5544
Garden waste	0.0056
Paper	0.0002
Wood and straw	0
Textile	0.02
Disposable nappies	0.04
Sludge	0
Industrial waste	0

Calculations of k values have been carried out by the method previously applied for the base case. In the calculation of M_r, in base case, the coefficient for organic waste was taken as 0.5. However, in scenario-1, the coefficient for organic waste was taken as 0.56 as expected. Also, the value of f was taken as 0.56. The values of k were calculated by using optimization method to run LandGEM model for the scenario-1. These values were found as given in Table 22.

Table 22.The value of k for scenario-1

L_0 (m^3/Mg)	**f**	**L_0' (m^3/Mg)**	**M_r (Mg)**	**Q_f (m^3/year)**	**A_{avg} (year)**	**k (1/year)**
48.22	0.56	27.00	664,337.5	44,078,029.5	3.37	1.77
34.49	0.56	19.31	664,337.5	44,078,029.5	3.37	1.55
20.75	0.56	11.62	664,337.5	44,078,029.5	3.37	1.155

3.3.7.2. Scenario-2 (Organic Waste Deposited)

Organic wastes are the most important waste type contributing to the formation of methane gas. Because of this, the change in the formation of the gas was investigated for a scenario where only organic waste is stored in the solid waste disposal site. In this scenario, it was assumed that organic wastes are separated from other wastes and the separated wastes are deposited in the other lot. This assumption would increase the service life of the lot in which all pipes and appurtenances are in place to generate electricity. Effects of organic deposition in the related lot on gas generation and service life of the lot were considered in this scenario. As already mentioned, it is predicted that first lot will be closed in 2018 for the current situation (base case). The yearly changes of total waste amount in Afyonkarahisar Landfill Site is given in the following figure. In this figure, red point indicates projection value to the 2018.

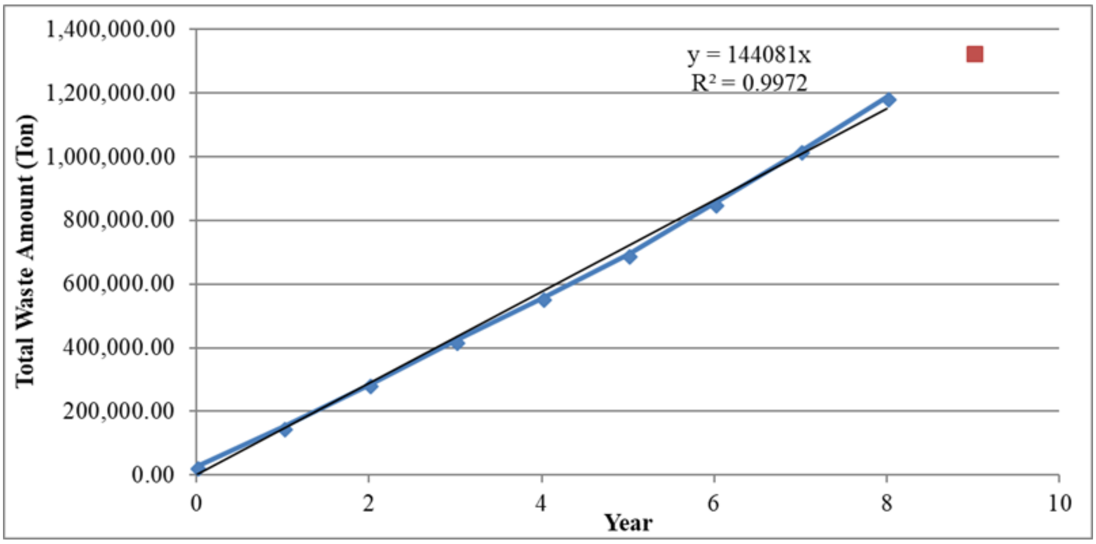


Figure 23.Yearly solid waste amount of the site

If organic wastes were separated in 2009-2018, deposited in the first lot and used for the production of energy, the theoretical additional service life would have been 9 years for the organic fraction of the total waste (665,119 tons) obtained by projection in 2018. In this calculation, as provided below, organic waste content is taken as 50% (base case).

$$Additional\ service\ life = \frac{(1{,}330{,}398 - 665{,}119)\ (ton) * (9\ years)}{(665{,}119\ ton)} = 9\ years$$

On the other hand, according to the 56% organic waste content considered in scenario-1, additional service life would be 7 years as shown below.

$$Additional\ service\ life = \frac{(1{,}330{,}398 - 745{,}023\ )(ton) * (9\ years)}{(745{,}023\ \ ton)} = 7\ years$$

The reason of the decrease in the additional service life obtained from 56% organic waste content is the increase in the waste amount stored.

These service periods were calculated as additional service life with respect to the current situation (base case). With scenario-2, the system consisting of gas collecting pipes, collectors, energy conversion units will be in service for 18 years and 16 years in total for 50% and 56% organic waste ratios, respectively, instead of 9 years. With the application of this scenario, additional investment cost for these systems would be minimized. For the extended service life and total amount of waste following the profile given in the Figure 23, total waste amounts entered into the LandGEM model up to 2027 are given in Table 23.

Table 23.Yearly total organic waste amount for scenario-2

Year	Yearly Waste Amount (Ton)	Yearly Organic Waste Amount According to 50% Organic Content (Ton)	Yearly Organic Waste Amount According to 56% Organic Content (Ton)
2009	26,192	13,096	14,668
2010	122,185	61,407	68,776
2011	134,368	67,184	75,246
2012	137,969	68,985	77,263
2013	134,101	67,051	75,097
2014	136,554	68,277	76,470
2015	160,265	80,132	89,748
2016	165,869	82,934	92,887
2017	168,185	84,092	94,183
2018	144,081	72,041	80,685
2019	144,081	72,041	80,685
2020	144,081	72,041	80,685
2021	144,081	72,041	80,685
2022	144,081	72,041	80,685
2023	144,081	72,041	80,685
2024	144,081	72,041	80,685
2025	144,081	72,041	80,685
2026	144,081	72,041	Lot full
2027	144,081	72,041	Lot full

The methane content in the landfill gas is one of the inputs in LandGEM model. This content was taken as 55.5% which was obtained from historical methane content data of Afyonkarahisar Landfill Site. The k values were calculated based on highest DOC and highest L_0 for 50% and 56% organic waste content. Since the highest L_0 and k values provided the best fit between measured and predicted gas production values during calibration, it was assumed that the k values were as same as base case and scenario-1. For scenario-2, assumed k and specifically calculated L_0 values were given in the Table 24 for this scenario. The fractions of waste types except for food and garden wastes were taken as zero. It can be seen that L_0 values are the same for both 50% and 56% organic content. The reason behind this is taking food waste as 99% and garden waste as 1% for both organic contents.

Table 24. Calculated k and L_0 values for scenario-2 according to the 50% and 56% organic content

	Deposited 50% Organic Waste Content By Separating	**Deposited 56% Organic Waste Content By Separating**
L_0 (m^3/Mg)	68.41	68.41
k (1/year)	1.56	1.77

3.3.7.3. Scenario-3 (Sorting of Recyclable Wastes)

In this scenario, separation of recyclable wastes from total wastes and storage of remaining parts of the total waste in the landfill site are considered. Recyclable wastes are metal, glass, plastic and paper-paperboard in this study. The ratio of these wastes to the total waste amount is 1.59%. The recyclable waste amount was taken away from the total waste amount. The remaining waste amount was entered to the

LandGEM model. The input waste amount values are given in Table 25. As coming recyclable waste amounts to the landfill site were low, separation of these wastes did not change the service life.

Table 25. Yearly remaining waste amount of scenario-3 after separating recyclable wastes

Year	**Waste Amount (Ton)**	**Remaining Waste Amount After Separation of Recyclable Wastes According to the 50% Organic Content (Ton)**	**Remaining Waste Amount After Separation of Recyclable Wastes According to the 56% Organic Content (Ton)**
2009	26,193	25,776	25,776
2010	122,185	120,862	120,862
2011	134,368	132,231	132,231
2012	137,969	135,776	135,776
2013	134,101	131,969	131,969
2014	136,554	135,972	135,972
2015	160,265	157,716	157,716
2016	165,869	163,231	163,231
2017	168,185	165,511	165,511
2018	144,081	141,790	141,790

The methane content in the landfill gas is one of the inputs in LandGEM model. This content was taken as 55.5% which was obtained from historical methane content of Afyonkarahisar Landfill Site. The k values were again assumed as same as highest k values of base case and scenario-1. L_0 values for 50% and 56% organic waste content were specifically calculated according to highest DOC values for this scenario. The model input values are given in below Table 26.

Table 26.Scenario-3-model inputs

	After Separation of Recyclable Wastes According to the 50% Organic Content	**After Separation of Recyclable Wastes According to the 56% Organic Content**
Ratio of food waste to total waste (%)	50.3	56.4
Ratio of garden waste to total waste (%)	0.51	0.57
Total $DDOC_m$(Gg organic carbon/Gg waste)	0.0402	0.0440
L_0 (m^3/Mg)	44.60	48.84
k (1/year)	1.56	1.77

3.3.7.4. Scenario-4 (Sorting of Ash)

In this scenario, separation of ash wastes from total wastes and storage of remaining parts of the total waste in the landfill site are considered. According to the received information from the Union, ratio of ash wastes to the total waste amount is equal to 50% of total inorganic waste amounts. Therefore, ash ratio was taken as 23.305%

and 20.305% for 50% and 56% organic waste content situations, respectively. The ash waste amount was taken away from the total waste amount. The remaining waste amount was entered to the LandGEM model. The input waste amount values are given in Table 27. The additional service life was approximately specified as 2 years for both 50% and 56% organic content situations.

Table 27. Scenario-4-yearly remaining waste amount after separating ash

Year	**Waste Amount (Ton)**	**Remaining Waste Amount After Separation of Ash According to the 50% Organic Content (Ton)**	**Remaining Waste Amount After Separation of Ash According to the 56% Organic Content (Ton)**
2009	26,193	20,088	20,874
2010	122,185	94,193	97,877
2011	134,368	103,053	107,084
2012	137,969	105,816	109,955
2013	134,101	102,846	106,872
2014	136,554	104,730	108,826
2015	160,265	122,915	127,723
2016	165,869	127,213	132,189
2017	168,185	128,989	134,035
2018	144,081	110,503	114,825
2019	144,081	110,503	114,825
2020	144,081	110,503	114,825

The methane content in the landfill gas was again entered as 55.5% in LandGEM model. The k values were assumed as same as highest k values of base case and scenario-1 due to the lack of data. L_0 values were specifically calculated for both situations in this scenario according to highest DOC values. The model input values are given in Table 28.

Table 28. Scenario-4-model inputs

	After Separation of Ash According to the 50% Organic Content	**After Separation of Ash According to the 56% Organic Content**
Ratio of food waste to total waste (%)	64.5	69.5
Ratio of garden waste to total waste (%)	0.65	0.70
Ratio of paper waste to total waste (%)	0.03	0.03
Total $DDOC_m$(Gg organic carbon/Gg waste)	0.0492	0.0523
L_0 (m^3/Mg)	54.54	58.02
k (1/year)	1.56	1.77

In the base case, ratio of paper waste to the total waste amount is 0.02% according to the waste characterization of Afyonkarahisar Landfill Site. In this scenario, in addition to changes in food and garden waste ratios, paper waste ratio was also changed due to separation of ash waste. In Table 28, new paper waste ratio was given.

3.4. Calculation of the GHG Emission Reduction

GHG reduction due to use of landfill gas for energy production at the Afyonkarahisar Landfill Site instead of fossil fuel usage is determined by the landfill gas energy benefits calculator developed through the Landfill Methane Outreach Program (LMOP) by EPA. With this calculator, direct, avoided and total GHG reductions can be estimated. In addition, environmental and energy benefits can be specified. GHG emissions are reduced by capturing and destroying the methane gas from landfill sites. Also, offset of CO_2 contributes to their reduction. CO_2 generated from fossil fuels burning with conventional power plants is reduced by generating electricity projects from methane gas in the landfill sites. Release of CO_2 is also reduced by using methane in LFG instead of fossil fuel for direct use. All of these reductions are considered in this GHGs reduction calculator (EPA, 2016a). Reduction of direct methane and indirect CO_2 as well as the equivalent benefits of obtaining electricity from LFG can be estimated (USEPA, 2017).

The calculator is Excel based. In the calculator, greenhouse gas emission reduction can be calculated by entering two types of inputs for landfill sites. These are electricity generation projects and direct-use projects. For electricity generation projects, megawatt capacity is entered to the calculator. On the other hand, for direct-use projects, landfill gas amount utilized by the project is entered.

3.4.1. Emission Reduction for Direct Use Projects

For the calculation of direct use emission reduction, the LFG amount is entered as standard cubic feet per minute. As mentioned before, LandGEM model simulates methane gas by using density of methane gas and LFG according to NTP conditions. However, for GHGs emission reduction calculator, the landfill gas amount should be in STP conditions. Therefore, LFG amounts were converted to the STP conditions by using ideal gas law (P*V= n*R*T). In the LandGEM model, LFG density is taken as 1.28 kg/m^3. The density for STP conditions was calculated as 1.38 kg/m^3 for LFG. The GHGs emission reduction was calculated by using highest k and L_0 values for base case, scenario-1, scenario-2, scenario-3 and scenario-4. In addition, LFG amounts were taken from 2009 to 2025 since the LFG and methane gas amounts will be much lower after 2025 as will be given in the results and discussion section.

