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TECHNICAL PAPER

Electricity generation from landfill gas in Turkey

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ABSTRACT
Landfill gas (LFG)-to-energy plants in Turkey were investigated, and the LFG-to-energy plant of a metropolitan municipal landfill was monitored for 3 years. Installed capacities and actual gas engine working hours were determined. An equation was developed to estimate the power capacity for LFG-to-energy plants for a given amount of landfilled waste. Monitoring the actual gas generation rates enabled determination of LFG generation factors for Turkish municipal waste. A significant relationship ($R = 0.524$, $p < 0.01$, two-tailed) was found between the amounts of landfilled waste and the ambient temperature, which can be attributed to food consumption and kitchen waste generation behaviors influenced by the ambient temperature. However, no significant correlation was found between the ambient temperature and the generated LFG. A temperature buffering capacity was inferred to exist within the landfill, which enables the anaerobic reactions to continue functioning even during cold seasons. The average LFG and energy generation rates were 45 m^3 LFG/ton waste landfilled and 0.08 MWhr/ton waste landfilled, respectively. The mean specific LFG consumption for electricity generation was 529 ± 28 m^3/MWhr.

Implications: The paper will be useful for local authorities who need to manage municipal waste by using landfills. The paper will also be useful for investors who want to evaluate the energy production potential of municipal wastes and the factors affecting the energy generation process mostly for economical purposes. Landfills can be regarded as energy sources and their potentials need to be investigated. The paper will also be useful for policymakers dealing with energy issues. The paper contains information on real practical data such as engine working hours, equation to estimate the necessary power for a given amount of landfilled waste, and son on.

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Introduction

The increased rate of production of all types of wastes, including municipal solid waste (MSW), industrial waste, and packaging waste, is the natural result of population growth and urbanization. MSW refers to waste generated in households, markets, streets, commercial areas, and industries (nonhazardous) (Zuber and Ali 2015).

Possible negative impacts of landfills on air, water, and land cause these facilities to be considered the last step in the waste management hierarchy. Biodegradable organic matter in landfilled MSW undergoes anaerobic degradation resulting in the production of landfill gas (LFG), for which the main components are typically represented by methane (CH_4: 55–60% v/v) and carbon dioxide (CO_2: 40–45% v/v) (Huber-Humer, Gebert, and Hilger 2008; Trapani, Bella, and Viviani 2013). The release of the LFG to the atmosphere without treatment contributes to global warming. This condition makes MSW landfilling one of the most important anthropogenic sources of greenhouse gas emissions (Aronica et al. 2009; Ishigaki et al. 2005; Trapani, Bella, and Viviani 2013).

LFG control systems are used to prevent the undesired dispersion of the gas into the atmosphere. The recovered LFG can be used to produce energy or flared under controlled conditions to abolish the discharge of hazardous components into the atmosphere (Tchobanoglous and Kreith 2002). Energy recovery from LFG decreases the greenhouse gas emissions resulting from landfilling (Calabro 2009). Johari et al. (2012) reported the environmental and economic benefits of energy recovery from LFG. Therefore, sanitary landfills may represent a renewable energy source with a sustainable development approach (Tsai 2007). Advancements in technology to recover energy from LFG have also contributed to reductions in greenhouse gasses compared to previous experiences (Weitz et al. 2002).

Nevertheless, MSW management scenarios should be carefully evaluated when landfilling is considered as an option, since LFG-to-energy plants may produce higher amounts of greenhouse gas emissions compared to the amounts produced by waste-to-energy plants (Kaplan, Decarolis, and Thorneloe 2009). The researchers

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attribute this to the fact that more electricity is produced from the same mass of waste with waste-to-energy configurations (Kaplan, Decarolis, and Thorneloe 2009). Therefore, the European Union (EU) adopted a progressive transition strategy from landfill-based MSW management to integrated waste management techniques, such as recycling, mechanical biological treatment (MBT), incineration with energy recovery, and landfilling, which have already led to reductions in greenhouse gas emissions as reported by Calabro, Gorib, and Lubello (2015). Gas collection efficiency was also noted as an important factor to be improved when landfilling is practiced because this would directly influence the magnitude of the impacts brought by the LFG (Calabro et al. 2011; Niskanen et al. 2013). Very limited landfill disposal with high levels of gas collection efficiency for residual waste management has been suggested to be the best option for landfilling (Calabro 2009; Calabro, Gorib, and Lubello 2015).

Despite its adverse environmental implications, landfilling is still the most common disposal method for MSW in developing countries such as Turkey. Landfilling is one of the most inexpensive MSW disposal techniques (Kumar and Sharma 2014), which may be a reason for it being the most preferred method. Revenues derived from the energy generated by the use of the LFG have led energy recovery to be a well-researched topic, not only by researchers but also by energy companies and landfill operators. Government incentives such as the feed-in tariff and renewable obligation certificates encourage increases in LFG-to-energy conversion practices (Emkes, Coulon, and Wagland 2015). Although the costs and revenues associated with the energy recovery vary among sites (Emkes, Coulon, and Wagland 2015), improvement of LFG generation and collection rates is always on the agenda of landfill operators.

