SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 11, No. 3, October 2014, 379-390

UDC: 628.4.08:662.99]:620.97(497.234) **DOI: 10.2298/SJEE140213027G**

Evaluation of Potential Opportunities for Electric Power Generation from Landfill Gas at "Tsalapitsa"

Ivaylo Ganev[1], Iliyana Naydenova[1]

Abstract: Potential opportunities for electric power generation from landfill gas (LFG) utilization were estimated for the second largest landfill site in Bulgaria, situated near the city of Plovdiv. The work performed was based on detailed analysis of experimentally obtained and model-predicted features of the "Tsalapitsa" landfill site. The study presents a short description of the site, the global characteristics of the disposed municipal solid waste, and the experimentally obtained methane composition of the LFG. Based on the above described observations, the potential for LFG recovery at "Tsalapitsa" was determined, together with that for electric power generation for the next 25 years. A set of recommendations was then developed regarding the parameters required for the installation of electric power generation from LFG in Plovdiv.

Keywords: Landfill gas, Landfills for municipal solid waste, Electric energy.

1 Introduction

The increasing amount of municipal solid waste produced by large urban areas worldwide has necessitated the development of adequate strategies for waste management and utilization at the national level [1 – 3]. A particular interest has focused on reducing the negative environmental impact [1, 2] of waste disposal, whilst simultaneously implementing waste utilization activities as sustainable economy-stimulating factors [1, 2]. This in turn has stimulated the development and evaluation of different methods and scenarios for energy generation from biogas utilization [1]. Essential for the development of an adequate method of LFG utilization is the reliable prediction of LFG generation/recovery [1 – 3].

The first system for electric power generation from LFG utilization in Bulgaria was completed in February 2011 with the construction of an installation at "Suhodol", the largest landfill site in Bulgaria, situated near Sofia [1, 2]. The successful implementation of this approach [1] prompted an investigation into the possible energy potential of landfills servicing the

[1]Technical University of Sofia, College of Energy and Electronics, blvd. St. Kliment Ochridski 8, 1000 Sofia, Bulgaria; E-mail: iganev@tu-sofia.bg; inaydenova@tu-sofia.bg

remaining large cities in Bulgaria. At present, most landfill sites in Bulgaria are being processed for closure or recultivation [1]. Recent investigations have examined the opportunity for LFG recovery and utilization as a sustainable renewable resource for electric power generation. Indeed, LFG utilization is an important environmental policy priority described in [2] and thus the greatest interest is currently focused on the largest landfills in the country.

Therefore, the goal of the present work was the assessment of the potential for electric power generation of the "Tsalapitsa" landfill site. This landfill serves as the municipal solid waste disposal site for Plovdiv, the second largest city in Bulgaria. The study also aimed to obtain a set of reliable technical parameters necessary for the development of an installation for LFG utilization. The global parameters influencing LFG recovery were defined as:

- Specific construction of the landfill,
- Morphology of the solid waste matter, and
- Total mass/volume of the disposed solid waste.

These and additional parameters were considered in the present investigation into the "Tsalapitsa" landfill site, with the results summarized in the following chapters.

2 Data for "Tsalapitsa"

The "Tsalapitsa" landfill site is located on 238 decares (useful area 180 decares) of land near the village of Tsalapitsa in Plovdiv Municipality [1], 18 km west of Plovdiv city. The site lies on the road from Plovdiv to Pazardzhik on the southern bank of the Maritsa River, west from the outflow of the Vutcha River.

An electricity distribution line (20 kV) is situated next to the site, but neither a gas distribution network nor any potential heat energy consumers are available. Residual heat energy from a potential co-generator could also be produced in the future as the landfill is located in an agricultural field.

The landfill comprises 12 cells, each of 13 m depth, for waste disposal, with the site structured in the shape of a pyramid of maximum height 17 m. A leachate collection system comprised of two sewer-catcher basins has been constructed, although with no provision for leachate recirculation.