3.4.2. Emission Reduction for Electricity Generation Projects

According to the calculator, emission reduction for electricity generation projects is calculated by entering megawatt capacity. Similar to the scheme mentioned in the previous section, methane gas amounts were again taken from 2009 to 2025 for the calculator.

Electrical energy calculation was done using the following equation:

$$\text{Electrical Energy} = \text{Flow rate of methane gas} * \text{Lower heating value of methane} * \text{Recovery rate of methane} * \text{Motor efficiency} \quad (17)$$

The LHV of methane was taken as 4230 kcal/m^3. The value was obtained from Afyonkarahisar Environment Service Union. 1 kcal is equal to 0.004184 MJ which gives LHV as 17.69832 MJ/m^3. The union stated that recovery rate or efficiency is 100% for energy generation and, recovery rate of methane gas was taken as it is. In addition, motor efficiency was stated as in the range of 41-43%. This efficiency value was selected as the highest which is 43% in this study.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Field Measurements

Measurements were obtained from 10 different locations in the site. Measurements obtained in the field study are provided in Table 29. According to the results given in Table 29, obtained methane ratio was between 45% and 59%. On the other hand, CO_2 ratio changed in between 25% and 39%. In addition, the water was found in some gas collection pipes. For measurement points, waste ages are as shown in Table 30. The waste age for gas collection points is given according to the field study time which is June 2017.

Table 29.Measurement results of Afyonkarahisar Landfill

Location	T [°C]	O_2 [%]	CO_2 [%]	Air Ratio	Pressure [hPa]	H2S [ppm]	Velocity [m/s]	Flow [l/s]	Excess Air [%]	CH_4 [%]	Net cal. val. [MJ/kg]	Net cal. val. [MJ/m³]	Gross cal. val. [MJ/kg]	Gross cal. val. [MJ/m³]
A-1	35.9	3.9	30.81	1.23	0.01	174	1	50	23	44.48	14.1	17.4	15.6	19.3
A-2	35.9	3.9	30.81	1.23	0.01	174	1	50	23	44.48	14.1	17.4	15.6	19.3
A-3	47.5	1.9	34.43	1.1	0.01	908	1	50	10	47.51	15	18.6	16.6	20.7
A-4	35.7	1.4	35.91	1.07	0.01	1321	0.9	45	7	54.41	17.5	21.3	19.4	23.7
A-5	38.2	0.1	37.94	1.01	0	14	0.6	30	1	55.95	18	21.9	19.9	24.3
A-6	40.4	0.1	38.38	1.01	0	100	0.6	30	1	58.66	19	23	21.1	25.5
A-7	38.5	0.1	38.73	1	0	140	0.6	30	0	58.21	18.8	22.8	20.8	25.3
A-8	-	3.8	25	-	-	-	-	-	-	48.5	-	-	-	-
A-9	33.4	3.2	32.1	1.18	0	282	-	-	18	45.62	14.4	17.9	16	19.8
A-10	32.9	2.2	33.12	1.12	0	1919	0.1	5	12	51.71	16.7	20.3	18.5	22.5

Table 30.Waste age for measured gas collection pipes

Measurement Point	Waste Age (months)
A-1	5
A-2	4
A-3	3
A-4	2
A-5	15
A-6	16-18
A-7	17-19
A-8	66

Table 30 suggests that methane gas amount is higher in the old parts of the site namely A-6, A-7 and A-8 than newer ones. However, for A-4, methane gas percentage is high despite the fact that waste age is only 2 months. The reason of that can be due to two situations. There can be higher coming waste with high organic content to the A-4. In addition, the measurements from this point can be more reliable due to well-conditioned gas collection pipe at A-4 point. The distribution of the methane gas percentages in the total landfill gas is shown in Figure 24 according to the location of field study measurement points. During the field study, location of measurement points was recorded by using GPS device for analyzing how gas generation changes according to the location in the site. In the lower location which includes A-7, A-6 and A-5 points, methane gas amount was observed as higher compared to other locations.

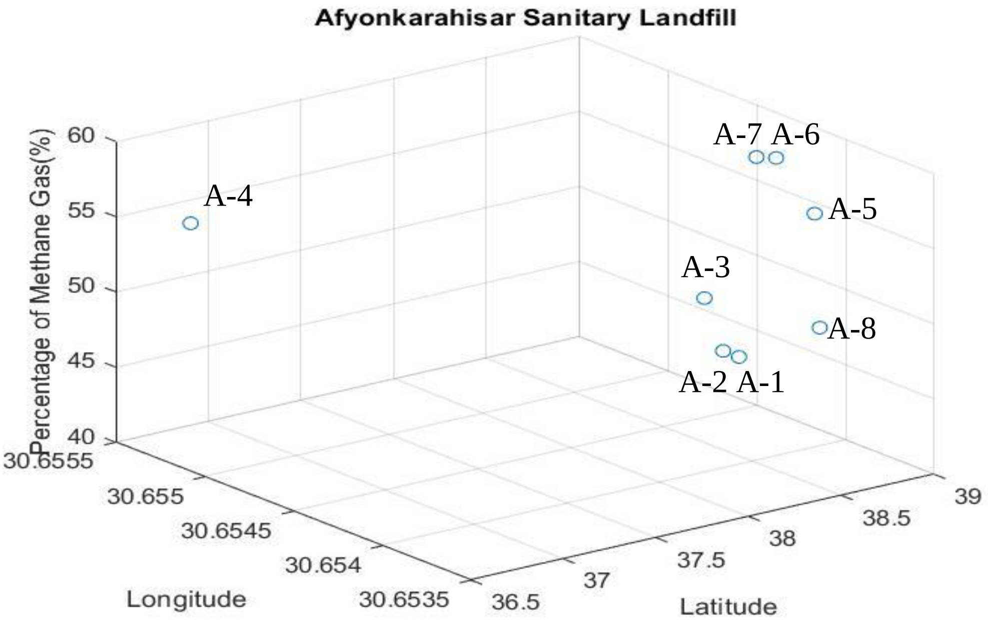


Figure 24. Methane gas percentage distribution for measurement points in the site

In Figure 25, gas collection pipe system of the site and measurement areas are given. The Area-I includes point 1, 2 and 3 which were given in the above. The Area-II includes point 4. The Area-III includes point 9 and 10 which are the main gas collectors. The Area-IV includes point 5, 6, 7 and 8. According to the measurement results, the Area-III had higher methane gas generation compared to other three areas. The lowest methane gas generation was observed in the Area-I which had lower waste age compared to Area-III.

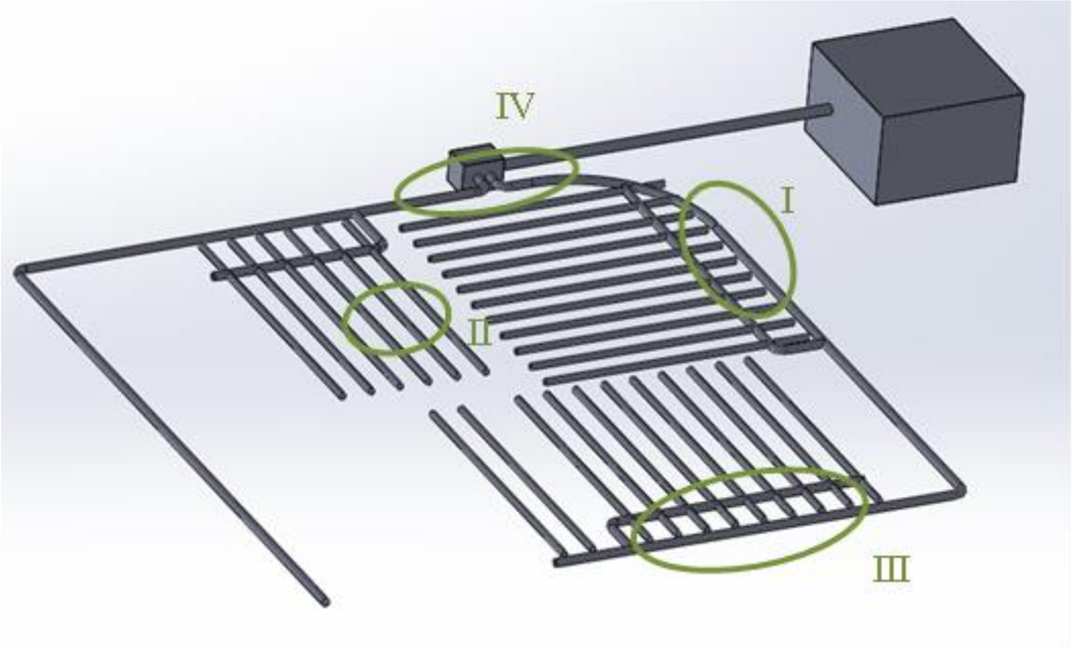


Figure 25. Gas collection pipe system of Afyonkarahisar Landfill Site

4.2. Modeling Results

4.2.1. Scenario-1 Results

When 56% organic waste content results are compared to base case having 50% organic waste content, it is seen that there is 11% increase in LandGEM and IPCC 2006 models in terms of peak methane generation amounts. The peak methane generation amount is obtained in the same year as for the base case. Therefore, the impact of increased organic matter content was on the amounts rather than the year the peak was observed. The age of the waste was the determinant of the peaking time. It was observed that increase in organic waste amount improved the methane generation amount.

In the base case, total methane gas generation amounts were calculated as 5.763E+07 and 7.227E+07 m^3 in LandGEM and IPCC 2006, respectively. According to scenario-1 results, these gas generation amounts were specified as 6.363E+07 and 7.945E+07 m^3 in LandGEM and IPCC 2006, respectively. In the LandGEM and IPCC model results, 9% increase was evaluated compared to base case.

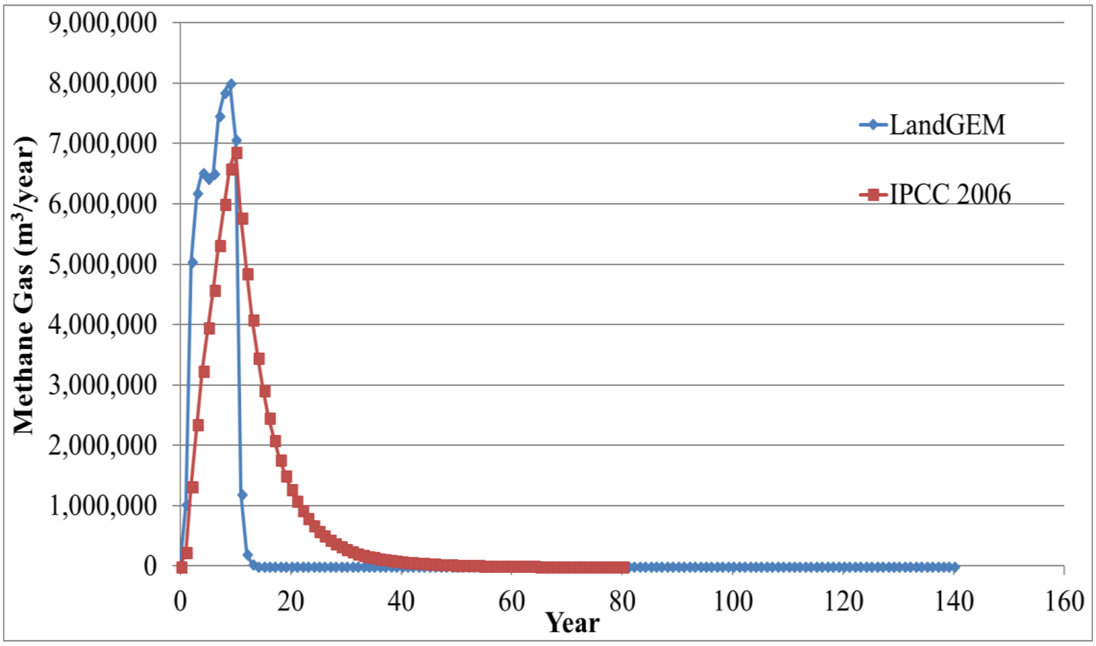


Figure 26.Scenario-1: Modeled methane generation curves

4.2.2. Scenario-2 Results

Figure 27 compares total methane gas generation obtained for LandGEM for scenario-2 to the base case. Figure 28 compares methane gas production per unit of waste stored obtained for LandGEM for scenario-2 to the base case for 4 years. scenario-2 involves separation of organic waste for storage. In Figure 29, comparison is between IPCC 2006 and LandGEM model results. In this figure, it can be seen that there are differences in methane gas generation amounts over years.

According to results in Figure 27, total methane gas generation amounts were specified as 5.763E+07 m^3 and 8.823E+07 m^3 for base case and scenario-2, respectively. It can be observed that the gas generation of the scenario is lower than the base case in the early years. Since there is longer service life in this scenario, more organic waste amounts will accumulate. Therefore, the total methane gas generation amounts are higher than the base case. The gas generation increase is approximately 53% compared to base case for scenario-2.

When Figure 28 is investigated, if only organic waste is stored in the lot, methane gas generation amount per unit waste amount increases significantly. The increase will be up to 55%. Figure 29 shows that there is 40% difference between unit gas production amounts obtained for two models for scenario-2. In addition, IPCC model shows lower peak gas generation value, but it has longer gas generation period as discussed earlier. Calibration results showed that LandGEM model was more efficient in prediction of gas generation and representation of the landfill site.