Estimation of LFG recovery potential is a deciding factor for designing LFG-to-energy projects. The amount of waste landfilled, the waste characteristics, the technologies used for handling and disposing of the waste, and the type of the landfill surface covering system will affect the final amount of gasses emitted from a landfill (Cossu and Muntoni 1997; Fecil, Heroux, and Guy 2003; Friedrich and Trois 2011). Other parameters include meteorological conditions and seasonal temperature variations (Barbaro et al. 2009; Czepiel et al. 2003). The factors influencing the amount of gasses are reported to vary between developing and developed countries (Friedrich and Trois 2010). Troschinetz and Mihelcic (2009) reported that developing countries have a higher variance in the material characteristics of all waste categories, but in particular for the organic part (due to seasonal factors, affluence, domestic fuel supply, and geography).

In many countries, LFG emissions are estimated using models, which are mostly based on the first-order decay of organic matter in the MSW (Aghdam et al. 2018). Limited information about landfills and practices, waste composition, amounts of landfilled waste, or changes in management practices may cause considerable uncertainty in the outputs of these models (Scharff and Jacobs 2006). Therefore, it is always necessary to have field measurements representing the waste characteristics, landfill operating principles, MSW management strategy of a specific community, and the climatic influence of the geographical region.

This study is an attempt to evaluate the potential of utilizing LFG in energy plants in Turkey. The influences of the factors affecting LFG generation and therefore energy generation were also investigated. Monitoring data from the practices of LFG collection and energy conversion are very limited in the existing literature of the field. This study aims to contribute to the existing literature by evaluating the real monitoring data from a metropolitan city, Bursa, in Turkey.

Materials and methods

This study was undertaken in two steps: (a) evaluation of Turkey's LFG-to-energy plants and energy potential, and (b) investigation of the factors influencing LFG production and energy generation in a sanitary landfill.

Data on Turkey's LFG-to-energy plants were obtained from the official reports published by the Energy Market Regulatory Board (EPDK) of the Turkish Republic. Official data were evaluated considering the installed capacities, the realized power generations, and the amount of the waste landfilled. The annual energy generation rates (kWhr), generation in the previous year (kWhr), installed power capacity (MW), and number of units in operation were studied. Data on the amount of the waste landfilled, which were gathered via personal communications with landfill authorities, were associated with the published reports.

The second step of the study consists of the evaluation of the monitoring data of LFG collection and energy utilization project of a municipal landfill for 3 years in a metropolitan city, Bursa, in Turkey, which was registered as a Gold Standard project activity (DNV 2012). The monitoring study was conducted at the Yenikent Landfill of the city of Bursa, where electricity is generated from LFG, and the excess LFG that cannot be used to generate electricity is flared.

The city of Bursa (geographic coordinates: 40.20°N, 29.08°E), located in the Marmara Region of Turkey (Figure 1), is an industrialized city with a population of 2,901,396 according to the census of 2016. Bursa is the fourth largest city in Turkey by population. The city hosts more than 75,000 business/employment establishments that account for 4% of the total business in Turkey (BCCI 2018). The main industrial sectors in the city are textiles (21.9%), construction (18.6%), food and agriculture (13.6%), automotive (7%), and the metal industry (5.4%) (BCCI 2018). In total, 80% of Turkish automotive exports and 60% of its apparel export production are carried out by their respective sectors in Bursa (BCCI 2018). Yenikent Sanitary Landfill (geographic coordinates: 40°15’57.67”N, 28°58’29.04”E), with an area of 83.09 ha, has been serving the solid waste disposal needs of the city since 1995.

The nonhazardous fractions of the waste generated by several industries, those that show MSW characteristics, are also accepted at the Yenikent Landfill along with the household waste. The fraction of nonhazardous industrial waste is approximately 5% by weight of the total waste accepted. Therefore, the Yenikent Landfill is classified as a second-class landfill (for nonhazardous waste) in accordance with the landfill legislation in force in Turkey.

The site serves a population of more than 2.3 million, which is 84% of the city population. The landfill has been projected for a 30-year lifetime. The total area for the entire project including the protection zone is 156.18 ha. The landfill consists of one main valley and four side valleys, namely, valleys X, Y, Z, and T. The construction of the valleys has been undertaken stage by stage. Figure 2 shows the borders of the valleys and the amount of the waste landfilled at each valley.

The Y valley and the last part of the main valley have not been constructed yet. After being compacted, the wastes are covered by an earth layer 0.40–0.60 m thick, three or sometimes fewer times per week. Except for the daily fill area of nearly 80 × 100 m, the waste body is always kept covered with an earth layer. Collection of LFG began in July 2012 from the main valley in the middle of the fifth lift. Monitoring data have been collected since July 2012. The methane and carbon dioxide levels of the LFG were measured on site by infrared spectroscopy (Siemens Ultramat 23). Total emission reductions from the project are estimated to be approximately 201,154 tCO_2 eq/yr (DNV 2012). Figure 2 shows the lifts of the main valley. The final height of the main valley is approximately 50 m. A horizontal gas extraction system that allows for gas collection earlier in the life of the valley, as described by Willumsen and Barlaz (2011), has been established. Perforated pipes were placed in the middle of the gravel-filled trenches opened on waste-filled sections of the valley. The trenches are connected to a main collection pipe, which is connected to a booster that

Figure 1. Location of Bursa city on Europe and Turkey maps.

