Energy Sources, Part B: Economics, Planning, and Policy

ISSN: 1556-7249 (Print) 1556-7257 (Online) Journal homepage: https://www.tandfonline.com/loi/uesb20

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To cite this article: A. D. Yucekaya (2013) Landfill Gas to the Energy Potential of Turkey: A Scenario-based Multi-period Simulation, Energy Sources, Part B: Economics, Planning, and Policy, 8:3, 227-234, DOI: 10.1080/15567249.2011.584113

To link to this article: https://doi.org/10.1080/15567249.2011.584113

Published online: 19 Feb 2013.

Energy Sources, Part B, 8:227–234, 2013

ISSN: 1556-7249 print/1556-7257 online
DOI: 10.1080/15567249.2011.584113

Landfill Gas to the Energy Potential of Turkey: A Scenario-based Multi-period Simulation

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Turkey is a developing country with increasing power demands and limited energy sources. Municipal solid waste processing, landfilling and utilization of the gas to generate electric power and lower emissions has been used in developed countries for decades, however, it is relatively new in Turkey. The new regulations force municipalities in the country to build landfills to safely store the waste and secure the emission gases. The landfill gas can be utilized to produce energy and heat, or if the quality is high it can be transported to a natural gas pipeline. In this article, an overview of landfill gas-to-energy plants in the world is presented, and the situation in Turkey is analyzed. A multi-period simulation methodology for municipalities is proposed to estimate the potential power generation and amount of methane that can be prevented. The municipalities in Turkey were classified into three categories and a scenario-based simulation is performed to estimate the energy generation and emission reduction that the country can gain if the landfill projects are activated according to the scenarios.

Keywords: emissions, landfill, landfill gas to energy, methane, municipal solid waste, simulation

1. INTRODUCTION

The storage and elimination of municipal solid waste (MSW) has become a problem of science and technology especially after the growth of urban areas and population. One common way to handle MSW is landfilling the waste and utilizing the landfill gas (LFG) in some way such as flaring, power generating, or heating. The idea behind the methods is the same and it is to control the output of waste and limit environmental impacts. Additionally, recycling the energy content of waste to another energy type and generating extra benefit out of it is another objective. The greenhouse gas (GHG) emissions released from the waste increases the pollution level and causes an explosion danger if the methane (CH_4) level increases. The economic, environmental, and safety issues related with MSW handling force governments to develop policies for waste processing. However, there is still a considerable amount of difference between developed countries and under-developed or developing countries in terms of MSW handling and landfilling. For example, almost no country on Africa still has an active landfill project whereas almost all European countries do. Global initiatives about the protection of the environment and the increase in energy demand force all countries to consider building landfill projects. The collected LFG can be flared to generate heat for boilers, space heating, cooling or co-firing. The higher quality of LFG can be utilized

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and transported to a natural gas network to be used as fuel. It is also possible to use LFG in the chemical manufacturing industry and soil remediation. When it is economical, the preferred option of LFG usage is to utilize the collected gas to generate electric power.

Jaramillo and Matthews (2005) present a work on the net private and social benefits of LFG to energy projects in the US. They do a background analysis, technology overview, economic analysis, and present case studies which LFG-to-energy project planners can use directly to evaluate the potential and feasibility of a particular landfill location. Themelis and Ulloa (2007) provide an overview of the CH_4 generation process in landfills and then show a good overview of LFG utilization in US states. It is estimated that 13% of GHG emissions in the world are generated from solid waste and the US has landfills to utilize to lower the emissions. Hao et al. (2008) show the LFG utilization in the world along with available technologies and show total energy and environmental benefits can be gained when the LFG-to-energy option is used. They analyze the landfills in Hong Kong and do an economic feasibility analysis for the case studies particularly to analyze the feasibility of trigeneration technology. Willumsen (2003) analyzes LFG-to-energy plants in the world, showing the number of plants in each country and generating capacity. Qin et al. (2001) discuss the details of fundamental and environmental aspects of the LFG-to-energy process. They analyze the effect of gas mixture on burn efficiency and emission outputs. Bove and Lunghi (2006) analyze the traditional and innovative technologies that are used in LFG-based energy generation. They first show the LFG generation phases and compare the available technologies that can be used for power generation and then present an economic analysis-based comparison for case studies. Thompson et al. (2008) aim to determine targets and strategies to reduce GHG emissions from landfills by modeling the LFG generation process. Balat (2007) provides an overview of biofuels and policies in the EU showing the sources and distribution of each country. Kaygusuz and Turker (2002) present a work for the biomass energy potential of Turkey. The US Environmental Protection Agency (EPA, 2011) provide a database for LFG generation models and technologies. A spreadsheet-based LFG generation estimation tool called LandGEM is provided along with different LFG generation models for China, Colombia, Ecuador, the Ukraine, Mexico, the Phippines, and Thailand. Shin et al. (2005) do a scenario analysis for the utilization of LFG-to-energy in South Korea considering other fuel resources and possible growth scenarios. Ediger and Kentel (1999) present an evaluation study for the renewable energy sources in Turkey.