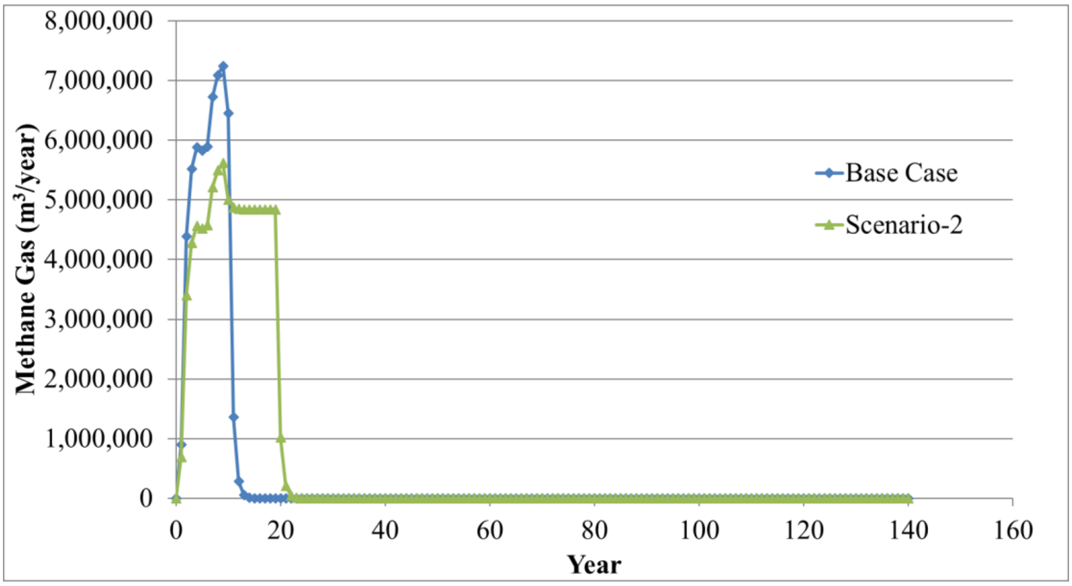


Figure 27. Comparison of scenario-2 and base case (mixed waste with 50% organic content) total gas distribution for LandGEM

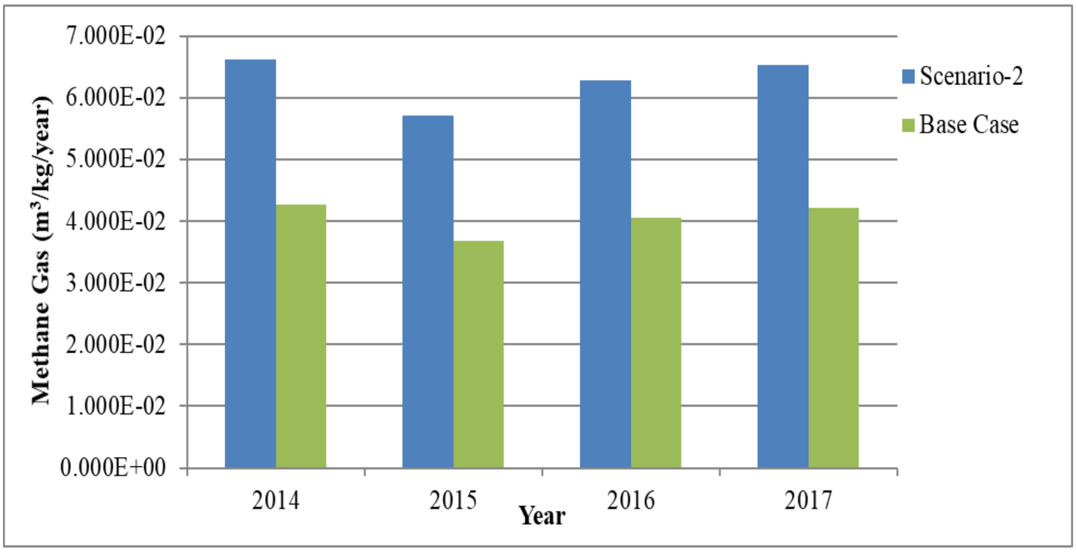


Figure 28.Comparison of scenario-2 and base case (mixed waste with 50% organic content) for LandGEM

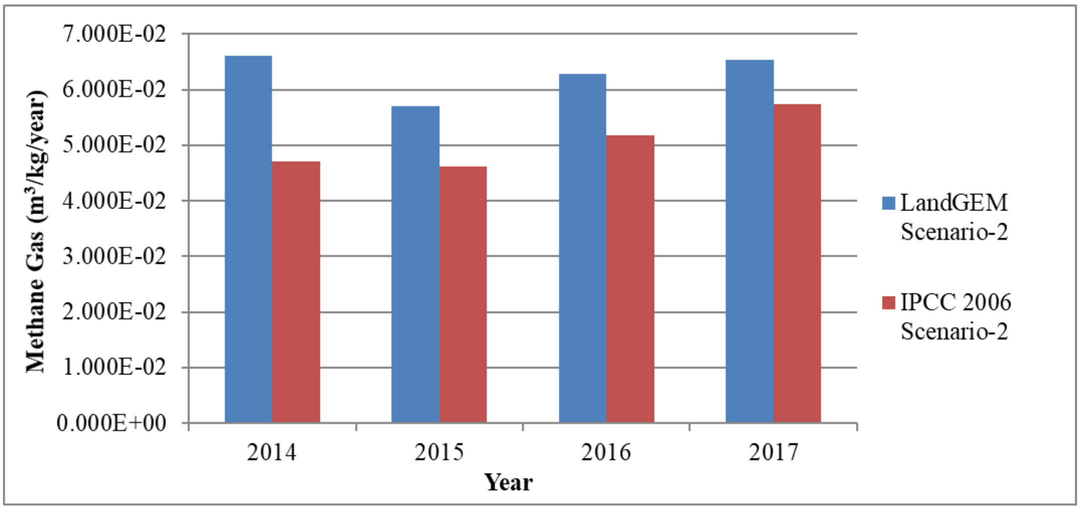


Figure 29.Comparison of LandGEM and IPCC 2006 models for scenario-2 (for 50% organic content)

In the following figures, scenario-2 results were given for 56% organic content. According to results in Figure 30, total methane gas generation amounts were specified as 6.363E+07 m^3 and 8.888E+07 m^3 for base case and scenario-2, respectively. The methane gas generation increase is approximately 40% compared to base case (with 56% organic content) for scenario-2.

According to the LandGEM model results in terms of m^3/kg/year, there is an increase up to 42% in the methane gas generation compared to base case, when organic content of the waste is 56%. As for the case of 50% organic content, IPCC model exhibited lower unit methane gas amount compared to the values obtained for LandGEM model.

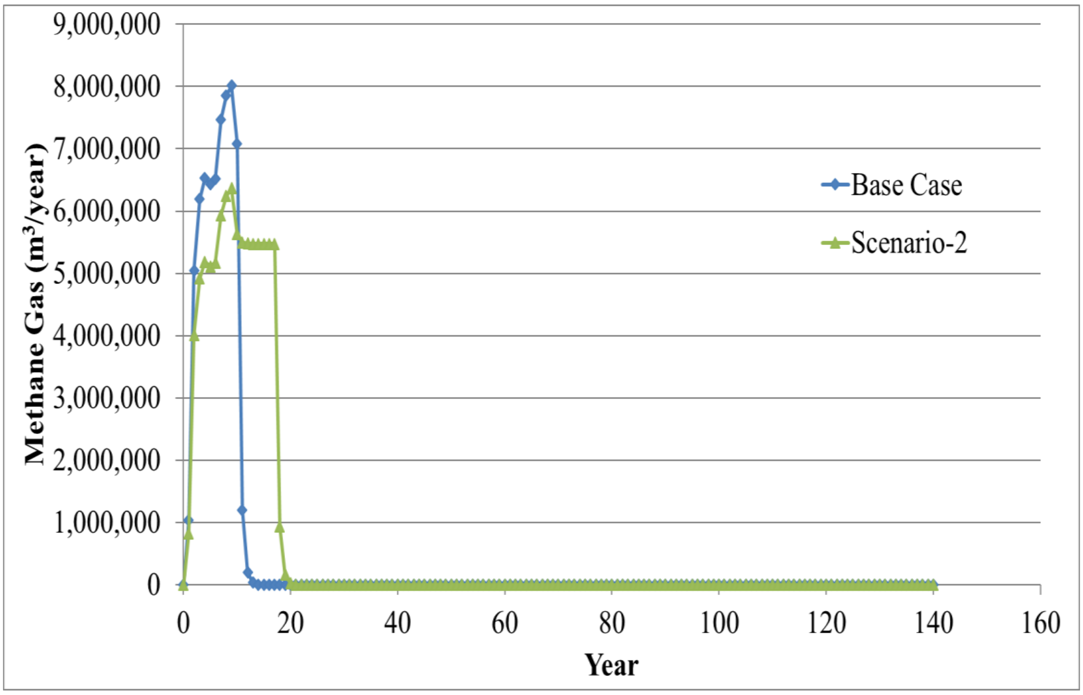


Figure 30. Comparison of scenario-2 and base case (mixed waste with 56% organic content) total gas distribution for LandGEM

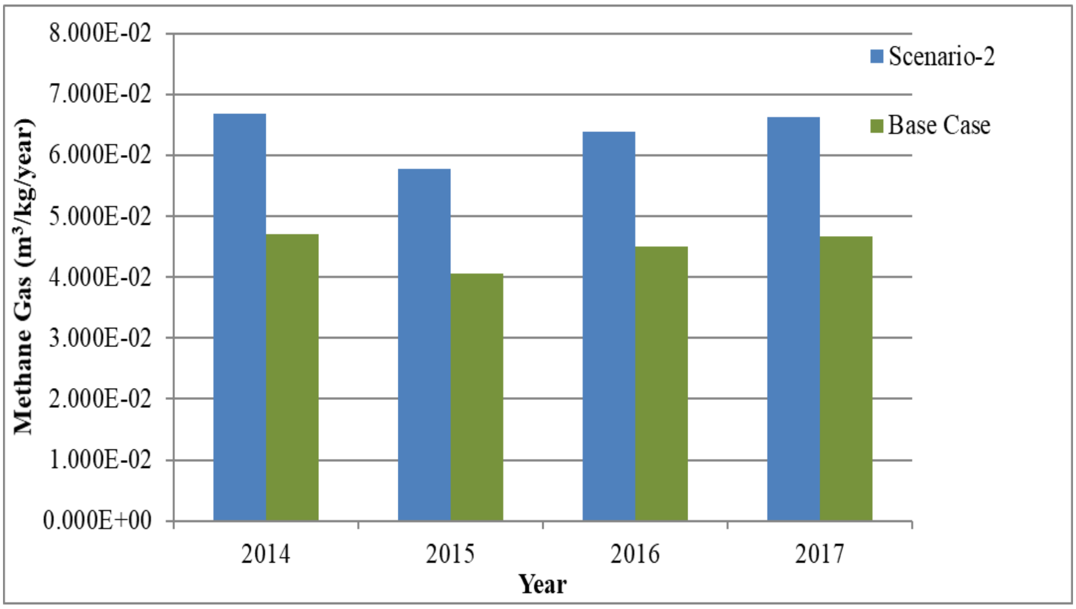


Figure 31. Comparison of scenario-2 and base case (mixed waste with 56% organic content) for LandGEM

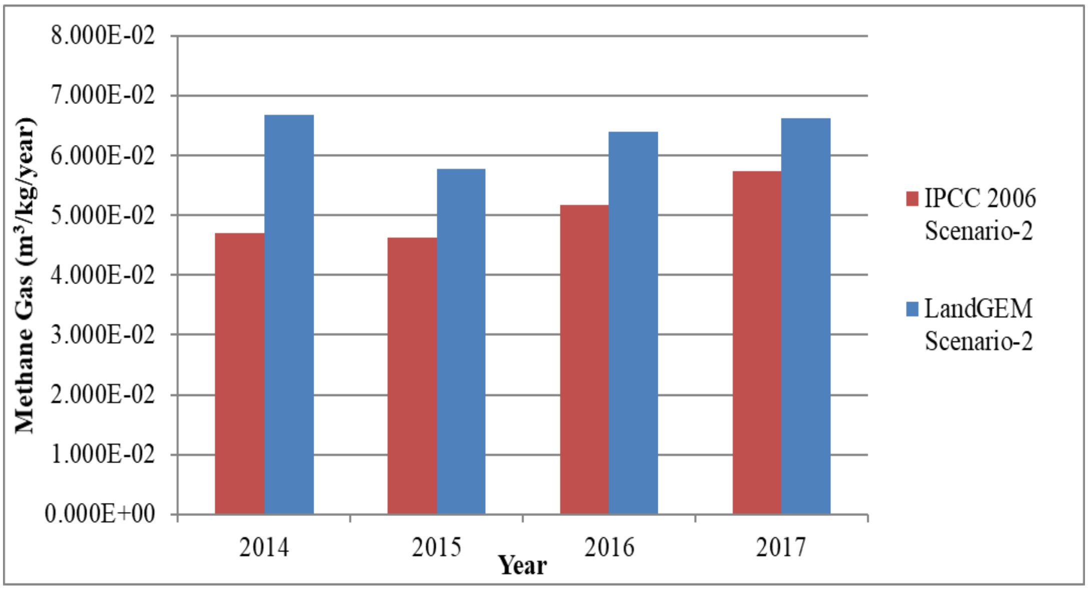


Figure 32. Comparison of LandGEM and IPCC 2006 models for scenario-2 (for 56% organic content)

4.2.3. Scenario-3 Results

Figure 33 compares total methane gas generation obtained for LandGEM for scenario-3 to the base case (50% organic content). According to results in the figure, total methane gas generation amounts were specified as 5.763E+07 m^3 and 5.740E+07 m^3 for base case and scenario-3, respectively. There is 0.4% decrease in the total gas generation amount compared to the base case. The reason of that is related to separation of paper wastes from total waste amount. Paper waste contributes to the methane generation. However, in this scenario, paper waste separation was considered as recyclable waste.

