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LANDFILL GAS TO ENERGY CONVERSION FROM ORADEA MUNICIPAL WASTE LANDFILL IN ROMANIA

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Abstract

This paper presents the results of theoretical estimations of the quantity of landfill gas (LFG), as well as the energy potential of Cell A from the municipal landfill in Oradea city, Romania, based on a mathematical model. Considering three scenarios for LFG recovery according to the capture system efficiency, the following LFG theoretical flows have been obtained: 157 m^3_{LFG}/h for 45% recovery efficiency; 209 m^3_{LFG}/h for 60% recovery efficiency; and 297 for 85% recovery efficiency, respectively. The current recovery system efficiency based on real data is about 45%. On-site measurements revealed that the LFG composition is 53% methane and 0.72% oxygen, thus, it is suitable for electrical energy generation using internal combustion engines. Consequently, by considering 35% motor-generator system efficiency and previous flows of LFG, the electric energy to be obtained is 299 kW_e, 398 kW_e, and 564 kW_e, respectively. At the same time, the electric energy of 281 kW_e has been obtained for the real data of the LFG flow of 148 m^3_{LFG}/h. Considering that the operating time is 7,446 h/yr; the energy generated for the year 2014 is 2,092 MWh_e. On the other side, from 2005 to 2030, according to the recovery system efficiency, the total electrical energy generated during this period is 40,222 MWh_e; 53,630 MWh_e and 75,975 MWh_e respectively, and the methane emissions have been estimated for about 1.53 million m^3_{CH4}, which represents 417 thousand of tons CO_2 equivalent, which may be reduced by using LFG for producing electricity.

Keywords: energy, landfill gas, mathematical models, methane emissions, solid waste

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1. Introduction

The landfills represent the main solution to manage large volumes of municipal solid wastes (MSW) in many countries, especially in developing countries. Thus, almost 410 million tons have been sent to landfills or to dumpsites worldwide (Ghinea et al., 2014; Hoornweg and Bhada-Tata, 2012), which represents approximately 60% of 680 million tons of total waste generated. At the EU level, most of the Member States have sent over 50% of the MSW generated to landfills (EEA, 2013; Schiopu et al., 2007). MSW contains mainly organic matter. In developed countries, 27-35% of MSW contain organic matter, while in developed countries this is over 55% (Burnley, 2007; EEA, 2013; Ghinea et al., 2014; Hoornweg and Bhada-Tata, 2012), since developed countries consume more processed and packed products. Landfills can be seen as huge bio-chemical reactors (Apostol and Marculescu, 2006; Grellier et al., 2007), where biological processes take place by decomposition of the organic fraction (food waste, leaves, paper, among others) (ATSDR, 2001). Two products result: liquid (i.e. leachate) and gas (i.e. landfill gas - LFG) with negative impact on the environment (Grellier et al., 2007; Kjeldsen and

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Christophersen, 2001; IPCC, 2006; Rusu et al., 2017), due to their composition. LFG is mainly composed of CH_4 and CO_2 and, in lower concentrations of non-organic methane compounds (NOMC) and water vapor (ATSDR, 2001; Bjelic et al., 2017; Dublein and Steinhauser, 2008). Methane is a potential greenhouse gas (GHG) of 21 times more powerful than CO_2 (Global Methane Initiative, 2010) and can cause fire risk in concentration of 5-15% in the air (US-EPA, 1996). Uncontrolled MSW landfill caused methane emissions of about 799 $Mt_{CO2\text{-}eq}$, which represents approximately 11% of 6,875 $Mt_{CO2\text{-}eq}$ methane emissions (Bogner et al., 2007; Global Methane Initiative, 2010; IPCC, 2006).