The bottoms of the cells are covered with half a meter of rammed clay, applied in several layers. Insulating foil covers both the cell bottoms and the top of the waste, and is in turn covered with sand and gravel. The same foil also lines the sidewalls, thus shaping the body of the landfill.

The site has been in operation since 2000, serving around 450,000 people. It is expected to exhaust its capacity by the end of 2014 and proceed to closure.

Around 1.5 million tons of domestic solid waste was previously disposed of in cells 1 to 3 when the latter formed part of an old local landfill site (before 2000). This waste matter has recently been used to cover the freshly disposed refuse.

The specific construction characteristics as well as the total amount of waste present at this landfill site indicate its potential for biogas generation. Therefore, the most effective method with which to utilize this LFG would be the development of a system for electricity generation through biogas utilization, which could eventually be enlarged for thermal energy production.

3 Waste Matter Specification

3.1 Morphology of the solid waste matter

Preliminary investigations carried out by the Bulgarian Ministry of Environment and Water (MOEW) previously examined waste matter morphology at “Tsalapitsa”. These data were obtained as part of a project examining the standard morphological composition of the municipal solid waste held at landfill sites serving the largest cities in the country with populations above 50,000 [1]. Therefore, additional analyses were not performed in the present study. A summary of solid waste morphology at “Tsalapitsa” is presented in **Table 1.**

Table 1

Morphology of solid waste matter.

№	Composition	%
1	Organic	–
2	Food waste	28.80
3	Paper	11.10
4	Paperboard	9.70
5	Plastics	12.00
6	Textile	3.20
7	Leather, rubber	1.30
8	Wood waste	1.30
9	Garden Waste	6.80
10	Non-Organic	-
11	Metals	1.70
12	Glass	9.90
13	Other	14.20

3.2 Total mass of the solid waste disposed of at "Tsalapitsa"

An important feature to be considered when assessing the potential for LFG recovery is the total mass/volume of the deposited refuse. Obviously, all landfill cells cannot be filled equally at the same instant in time. In the case of the "Tsalapitsa" landfill site, cells 1 to 6 were first occupied, followed by cells 7 to 9 and finally by cells 10 to 12. As described above, it is expected that the site will exhaust its capacity by the end of the year and thence proceed to closure. In this context it is worth mentioning that the site was also used for the disposal of municipal solid waste from Sofia in 2006, 2007 and 2010. **Table 2** presents the total mass of annually disposed refuse at "Tsalapitsa" between 2000 and 2013 [15].

Table 2

Mass of solid waste annually disposed of at the "Tsalapitsa" landfill site.

Year	Mass of disposed waste [tons]			
	Cell numbers			Total per year
	"1-6"	"7-9"	"0-12"	
2000	78,000	48,000	–	126,000
2001	78,000	48,000	–	126,000
2002	78,000	48,000	–	126,000
2003	78,000	48,000	–	126,000
2004	78,000	48,000	–	126,000
2005	60,000	50,000	–	110,000
2006	176,000	8,000	–	184,000
2007	80,000	141,000	135,000	356,000
2008	–	65,000	15,000	80,000
2009	–	20,000	126,000	146,000
2010	–	–	250,000	250,000
2011	–	–	100,000	100,000
2012	–	25,000	88,000	113,000
2013	–	33,000	78,000	111,000
Total	**706,000**	**582,000**	**792,000**	**2 080,000**

4 Results and Discussion

4.1 Experimentally measured landfill gas composition

Annual variation in average methane generation was experimentally measured at the "Tsalapitsa" landfill site [15] in accordance with the methodology described in [1]. For that purpose the following technical tools were employed: aneroid barometer, thermometer, a pitot tube of 1 m length, manometer, hydrometer, and gas analyzer. The observations were carried out for a period of 18 months between January 2012 and June 2013. Additionally, control measurements were performed at the Technical University of Sofia in September 2013 using the same methodology. A strong correlation was found between the results obtained from the two independent laboratories, thus confirming the expected quantitative and qualitative properties of biogas composition. According to [11, 17] the gas composition and CH_4 concentration in each cell varies with time, depending on atmospheric conditions, periods of waste disposal, gas recovery etc.