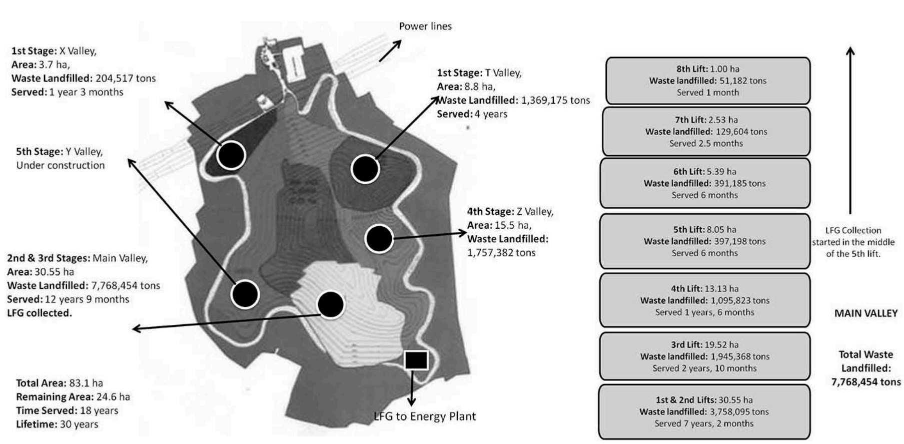

Figure 2. Yenikent Landfill site: valleys, capacities.

Table 1. Key financial parameters for the LFG-to-energy facility (DNV 2012).

Parameter	Unit	Value
Total investment cost	$	17,432,000
Installed capacity	MW	9.8
Annual electricity generation	GWhr/yr	68.6
Annual operational expenses	$	1,764,000
Share of the municipality	%	41

extracts the gas from the landfill and conveys it to the utilization system. The collected gas is used for energy production by 7 sets of GE Jenbacher 1.4-MW gas engines. The generated electricity is delivered to the national grid through the Bursa transformer station at a medium voltage level. Table 1 gives the key financial parameters for the LFG-to-energy facility.

Monitoring data consist of the amount and composition of the solid waste accepted at the landfill; the leachate characteristics such as flow rate and composition; the LFG composition and flow rate; and the electricity generated. The monitoring data were statistically evaluated by the SPSS program (PASW Statistics v. 18.0.0). The relationships among the parameters such as LFG flow rate, amount of the solid waste landfilled, seasonal temperature variations, leachate flow rate, and energy generation rate were explored.

Results and discussion

LFG-to-energy plants in Turkey

Utilization of renewable energy resources for electricity generation is regulated and supported by the Renewable Energy Resources Law (RER Law, No. 6094) in Turkey, which was enacted in 2010. The law includes electricity selling prices, terms, conditions, procedures, and principles concerning the payments to investors generating energy by using renewable energy resources and technologies. The electricity selling prices, which are valid for 10 years, are shown in Table 2.

Accordingly, renewable energy investors can sell the electricity they have generated to the electrical wiring interconnect system with the permission of the Republic of Turkey Energy Market Regulatory Board (EMRB). As a result, all the relevant and actual data about these facilities can be published officially by the EMRB every year. Figure 3 shows the installed capacities and energy generation rates of the LFG-to-energy facilities in Turkey between the years 2011 and 2017.

Table 2. Electricity selling prices based on RER Law.

Type of facility	Prices applicable ($ cent/kWhr)
Hydroelectric	7.3
Wind	7.3
Geothermal	10.5
Biomass (including LFG)	13.3
Solar power	13.3

As shown in Figure 3, the installed capacity of the LFG-to-energy facilities in Turkey showed a linear increase (R^2 = 0.98) between the years 2011 and 2017 after the enactment of the RER Law. According to the RER Law, the facilities are registered and licensed based on the annual electricity generation rates that they could produce with their installed capacity. The RER Law also requires the facilities to apply for the incentives annually; therefore, the facilities make commitments for the following year's energy generation every year. The facilities estimate their annual electricity production rates considering their installed capacities and assuming an average production duration of 8000 hr/yr and make their commitments accordingly. It was found that the facilities realized the electricity generation at an average of 70.5 ± 10.6% of their committed levels. The difference between the committed and realized levels may be attributed to the variations in the LFG generation rates at the landfills and technical malfunctions and disturbances experienced by the gas engines.

An important design parameter for the LFG engine producers is the working hours of the motors. As this value is taken as 8000 hr/yr, the average lifetime for an LFG engine is calculated as 60,000 hr (U.S. EPA 2011). Figure 4 shows the average levels of actual working hours of LFG engines as reported to the EMRB.

The working hours of the LFG engines were committed as 7000 hr/yr by the facilities. Actual data for the 6 years show that the realized hours were below the committed hours. The average of the 6 years of data was calculated as 5697.97 ± 1671.56 hr.

Figure 5 shows the variation in the installed power capacities per 100 tons of MSW landfilled per day of the

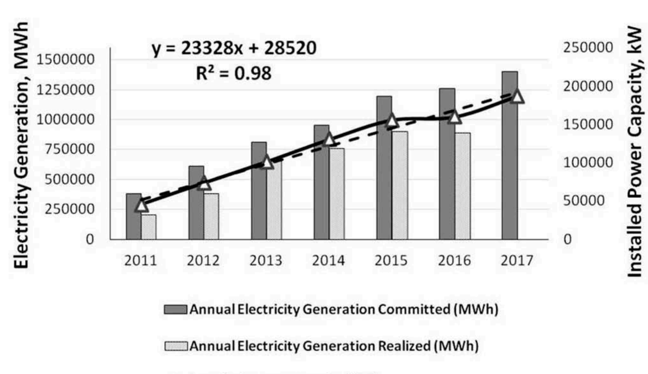

Figure 3. Installed capacities and electricity generation rates by the facilities in Turkey.