In this regard, dedicated strategies and policies have been implemented (UNECE PRTR, 2013; EC Decision, 2009) in order to reduce the GHG emissions at establishing targets. Thus, according the EC Decision (2009), GHG emissions should be reduced by 30% up to 2020 compared with 1990. Consequently, the projects regarding the recovery and use of LFG as main fuel for electric and/or thermal power generation have become very important, due to the high methane content in the LFG composition and environmental and economic benefits. Among the benefits, we can mention (IPCC, 2006; Scharff and Jacobs, 2006; Terraza and Willumsen, 2009): reduction of conventional fuel consumption; economic benefits from selling the recovered energy (green certificates); creation of new jobs; low risk of failure to apply the environmental legislation; lower GHG emissions; lower risk of fire. For these purposes, worldwide, LFG energetic recovery systems are being used (Willumsen, 2004). The largest applications are in the USA and Europe.

Generally, the recovered LFG from landfills can be used in three ways (Dublein and Steinhauser, 2008; Willumsen, 2004): direct combustion for heat production; electrical power generation; supply of natural gas in networks or as a car fuel after being filtered in order to improve the calorific value. At the same time, there are several technologies for LFG conversion in electrical and thermal energy (Bove and Lunghi, 2006; Global Methane Initiative, 2012; Willumsen, 2004): modified internal combustion engines, gas turbines, Stirling engines, fuel cells. Among them, it can be mentioned electrical power conversion by means of internal combustion engines which use LFG as primary fuel, due to the fact that it is more economic with a higher efficiency (cogeneration). Worldwide, over 1,150 LFG recovery systems have been identified, which used to produce electrical energy with an installed power of about 4,000 MW and an average extraction flow of 4 m^3/tons waste/yr (Terraza and Willumsen, 2009), out of which 63.7% are in Europe and 30.7% in the USA. Among the 1,150 recovery systems, about 50.4% use internal combustion engines for electrical energy generation (Terraza and Willumsen, 2009).

When using LFG as primary fuel for energy generation, technical issues have to be considered (Terraza and Willumsen, 2009; SCS Engineers, 2008): assessment of the LFG capacity inside the landfills; the type of recovery system (horizontal or vertical extraction well); pumping tests in order to determine the LFG flow which can be recovered as well as the quality of LFG (content of methane and oxygen), in order to establish its operational options; the applied technology. The assessment of the quantity of LFG is based on mathematic models described by the technical literature data (Faour et al., 2007; Kamalan et al., 2011; Scharff and Jacobs, 2006; US-EPA, 2005): LandGEM, Mexican, Scholl Canyon, SWANA, EPER Frances, TNO, Afvalzorg, among others. These are based on the decomposition speed of the organic fraction of waste and depend on the quantity and the composition of waste, life time, landfill management, as well as the environmental weather conditions of the landfill area. The accuracy of the results strongly dependents on the parameters mentioned above (Scharff and Jacobs, 2006; Thomson et al., 2009).

This paper presents the results of the study performed in order to assess the energetic potential of the Cell A of the municipal landfill in Oradea city, Romania. These results will be useful to establish a method for the LFG utilization as an alternative source of primary energy for production of electrical and thermal energy. Thus, the assessment of LFG production has been performed based on the Mexican mathematical model, developed by the Company SCS Engineers, due to the similarity of input data regarding the municipal landfill exploitation requirements (e.g. waste composition, environmental weather conditions, among others). Based on real measurements, the LFG flow has been determined through the pumping method; also, the LFG quality (methane and oxygen content) has been assessed for electrical energy production using internal combustion engines. Thus, the results of the mathematical model and the landfill gas efficiency recovery can be validated.

2. Material and methods

Landfills represent an alternative source of energy which can be used for power generation. Estimations of the LFG potential and of the energetic potential of Cell A from the landfill in Oradea city have been performed according to the following steps: 1) Visits to the landfill location in order to collect data, such as: quantity of landfilled waste; landfill constructive and exploitation characteristics; 2) Determination of waste composition; 3) Theoretical assessment of LFG potential based on the guidelines of the Mexican model by SCS Engineer (2009), IPCC (2006) and US-EPA (2005); 4) Determination of LFG flow and structure through on-site measurements; 5) Determination of the generated electrical energy and methane emissions for the period 2005-2030.