Fig. 1 presents the experimentally measured monthly variation in averaged methane concentrations from cells 1 to 12, covering a period of 15 months. The solid line in Fig. 1 denotes the experimentally obtained average CH_4 concentration, whereas the dashed line represents its trend, obtained as the best-fit of the logarithmic trend of the experimentally measured results.

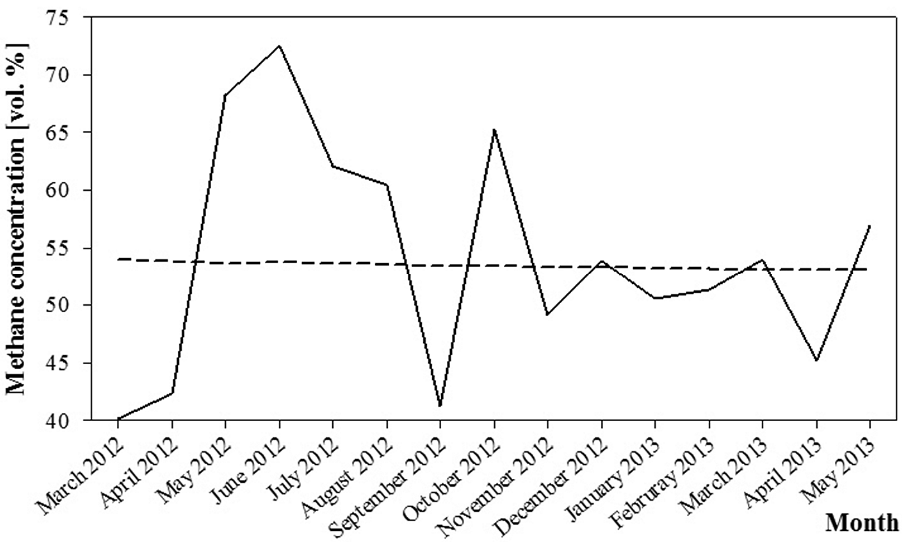

Fig. 1 – *Experimentally measured average values (solid line) and corresponding best-fit curve (dashed line) of methane concentration.*

It is important to note that the experiments were carried out while the observed landfill site was still in operation, and as such were greatly influenced by circumstances such as meteorological and operational conditions. Moreover, the cells at the studied site are situated at relatively shallow depth, increasing the sensitivity of the process of CH_4 generation to atmospheric and weather conditions. As a result, the formation of methane within each cell is not a constant process in time. All of these circumstances should be taken into account when examining the annual variation in CH_4 concentrations at "Tsalapitsa" [7, 17].

The data presented in Fig. 1 show that during months characterized by warm and humid weather, CH_4 concentrations almost double, with the calculated trend curve for the same period showing an average CH_4 concentration of around 52 – 53 %. The results thus confirm that the investigated LFG is suitable for electric power generation.

4.2 Landfill gas recovery and flow rate

LFG recovery is another important characteristic, the understanding of which is necessary for determining the potential for electric power generation at any site. In this particular study the flow rate of LFG recovery was predicted using the Landfill Gas Emissions Model (LandGEM) developed by the United States Environmental Protection Energy (EPA) [11], together with the latest modifications for the Central-Eastern Europe model, version 1.0, as described in [1].