The research about the utilization of MSW and LFG in Turkey is limited in the literature. An LFG generation model that is developed for Turkey and research for the potential of LFG-to-energy plants and its effect of GHG reduction should be analyzed. The objective of this research is to evaluate the current status of Turkey and analyze the LFG-to-energy potential of the country using population scenarios.

2. LFG TO ENERGY GENERATION TECHNOLOGY

The first step should be to determine if the CH_4 gas generation in a landfill site is sufficient to support a power plant. The possible screening criteria might include minimum MSW amount, depth, annual precipitation, the close date of the landfill, and waste that can be provided to support the landfill. If the landfill passes the first screening process, the next step should be to estimate the gas flow per year that will show the amount of power that can be generated. LandGEM is one of the options that can be used at this step (EPA, 2011).

The municipal solid waste is collected and the landfill area is closed to additional waste placement. LFG generation may begin as soon as waste decomposition begins and the gas can be collected. The typical way to collect the gas is to embed vertical wells in the waste area to collect the gas outputs from the decomposed waste. The wells are connected to a lateral piping system which pumps gas to a central manifold for further processing. Horizontal piping that is used especially for deeper landfills is another option for gas collection. It is also common to use a mix of vertical and horizontal piping for landfills. The content of the produced LFG varies and depends on the waste composition. However, typical LFG contents are summarized in Hao et al. (2008), Bove and Lunghi (2006), and Themelis and Ulloa (2007).

Almost 95% of LFG consists of CH_4 and carbon dioxide (CO_2) which are accepted as harmful for the environment if not prevented. The global warming potential of CH_4 is 23 times higher than that of CO_2, which increases the importance of CH_4 capture. The released CH_4 and CO_2 have the potential of harming vegetation and causing undesired odors. When the CH_4 concentration in the air reaches 5–15%, an explosive mixture is formed that causes an unsafe condition for the public (Hao et al., 2008; EIA, 2011).

In an LFG-to-energy system, the LFG collection system is connected to a power generator that typically uses gas as the energy resource. The common electricity generation technologies can be classified as reciprocating internal combustion engine, gas turbine, steam turbine, stirling cycle engine, and fuel cells. The newly developed combined heat and power systems are also able to produce both heat and electrical power (EPRI, 2002; Bove and Lunghi, 2006; Hao et al., 2008).

The GHG outputs of the landfills are decreased if proper LFG control technologies are used. The 60–90% of the CH_4 that is generated in a landfill will be captured depend on the design and effectiveness of the system. This method directly reduces the GHG emissions as the captured CH_4 is burned to produce electricity or heat. On the other hand, the energy that is gained from the LFG displaces fossil fuels that are needed to generate the same amount of energy. Hence, the GHG outputs from such fuels will be saved indirectly.

3. LFG-TO-ENERGY IN TURKEY AND THE WORLD

The LFG generation depends on the amount of landfilled waste, the mixture of the waste, and the physical structure of the environment where the waste is disposed. In the US, 250 million tons of MSW were produced in 2008 and 54% of the waste was landfilled. Each million tons of waste is able to produce roughly 4,465,000 m^3 LFG each year for up to 30 years after it is landfilled and roughly 284 MWh/y of power can be generated using the LFG with various technologies. There are more than 500 LFG energy projects currently operating in the US of which 354 of them generate electricity and the remaining projects provide heat and pipeline gas. It is estimated that 13,000 GWh/y of electricity is generated and 100 billion cf of LFG is produced for heating and pipelines.

In Europe on the other hand, the LFG projects are widely used for waste disposal. Germany, the UK, and Italy are the countries with the three largest numbers of LFG-to-energy plants, respectively. Table 1 shows the distribution of LFG-to-energy plants in the world (Willumsen, 2003; Hao et al., 2008; EPDK, 2011).

It is shown that the utilization of LFG is increasing as the population density and development level increases. The utilization of LFG in Turkey is new, having started after 2000. The explosions of waste disposal sites in the '90s, the environmental regulations, and the efforts to integrate into the EU have forced Turkey to take new precautions for the handling of waste. The new legislations which came to play in 2005 about the processing of MSW brought regulations for municipalities to build landfills for the disposal of MSW. Furthermore, minimum price and purchase guarantees are provided for the electricity produced from LFG. As a result, new plants were build and municipalities are planning new facilities (EPDK, 2011).

The flaring of LFG in landfills reduces the GHG in MSW and hence decreases GHG contribution to total emissions. Figure 1 shows the share of waste-based GHG emissions on total emissions both in Turkey and 27 European countries (EC, 2011).

TABLE 1
LFG-to-Energy Projects in the World

Country	*Plants*	*Capacity, MW*	*Country*	*Plants*	*Capacity, MW*
Australia	18	76	Latvia	1	5
Austria	15	22	Mexico	1	7
Brazil	7	11	Norway	30	28
Canada	15	106	Poland	19	18
Czech Republic	6	7	Portugal	1	2
China	4	4	South Africa	4	4
Denmark	23	22	Spain	14	36
Finland	14	12	Sweden	61	55
France	26	30	Switzerland	7	7
Germany	182	270	Taiwan	4	20
Greece	1	13	Turkey	6	39
Holland	47	62	UK	151	320
Hong Kong	8	32	USA	354	2,378
Italy	135	362	Total:	1,157	3,694
Korea	3	16			

Notice that when the LFG plants increase, the contribution of waste to emissions decreases. There is a huge difference between Turkey and Europe and the way to decrease the gap is to build LFG plants to flare the LFG.

4. ESTIMATION OF LFG AND ENERGY GENERATION

There are some models that are developed to estimate the amount of LFG that can be generated. The model that is most widely used as an industry standard is the model that is developed by the US Environmental Protection Agency. The gas generation from a solid waste depends on how long the waste has waited underground, CH_4 generation rate, potential CH_4 generation capacity,

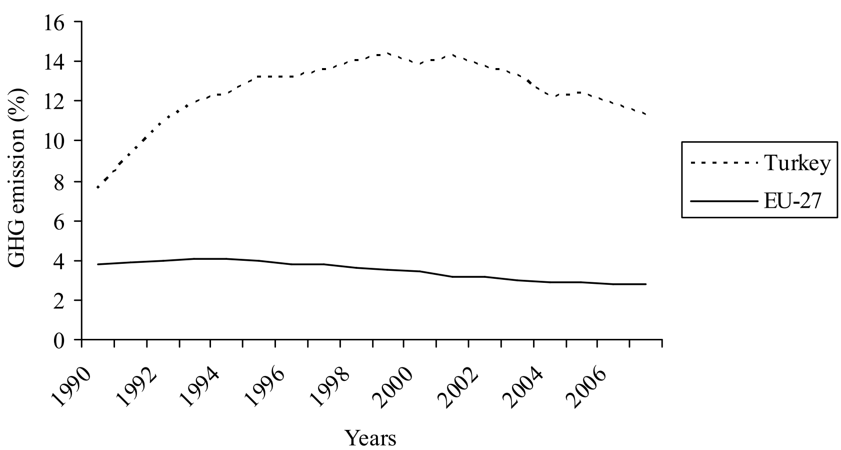

FIGURE 1 Percentage of waste-based GHG emissions in Turkey and Europe.

and the age of disposed waste mass as shown:

$$LFG_T = 2\sum_{i=1}^{n}\sum_{j=0.1}^{1} kL_o\left(\frac{M_i}{10}\right)e^{-kt_{ji}}. \tag{1}$$

LFG_T is the estimated LFG generation at year T (m^3/y) and i is the year index. n is the calculation period which is the year of the calculation minus the year where the waste acceptance begins. j is the partial time increments in a year which is taken as 0.1 for the case. j is used to evaluate the state of MSW in terms of decomposition and LFG generation at different times in a year given that each time step j is 10% of 1 year. In other words, considering 365 days in a year for $j = 0.2$ the state of the MSW on day 73 is evaluated. k is defined as the constant CH_4 generation rate (1/y), L_o is the potential CH_4 generation capacity (m^3/Mg), t_{ij} is the age of j section of the waste which is disposed in i year. Note that t_{ij} represents the decimal years at which the waste is evaluated to gain a more accurate calculations of the waste. M_i represents the amount of solid waste disposed at year i (ton).

The LFG typically contains about 50% CH_4 and other gases. The total LFG amount should be calculated for each year to estimate the power generation from the landfill. The model requires the inputs of k, L_o, and M_i. Once the LFG amount is determined, the annual energy generation at year T (AEG_T) can be calculated as:

$$AEG_T = \frac{LFG_T\,\eta_{col}E_C U_t(1-\eta_{loss})}{H}. \tag{2}$$

η_{col} is the gas collection efficiency in the system which is usually accepted as 85%, E_c is the energy content of LFG (usually 17,500 BTU/m^3), U_t is the utilization of the power system (the percentage of time that the power generation system is working), η_{loss} is the energy lost during the generation (typically 2% for internal combustion engines), and H is the heat rate of the engine. The CO_2 output, G_{T,CO_2} and CH_4 output G_{T,CH_4} of the landfill can be estimated based on the LFG generation:

$$G_{T,CO_2} = \delta_{CO_2}\tau_{CO_2}LFG_T, \tag{3}$$

$$G_{T,CH_4} = \delta_{CH_4}\tau_{CH_4}LFG_T. \tag{4}$$

Assuming 100% burn efficiency for CH_4 in the flaring process, the amount of CH_4 at year T, C_{T,CH_4} and produced CO_2 at year T, C_{T,CO_2} can be calculated as:

$$C_{T,CH_4} = (1-\eta_{col})G_{T_{CH_4}}, \tag{5}$$

$$C_{T,CO_2} = G_{T,CO_2} + 2.75\eta_{col}G_{T,CH_4}. \tag{6}$$

Notice that collected CH_4 would be burned and only uncollected CH_4 have to be controlled. 2.75 in the equation represent the molecular weight of CO_2/CH_4.

4.1. A Simulation Methodology for Municipalities

The municipalities need to do analysis of feasibility to determine the best option of MSW processing before any investment decision. The amount of MSW in a municipality can be estimated based on the population given that the daily waste amount per person is a known variable. The population growth projections can be used to determine the waste inputs in future years and a simulation methodology can be employed to evaluate a landfill. In this research, a multiple period simulation methodology is developed to analyze the LFG potential of municipalities. The pseudo code of the methodology is given as:

```
Set number of municipalities = M
Set years of analysis period = T
      For each m
            For each t
                  Estimate the population for m at t
                  Estimate the waste amount for m at t
                  Calculate the AEG_t
                  Calculate prevented CH4 amount
            Next t
      Next m
End
```

Notice that the estimation of population growth for future periods is important as the waste output will be determined based on the population. Once the disposed amount of waste is determined each year, the amount of LFG generation can be calculated as the gas generation would start short after the waste burial. The potential of LFG and energy from the gas help decision-makers to decide on the energy project.

5. A SCENARIO-BASED LFG-TO-ENERGY POTENTIAL ANALYSIS FOR TURKEY

The MSW of municipalities in Turkey was usually stored in open sites outside the public area and it was not secure and safe for the public in '90s. However, according to new regulations which became effective in 2005, the municipalities that have a population of 50,000 or more have to store the MSW in landfills. Different options are available to utilize the collected LFG but LFG-to-energy is the most likely option that the municipalities consider to build. However, the waste amount that is stored and will be provided in the future plays an important role for the feasibility of the LFG project. There are municipalities that are currently building LFG-to-energy projects, or planning and considering and in negotiations with power companies for building such systems. In order to evaluate the potential of the country, the municipalities in Turkey are classified into three different categories based on their population and three different scenarios were considered. The First Scenario (I) assumes that all the municipalities (TUIK, 2010) that have a population of more than 100,000 (74 municipalities) will build an LFG-to-energy project, that a landfill is opened in 2005 and will be closed in 2025, and that the energy generation would begin in 2013. The other scenarios (II and III) assume that the municipalities with population of more than 250,000 (23 municipalities) and 500,000 (11 municipalities), respectively, build an LFG-to-energy project and generate electricity. The estimated parameters for LFG are $k = 0.05$ (1/y), $L_o = 170$ (m^3/Mg) and $CH_4 = \%50$.[1]

The scenarios can also be considered as the best, moderate, and worst scenario. The proposed simulation methodology is applied for three scenarios in which $M = 74$, $M = 23$, and $M = 11$ municipalities, respectively. The analysis period is $T = 50$ years where the analysis starts in 2005. For each municipality, the population is estimated for 25 years using growth projections, and the annual waste amount is calculated based on the waste per person. Then in 2013, the annual amount of generated electricity and CH_4 that is saved from landfills are simulated using

[1] 1A detailed version of the paper that includes the tables and simulation details is available at https://docs.google.com/viewer?a=v&pid=explorer&chrome=true&srcid=0B64KvEJz9AkrOTM2ZGRhYzAtMzJiNS00MTFiLWEyMTgtYTY2OGUwMTVkYWVm&hl=en&authkey=CJfj-sEE.

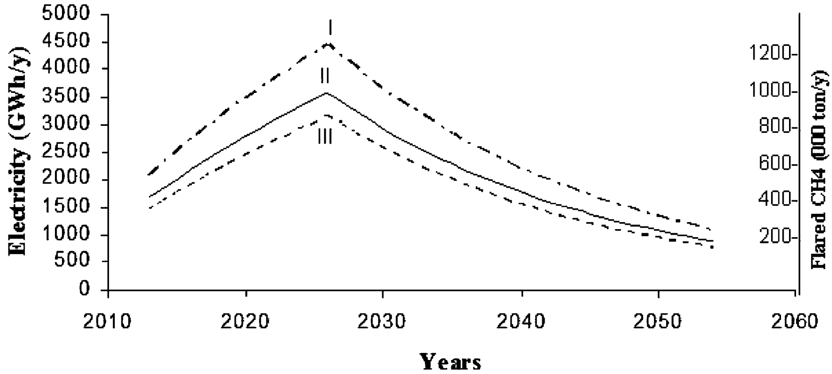

FIGURE 2 Annual electricity generation and amount of CH_4 flared in each scenario.

the LFG generation model. The amount of CH_4 that is flared is also important to evaluate to utilize the LFG projects. Figure 2 shows the annual energy amount that can be gained and the amount of CH_4 that is burned in each scenario. Notice the numbers should be multiplied with 23 to find CO_2 equivalent.

The landfill area is closed in year 25 and the power and CH_4 generation peaks around this time as expected. The generation decreases after this time, however it should be noted that new landfills that will replace the old ones can be activated and begin operating that will keep the generation at high levels. Results show that if the best scenario is applied, the share of the waste-based emissions in the country will be in the same range with that of Europe. The Scenarios II and III still decrease the emissions and are applicable. The amount of power that can be generated provides revenue to the municipality and displaces the fossil fuel-based power generation. In addition to the reduction of waste-based emissions, the emission reduction of fossil fuel-based generation should also be considered.

6. CONCLUSION

Developed countries increase their investments on the efficient storing of MSW in landfills and energy or heat generation from LFG to utilize the energy sources efficiently. In this article, an overview of LFG usage in the world is presented, and then the situation in Turkey is explained. Then the models for LFG production and energy generation from LFG are presented. A multi-period simulation methodology for municipalities is proposed to estimate the potential power generation and amount of CH_4 that can be prevented. The simulation was performed for three different population-based scenarios to evaluate the potential of the country. The analysis does not include all the municipalities in the country, however it includes all the large cities that are likely to be LFG to energy plants. Results show that if the projects are completed, the emissions can be decreased to European standards and MSW can be utilized to generate more power.

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