2.1. General description of the landfill

The municipal landfill is placed near Oradea, at about 1.2 km away from the inhabited area. This landfill collects MSW coming from Bihor County. The total surface is 36 ha, of which 22.8 ha is the landfill area. The landfill is structured into 6 cells with a total capacity of about 4.5 Mt (750 thousands of tons/cell). Exploitation operations have begun in 2005 and they will last until about 2025. Fig. 1 presents the quantity of waste landfilled in Cell A between years 2005-2011. In 2011, Cell A with about 686.74 thousands of tons of landfilled waste has been covered.

The total height of the landfill is 20 m, over the current ground level. This cell is fitted with sealing systems – basic and slope drainage, as well as with and coating systems for the collection of the fermentation gases, according to the European standards (EC Directive, 1999) and the Romanian legislation in force (MMGA, 2004). LFG collection system is the active type, consisting of 45 vertical wells. Currently, the final coverage has a layer of soil of 0.5 m. In the end, the landfill will be covered with an insulation layer which will remove any inside water infiltration. The landfill sealed this way will be covered with two meters of soil and grass, thus integrating again in the surrounding natural landscape.

The climate of the area is temperate continental with Atlantic influences. According to the National Meteorological Administration, average air temperature of the landfill location is 10.4°C, and the average annual rainfall is 600-700 mm/year.

2.2. Input parameters for assessment of LFG potential

MSW landfilling represents currently the main method of waste treatment (Hoornweg and Bhada-Tata, 2012; EEA, 2013). In Romania, 93% of MSW is landfilled (ANPM, 2013). Inside these landfills, bio-chemical processes are performed by aerobic and anaerobic microorganisms which cause decomposition of waste organic fraction. Degradation of organic matter leads to the production of LFG, whose composition is shown in Table 1 (ATSDR, 2001).

Table 1. Typical composition of LFG (ATSDR, 2001)

Component	***Symbol***	***Percent by volume [%]***
Methane	CH_4	45-60
Carbon dioxide	CO_2	40-55
Nitrogen	N_2	2-5
Oxygen	O_2	0.1-1
Ammonia	NH_3	0.1-1
Hydrogen sulfide	H_2S	0 - 1
NMOCs (Non-organic methane compounds)	---	0.01-0.6
Hydrogen	H_2	0-0.2
Carbon monoxide	CO	0-0.2
Moisture	H_2O	Saturated

The presence of methane in the LFG composition improves combustion properties; the low heating value can reach 16.8MJ/m^3 (Dublein and Steinhauser, 2008) for a concentration of 50% CH_4.

Widely used in industry, LFG generation rate can be described by a first order decay equation. Thus, in order to determine the LFG production, various mathematic models described by the technical literature have been developed (Fauor et al., 2007; Kamalan et al., 2011; Scharff and Jacobs, 2006; Thomson et al., 2009; US-EPA, 2012). Such models require specific information about landfills, such as: quantity, composition and life time of landfilled waste, the landfill exploitation method and environmental weather conditions (temperature and rainfalls). LFG estimations for different landfills in America and Europe (Ferran et al., 2013; Scharff and Jacobs, 2006; Thomson et al., 2009) shows that LandGEM v3.2 model is overestimated in terms of LFG generation compared with real data.

In Romania there are no statistical data regarding the estimation potential of LFG using a mathematical model and also no specific methodology. In this study the Mexican model v2.0 developed by the Company SCS Engineers for determination of LFG potential was used (SCS Engineers, 2009).