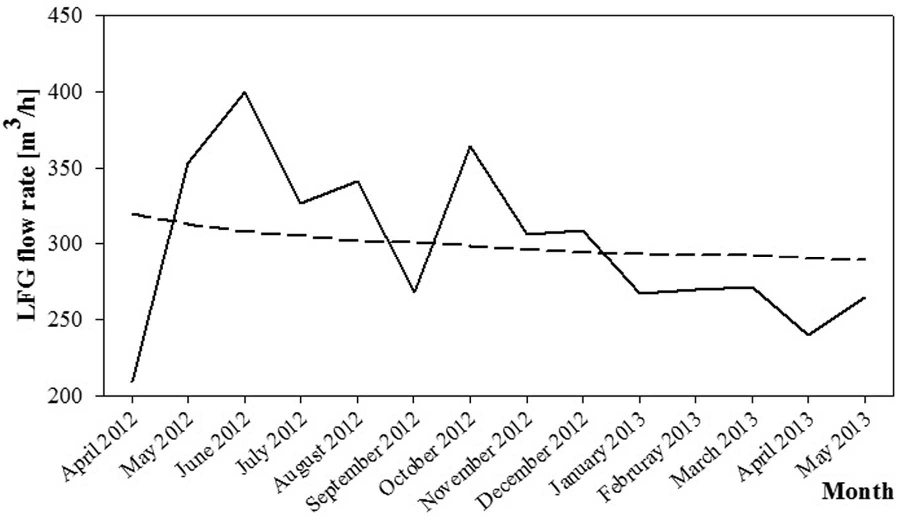

Fig. 2 – *Experimentally measured values (solid line) and corresponding best-fit curve (dashed line) of LFG flow rate.*

Fig. 2 presents the experimentally measured results [14, 15] and calculated best-fit data for the logarithmic trend of monthly variation in LFG recovery at the "Tsalapitsa" landfill site. As expected, the LFG flow rate exhibits a behavior similar to the experimentally obtained variation in CH_4 concentrations (see Fig. 1). A significant decrease in both variables was observed during the winter period, with a near doubling taking place during summer and autumn.

The LandGEM model was implemented based on the Central-Eastern Europe model, version 1.0 [18], with LFG recovery expressed as a first-order decomposition rate equation as follows:

$$Q_{LFG} = \sum_{i}^{n} \sum_{j=0.1}^{1} 2kL_0 \left[\frac{M_i}{10} \right] \left(e^{-kt_{ij}} \right) \left(MCF \right) \left(F \right), \tag{1}$$

where

Q_{LFG} – LFG recovery in m^3/year

i – 1 year time increment

n – (year of the calculations) - (initial year of waste acceptance)

j – 0.1 year time increment;

k – rate of CH_4 generation in year^{-1};

L_0 – potential CH_4 generation capacity in m^3/Mg or m^3/t solid waste matter

M_i – mass of solid waste disposed of in the i^{th} year

t_{ij} – age of the j^{th} section of waste mass M_i in the i^{th} year

MCF – CH_4 correction factor

F – fire adjustment factor

The employed model contains several key parameters. For instance, the k - coefficient expresses the rate at which the refuse decays and produces CH_4. According to [18] this coefficient is related to the half-life of the disposed waste through the term

$$t_{1/2} = \ln 2 / k \, . \tag{2}$$

The rate of CH_4 generation is a function of refuse moisture conditions, the availability of nutrients for bacteria stimulating CH_4 formation, as well as the *pH* and temperature of the disposed solid waste. Based on these properties for each Eastern European country the model suggests estimated generation rate values [18].

The potential CH_4 generation capacity of landfill represents the total amount of CH_4 potentially produced by a ton of refuse, as it decays. Theoretically it should vary between 6 and 270 m^3/t [18], but this particular variable depends mostly on the morphology of the disposed solid waste. Thus, one must obtain the percentage concentration of biologically degraded components in the refuse together with the rate of waste degradation, based on projected country-specific values. Rates are typically defined as low, middle or fast.

The MCF - factor is an adjustment of the model to the estimated LFG recovery. Denoting the degree to which the waste decays aerobically, this factor depends mostly on cell depth and the type of solid waste deposited. According to [18] this variable varies between 0.4 and 1.

The F - factor represents the severity of fire impact. This model parameter decreases the rate of LFG recovery by the percentage of solid waste disposal area impacted by fires. It is multiplied by 1/3 for low impact, 2/3 for middle and 1 for severe impact [18].

Equation (1) was used to obtain total LFG recovery for a period of one year. A multi-year projection was then made by varying the projection year and reapplying the algorithm.