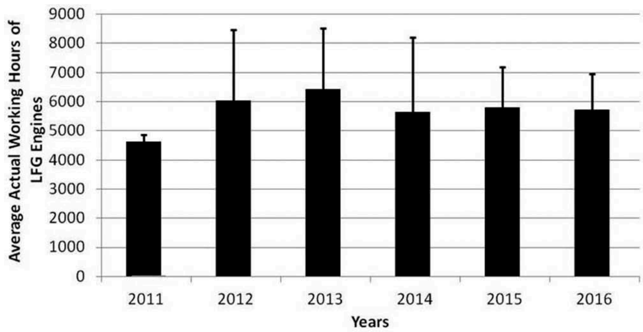

Figure 4. Average actual working hours of LFG engines of the LFG-to-energy plants.

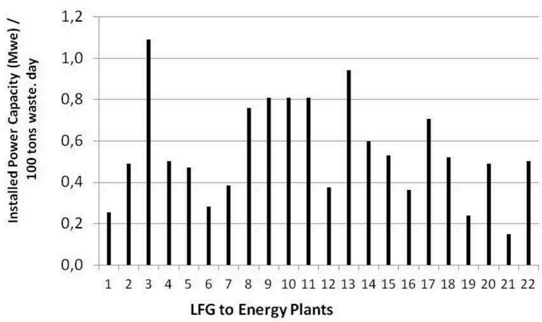

Figure 5. Installed power capacities of LFG-to-energy plants per 100 tons of MSW landfilled.

facilities in Turkey. Accordingly, the average capacity of the plants can be calculated as 0.55 ± 0.24 MWe/100 tons of MSW landfilled per day.

LFG-to-energy plants serving varying capacities of landfills between 200 and 2000 tons of waste in Turkey were analyzed to obtain a correlation relationship between landfill capacity and installed power capacities. The linearity equation that can be used to estimate the approximate power necessary for an LFG-to-energy plant for a given amount of MSW landfilled per day in Turkey was found as follows:

$$y = 0.35x + 1.02 \quad (1)$$

where y and x are power capacity (MWe) necessary for an LFG-to-energy plant and the amount of the MSW landfilled (100 tons/day), respectively. Figure 6 shows the relationship.

Currently, nearly 70% of the population in Turkey is served with landfills. As of 2015, the number of landfills in Turkey was 80, and 32 of these landfills had licenses for electricity generation from LFG (Salihoglu et al. 2018). The capacity of the LFG-to-energy facilities was approximately 187 MW of electricity (Salihoglu et al. 2018).

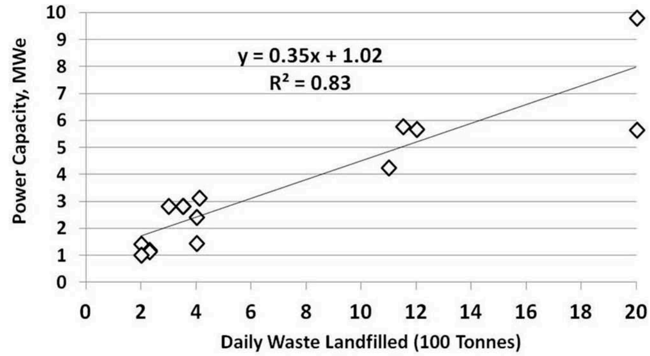

Figure 6. Relationship between the waste landfilled and installed power capacity of the facilities.

Municipal waste generation: Yenikent Landfill case study

The Yenikent Landfill has been serving the city since 1995. The population of the city increased from 1,603,137 to 2,901,396 between the years 1990 and 2017. In this time period, the waste collected and landfilled followed an increasing trend. The average daily MSW landfilled was approximately 2229 ± 658 tons/day. However, the daily amount of the MSW collected depends on the day of the week. For example, the average amount for Sundays was 909 ± 548 tons/day, whereas the average for Mondays was 2904 ± 287 tons/day. Since Sunday is a weekend holiday, waste collection and transportation are not undertaken in several parts of the city. The MSW landfilled consisted mostly of kitchen waste. The kitchen waste portion was 48.84 ± 3.67% in summer and 40.86 ± 12.91% in winter. Kitchen waste was followed by plastic waste, which was 19.12 ± 9.57% and 19.60 ± 3.62% in summer and winter, respectively. During the gas collection time period that this paper is based on, 2,637,344 tons of waste was landfilled. The weekly distribution and components of the waste landfilled in the Yenikent Landfill are shown in Figure 7.