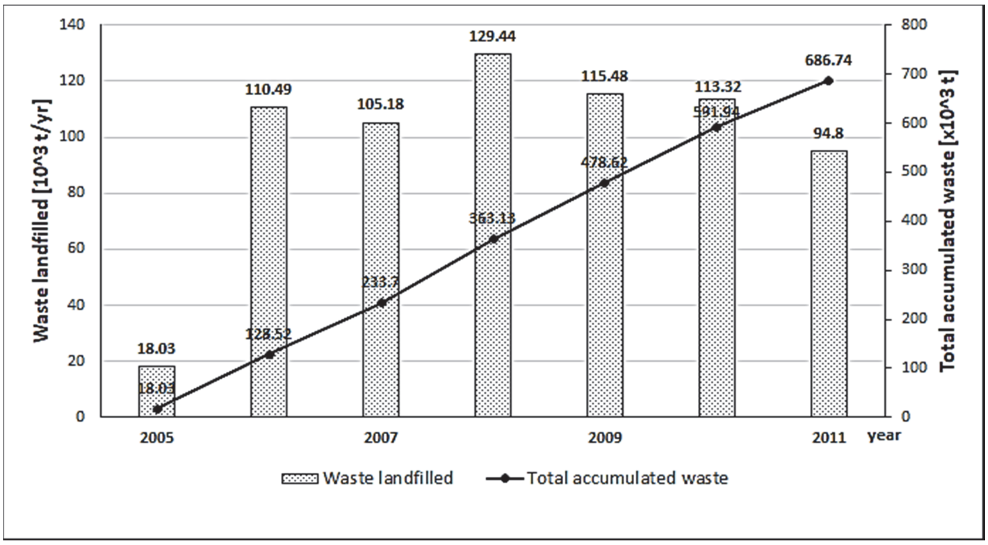

Fig. 1. Quantity of landfilled waste between years 2005-2011 in Cell A

The Mexican model is an improvement of the LandGEM v3.2 model and is based on the first order decay process of the waste organic fraction degradation, according to (Eq. 1). The Mexican model v2.0 takes into account two correction factors: the constructive characteristics of the landfill, through the methane correction factor (MCF); and also the fire adjustment factor of the landfill (F). These two parameters have been included in order to obtain more conclusive results (Ferran et al., 2013) in similar operating and environmental weather conditions as the landfill in our case study.

$$Q_{LFG} = 2 \cdot MCF \cdot F \cdot k \cdot L_o \cdot \sum_{i=1}^{n} \sum_{j=0.1}^{1} \left[\frac{M_i}{10} \right] \cdot e^{-kt_{ij}} \text{ [m}^3\text{LFG/h]} \quad (1)$$

where: Q_{LFG} – LFG generation quantity [m^3_{LFG}/h]; MCF – methane correction factor according to the landfill management; F – fire factor, if were produced, L_o – potential methane generation capacity [m^3/t_{waste}]; k – waste decay constant [1/yr]; M_i – mass of waste accepted in the i^{th} year [t]; t_{ij} – age of the j^{th} section of the waste mass M_i accepted in the i^{th} year.

● **Methane generation potential (L_o)** takes into account the waste composition, by means of degradable carbon content (DOC) which includes four classes of waste (Aguilar et al., 2011; IPCC, 2006; SCS Engineers, 2008): rapidly degradable (food and vegetable waste); moderately rapidly degradable (paper and cardboard, sanitary textile; leather and natural textile fibers); moderately slowly degradable (gardens and parks waste – leaves and others, excluding foods); slowly degradable (wood, rubber, bones, straws). Also, L_o considers the type of landfill management and the stoichiometric conversion factor (molecular weight ratio CH_4/C). Consequently, the methane generation potential (L_o) is determined by using the IPCC methodology (Aguilar et al., 2011; IPCC, 2006), according to the (Eq. 2):

$$L_o = MCF \cdot DOC \cdot DOC_f \cdot F \cdot \left(\frac{16}{12} \right) \text{ [m}^3/\text{t}_{waste}] \quad (2)$$

where: *MCF* – factor which considers landfill management; *DOC* – degradable organic carbon inside waste [kgC/kg_{waste}]; DOC_F – is a fraction of DOC that converted in methane – depends on the landfill internal temperature; *F* – methane content of LFG; $\frac{16}{12}$ - stoichiometric factor (SF).

● **Decay constant (k)** of waste landfilled is related to the life time of waste and it is the time required by the DOC organic fraction to decompose up to half of its initial weight (IPCC, 2006), therefore represents the rate at which organic matter landfilled decays and produces methane. The value of this constant depends mainly on the waste moisture, the value of pH, nutrients and environmental weather conditions (temperature and rainfall) of landfill location (IPCC, 2006). Whereas, the pH and nutrients are complex to be determined through tests, also landfill internal temperature is independent of the environment at depths greater than 4 meters due to the biological process of anaerobic decomposition, the k constant is calculated based on the average annual rainfall (Golder Associates, 2008; IPCC, 2006; Thomson et al., 2009), by (Eq. 3):

$$k = 6.4 \cdot 10^{-5} x + 0.01 \text{ [yr}^{-1}] \quad (3)$$

where: *x* – average annual rainfall [mm].

Moreover, once estimated the annual LFG production is possible to determine the methane emissions in tons of carbon dioxide equivalent (t_{CO2-eq}), with the following mathematical relation, Eq. (4) (Panesso et al., 2012):

$$T_{CO_2-eq} = 21 \cdot \rho_{CH4} \cdot CH_4 \cdot Q_{LFG} \text{ [t}_{CO2-eq}] \quad (1)$$

where: ρ_{CH4} – methane density (0.717 kg/m^3); CH_4 – methane content [%]; Q_{LFG} – annual LFG production [m^3/yr].

2.3. LFG capture system

Integrating a LFG capture system, the air pollution caused by the GHG gas emissions by the anaerobic degradation processes of municipal waste organic matter is decreased. LFG collection is possible only by means of specific facilities, which depend upon the technical and physical operating characteristics of the landfill (SCS Engineers, 2008).

The LFG collection system, installed in Cell A, of Oradea city landfill is consisted of: 45 wells placed vertically inside the waste mass, to 10 – 17 meters deep; gas collection pipe network; flow gas adjustment and control station; steam separator (condensation tank); impurities and drop separator; vacuum pumps; instruments and apparatus for gas monitoring and analyze; and gas torch. The LFG capture system efficiency is strongly influenced by landfill design, the type of recovery system, and operational conditions (SCS Engineers, 2008; Terraza and Willumsen, 2009). In this regard, the material used for covering and the period of time of final covering can significantly affect the capture efficiency of LFG (Spokas et al., 2006; US-EPA, 1996), thus, three scenarios can be differentiated for gas recovery, according to Table 2.

Table 2 shows that the impermeable layer for final sealing provides a better collection of LFG, the efficiency can reach up to 95%. The increased collection efficiency of LFG facility involves a reduction of GHG emission in the air, thus contributing to achieve the targets established by the legislation in force (EC Decision, 2009).

2.4. Use of landfill gas

Alternative use of recovered LFG depends on the quality of gas (IPCC, 2006; SCS Engineers, 2008).

Table 3 presents the possibilities to use LFG according to the content of methane and oxygen.

Table 2. LFG recovery efficiency (Spokas et al., 2006; US-EPA, 1996)

Sealing layer	*Efficiency [%]*
< 1 m soil	40-60
>1 m soil	50-70
Impermeable multiple-layer	80-95

Table 3. Alternative use of LFG (SCS Engineers, 2008)

Type of use	*CH_4 content [%]*	*O_2 content [%]*
Power generation	45-50	< 1
Direct combustion (torch)	30-40	< 3
Direct use (heat production)	40-50	< 2

In general, for electrical energy generation, diesel internal combustion engines are used, which operate with de 20% air excess. In this regard, the oxygen content of the fuel has to be controlled so that the combustion to achieve under suitable conditions. For this reason, the oxygen contained by LFG is limited to less than 1%.

Generally, LFG energy conversion units are based on motor-generator groups with power up to 20 MW_e (Bove and Lunghi, 2006; Terraza and Willumsen, 2009). These are equipped with the following elements (Bove and Lunghi, 2006): gas and air feeding systems; engine cooling (cooling water, oil and air circuits) and lubricating system; H_2S filters; exhausting system equipped with lambda sensor for controlling NO_x emissions; automatic operation system. The global efficiency of the energy conversion unit is 70% to 85% for cogeneration, while the electric energy efficiency varies between 25% and 45% (Panesso et al., 2012; Willumsen, 2004). Power generation P_G [kW_e] depends on: the quantity of thermal energy W_{LFG} [kWh_t] contained by LFG burned in the engine; the recovery system efficiency (R); the efficiency of motor-generator group (η_{el}) (Apostol and Marculescu, 2006; Suroop and Mohee, 2011). The electric power generation P_G is calculated based on the (Eq. 5):

$$P_G = W_{LFG} \cdot R \cdot \eta_{el} \quad [\mathrm{kW_e}] \tag{2}$$

Thermal energy W_{LFG} contained by LFG, expressed in [kWh_t], is determined according to the LFG volume (V) [m^3] recovered per hour, the percentage of methane (CH_4) in LFG composition and the low heating value of methane (LHV_{CH4}) [MJ/m^3] (Panesso et al., 2012; Suroop and Mohee, 2011), according to (Eq. 6):

$$W_{LFG} = 0.2778 \cdot V \cdot CH_4 \cdot LHV_{CH_4} \quad [\mathrm{kWh_t}] \tag{3}$$

where: the numeric index is determined by the conversion of MJ to kWh_t. *LHV* of methane is 35.8 MJ/m^3 (Dublein and Steinhauser, 2008).

3. Results and discussion

3.1. Estimation of LFG production

When determining the LFG production from a landfill, the waste composition must be carefully considered, in particular organic matter content, moisture and "degradability" of waste fractions, because they determine the quantity of generated LFG and the period of gas production inside the landfill. Thus, based on the previous researches, the composition of MSW from urban and rural areas of Bihor County has been determined. Average annual composition of MSW of Bihor County is presented in Fig. 2.

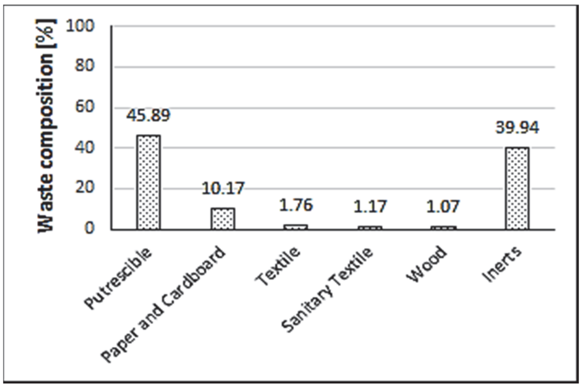

Fig. 1. Average annual MSW composition

Fig. 2 shows that the bio-degradable organic fraction consisted in putrescible waste (food waste, vegetables, among others) - 45.89%, paper and cardboard - 10.17%, textile - 1.76%, sanitary textile - 1.17% and wood - 1.07% are high (60.06%). Thus, considering the information of waste composition, constructive and exploitation characteristics of the Oradea municipal landfill, as well as the average annual rainfall, the input parameters are shown in Table 4. By dividing L_o with the methane density (0.717 kg/m^3), is obtained the L_o value of 71.28 m^3_{CH4}/t_{waste} (142.56 m^3_{LFG}/t_{waste}). The literature data shows values of L_o that vary between 6.2 – 270 m^3_{CH4}/t_{waste} (US-EPA, 1996), while the typical data of this parameter are between (125 – 310) m^3_{CH4}/t_{waste} (SCS Engineers, 2009). The default value suggested by US-EPA is 100 m^3_{CH4}/t_{waste}, thus one may consider that estimated LFG production is within the acceptable limits.

Table 4. Input parameters

Parameter	*MCF*	*DOC*		*DOC_f*	*F*	*SF*	*L_o*	*K*
Unit	--	kg_C/kg_{waste}		--	%	kg_{CH4}/kg_C	ton_{CH4}/ton_{waste}	yr^{-1}
Value	0.8	0.124		0.77	50	16/12	51.11	0.054

The results of L_o compared with literature data slightly vary because the waste composition is different from one country to another. In Bihor County in the organic fraction, the putrescible compounds as food waste, vegetables, garden waste, agricultural waste is predominant, L_o depends on the cellulosic content from the organic fraction (IPCC, 2006).

Also, considering the average annual rainfall as 680 mm, it has been obtained the value of constant k=0.054 yr^{-1}. The current values of k constant for temperate-continental climatic areas similar to those in Oradea are between (0.02 - 0.07) yr^{-1} (IPCC, 2006; Kamalan et al., 2011). Faour et al. (2007) has shown that k varies from 0.12 to 0.21 yr^{-1} and L_o from 87 to 115 m^3_{CH4}/t_{waste}. