Landfill Gas (LFG) Plants: An application on energy regarding environmental impact

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The energy production from renewable sources is one of the main issues to reduce environmental damage and more precisely greenhouse gases (GHGs) emissions. The utilization of landfill gas as fuel for electrical energy production can be an important way to reduce the landfill impact on the environment as it represents one of the major emission sources of GHGs.

1. Introduction

The recovery of landfill gas (LFG) for use as an energy resource has become the center of interest since it solves both environmental pollution and energy shortage. Unlike other forms of renewable energy, biogas neither has any geographical limitations and nor requires advanced technology for producing energy.

Landfills can be regarded as conversion biogas plants to electricity, not only covering internal consumptions of the facility but contributing in the power grid as well. A landfill gas (LFG) plant consists of a recovery and a production system. Biogas is pumped from vertical wells (perforated piping in bulk of waste) and guided in well stations by horizontal pipes that connect each well with one well station. In well stations, biogas is rounded up and transmitted by primary horizontal network in the electric power station, [1, 2]. There, biogas is passed through appropriate equipment of dehumidification and elaboration (e.g. freeze) and after is supplied in the generator unit for combustion and electric power production.

But what makes biogas distinct from other renewable energies is its importance in controlling and collecting organic waste material, producing electric power and at the same time reducing the greenhouse emissions to the environment, [3].

The objective of this paper is the utilization of the appraised recuperated biogas in the Municipal Solid Waste (MSW) site of Heraklion for electric power generation regarding the estimated reduction of LFG emissions.

2. Measurements

Landfill Gas (LFG) production is generated by degradation of biodegradable fraction and is influenced by physicochemical composition of waste and environmental variables. LFG is composed of approximately equal parts of methane and carbon dioxide with trace concentrations of other gases.

The rate of biogas production or recovery depends on the generation and transport rates of the individual gases generated during the decomposition of organic refuse deposit as well as masses of parameters that define the conditions of decomposition (such as age and constitution of waste, temperature, humidity, ph-varies with depth of filling, population of microbes, quality and quantity of alimentary substances), [4, 5].

The usual way of appraising the rate of Volatile Organic Compounds (VOCs) is by the use of a first order kinetic equation, which is expressed mathematically as, [6]:

$$\frac{dC}{dt} = -kC \qquad (1)$$

Where:
C,   is VOCs concentration,
k,   is a rate constant

Under practical conditions in a waste repository, the VOCs concentration is in equilibrium that means the rate of VOCs production equals the rate of decay, [7]. The term is used in radioactive decay and first order chemical kinetics. If the rate of change of a quantity is proportional to the amount (or concentration) remaining, as in first order kinetic equation (1).

Including the above kinetic equation and empirical data, a mathematical model "Landfill Gas Emissions Model" (LandGEM) Version 3.02 has been designed under the supervision of EPA (Environmental Protection Agency), [8].

LandGEM is an automated tool for estimating emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds (NMOCs) and

individual air pollutants from MSW landfills. The model can be run using site specific data for the parameters needed to estimate emissions or, if no site-specific data are available, using default values. There are two sets of default values:

- **CAA Defaults.** The CAA defaults are based on requirements for MSW landfills laid out by the Clean Air Act (CAA), including the NSPS/EG and NESHAP. This set of default parameters yields conservative emission estimates and can be used for determining whether a landfill is subject to the control requirements of the NSPS/EG or NESHAP.
- **Inventory Defaults.** With the exception of wet landfill defaults, the inventory defaults are based on emission factors in the U.S. Environmental Protection Agency's (EPA's) *Compilation of Air Pollutant Emission Factors* (*AP-42*). This set of defaults yields average emissions and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data.

As well, knowledge of the following parameters is required:
- The design capacity of the landfill,
- The amount of refuse in place in the landfill, or the annual refuse acceptance rate for the landfill,
- The methane generation rate (k),
- The potential methane generation capacity (L_0),
- The concentration of total nonmethane organic compounds (NMOC) and speciated NMOC found in the landfill gas,
- The years the landfill has been in operation, and
- Whether the landfill has been used for disposal of hazardous waste (codisposal).

The empirical method for calculation of biogas production (considering time) is expressed mathematically, [9]:

$$LFG = L_0 R\left(e^{-kc} - e^{-kt}\right)$$

where

LFG — Total landfill gas generation rate

L_0 — Potential methane generation capacity (m^3/ton)

R — Annual quantity of waste disposal (ton)

k — Methane generation rate (year^{-1})

c, t — Number of years since the landfill closed and opened

The most considerable parameters of the above equation for biogas production are L_0 (potential methane generation capacity) and k (methane generation rate). According to EPA, the parameters L_0 and k were defined as follows (Table 1):

Table 1. CAA & AP-42 default values of parameters.

Parameter	CAA Default Value	AP-42 Default Value
L_0	170 m^3/ton	100 m^3/ton
k	0.05/yr (non-arid region)	0.04/yr (non-arid region)
k	0.02/yr (arid region)	0.02/yr (arid region)

Applying the model for biogas production in the landfill of Heraklion, we have taken under consideration the CAA default values:
- k = 0.05/year,
- L_0 = 170 m^3/ton,
- NMOC concentration = inventory no or unknown co-disposal 600 ppmv,
- methane volume content = 50%,
- average annual waste disposal equal to 100,000 tons.

3. Results

Considering EPA regulations for biogas collection and recovery systems, recuperation rate of biogas production is defined between 75-85% due to losses of the plant.

In the under investigation landfill the minimum rate (75%) was taken into account. Furthermore, CH_4 calorific value equal to 4475 kcal/m^3 and 1 kWh equal to 860 kcal were presupposed.

According to the calculations, the average recuperated biogas production was estimated at 1227.51 m^3/hr and the average electric power generation at 55.95 GWh/yr (Table 2).

Table 2. Annual energy capacity for 20 year horizon.

Year	Biogas production (m^3/hr)	Recuperated biogas (m^3/hr)	Electric energy capacity of recuperated biogas (GWh/yr)
2006	2375.63	1781.72	81.22
2007	2468.51	1851.38	84.39
2008	2348.12	1761.09	80.28
2009	2233.60	1675.20	76.36
2010	2124.67	1593.50	72.64
2011	2021.05	1515.79	69.09
2012	1922.48	1441.86	65.72
2013	1828.72	1371.54	62.52
2014	1739.53	1304.65	59.47
2015	1654.69	1241.02	56.57
2016	1573.99	1180.49	53.81
2017	1497.23	1122.92	51.19
2018	1424.21	1068.16	48.69
2019	1354.75	1016.06	46.31
2020	1288.68	966.51	44.06

2021	1225.83	919.37	41.91
2022	1166.04	874.53	39.86
2023	1109.17	831.88	37.92
2024	1055.08	791.31	36.07
2025	1003.62	752.72	34.31
2026	954.68	716.01	32.64
AVERAGE	**1636.68**	**1227.51**	**55.95**

4. Plant's sizing

Biogas, as a by-product obtained from anaerobic digestion in fermentation of municipal waste in landfill systems, can be used for both heat and power generation through combustion procedure.

Landfill gas (LFG) is a valuable energy resource since its total chemical energy is sufficient to sustain the operation of an electric power generator, as a supplementary or primary fuel contributing to the total electric power generation.

The combustion of the recuperated landfill biogas is occurred by conversion of methane in carbon dioxide (oxidation), as it is described in the following chemical reaction, [10].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
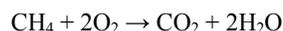
Biogas at a constant concentration of 50% CH_4 and 50% CO_2 is flammable when its concentration in air is between 9% and 20%, approximately, and it will not bum using a conventional gas combustor if its CO_2 concentration is more than 75%, [11]. In these cases, new techniques involving heat-recirculating particulate beds such as fluidized bed, spouted bed, and crater bed have been introduced in order to overcome the limitations, [12, 13].

The LFG conversion in electric power is implemented by engine/generator system (mostly 1 to 5 MW) that needs supply of a dried gas, with pressure capacity at least 50 mbar, [14]. Thus, power engines must be regulated based on LFG concentration, and basically on methane conciseness.

Generally, landfill gas to electricity technology is established in several countries worldwide. LFG is able to feed the selected engine/generator systems for a steady state operation, in contrury to other renewable energy technologies with undetermined primary source (wind, solar, etc).

Several surveys of operating and planned LFG recovery projects have been conducted in recent years. Survey results have varied significantly, due to the relatively long project development times, small project sizes, and large number of small developers. In parallel, the general energy market is one of the major factors that influence the viability of LFG recovery. Concluding, LFG electric power generation use one of the categories presented in the following Table 3.

Table 3. LFG electric generation application.

Engine/Generator Type	Use
Internal Combustion Engines	Most Common
Gas Turbines	Common
Steam Turbines	Limited

Internal combustion (IC) engines used to generate electricity are most commonly lean fuel burn turbocharged designs that burn fuel with excess air. Less commonly, IC engines may be operating without turbocharging. These engines are less complex, but they have reduced power output and higher emissions. When operated on LFG, engine power ratings are commonly reduced by 5 to 15 percent compared to operation on natural gas. The overall heat rate ranges from 11,000 to 14,000 Btus of LFG per kWh. These IC engines that drive generators to produce electrical power, are specially designed for LFG applications, [15].

Gas turbines used to generate electricity at landfill sites take large quantities of atmospheric air, compress the air, burn fuel to heat the air, and then expand the air in the power turbine to develop power. This power is used to drive electrical generators. Gas turbines should be operated at full capacity to optimize performance and limit operational problems, [16, 17].

Steam-electric turbines are used at several sites where the LFG is burned in a boiler to produce high-pressure steam, which drives a steam turbine to generate electricity. Worldwide, one of the largest LFG recovery project has a nominal capacity up to 50 MW of electric power, [18].

In this study, the operation of two different types of LFG power units; an internal combustion unit and a gas turbine has been examined. The conversion efficiency in each engine/generator system is assumed to be about 25% to 30% in total.

Additionally, the landfill gas combustion's emissions of each examined power units are presented in the following Table 4:

Table 4. LFG power units' emissions.

Emission	Reformed IC (mg/m^3)	Gas turbine (mg/m^3)
Particles	4.3	9
CO	800	14
HC	22	15
NOx	795	61
HCI	12	38
SO$_2$	51	6
Dioxines	0.4	0.6
Furans	0.4	1.2

Taking into account previous energy capacity of recuperated biogas in GWh per year, as it is presented in Table 1, and assuming total conversion efficiency in the

engine/generator system of 25%, LFG power plant should supply an amount of 20.31 GWh in the first year of its operation.

Considering the recorded electric energy capacity of recuperated biogas (GWh/yr) and taking into account the technical restrictions (system conversion efficiency), the estimated hourly production of LFG should be able to generate an amount of 1.6 MW end-use electric power, regarding the average annual energy capacity of the next 20 years.

In the following Fig. 1, SHANKEY diagram is used in order to represent the total energy balance of the examined LFG power plant.
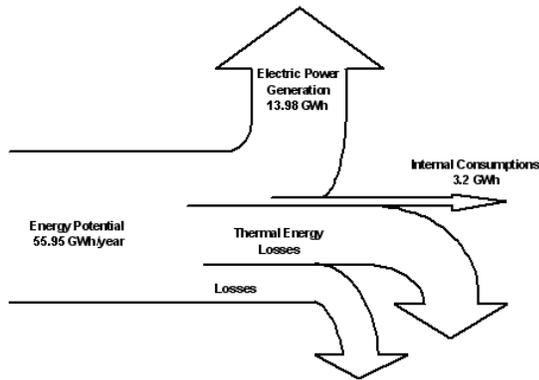

Fig. 1. SHANKEY diagram.

As it is mentioned in the previous paragraph, regarding the sizing of the under investigation plant, the required installed power capacity must run at maximum 2.5 MW, as depicted in Fig. 2. Aiming at the optimal operation of the plant, both in its short-term and long-term (life-cycle) planning, four (4) gas turbines of 625 kW were selected for this study due to reliability and security reasons.
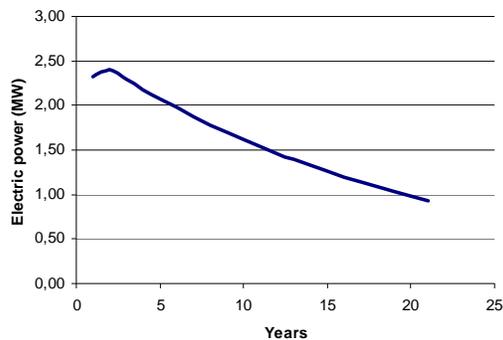

Fig. 2. Appraised power generation per year.

Records of electrical usage over a one-year period indicate an average demand of about 365.3 kW, which is lower in winter and higher in summer with peak load demand up to 500 kW approximately. Therefore, it is estimated that the system would be able to produce enough biogas in order to cover all the internal power consumptions as well as a significant amount of electric energy to the grid (13.98 GWh as depicted in SHANKEY diagram).

5. Environmental impacts

Energy demand must be managed to cope not only with energy but with environmental problems, as well. The energy production from renewable sources is one of the main issues to reduce environmental damage and greenhouse gases emissions, as climate agreements encourage non fossil fuel use in the future.

Landfill gas is a flammable and potentially harmful gaseous mixture consisting mainly of CH_4 and CO_2 with trace amounts of volatile organic compounds (VOCs). The air quality deterioration derived from LFG can be controlled by combustion (gas turbines) and chemical cleaning, [19]. The calculations of LandGEM for the annual emissions of total LFG, CH_4, CO_2 and NMOCs in m^3/yr are represented in the Fig. 3.
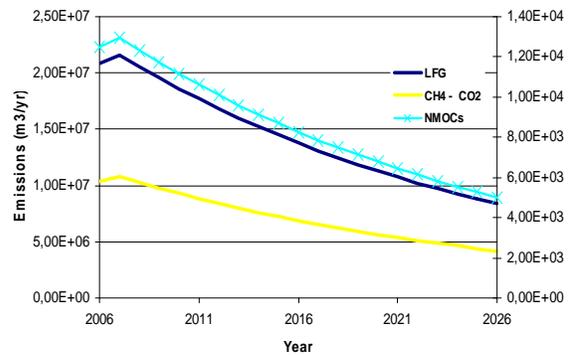

Fig. 3. Landfill emissions.

Landfill gas electricity generation constitutes an environmentally sound eliminating the emission of CH_4, one of the two greenhouse gases emitted by convert it to CO_2 via combustion.

In this study, an environmental assessment of LFG electricity generation was accomplished, using 'Long-range Energy Alternatives Planning system' (LEAP software system, a scenario-based energy-environment modeling tool) and the associated Technology and Environmental Database (TED) in order to estimate the environmental emissions of the energy utilization, [20, 21].

More precisely, the comparison of two scenarios, emissions of crude oil and LFG respectively as fuel type of power production units was implemented.

Both LFG power plant and an equavalent conventional oil-fired power plant have been modeled within the LEAP energy modeling framework to compare their results of greenhouse gas emissions and the corresponting savings potential. The summarized results are presented in the following Table 5.

Table 5. LFG and Oil emissions.

Generation Type	CO_2 (tn/y)	CO (kg/y)	NO_x (kg/y)	SO_2 (kg/y)
LFG / IC	14434	8602.39	8548.63	548.40
LFG / Gas	9876	150.54	655.93	64.52
Oil - Fired	57.9	5035.5	6714	-

The complete exploitation of LFG for electric energy generation at the emamined landfill leads to approximately 4933.86 tons of oil equivalent (TOE) saving and additional increase of 57.9 tons of CO_2 reduction.

The carbon dioxide released from burning landfill gas is considered to be a part of the natural carbon cycle of the earth. Producing electricity from landfill gas avoids the need to use non-renewable resources to produce the same amount of electricity. In addition, burning landfill gas prevents the release of methane, a potent greenhouse gas, into the atmosphere.

6. Conclusions

Energy recovery from waste is a clean, viable and internationally established waste management technology. Not only reduce GHGs emission but reliance on other fuel sources as well.

Taking under consideration the results, as they are depicted in previous figures, collection and utilization systems must be installed in the open year of the landfill in order to achieve the increasing peak rates and avoid at the same time the following observed reduction.

Consequently in the current landfill, although the biogas production thus the electric power generation increases only for one year due to the fact that LFG collection and utilization system was established after almost 20 operation years, its amount is considerable for covering not only biogas plant's consumptions but contribution to electric grid as well.

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