When recyclable waste types are separated from the total waste for 50% organic content, slight improvement can be achieved in the methane generation per unit of stored waste compared to the base case according to the LandGEM model results. This improvement is approximately 2%. This improvement may not be valuable given the potential separation costs at the site. This situation is related to the low recyclable waste amounts in the total waste amount. IPCC and LandGEM model results and comparison are given in Figure 35.

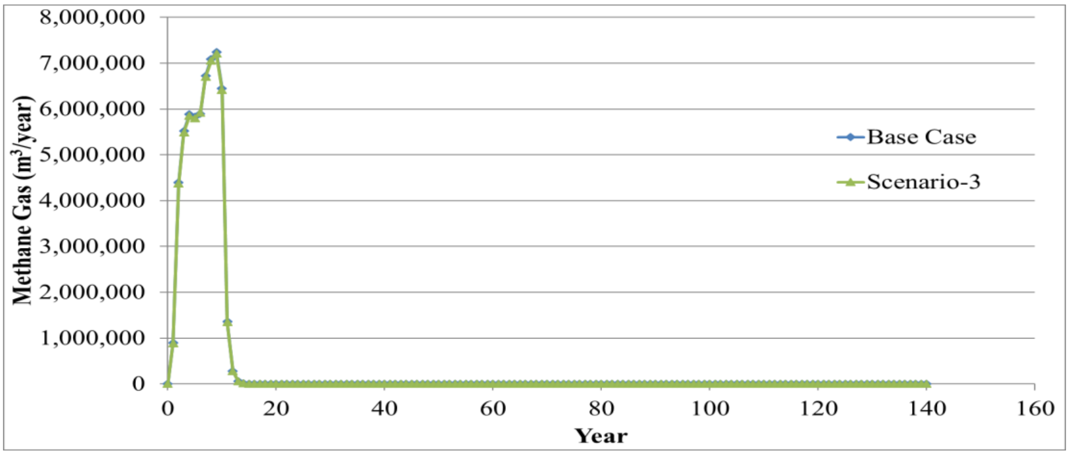


Figure 33. Comparison of scenario-3 and base case (separation of recyclables from waste containing 50% organic content) total gas generation for LandGEM

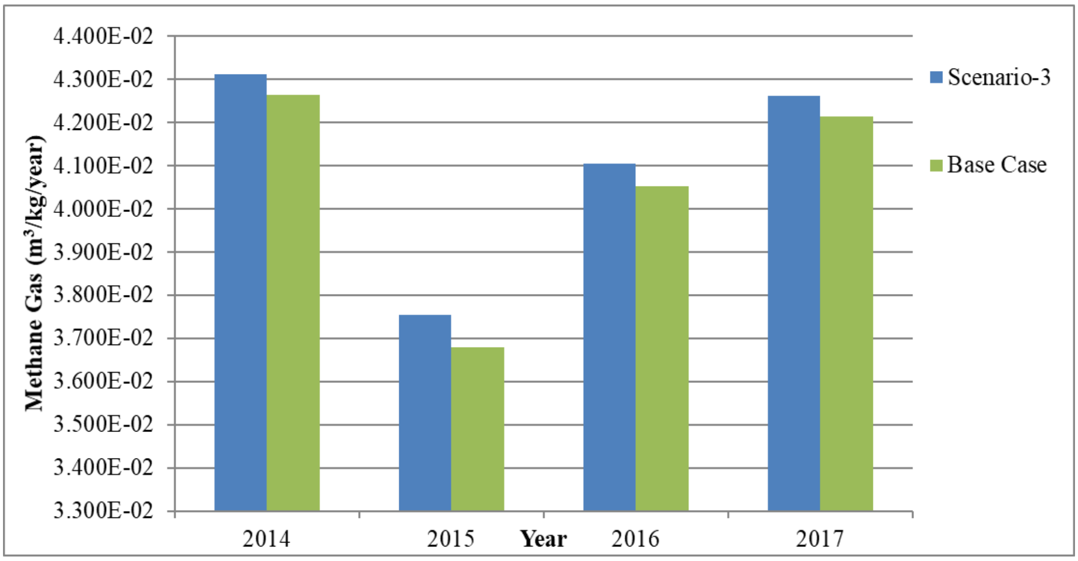


Figure 34.Methane gas generation per unit of waste stored for LandGEM (separation of recyclables from waste containing 50% organic content)

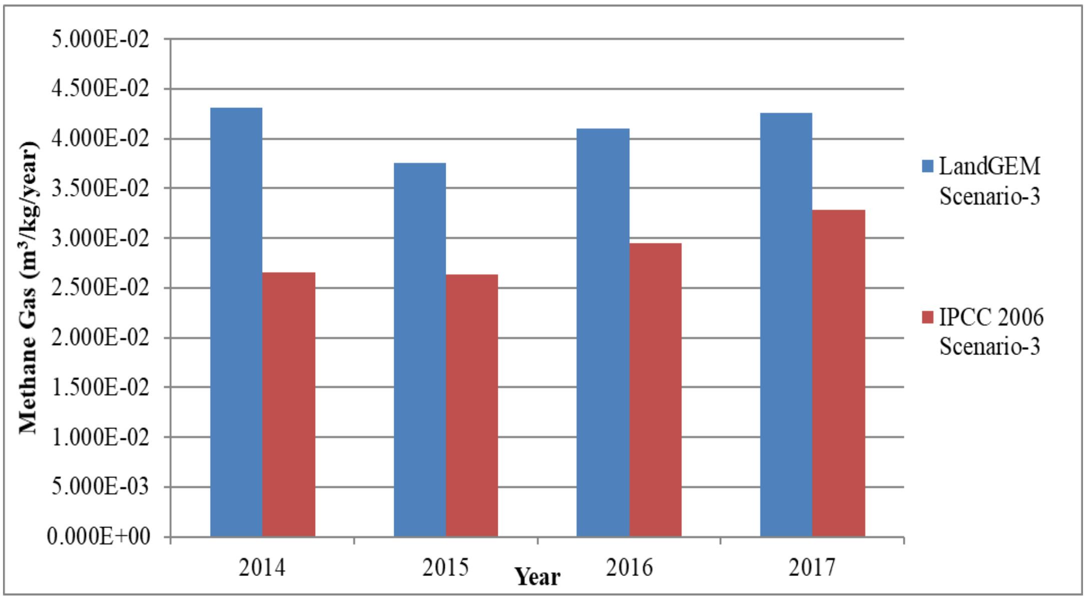


Figure 35. Comparison of Scenario-3 (separation of recyclables from waste of 50% organic content) for LandGEM and IPCC 2006)

Figure 36 compares total methane gas generation obtained for LandGEM for scenario-3 to the base case (56% organic content). According to results in the figure, total methane gas generation amounts were specified as 6.363E+07 m^3 and 6.350E+07 m^3 for base case and scenario-3, respectively. There is 0.2% decrease in the total gas generation amount compared to the base case.

When recyclables are separated from the total waste containing 56% organic content, improvement in unit gas production was again approximately 2% compared to the base case. Results are provided in Figure 36, Figure 37 and Figure 38. According to these results, recyclable waste separation scenario does impact gas generation. The reason is the low recyclable waste content in the total waste amount. The DOC value of paper is high. In other words, paper waste supports gas generation. With separation of recyclable wastes, this waste type is lost in the lot. Yet, as the percentage of paper in the waste is low the impact was not observed at significant levels. Therefore, given the costs, separation of recyclables from waste is not a viable option to increase methane gas generation amount.

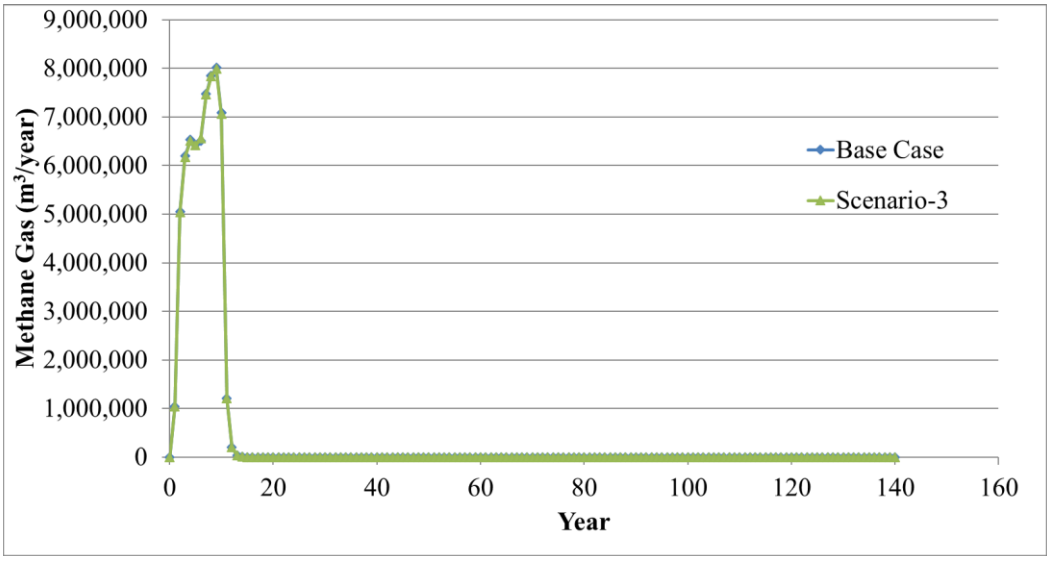


Figure 36. Comparison of scenario-3 and base case (separation of recyclables from waste containing 56% organic content) total gas generation for LandGEM

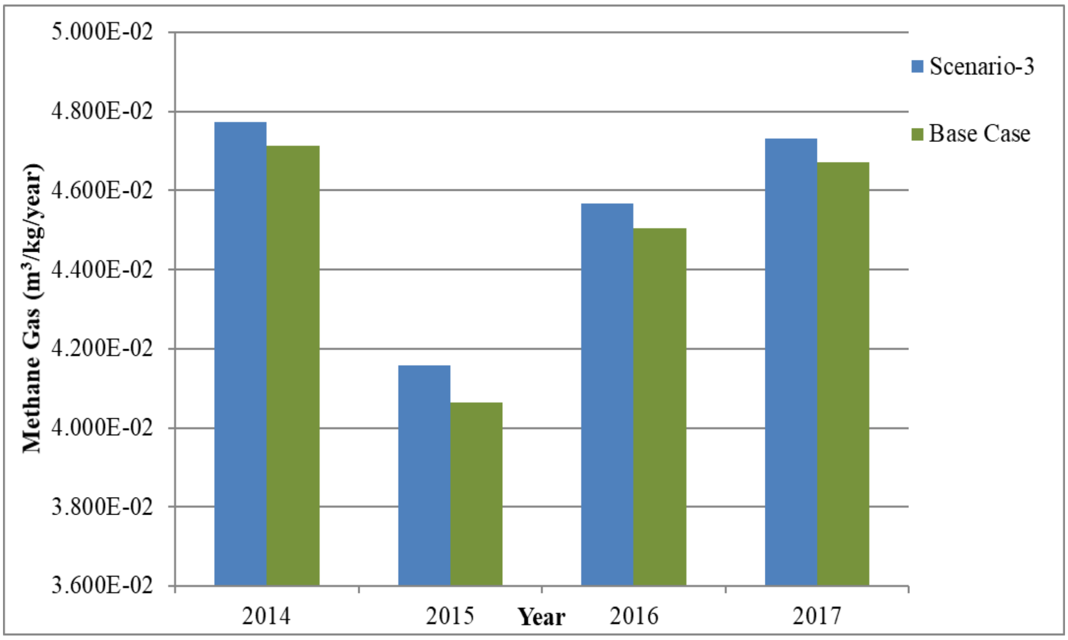


Figure 37. Unit methane gas production for LandGEM (separation of recyclables from waste of 56% organic content)

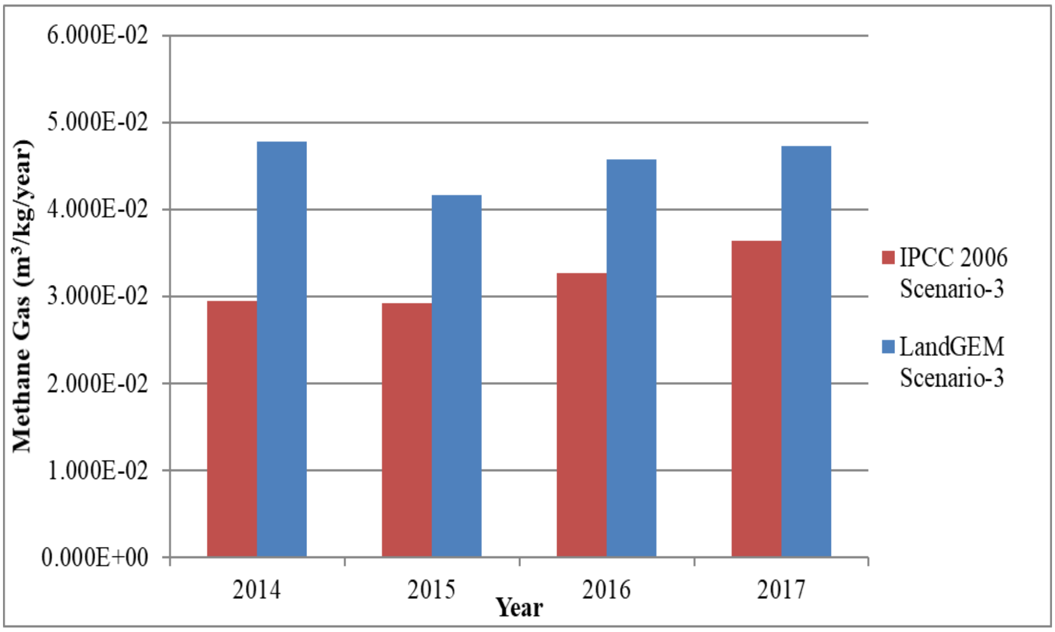


Figure 38. Comparison of scenario-3 for LandGEM and IPCC 2006 (separation of recyclables from waste of 56% organic content)

4.2.4. Scenario-4 Results

Figure 39 compares total methane gas generation obtained for LandGEM for scenario-4 to the base case (50% organic content). According to the results in the figure, total methane gas generation amounts were specified as 5.763E+07 m^3 and 6.647E+07 m^3 for base case and scenario-4, respectively. There is approximately 16% increase in the total gas generation amount compared to the base case. The reason of that is related to increases in the food, garden and paper waste ratios.

According to the methane gas generation per unit of stored waste, 24% increase can be obtained compared to the base case in LandGEM model results.

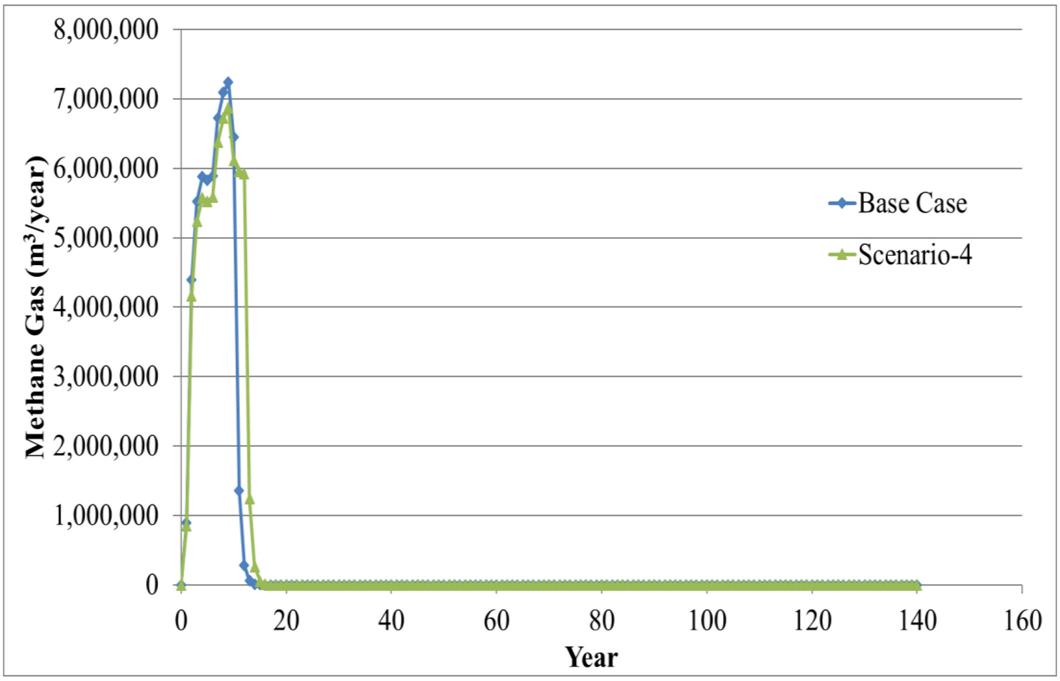


Figure 39. Comparison of scenario-4 and base case (separation of ash from waste containing 50% organic content) total gas generation for LandGEM

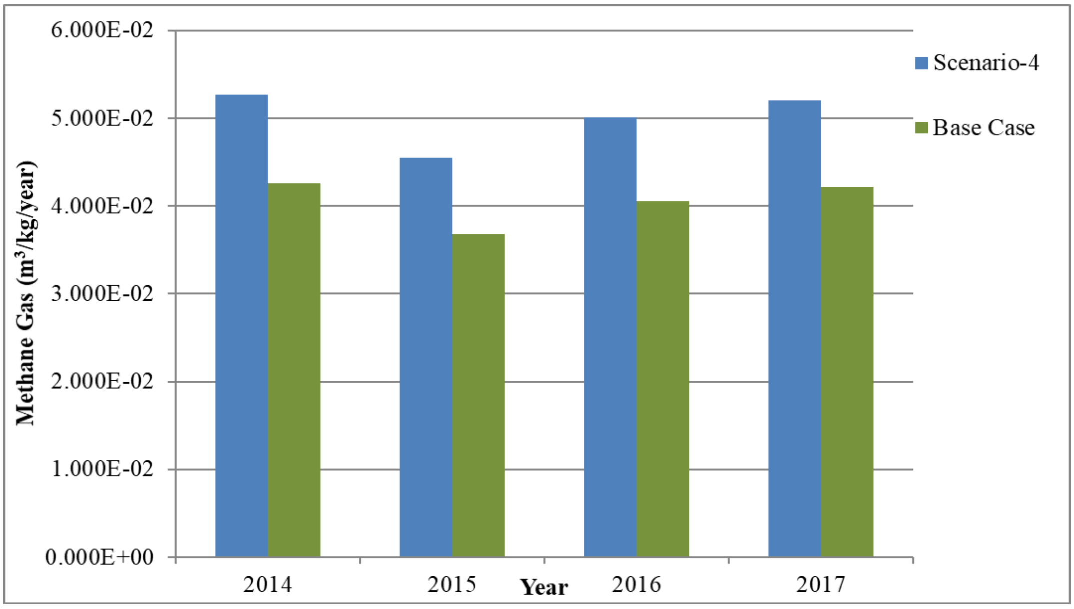


Figure 40. Methane gas generation per unit of waste stored for LandGEM (separation of ash from waste containing 50% organic content)

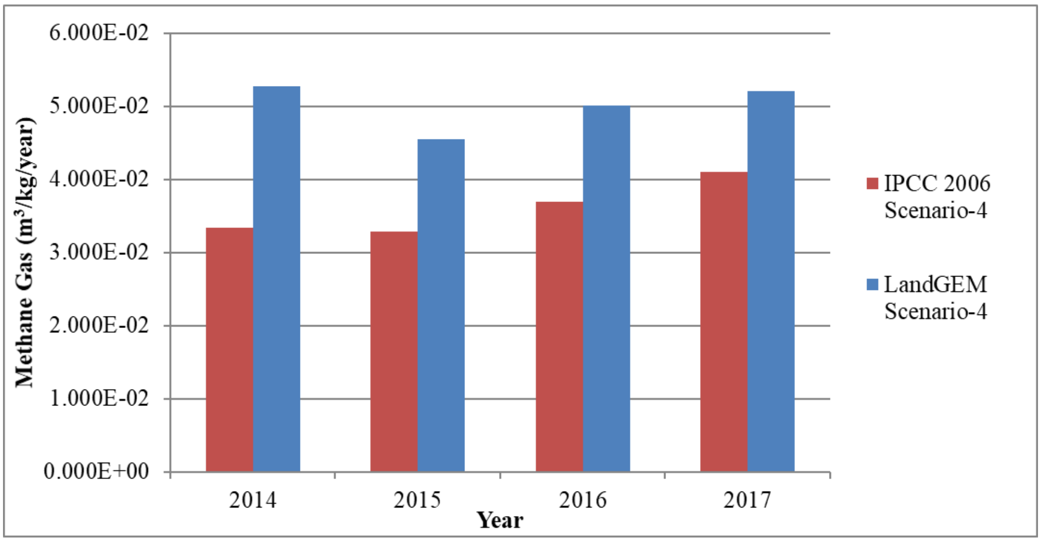


Figure 41. Comparison of scenario-4 (separation of ash from waste of 50% organic content) for LandGEM and IPCC 2006

Figure 42 compares total methane gas generation obtained for LandGEM for scenario-4 to the base case (56% organic content). According to the results in this figure, total methane gas generation amounts were specified as 6.363E+07 m^3 and 7.424E+07 m^3 for base case and scenario-4, respectively. There is approximately 17% increase in the total gas generation amount compared to the base case.

According to the methane gas generation per unit of stored waste, 20% increase can be obtained compared to the base case in LandGEM model results.

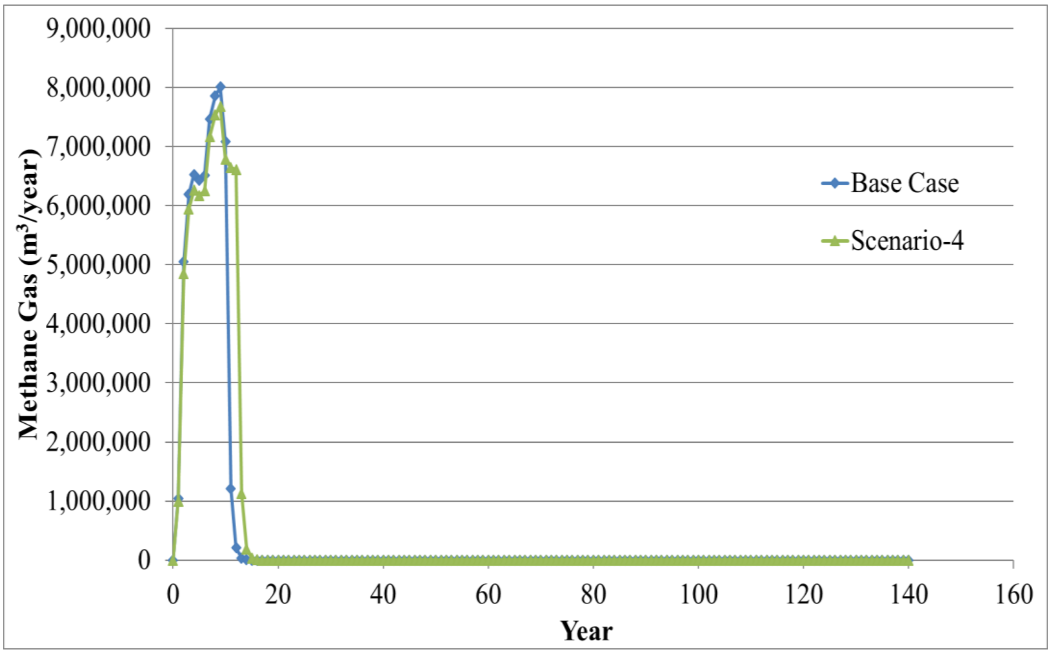


Figure 42. Comparison of scenario-4 and base case (separation of ash from waste containing 56% organic content) total gas generation for LandGEM

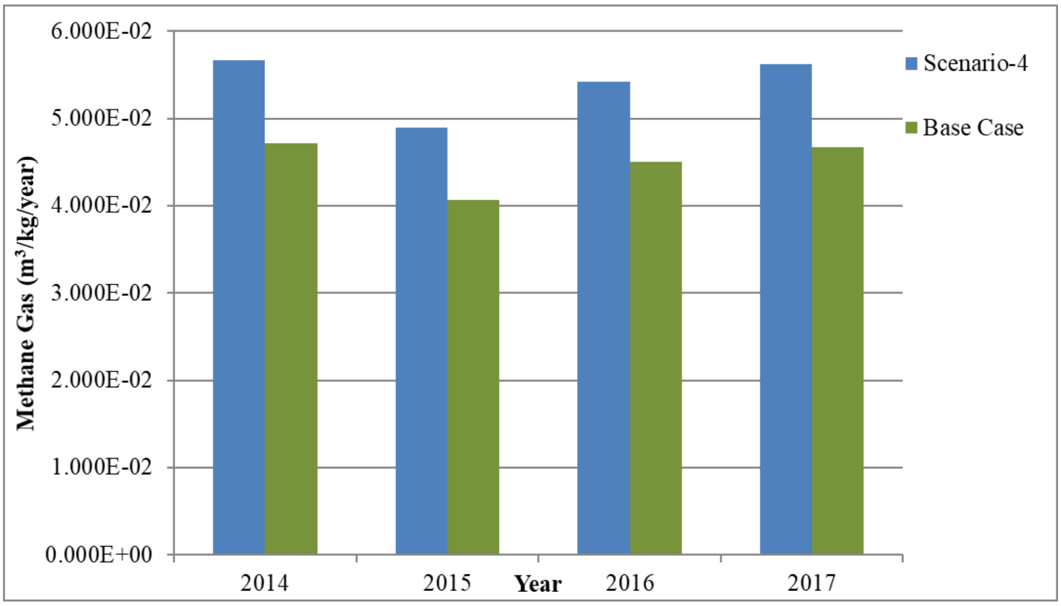


Figure 43. Methane gas generation per unit of waste stored for LandGEM (separation of ash from waste containing 56% organic content)

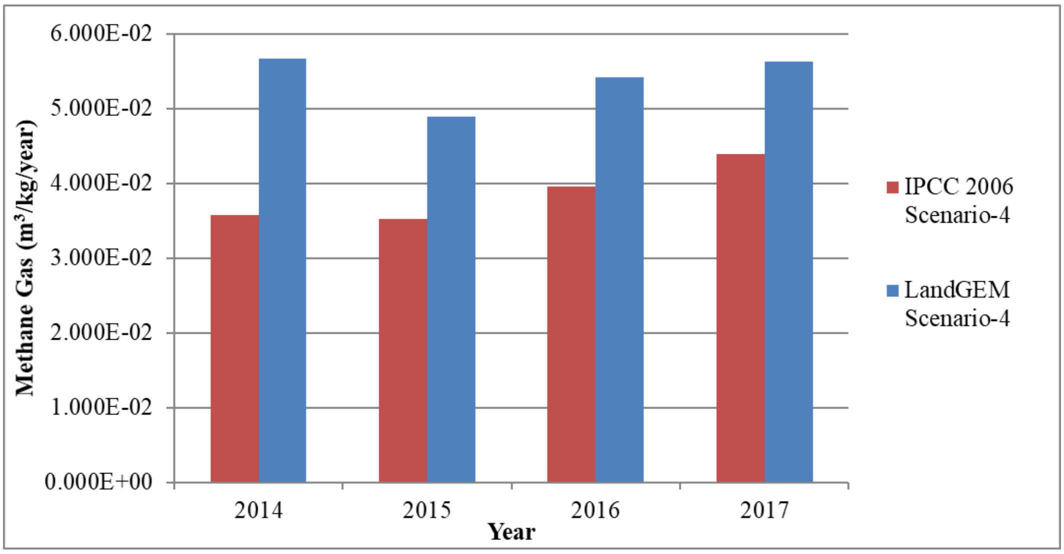


Figure 44. Comparison of scenario-4 (separation of ash from waste of 56% organic content) for LandGEM and IPCC 2006

4.2.5. Summary of Comparison for LandGEM Model

Calibration results showed that LandGEM model better simulated the gas production at the Afyonkarahisar Landfill Site. The results of current situation (base case) and scenarios are summarized in Figure 45 and Figure 46. The base case represented in the Figure 45 and Figure 46, shows 50% and 56% organic content results, respectively. As shown in the figures, methane gas generation amounts were represented in terms of m^3/kg/year. For base cases, scenario-2, scenario-3 and scenario-4, methane gas generation results (m^3/year) were divided by waste amounts of them. For base case, gas generation results were divided by total deposited waste amounts in the site. Methane gas amount results of scenario-2 were divided by deposited organic waste amounts. For scenario-3, the gas amounts of this scenario were divided by deposited remaining waste amounts which were separated from recyclable wastes. For scenario-4, the gas amounts were divided by deposited remaining waste amounts which were separated from ash.

For both 50% and 56% organic content situations, significant improvement was not obtained for scenario-3 since recyclable waste amounts were low (1.59%). In scenario-4, approximately 24% increase was obtained depending on organic waste content (50% and 56%) in terms of gas generation amount per kg waste. Scenario-2 which included the storage of only organic wastes provided significant increase in the methane generation. This scenario is important for obtaining energy from the landfill site and increasing methane gas generation amount.

Figure 45.Yearly methane gas generation change according to LandGEM (50% organic content)

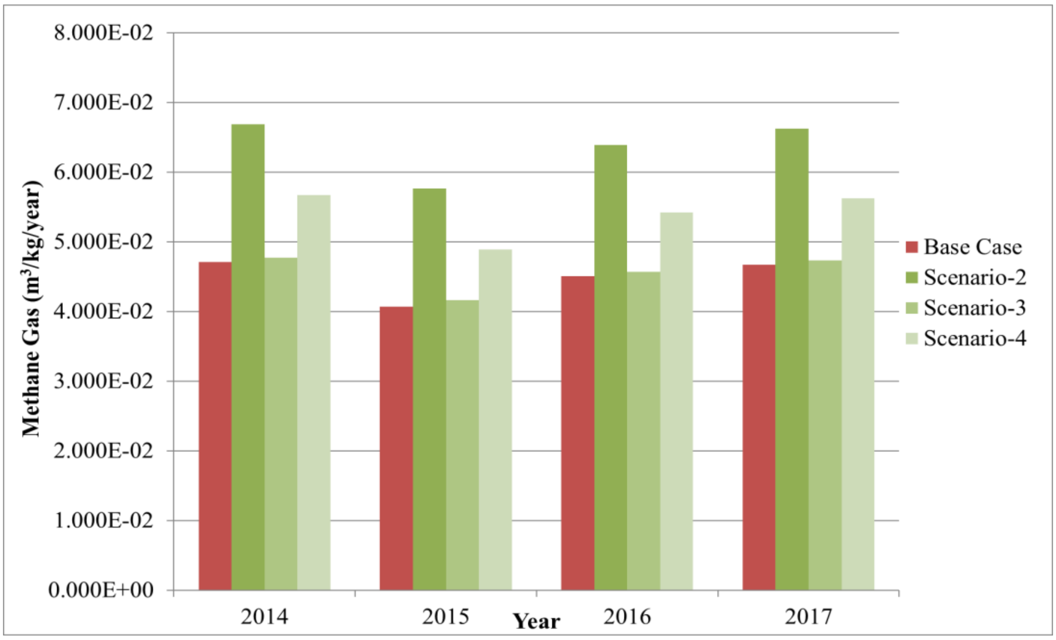


Figure 46.Yearly methane gas generation change according to LandGEM (56% organic content)

Along with the problems associated with site selection, site construction and amount of gas production; the duration of service of lots at the landfill site is an important criterion. Following figures show how service life change according to 50% and 56% organic content. For 50% organic content, service life of a single lot is 9 years in the base case. However, if only organic waste is put into the lot, service life will be 18 years. Likewise, for 56% organic content, if only organic waste is put into the lot, service life will be 16 years. In the application of scenario-3, there will be no significant increase in the service life since ratio of recyclable wastes to the total waste is quite low. In scenario-4, service life of a single lot will be 11 years.

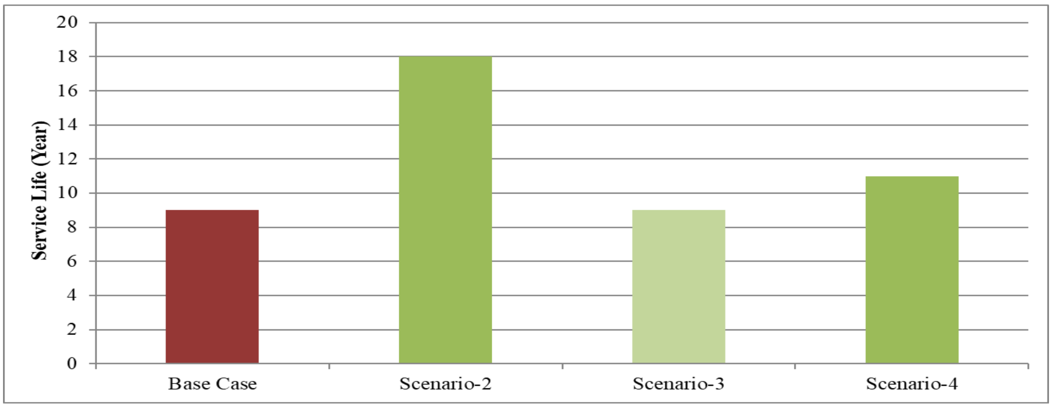


Figure 47.Service life periods for 50% organic content

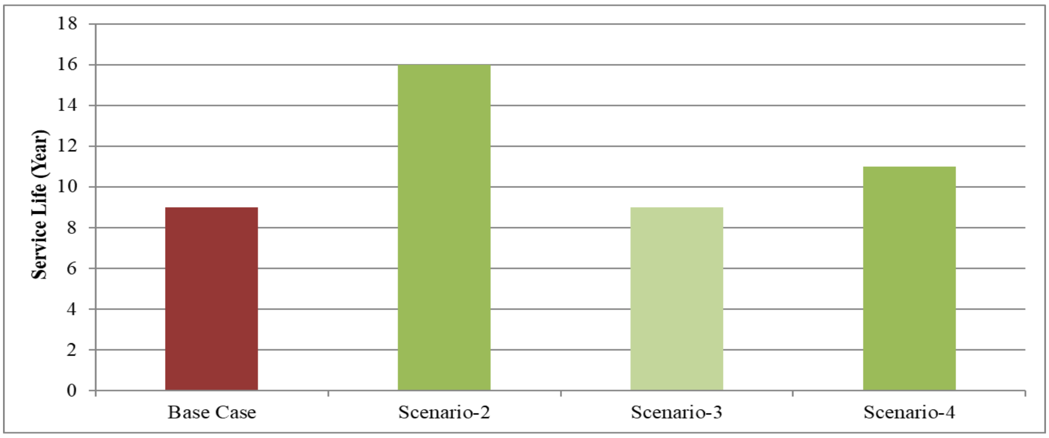


Figure 48. Service life periods for 56% organic content

4.3. Greenhouse Gas Emission Reduction Calculation and Related Results

4.3.1. Emission Reduction for Direct Use Projects

Average LFG amounts used in calculation of GHG reduction amounts from 2009 to 2025 is given in Table 31.

Table 31.LFG amount as input for GHGs emission reduction calculator

	LFG Amount (feet^3/min)
Base Case (50% Organic Content)	382.54
Scenario-1 (56% Organic Content)	422.38
Scenario-2 (For 50% Organic Content)	480.74
Scenario-2 (For 56% Organic Content)	546.16
Scenario-3 (For 50% Organic Content)	381.01
Scenario-3 (For 56% Organic Content)	421.52
Scenario-4 (For 50% Organic Content)	441.21
Scenario-4 (For 56% Organic Content)	429.74

According to these amounts, reduction results were obtained and given in Table 32, Table 33, Table 34, Table 35, Table 36, Table 37, Table 38 and Table 39 for the scenarios provided in Table 31. In these tables, direct equivalent emissions reduced shows the reduction of methane emitted directly from the landfill. The avoided equivalent emission reduced indicates the offset of carbon dioxide from avoiding the use of fossil fuels. The total equivalent emissions reduced is the summation of direct and avoided emission reductions.

Table 32.Reduction in GHG emissions and benefits of it for base case (50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0482	0.0048	0.0530
Tons CH$_4$/year	2,126	-	2,126
Tons CO$_2$/year	-	5,248	5,248
BENEFITS			
CO$_2$ emissions from barrels oil consumed	112,147	11,073	123,220
CO$_2$ emissions from gallons of gasoline consumed	5,426,258	535,762	5,962,020
ENERGY BENEFITS			
Heating homes	1,321		

Table 33.Reduction in GHG emissions and benefits of it for scenario-1 (56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0532	0.0053	0.0585
Tons CH_4/year	2,348	-	2,348
Tons CO_2/year	-	5,795	5,795
BENEFITS			
CO_2 emissions from barrels oil consumed	123,827	12,226	136,053
CO_2 emissions from gallons of gasoline consumed	5,991,381	591,560	6,582,941
ENERGY BENEFITS			
Heating homes	1,459		

Table 34.Reduction in GHG emissions and benefits of it for scenario-2 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0606	0.0060	0.0666
Tons CH_4/year	2,672	-	2,672
Tons CO_2/year	-	6,596	6,596
BENEFITS			
CO_2 emissions from barrels oil consumed	140,936	13,915	154,851
CO_2 emissions from gallons of gasoline consumed	6,819,207	673,295	7,492,502
ENERGY BENEFITS			
Heating homes	1,660		

Table 35.Reduction in GHG emissions and benefits of it for scenario-2 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0688	0.0068	0.0756
Tons CH_4/year	3,036	-	3,036
Tons CO_2/year	-	7,493	7,493
BENEFITS			
CO_2 emissions from barrels oil consumed	160,114	15,809	175,923
CO_2 emissions from gallons of gasoline consumed	7,747,177	764,918	8,512,096
ENERGY BENEFITS			
Heating homes	1,886		

Table 36.Reduction in GHG emissions and benefits of it for scenario-3 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0480	0.0047	0.0528
Tons CH_4/year	2,118	-	2,118
Tons CO_2/year	-	5,227	5,227
BENEFITS			
CO_2 emissions from barrels oil consumed	111,698	11,029	122,727
CO_2 emissions from gallons of gasoline consumed	5,404,555	533,619	5,938,175
ENERGY BENEFITS			
Heating homes	1,316		

Table 37.Reduction in GHG emissions and benefits of it for scenario-3 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0531	0.0052	0.0584
Tons CH$_4$/year	2,343	-	2,343
Tons CO$_2$/year	-	5,783	5,783
BENEFITS			
CO$_2$ emissions from barrels oil consumed	123,574	12,201	135,776
CO$_2$ emissions from gallons of gasoline consumed	5,979,182	590,355	6,569,537
ENERGY BENEFITS			
Heating homes	1,456		

Table 38. Reduction in GHG emissions and benefits of it for scenario-4 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0556	0.0055	0.0611
Tons CH$_4$/year	2,452	-	2,452
Tons CO$_2$/year	-	6,053	6,053
BENEFITS			
CO$_2$ emissions from barrels oil consumed	129,347	12,771	142,118
CO$_2$ emissions from gallons of gasoline consumed	6,258,481	617,932	6,876,413
ENERGY BENEFITS			
Heating homes	1,524		

Table 39. Reduction in GHG emissions and benefits of it for scenario-4 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0621	0.0061	0.0682
Tons CH$_4$/year	2,739	-	2,739
Tons CO$_2$/year	-	6,760	6,760
BENEFITS			
CO$_2$ emissions from barrels oil consumed	144,454	14,263	158,716
CO$_2$ emissions from gallons of gasoline consumed	6,989,425	690,102	7,679,526
ENERGY BENEFITS			
Heating homes	1,702		

In the results, it is seen that LFG utilization contributes to GHGs emission reduction. The calculator is based on United States data especially for heating homes value. Average annual household heating usage is taken as 66,000 cubic feet of natural gas per household. For CO$_2$ emissions from barrels of oil consumed, it is assumed that 0.43 metric tons of carbon dioxide is emitted per consumed barrel of oil. For CO$_2$ emissions from gasoline consumption, it is assumed that 0.00889 metric tons of carbon dioxide emitted per consumed gallon of gasoline. Gasoline consumption of the calculator has similar values for Turkey. In Turkey, average annual household natural gas usage was specified as 1,032 m^3/household in 2017 (Natural Gas Distributors Association of Turkey, 2017). According to the calculator, this value is taken as 1,698 m^3/household. For natural gas usage, Turkey's value and calculator value are closer to each other. Therefore, use of calculator values was verified.