The relationship between the ambient temperature and the MSW landfilled was examined. Table 3 gives the correlation relationships between the amounts of the waste landfilled and the ambient temperature. Accordingly, a significant relationship (R = 0.53, correlation significant at the 0.01 level, two-tailed) was found between the amount of landfilled waste and the ambient temperature. In total, 27% of the increase in the waste amount can be explained by the increase in the ambient temperature (R^2 = 0.27). The relationship is stronger for the household waste amount and ambient temperature (R = 0.61, p < 0.01), and 36% of the increase in the household waste amount can be explained by the increase in the ambient temperature (R^2 = 0.36). This correlation can be explained by the changes in the food consumption

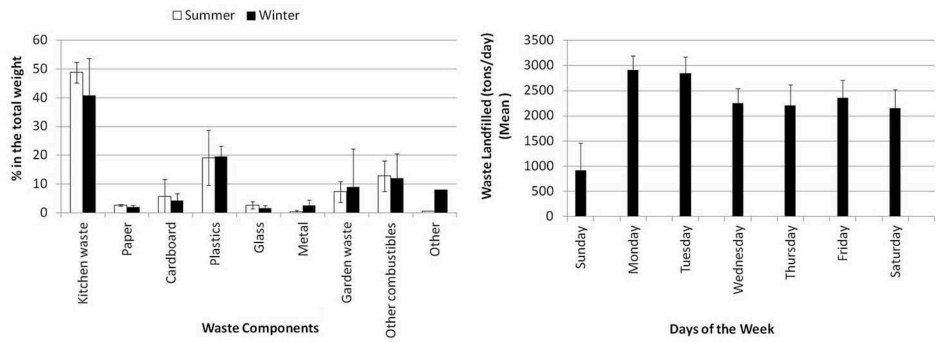

Figure 7. Weekly distribution and components of the waste landfilled.

Table 3. Correlations between waste amounts, ambient temperature, LFG flow rate, and electricity.

		MSW amount	Temperature	LFG flow rate	Electricity
MSW amount	Pearson correlation	1	.608**	.464*	.441*
	Significance (two-tailed)		.001	.015	.021
	N	27	27	27	27
Temperature	Pearson correlation	.608**	1	.292	.044
	Significance (two-tailed)	.001		.140	.828
	N	27	27	27	27
LFG flow rate	Pearson correlation	.464*	.292	1	.864**
	Significance (two -tailed)	.015	.140		.000
	N	27	27	27	27
Electricity	Pearson correlation	.441*	.044	.864**	1
	Significance (two-tailed)	.021	.828	.000	
	N	27	27	27	27

Notes. *Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

patterns of households that are influenced by the weather variables. During the growing season and when the temperatures are warmer, households in Turkey tend to consume more fruits and vegetables and generate more kitchen waste, which results in an increase in the amount of waste. According to the Organization for Economic Cooperation and Development (OECD 2008), yard waste increases when the temperatures are warmer and there is more precipitation, and rain augments the weight of all types of absorptive waste. This may be another reason for the significant correlation between the waste amounts and the ambient temperatures. It is clear that waste composition changes with time, geographical location, economic conditions, and lifestyle (Guermoud et al. 2009). Since nutritional habits are influenced by the seasonal changes, waste generation amounts change accordingly.

Landfill gas collected: gas amounts

The mean LFG flow rate was found to be 4585 ± 486 m^3/hr, ranging between 3110 and 5680 m^3/hr from the landfill receiving 2229 ± 658 tons of waste landfilled/day. A significant correlation ($p < 0.05$, two-tailed) was found between the LFG flow rate and the household waste landfilled, as shown in Table 3. Although the correlation is significant, the correlation coefficient ($R = 0.46$) was not high enough. One reason may be the limited efficiency of the gas extraction system, which is not able to extract most of the LFG generated. Figure 8 shows the relationship between LFG flow rate and the household waste landfilled.

Gas extraction or recovery system efficiency is an important parameter that affects both the environmental impact of the landfill and the economic revenue

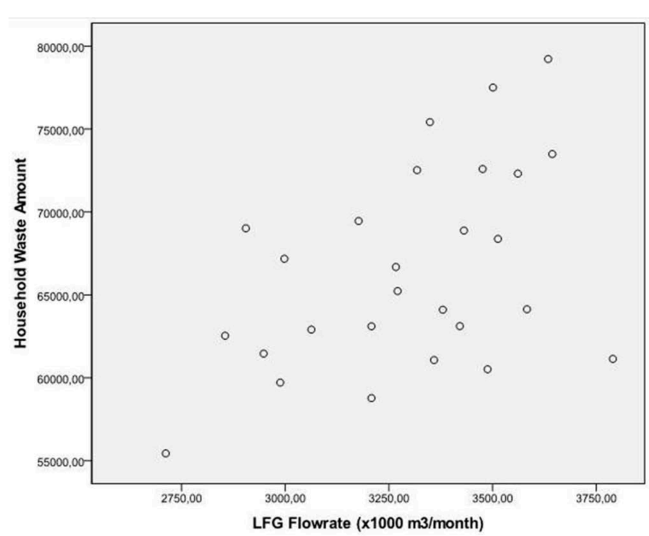

Figure 8. Relationship between the LFG flow rate and the household waste landfilled at the site.