Annual variation in the average LFG recovery flow rate calculated via the LandGEM model is presented together with the experimentally measured results in Fig. 3. Two sets of experiments were carried out at two independent laboratories (see Section 4.1). The results of the LandGEM model calculations cover a period of 25 years. The calculated rate of LFG recovery in the middle of 2013 was 359 m^3/h (see Fig. 3), with the corresponding experimentally measured rate being 331 m^3/h. This latter result was obtained as the average value of measurements performed over a period of one year (between June 2012 and May 2013). Both the experimentally measured and predicted results were obtained using a default CH_4 concentration, which was taken to be equal to 50% in accordance with [11, 14 – 18]. Thus, the coincidence between the calculated and experimentally measured results is very good, with a difference of less than 8%.

The modeled and experimentally measured results were then compared with values for LFG recovery (see Fig. 3) calculated by the EPA under the Global Methane Initiative “Methane to Markets” program in 2009 for the same landfill site [1]. The results for LFG recovery (Global Methane model) presented in [19] were divided by a factor of 2. The observed differences between the two modeling studies are due to several factors. First, whereas the calculations in [19] are predominantly based on predictions, those in the present study involve recent experimentally measured data. Thus, several key parameters were overestimated in [19]. For instance, the refuse disposal prognosis is about 25 % higher than that obtained in the present work. At the same time, the significant influence of the global economic crisis (from 2009 onward) and the effect of several fires at the landfill site after 2009 that have considerably reduced LFG recovery, could not have been taken into account in the previous study [19]. Nevertheless, the modeling results produced by the two studies show similar tendencies regarding LFG recovery at “Tsalapitsa”. The present work was based on the detailed investigation of experimentally measured data, the refuse deposited at the site and the landfill's operational parameters, which explains the significantly improved correlation between the experiments and the recent model predictions.

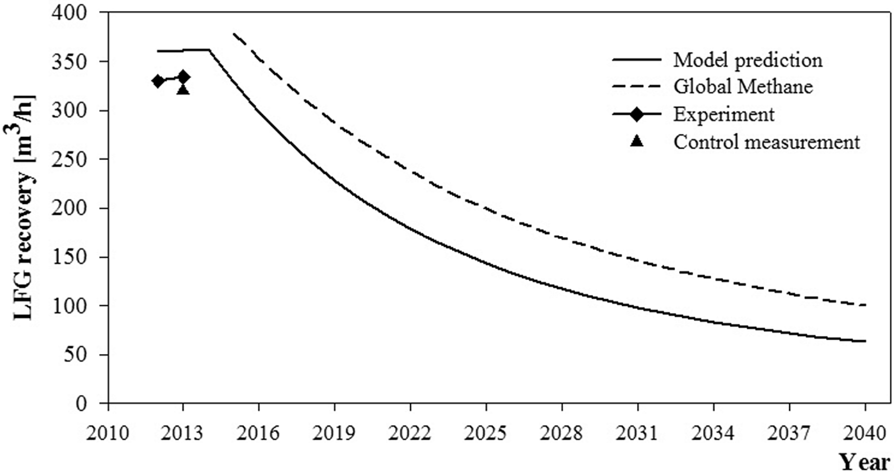

Fig. 3 – *Experimentally measured values (dotted line and triangle), as well as those calculated in this work (solid line) and via the Global Methane model (divided by a factor of 2; dashed line), of LFG recovery.*

4.3 Estimated potential for electric power generation at the "Tsalapitsa" landfill site

The potential for electric power generation from LFG recovery at "Tsalapitsa" was estimated using the following equation:

$$P_{el} = Q_{CH4} B \eta \,, \tag{3}$$

where

P_{el} – electric power in kW

Q_{CH4} – flow rate of CH_4 recovery in Nm^3/h,

η – efficiency capacity of the installation for electric power generation from LFG. Most installations for biogas utilization function using an Otto-type engine. The efficiency coefficient of such systems usually varies between 30% and 42%, depending on the properties of the installed engine. In this particular investigation, η was chosen to be equal to 35%

B – low heat value (LHV) equal to 9.7 kWh/Nm^3

The flow rate of CH_4 recovery can be easily calculated via the following equation:

$$Q_{CH4} = Q_{LFG} C_{CH4}, \quad (4)$$

where C_{CH4} is volumetric fraction of CH_4 in the LFG and Q_{LFG} is rate of LFG recovery in Nm^3/h.