With the application of scenario-2, 0.0666 and 0.0756 million metric ton CO$_2$ equivalent emission reductions can be obtained in a year for scenario-2 with 50%

organic content and scenario-2 with 56% organic content, respectively. With scenario-2 with 50% organic matter, 26% more reduction is obtained compared to base case (50% organic content). For scenario-2 with 56% organic content, 29% more emission reduction is provided compared to scenario-1 (56% organic content). On the other hand, with scenario-3 (50% organic content and 56% organic content), there was no further contribution to emission reduction compared to base case. There is a decrease in GHG emission reduction for scenario-3. For scenario-4, 0.0611 and 0.0682 million metric ton CO_2 equivalent emission reductions can be obtained in a year with 50% and 56% organic content, respectively. With scenario-4 with 50% organic matter, 15% more reduction is obtained compared to base case (50% organic content). For scenario-4 with 56% organic content, 16% more emission reduction is provided compared to scenario-1 (56% organic content). These results show that more emission reduction can be obtained for higher organic content cases due to higher gas generation. In addition, heating home numbers can be increased by evaluating gas generation.

4.3.2. Emission Reduction for Electricity Generation Projects

The flowrates of methane gas used for the calculations are provided in Table 40, Table 41, Table 42, Table 43 and Table 44 for different scenarios.

Table 40.Methane gas generation results of base case for 2009-2025 according to LandGEM

Year	**Methane Flow Rate (m^3/year)**
2009	0
2010	8.962E+05
2011	4.391E+06
2012	5.520E+06
2013	5.881E+06
2014	5.824E+06
2015	5.896E+06
2016	6.723E+06
2017	7.088E+06
2018	7.244E+06
2019	6.452E+06
2020	1.356E+06
2021	2.849E+05
2022	5.987E+04
2023	1.258E+04
2024	2.644E+03
2025	5.555E+02

Table 41.Methane gas generation results of scenario-1 for 2009-2025 according to LandGEM

Year	**Methane Flow Rate (m^3/year)**
2009	0
2010	1.039+06
2011	5.051E+06
2012	6.192E+06
2013	6.530E+06
2014	6.434E+06
2015	6.515E+06
2016	7.469E+06
2017	7.855E+06
2018	8.012E+06
2019	7.082E+06
2020	1.206E+06
2021	2.055E+05
2022	3.500E+04
2023	5.962E+03
2024	1.015E+03
2025	1.730E+02

Table 42.Methane gas generation results of scenario-2 for 2009-2025 according to LandGEM

Year	**Methane Flow Rate for 50% Organic Content (m^3/year)**	**Methane Flow Rate for 56% Organic Content (m^3/year)**
2009	0	0
2010	6.948E+05	8.258E+05
2011	3.404E+06	4.013E+06
2012	4.280E+06	4.920E+06
2013	4.559E+06	5.188E+06
2014	4.515E+06	5.112E+06
2015	4.571E+06	5.176E+06
2016	5.212E+06	5.934E+06
2017	5.495E+06	6.240E+06
2018	5.616E+06	6.365E+06
2019	5.002E+06	5.627E+06
2020	4.873E+06	5.501E+06
2021	4.846E+06	5.479E+06
2022	4.840E+06	5.476E+06
2023	4.839E+06	5.475E+06
2024	4.839E+06	5.475E+06
2025	4.839E+06	5.475E+06

Table 43.Methane gas generation results of scenario-3 for 2009-2025 according to LandGEM

Year	**Methane Flow Rate for 50% Organic Content (m^3/year)**	**Methane Flow Rate for 56% Organic Content (m^3/year)**
2009	0	0
2010	8.915E+05	1.036E+06
2011	4.368E+06	5.034E+06
2012	5.491E+06	6.172E+06
2013	5.850E+06	6.509E+06
2014	5.794E+06	6.413E+06
2015	5.921E+06	6.558E+06
2016	6.699E+06	7.456E+06
2017	7.054E+06	7.831E+06
2018	7.207E+06	7.986E+06
2019	6.419E+06	7.059E+06
2020	1.349E+06	1.202E+06
2021	2.834E+05	2.048E+05
2022	5.956E+04	3.489E+04
2023	1.252E+04	5.942E+03
2024	2.630E+03	1.012E+03
2025	5.527E+02	1.724E+02

Table 44. Methane gas generation results of scenario-4 for 2009-2025 according to LandGEM

Year	Methane Flow Rate for 50% Organic Content (m^3/year)	Methane Flow Rate for 56% Organic Content (m^3/year)
2009	0	0
2010	8.497E+05	9.967E+05
2011	4.163E+06	4.843E+06
2012	5.234E+06	5.938E+06
2013	5.575E+06	6.262E+06
2014	5.522E+06	6.169E+06
2015	5.590E+06	6.247E+06
2016	6.374E+06	7.163E+06
2017	6.720E+06	7.532E+06
2018	6.868E+06	7.683E+06
2019	6.117E+06	6.791E+06
2020	5.959E+06	6.639E+06
2021	5.926E+06	6.614E+06
2022	1.245E+06	1.127E+06
2023	2.617E+05	1.919E+05
2024	5.499E+04	3.268E+04
2025	1.156E+04	5.567E+03

The calculation of yearly electrical energy production was performed as in the example provided below:

$$Electrical\ energy\ (kWh) = \left(8.962 * 10^5\ \frac{m^3}{year}\right) * \left(17.69832\ \frac{MJ}{m^3}\right) * (100\%) * (43\%) * (\frac{1\ kWh}{3.6\ MJ})$$

$$Electrical\ energy\ (kWh) = 1.895 *\ 10^6$$

The MW capacity was calculated in terms of electrical energy by considering 1 MJ/s is equal to the 1 MW.

$$MW\ Capacity = \left(8.962 * 10^5\ \frac{m^3}{year}\right) * \left(17.69832\ \frac{MJ}{m^3}\right) * (100\%) * (43\%) * (\frac{1\ year}{365\ days * 24\ hour * 60\ minute * 60\ second})$$

$$MW\ Capacity = (0.216\ MW)$$

The calculated electrical energies in terms of kWh and MW are as shown in for different scenarios. Table 45, Table 46, Table 47, Table 48 and Table 49 for different scenarios.

Table 45.Electrical energy calculation results for base case

Year	**kWh**	**MW**
2009	0	0
2010	1.895E+06	0.216
2011	9.281E+06	1.059
2012	1.167E+07	1.332
2013	1.243E+07	1.419
2014	1.231E+07	1.405
2015	1.246E+07	1.422
2016	1.421E+07	1.622
2017	1.498E+07	1.710
2018	1.531E+07	1.748
2019	1.364E+07	1.557
2020	2.866E+06	0.327
2021	6.023E+05	0.069
2022	1.266E+05	0.014
2023	2.660E+04	0.003
2024	5.589E+03	0.006E-01
2025	1.174E+03	0.001E-01

Table 46.Electrical energy calculation results for scenario-1

Year	**kWh**	**MW**
2009	0	0
2010	2.197E+06	0.251
2011	1.068E+07	1.219
2012	1.309E+07	1.494
2013	1.380E+07	1.576
2014	1.360E+07	1.552
2015	1.377E+07	1.572
2016	1.579E+07	1.803
2017	1.660E+07	1.895
2018	1.694E+07	1.933
2019	1.497E+07	1.709
2020	2.550E+06	0.291
2021	4.344E+05	0.049
2022	7.399E+04	0.008
2023	1.260E+04	0.001
2024	2.147E+03	0.002E-01
2025	3.656E+02	0.004E-02

Table 47.Electrical energy calculation results for scenario-2

Year	**For 50% Organic Content**		**For 56% Organic Content**	
	kWh	**MW**	**kWh**	**MW**
2009	0	0	0	0
2010	1.469E+06	0.167	1.746E+06	0.199
2011	7.196E+06	0.821	8.483E+06	0.968
2012	9.047E+06	1.033	1.040E+07	1.187
2013	9.638E+06	1.100	1.097E+07	1.252
2014	9.545E+06	1.089	1.081E+07	1.233
2015	9.663E+06	1.103	1.094E+07	1.249
2016	1.102E+07	1.258	1.254E+07	1.432
2017	1.162E+07	1.326	1.319E+07	1.505
2018	1.187E+07	1.355	1.346E+07	1.536
2019	1.057E+07	1.207	1.189E+07	1.358
2020	1.030E+07	1.176	1.163E+07	1.327
2021	1.024E+07	1.169	1.158E+07	1.322
2022	1.023E+07	1.168	1.158E+07	1.321
2023	1.023E+07	1.168	1.157E+07	1.321
2024	1.023E+07	1.168	1.157E+07	1.321
2025	1.023E+07	1.168	1.157E+07	1.321

Table 48.Electrical energy calculation results for scenario-3

Year	**For 50% Organic Content**		**For 56% Organic Content**	
	kWh	**MW**	**kWh**	**MW**
2009	0	0	0	0
2010	1.885E+06	0.215	2.190E+06	0.250
2011	9.233E+06	1.054	1.064E+07	1.215
2012	1.161E+07	1.325	1.305E+07	1.489
2013	1.237E+07	1.411	1.376E+07	1.570
2014	1.225E+07	1.398	1.356E+07	1.547
2015	1.252E+07	1.429	1.386E+07	1.582
2016	1.416E+07	1.616	1.576E+07	1.799
2017	1.491E+07	1.702	1.655E+07	1.889
2018	1.524E+07	1.739	1.688E+07	1.927
2019	1.357E+07	1.549	1.492E+07	1.704
2020	2.851E+06	0.325	2.542E+06	0.290
2021	5.992E+05	0.068	4.330E+05	0.049
2022	1.259E+05	0.014	7.375E+04	0.008
2023	2.646E+04	0.003	1.256E+04	0.001
2024	5.560E+03	0.006E-01	2.140E+03	0.002E-01
2025	1.168E+03	0.001E-01	3.645E+02	0.004E-02

Table 49. Electrical energy calculation results for scenario-4

Year	**For 50% Organic Content**		**For 56% Organic Content**	
	kWh	**MW**	**kWh**	**MW**
2009	0	0	0	0
2010	1.796E+06	0.205	2.107E+06	0.240
2011	8.800E+06	1.004	1.024E+07	1.169
2012	1.106E+07	1.263	1.255E+07	1.433
2013	1.179E+07	1.345	1.324E+07	1.511
2014	1.167E+07	1.332	1.304E+07	1.489
2015	1.182E+07	1.349	1.321E+07	1.507
2016	1.347E+07	1.538	1.514E+07	1.728
2017	1.421E+07	1.622	1.592E+07	1.817
2018	1.452E+07	1.657	1.624E+07	1.854
2019	1.293E+07	1.476	1.436E+07	1.639
2020	1.260E+07	1.438	1.404E+07	1.602
2021	1.253E+07	1.430	1.398E+07	1.596
2022	2.633E+06	0.300	2.381E+06	0.272
2023	5.532E+05	0.063	4.056E+05	0.046
2024	1.162E+05	0.013	6.909E+04	0.008
2025	2.443E+04	0.003	1.177E+04	0.001

Comparison for electricity generation, necessary MW capacity values were done based on the average values over the years between 2009 and 2025 in calculation of GHGs emission reductions. The values are as given in the Table 50.

Table 50.Average electrical energy in MW for 2009-2025

	Average MW for 2009-2025
Base Case (50% Organic Content)	0.818
Scenario-1 (56% Organic Content)	0.903
Scenario-2 (For 50% Organic Content)	1.028
Scenario-2 (For 56% Organic Content)	1.168
Scenario-3 (For 50% Organic Content)	0.815
Scenario-3 (For 56% Organic Content)	0.901
Scenario-4 (For 50% Organic Content)	0.943
Scenario-4 (For 56% Organic Content)	1.053

According to these average MW electrical energy amounts, obtained GHG reductions are shown in Table 51, Table 52, Table 53, Table 54, Table 55, Table 56, Table 57 and Table 58 for different scenarios.

Table 51.Reduction in GHG emissions and benefits of it for base case (50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0370	0.0031	0.0401
Tons CH$_4$/year	1,630	-	1,630
Tons CO$_2$/year	-	3,411	3,411
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	197	16	213
CO$_2$ emissions from gallons of gasoline consumed	4,158,569	348,187	4,506,756
ENERGY BENEFITS			
Powering homes	490		

Table 52.Reduction in GHG emissions and benefits of it for scenario-1 (56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0408	0.0034	0.0442
Tons CH$_4$/year	1,799	-	1,799
Tons CO$_2$/year	-	3,765	3,765
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	217	18	235
CO$_2$ emissions from gallons of gasoline consumed	4,590,695	384,368	4,975,062
ENERGY BENEFITS			
Powering homes	541		

Table 53.Reduction in GHG emissions and benefits of it for scenario-2 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0464	0.0039	0.0503
Tons CH$_4$/year	2,048	-	2,048
Tons CO$_2$/year	-	4,287	4,287
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	247	21	268
CO$_2$ emissions from gallons of gasoline consumed	5,226,173	437,575	5,663,747
ENERGY BENEFITS			
Powering homes	615		

Table 54.Reduction in GHG emissions and benefits of it for scenario-2 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0528	0.0044	0.0572
Tons CH$_4$/year	2,327	-	2,327
Tons CO$_2$/year	-	4,870	4,870
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	281	24	305
CO$_2$ emissions from gallons of gasoline consumed	5,937,908	497,166	6,435,075
ENERGY BENEFITS			
Powering homes	699		

Table 55.Reduction in GHG emissions and benefits of it for scenario-3 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0368	0.0035	0.0452
Tons CH$_4$/year	1,624	-	1,839
Tons CO$_2$/year	-	3,849	3,849
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	196	16	213
CO$_2$ emissions from gallons of gasoline consumed	4,143,318	346,910	4,490,228
ENERGY BENEFITS			
Powering homes	488		

Table 56.Reduction in GHG emissions and benefits of it for scenario-3 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
MMTCO$_2$E/year	0.0407	0.0034	0.0441
Tons CH$_4$/year	1,795	-	1,795
Tons CO$_2$/year	-	3,757	3,757
BENEFITS			
CO$_2$ emissions from railcars' worth of coal burned	217	18	235
CO$_2$ emissions from gallons of gasoline consumed	4,580,527	383,516	4,964,043
ENERGY BENEFITS			
Powering homes	539		

Table 57. Reduction in GHG emissions and benefits of it for scenario-4 (for 50% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0426	0.0036	0.0462
Tons CH_4/year	1,879	-	1,879
Tons CO_2/year	-	3,932	3,932
BENEFITS			
CO_2 emissions from railcars' worth of coal burned	227	19	246
CO_2 emissions from gallons of gasoline consumed	4,794,048	401,394	5,195,441
ENERGY BENEFITS			
Powering homes	564		

Table 58. Reduction in GHG emissions and benefits of it for scenario-4 (for 56% organic)

	Direct Equivalent Emissions Reduced	**Avoided Equivalent Emissions Reduced**	**Total Equivalent Emissions Reduced**
$MMTCO_2E$/year	0.0476	0.0040	0.0516
Tons CH_4/year	2,098	-	2,098
Tons CO_2/year	-	4,391	4,391
BENEFITS			
CO_2 emissions from railcars' worth of coal burned	253	21	275
CO_2 emissions from gallons of gasoline consumed	5,353,268	448,216	5,801,484
ENERGY BENEFITS			
Powering homes	630		

The results suggest that LFG utilization contributes to GHGs emission reduction. Average annual electricity usage is taken as 11,320 kWh per household. For CO_2 emissions from railcar of coal burned, it is assumed that 187.78 metric tons of carbon dioxide is emitted per railcar of coal burned. For CO_2 emissions from gallons of gasoline consumed, it is assumed that 0.00889 metric tons of carbon dioxide is emitted per gallon of gasoline consumed. As mentioned previous section, gasoline consumption per household has similar values for Turkey.

The highest emission reduction is provided in scenario-2. With the application of scenario-2, 0.0503 and 0.0572 million metric ton CO_2 equivalent emission reductions can be obtained in a year for scenario-2 with 50% organic content and scenario-2 with 56% organic content, respectively. Similar to previous section results, there is an 25% and 29% increase in the emission reduction for scenario-2 in both cases (50% and 56% organic content).

According to the statements of Afyonkarahisar Environment Service Union, average electric consumption is 1,010 kWh per household in Afyonkarahisar. When the emission reduction calculator’s home powering value is compared to the Afyonkarahisar value, electric consumption per household in the calculator becomes 11 times higher than Afyonkarahisar value. Therefore, energy benefit results in terms of powering homes should be considered for this situation. Based on this approach, the number of powering homes for Afyonkarahisar is shown in Table 59.

Table 59.Number of homes powered by converting methane gas to the energy

	Number of Powered Homes (yearly)
Base Case (50% Organic Content)	5,390
Scenario-1 (56% Organic Content)	5,951
Scenario-2 (For 50% Organic Content)	6,765
Scenario-2 (For 56% Organic Content)	7,689
Scenario-3 (For 50% Organic Content)	5,368
Scenario-3 (For 56% Organic Content)	5,929
Scenario-4 (For 50% Organic Content)	6,204
Scenario-4 (For 56% Organic Content)	6,930

In the report published by Directorate General of Turkish Electricity Transmission Corporation for 2017-2026, electric consumption estimations are stated for each electricity distribution corporations. From these corporations, Osmangazi Electricity Distribution Corporation includes Eskişehir, Afyonkarahisar, Kütahya, Uşak and Bilecik. For these 5 cities, it is estimated that there will be 4% increase in gross electricity consumption in 2026 (Türkiye Elektrik İletim A.Ş. Genel Müdürlüğü, 2017). Based on this information, electricity demand is continuously increasing in Afyonkarahisar. It is proposed that a portıon of this energy demand can be met by converting methane gas to energy.

When both electrical energy generation and direct use project results are considered, it can be seen that there are important total GHGs emission reductions. Compared to base case, increase in the reduction can reach to 29% in scenario-2. The given results are in million metric tons in unit. In other words, the changes in the reduction are significant. As mentioned in the literature part, methane is 25 times more potent than carbon dioxide in creating greenhouse effect. The third largest anthropogenic source of methane emissions is landfills containing municipal solid wastes in U.S. (EPA, n.d.). Within waste sectors, approximately 70% of the GHG emission is due to solid waste disposal sites in Turkey. Majority of GHG emission is based on waste sector. In addition, GHG emissions increased 10% from 1990 to 2015 due to solid waste disposal in Turkey (United Nations Framework Convention on Climate Change, 2016). Based on the results of both direct use and electrical generation projects, the highest emission reduction value can be obtained with scenario-2 (56% organic content) as 0.0756 million metric ton CO_2 equivalent per year. This value is equal to 75,600 $MTCO_2e$/year or 75,600 $MgCO_2e$/year. By considering the figures for total methane emission and methane emission due to solid waste disposal for Turkey, the methane emission due to solid waste disposal was approximately 12,500,000 $MgCO_2e$/year in 2015 (EEA, 2017). 75,600 $MgCO_2e$/year reduction is 0.6% of the methane emission in 2015 for Turkey. By applying the scenario-2 to only Afyonkarahisar Sanitary Landfill Site, the overall reduction in Turkey could be improved to 0.6%.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In this study, LandGEM and IPCC 2006 models were used for determining landfill gas generation for different waste composition scenarios in Afyonkarahisar Sanitary Landfill Site. During field study, problems were observed in operation of the site. One of them is that water was observed in gas collection pipes. The landfill site area was quite wet. As a result, although the site was not designed accordingly, it was operated as a bioreactor landfill site. In summer periods, recycling of leachate was applied for that purpose. If the design had been conducted to enhance methane generation, the site could have been operated more efficiently. Ash is received in the landfill in winter months. Ash due to wood burning for heating purposes are originating especially in the villages and brought to the site as mixing in the total waste amount. Ash can decrease gas generation efficiency. In scenario-4, effect of separating ash from the site was investigated in terms of gas generation.

According to the results of the gas generation amounts by using models, it is seen that lower methane gas amounts are obtained or collected compared to potential due to the operating conditions. The L_0 value of the site used in LandGEM was found within the range given in literature studies. The k value is generally lower in the literature studies which have k value range in between 0.035 and 0.35 1/year. In the LandGEM model guide, the range is in between 0.05 and 0.7 1/year. However, as mentioned before, the k value was found as 1.56 1/year for base case and 1.77 1/year for scenario-1. According to literature on wet landfill sites, methane generation rate is closer to the 1.72 1/year. Because the site is wet and operated like a bioreactor, the calculated k value is appropriate for this site.

In this study, there 3 scenarios were developed. The scenarios are related to changes in waste composition and amounts in terms of organic matter contents; 56% organic content, storage of only the organic portion of waste, and separation of recyclables from waste. The gas generation amounts for different scenarios were compared to the base case, which represents the calibrated LandGEM model to the base case. The highest methane gas generation was obtained in the scenario-2. The gas generation was found as 40% higher than the base case according to methane gas generation per unit waste amount. There was an increase in methane gas generation as 53% when the total gas generation was taken into consideration. With scenario-2, the service life of the site also increased such that it was doubled compared to current service life of the lots. In scenario-4, 24% increase in methane gas generation amount per kg waste was obtained for the site. With the application of this scenario, 2-year additional service life can be also obtained. However, in the scenario-3, the gas generation improvement was low compared to the base case. Therefore, it can be said that recyclable waste separation from total waste does not affect gas generation for the Afyonkarahisar site. Scenario-3 application does not seem feasible to improve gas generation.

GHG emission from landfill sites is an important environmental problem. With the using of methane gas for energy generation, GHG emission reduction can be obtained. For this purpose, in the study, GHG emission reduction was specified based on gas generation amounts by modeling. With the application of scenario-2, highest GHG emission reduction can be obtained for Afyonkarahisar. Overall contribution is predicted to be 0.6% on the GHG emissions reduction for Turkey. Also, higher energy generation can be obtained with the application of scenario-2.

In the world, reduction of organic waste storage in landfill sites is applied. Also, according to the National Waste Management and Action Plan of Turkey, reuse of organic wastes is stated. For Afyonkarahisar Sanitary Landfill Site, since there is already electrical energy generation from the site, scenarios have been investigated in this study in order to support electricity production and site management. The contributions that can be applied at the landfill site are determined in the study. For future studies, application of organic waste reduction strategies can be investigated to the site.

As mentioned before, wood ash is one of the problems in the site. Storage of ash in the landfill site affects the area and gas generation. Wood ash quality can change according to the raw material burnt. Mainly, sodium, phosphorus, magnesium, aluminum, potassium and calcium are present in wood ash. It is stated that wood ash can be used as a limiting agent. The ash has high calcium content. Therefore, its usage in land increases the pH of soil. In addition, as plants extensively use phosphorus and potassium from the soil, these mineral amounts are important in the soil. It is stated that approximately 5% increase can be achieved in the phosphorus amount in the soil by using wood ash (Griffin, 2004). The similar information and application to the soil examples are also given in the study about wood ash usage environmental impacts (Pitman, 2006). Therefore, use of wood ash in land can be preferred over disposing it in the landfill in order to aid in increasing gas generation as well achieving a beneficial use of ash.

Three main suggestions were specified for Afyonkarahisar Sanitary Landfill Site. Characterization of wastes should be done for years. In the site, planning should be better. The gas generation results of the study can be taken into consideration for electrical energy generation in the site. Also, ash problem can be solved by applying suggestions.

In this study, DOC values were selected from the range in the IPCC guideline since there is no specific DOC values for wastes in the Afyonkarahisar. Therefore, three L_0 and k values were used as model input for LandGEM. These input values were specified by using equations stated in model guidelines. These values can be also determined by different approaches. According to the calibration results, highest L_0 and k values were selected to the site by using 4-year measured data. For future studies, if there is more historical data for landfill gas generation, better model results can be obtained. As mentioned before, methane generation rate (k) changes according to moisture content, pH of wastes, temperature of wastes and whether there are active microorganisms or not. In this study, k values were taken as same as highest values of the base case and scenario-1 for scenario-2 and scenario-3 since there was lack of data for specifically calculating k values to the scenarios. For future studies, k value should be specified according to the change in factors that affect it. If there are monthly data of landfill sites, monthly change in k value and gas generation can be determined. In addition, gas generation of landfill sites should be analyzed while obtaining gas generation from landfill sites is planning in Turkey. Besides, greenhouse gas emission reduction should be also considered during waste to energy projects.

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APPENDIX

Total $DDOC_m$ =   Gg organic carbon/Gg waste

$$L_0 = DDOC_m * F * 16/12$$

F was specified as 55.5% according to yearly methane gas values in Afyonkarahisar Sanitary Landfill Site.

For high DOC

$$L_0 = \left(0.0397\ Gg\frac{C}{Gg}waste\right) * (0.555) * (16/12)$$

$$L_0 = 0.0294\ \ \frac{Gg\ methane}{Gg\ waste}$$

Methane gas density was taken as 0,667 kg/m^3.

$$L_0 = \frac{0.0294\ \frac{Gg\ methane}{Gg\ waste}}{0.667\ kg/m^3} * \frac{10^6\ kg}{1\ Gg\ methane} * \frac{1\ Gg\ waste}{1000\ Mg}$$

$$L_0 = 44.12\frac{m^3}{Mg}$$

For medium DOC

$$L_0 = \left(0.0285\ Gg\frac{C}{Gg}waste\right) * (0.555) * (16/12)$$

$$L_0 = 0.0210\ \ \frac{Gg\ methane}{Gg\ waste}$$

Methane gas density was taken as 0,667 kg/m^3.

$$L_0 = \frac{0.0210\ \frac{Gg\ methane}{Gg\ waste}}{0.667\ kg/m^3} * \frac{10^6\ kg}{1\ Gg\ methane} * \frac{1\ Gg\ waste}{1000\ Mg}$$

$$L_0 = 31.60\ \frac{m^3}{Mg}$$

For low DOC

$$L_0 = \left(0.0172\ Gg\frac{C}{Gg}waste\right) * (0.555) * (16/12)$$

$$L_0 = 0.0127\ \ \frac{Gg\ methane}{Gg\ waste}$$

Methane gas density was taken as 0,667 kg/m^3.

$$L_0 = \frac{0.0127\ \frac{Gg\ methane}{Gg\ waste}}{0.667\ kg/m^3} * \frac{10^6\ kg}{1\ Gg\ methane} * \frac{1\ Gg\ waste}{1000\ Mg}$$

$$L_0 = 19.09\ \frac{m^3}{Mg}$$