Table 4. Gas generation factors obtained by the existing study and published literature.

m^3 LFG/ton waste landfilled	MWhr/ton waste landfilled	Source of the data	Reference
45	0.08	Field result	This study
40	0.14	Estimation	(Idehai & Akujieze, 2015; Taherzadeh, 2009)
133	0.23	Estimation	(Johari et al. 2012; Tsai 2007)
79.8–88.2		Estimation	(Scarlat et al., 2015)
86–100		Field result by CIWMB	(Themelis and Ulloa 2007)
26.8	0.03	Field result by Berenyi (1999)	(Themelis and Ulloa 2007)

Note. CIWMB: California Integrated Waste Management Board.

obtained from gas recovery (Aghdam et al. 2018; Calabro 2009; Calabro et al. 2011). The amount of the LFG that can be extracted and used is only a fraction of the total LFG generated in the landfill (Bogner and Spokas 1993; Calabro et al. 2011; Themelis and Ulloa 2007). The total methane generated in the landfill is the sum of the methane extracted and recovered, migrated laterally, microbially oxidized when passing through the landfill cover, or internally stored in the landfill (Aghdam et al. 2018; Bogner and Spokas 1993). The gas generation factors of the site (Table 4) show that the recovered fraction is smaller than the generated amount. Table 4 gives a comparison of the LFG generation factors calculated for the site investigated with the published results of several researchers (Idehai and Akujieze, 2015; Taherzadeh, 2009; Johari et al. 2012; Tsai 2007; Scarlat et al., 2015; Themelis and Ulloa 2007; Berenyi, 1999). Table 4 is a compilation of both field results and model estimates of published literature. Large differences were seen in the results given by the models compared to the field values. Several researchers reported that models tend to overpredict the methane emissions (Gollapalli and Kota 2018; Karanjekar et al. 2015), which can be clearly inferred from Table 4. Table 4 compares field values with model estimation values. The results of this study are in line with the field values given in Table 4, rather than the model estimation values. Aguilar-Virgen et al. (2014) reported a possible range of landfill generation to vary between 50 and 400 m^3/ton waste, and Lou and Nair (2009) reported a range of 40–250 m^3/ton waste landfilled (including theoretical and experimental studies). The LFG volume in this study, which is 45 m^3 per ton MSW landfilled, is close to the lower end of these ranges, although very close to the field results reported by Themelis and Ulloa (2007).

The discrepancies between the field results and estimations can be attributed to several factors, including the LFG collection system efficiency, which varies according to the configuration of the system installed and by operation management (Calabro 2009). The presence and type of top cover are also important (Aghdam et al. 2018). The low levels of gas generation obtained in this study can be attributed to several managerial and technical factors: The interim soil cover is not regularly applied, and sometimes application thickness is not appropriate during the landfill operations, which causes easier emission of the LFG to the atmosphere. Sometimes the heights of the lifts are not kept at the projected value, which causes an enlargement of the slopes. A portion of the LFG is emitted to the atmosphere from slopes (Scheutz et al. 2011). The contractors who operate the landfill and the contractor who operates the LFG-to-energy plant are different. Landfill operators do not prioritize the LFG extraction, and installation of the recovery system starts when the landfill operator gives permission. The difference between the priorities of both contractors causes physical confusion on the site. Since the distribution of the LFG extraction pipelines needs to be adjusted to reach and collect most of the LFG generated on the site, coordination is necessary between the landfill operator and energy plant operator. A deficiency in this coordination would result in a less efficient LFG extraction system with scheduling and allocation failures.

The methane gas component in the LFG was 52.22 ± 1.64%, followed by carbon dioxide at 36.28 ± 2.76%. The nonmeasured part of the LFG may be composed of oxygen (O_2), nitrogen (N_2), and other gasses including nonmethane organic compounds, sulfides, hydrogen, and carbon monoxide (Jaramillo and Matthews 2005; Yechiel and Shevah 2016). Methane gas values are in the higher part of the range of the typical constituents reported by Tchobanoglous and Kreith (2002). The typical ranges for methane, carbon dioxide, and oxygen were reported as 45–60%, 40–60%, and 0.1–1.0%, respectively (Tchobanoglous and Kreith 2002). Carbon dioxide levels in the LFG found in this study were slightly lower than the reported values. Figure 9 shows the variations in the levels of the methane and carbon dioxide flow rates.

The correlation between the LFG flow rate and the ambient temperature was investigated, and a weakly significant relationship was found (R = 0.11, correlation significant at the 0.01 level, 2-tailed). The weak relationship suggests that only 1% (R^2 = 0.01) of the LFG flow rate can be explained by the increase in the ambient temperature. The ambient temperature during the LFG

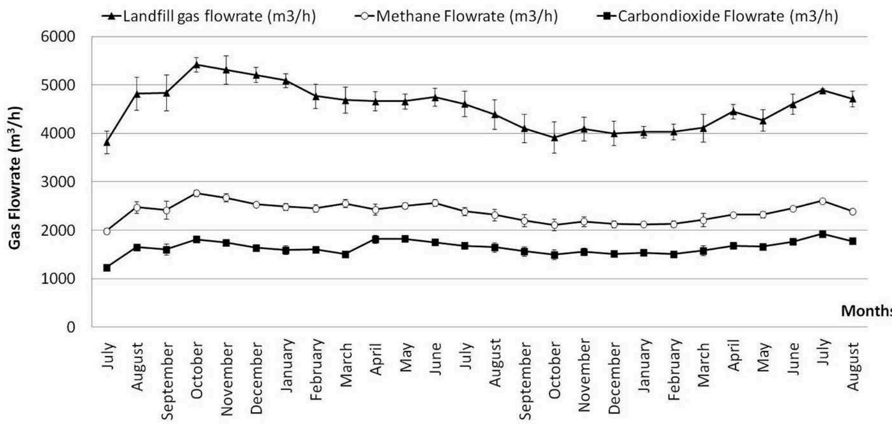

Figure 9. Variations in the levels of the LFG components.

monitoring period ranged between −3.7 and 28.7°C, with a mean level of 16.7 ± 7.5°C. Temperature is an important factor in LFG generation since it has a key role in microbial processes. Christensen, Kjeldsen, and Lindhardt (1996) reported that an increase in temperature from 20 to 30°C doubles the methanogenesis rate, and elevated temperatures convert organic waste more quickly. The temperature mentioned in the study of Christensen, Kjeldsen, and Lindhardt (1996) is the temperature that directly influences biochemical reactions, mostly the temperature within the landfill. Gollapalli and Kota (2018) used the flux chamber technique to collect LFG samples and examined correlations between methane levels and the temperature within the flux chamber. They found that methane fluxes were maximum in summer and minimum in winter (Gollapalli and Kota 2018).

The results of the study presented here show that the ambient temperature had a very poor influence on the LFG generation inside the landfill, which implies that the ambient temperature barely influenced the temperature inside. The main reason could be that the conditions within the landfill are mostly isolated from the ambient conditions and might have buffered cold weather conditions. It is also known that a deep landfill provides better insulation than a shallow landfill (Christensen, Manfredi, and Knox 2011). The depth of the landfill section, which was 50 m, might have provided such insulation. However, the findings of Yang et al. (2015) disagree with the findings of this study. They found that ambient temperature exhibited strong correlations with LFG components (Yang et al. 2015). One of the differences between the landfill presented by Yang et al. (2015) and the one presented here was the high-density polyethylene (HDPE) membrane that was used as intermediate cover, which could have influenced the LFG recovery efficiency.

Energy production

The electricity and the LFG flow rate had a strong significant correlation (R = 0.86, significant at the 0.01 level, 2-tailed) (Table 3), as would be expected. The correlations between electricity and the methane gas and carbon dioxide gas were also statistically significant (R = 0.88, two-tailed, p < 0.01; R = 0.56, two-tailed, p < 0.01, respectively).

Figure 10 shows the seasonal variations of the electricity and the LFG produced. From the figure, it can clearly be seen that although the average levels of seasonal temperature varied between 7°C and 26°C, the LFG flow rates and the electricity levels did not show such a large variation. No significant correlation was found either between the ambient temperature and the LFG produced or between the ambient temperature and the electricity. No significant difference was found when the mean electricity and LFG flow rate levels of hot (spring and summer) and cold (autumn and winter) seasons were compared (t-test, two-tailed, p < 0.05).

The mean electricity level in summer and spring was 17,992.5 ± 381 MW/3 months, while that in autumn and winter was 18,343.0 ± 1776 MW/3 months. The mean landfill gas flow rate level in summer and spring was 10,107,000 ± 462,000 m^3/3 months, while that in autumn and winter was 10,014,000 ± 1,091,000 m^3/3 months. It can be inferred that the gas production rates were not affected by the seasonal differences, as would be expected based on our knowledge of temperature effects on biochemical reactions. It can also be inferred that a temperature buffering capacity exists within the landfill, which enables the anaerobic reactions to continue functioning. The findings of Vaverkova and Adamcova (2015) are in line with the findings of this study. The researchers investigated the variation of ambient temperatures and the temperatures inside a landfill in the Czech Republic and

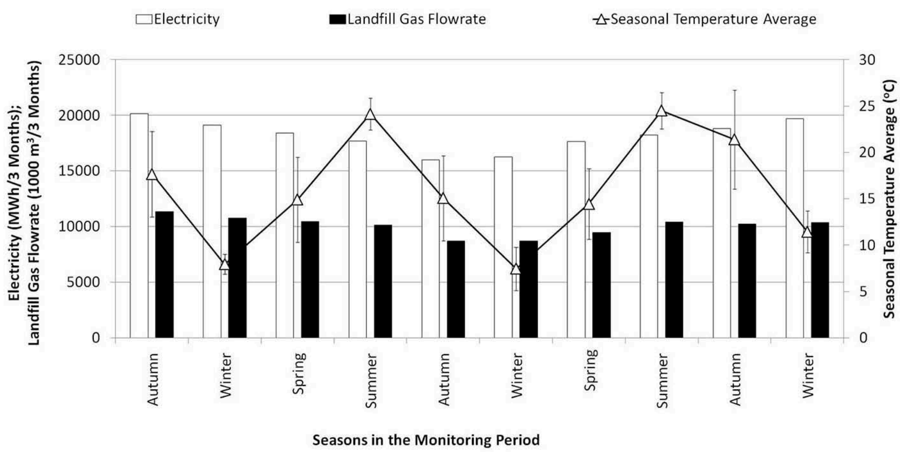

Figure 10. Seasonal variations of the electricity and the LFG produced.

found that the mean temperature at the surface of the landfill was 3.2°C higher than the ambient temperature (Vaverkova and Adamcova 2015).

Willumsen and Barlaz (2011) reported ultimate methane yields ranging between 82 and 340 m^3 CH_4/ton of dry waste. Estimates of the amount of LFG generated throughout the lifetime of the landfill site are reported to be highly variable with estimates between 39 and 500 m^3/ton (McBean, Rovers, and Farquhar 1995; Williams 2005). For the estimation of LFG throughout the lifetime of a site for the assessment of energy recovery from LFG utilization, values between 150 and 250 m^3/ton are typically used (Loening 2003; Williams 2005). Annual rates of gas production have been estimated for a typical MSW landfill at between 6 and 8 m^3/ton/yr, but much higher rates of over 25 m^3/ton/yr have been recorded (Williams 2005). This study showed a gas production rate of 45 m^3 LFG/ton of waste landfilled for the household waste. The electricity generated per ton of waste landfilled was 0.08 MWhr (Table 4). As shown in Table 4, the energy produced per ton of the waste landfilled investigated in this study was close to the field results published. However, the model estimations published are generally higher than the field results. For example, Johari et al. (2012) estimated that 8,196,000 tons MSW landfilled in Peninsular Malaysia can generate 1.9 billion kWhr electricity/yr. This makes 0.23 MWhr/ton landfilled MSW, which is 2.8 times higher than the field result of the study presented here.

Figure 11 shows the annual energy generation from the MSW landfilled between the years 2012 and 2016. The electricity generated per ton of MSW landfilled ranged between 0.06 and 0.09 MWhr during these years; the mean value was 0.08 ± 0.01 MWhr/ton MSW. The mean specific LFG consumption for electricity generation was 529 ± 28 m^3/MWhr, ranging between 491 and 560 m^3/MWhr. These values agree with the findings of Yechiel and Shevah (2016) and USEPA (2012). Yechiel and Shevah (2016) reported the specific LFG consumption for electricity generation to be nearly 550–600 m^3/MWhr for the MSW landfill in the north of Israel, and USEPA (2012) stated that between 500 and 540 m^3/hr of LFG at 50% methane is necessary to generate 1 MWhr of electricity.

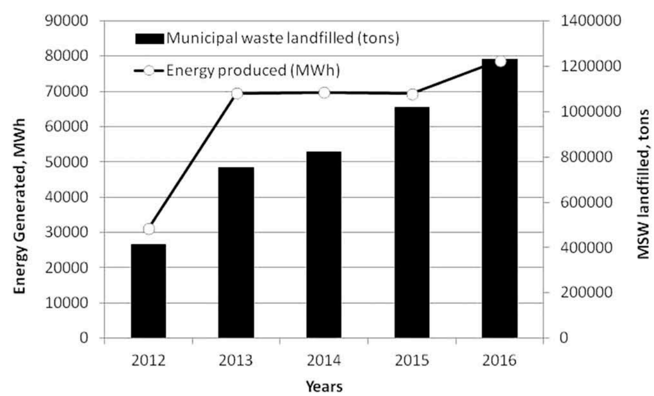

Figure 11. Annual energy generation from the MSW landfilled at the site investigated.

Conclusion

Within the scope of this research, LFG-to-energy plants in Turkey were investigated, and the LFG-to-energy plant of a metropolitan municipal landfill was monitored for 34 months. Based on the findings obtained, the following conclusions can be drawn:

- LFG-to-energy facilities in Turkey committed to generating electricity with an average of 7000 hr of annual gas engine operating hours. However, operational data of 6 years showed that the actual engine working hours were lower than the committed values. Average gas engine working hours amounted to 5697.97 ± 1671.56 hr.

- Installed power capacities of the LFG-to-energy plants that serve landfills with varying capacities between 200 and 2000 tons of MSW yielded an equation to estimate the power capacity, which is $y = 0.35x + 1.03$, where "y" refers to power capacity (MWe) and "x" refers to the MSW landfilled (100 tons) ($R^2 = 0.83$).
- A significant relationship ($R = 0.53$, $p < 0.01$) was found between the amounts of landfilled waste and the ambient temperature. This correlation can be explained by the changes in the food consumption patterns of households influenced by the weather variables, which lead to the changes in waste generation amounts. The waste landfilled was mostly composed of kitchen waste. The kitchen waste was 48.84 ± 3.67% in summer and 40.86 ± 12.91% in winter. Therefore, the seasonal effect on the waste amounts, especially on the amounts of kitchen waste, may be associated with seasonal changes in the consumption behavior of the citizens.
- The mean methane percentage in the LFG was 52.22 ± 1.64%, followed by carbon dioxide at 36.28 ± 2.76%.
- Although the seasonal temperature varied between 7 and 26°C during the monitoring periods, the LFG flow rates and the electricity levels did not show such a large variation. No significant correlation was found between the ambient temperature and the LFG produced. It can be inferred that the gas production rates were not affected by seasonal differences, as would be expected based on our knowledge of the temperature effects on biochemical reactions. It can also be inferred that a temperature buffering capacity exists within the landfill, which enables the anaerobic reactions to continue functioning.
- The gas and energy generation rates were 45 m^3 LFG/ton MSW landfilled and 0.08 MWhr/ton MSW landfilled, respectively. The mean specific LFG consumption for electricity generation was 529 ± 28 m^3/MWhr.
- The differences between the field results of LFG generation of this study and estimation-based generation factors published in the literature implied limited efficiency of the LFG extraction system. Several issues, such as the standard thickness of intermediate covers in landfills and management issues, which become complicated when landfill operation and LFG operation are managed by different people, should be considered to achieve high LFG extraction efficiency.

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