The results of calculations regarding the possibility for electric power generation from LFG utilization at the "Tsalapitsa" landfill site are presented in Fig. 4. Examination of this figure reveals that the potential reserves for CH_4 recovery would secure electric power generation at the site for at least 25 years.

Combined analysis of experimentally measured results and model predictions has confirmed that "Tsalapitsa" contains all the features necessary for biogas-driven electric power generation.

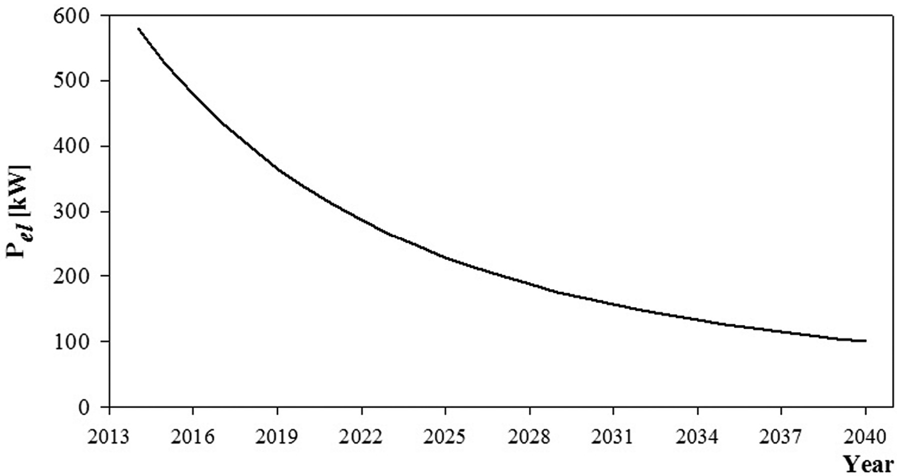

Fig. 4 – *Calculated annual variation in electric power generation.*

An installation for LFG utilization that would be suitable for implementation at "Tsalapitsa" should fulfill the following technical requirements:

- Capacity to operate at an average CH_4 concentration of around 50 %,
- Installed power capacity of 200 kW,
- Operation power of 200 kW for a period of 10 years,
- Operation power of between 100 and 200 kW for a period of 15 years, and
- Total operation term of 25 years.

5 Conclusion

The current work presents the results of an experimental and theoretical investigation into the potential opportunities for LFG recovery and utilization for electric power generation at the “Tsalapitsa” landfill site serving Plovdiv, the second largest city in Bulgaria.

The study was prompted by the fact that “Tsalapitsa” will soon be processed for closure and recultivation. As the site’s operating term expires at the end of 2014, the present work focused on determining the global parameters necessary for an adequate installation choice for LFG–based electric power generation.

It is well known that the process of LFG recovery depends on factors including site operating conditions, moisture content, landfill construction (e.g., outline and depth), the existence of conditions insuring the anaerobic and aerobic gasification of the disposed solid waste, atmospheric and climatic conditions etc. Thus, the experimentally measured and calculated results regarding CH_4 concentrations, the rate of LFG recovery and predicted electric power generation all confirm the potential for a biogas utilization and electric power generation plant at the “Tsalapitsa” landfill site. Analysis of the obtained data shows that the potential resources for CH_4 recovery at the site would secure the exploitation of such an installation for a period of 25 years.

6 Acknowledgment

Ivaylo Ganev expresses his deep felt gratitude towards colleagues in Plovdiv Municipality for their assistance in this investigation. Iliyana Naydenova was supported by COST Action CM 0901.

7 References

[1] Operational Programme “Environment 2007-2013”, CCI No: 2007BG161PO005, Sofia, 2007, www.ope.moew.government.bg/en.

[2] Operational programme “Environment 2014-2020” – in progress www.ope.moew.government.bg/en.

[3] J.E. Santibanes-Aguilar, J.M. Ponce-Ortega, J.B. Gonzalez-Campos, M. Serena-Gonzales, M.M. El-Halwagi: Optimal Planning for the Suitable Utilization of Municipal Solid Waste, Waste Management, Vol. 33, No. 12, Dec. 2013, pp. 2607 – 2622.

[4] E.S Karapidakis, A.A. Tsave, P.M. Soupios, Y.A. Katsigiannis: Energy Efficiency and Environmental Impact of Biogas Utilization in Landfill, International Journal of Environmental Science & Technology, Vol. 7, No. 3, June 2010, pp. 599 – 608.

[5] S. Chen, B. Chen: Energy Efficiency and Sustainability of Complex Biogas Systems: A 3-level Emergetic Evaluation, Applied Energy., Vol. 115, Feb. 2014, pp. 151 – 163.

[6] The Europe 2020 Strategy for Intelligent, Sustainable and Joined Growth, European Commission, Brussels, Belgium, March 2013.

[7] International Best Practices Guide for Landfill Gas Energy Projects. U.S. Environmental Protection Agency, International Solid Waste Association, Global Methane Initiative, 2012 (https://www.globalmethane.org).

[8] J. Havukainen, V. Uusitalo, A. Niskanen, V. Kapustina, M. Horttanainen: Evaluation of Methods for Estimating Energy Performance of Biogas Production, Renewable Energy, Vol. 66, June 2014, pp. 232 – 240.

[9] Q. Aguilar-Virgen, P. Taboada-González, S. Ojeda-Benítez, S. Cruz-Sotelo: Power Generation with Biogas from Municipal Solid Waste: Prediction of Gas Generation with In Situ Parameters, Renewable and Sustainable Energy Reviews, Vol. 30, Feb. 2014, pp. 412 – 419.

[10] S. Thompson, J. Sawyer, R. Bonam, J.E. Valdivia: Building a Better Methane Generation Model: Validating Models with Methane Recovery Rates from 35 Canadian Landfills, Waste Management, Vol. 29, No. 7, July 2009, pp. 2085 – 2091.

[11] Landfill Gas Emissions (LandGEM) Model, Version 3.02, User's Guide, United States Environmental Protection Energy, EPA-600/R-05/047, Washington, DC, USA, May 2005.

[12] I. Ganev, I. Naydenova, B. Dimitrov: Development and Implementation of the First System for Efficient Energy Utilization of Landfill Gas in Bulgaria, In Scientific Report "Cleaner Combustion", 2nd Annual Meeting of the COST Action CM0901, "Detailed Chemical Kinetic Models For Cleaner Combustion", Saragossa, Spain, 07 – 09 Sept. 2011, pp. 226 – 229.

[13] I. Ganev, I. Naydenova: Preliminary Assessment of the Greenhouse Gas Emissions During Capturing and Flaring the Landfill Gasses from the Solid Waste Landfills in Bulgaria, 34th International Symposium of Combustion Institute, Warsaw, Poland, 29 July – 03 Aug. 2012, Poster-WIP143.

[14] I. Ganev: Validation of a Model Predicting the Mean, Annual Landfill Gas Generation in Landfill "Suhodol", Proceedings of Technical University - Sofia, Vol. 62 No. 3, 2012, pp. 193 – 198. (In Bulgarian).

[15] Plovdiv Municipality, www.plovdiv.bg/en.

[16] National Waste Management Programme 2009-2013, www.moew.government.bg.

[17] Complex License N 355-H0/2008 of Plovdiv Municipality (www.plovdiv.riosv.com/) and ISO 10780:1994; ФМ 02/08:2008; ФМ 03/08:2008.

[18] User's Manual Central-Eastern Europe Landfill Gas Model, Model Version 1.0, United States Environmental Protection Energy, Washington, DC, USA, March 2013.

[19] Assessment of Landfill Gas Recovery and Utilization in Bulgaria, https://www.globalmethane.org/projects/projectDetail.aspx?ID=1185.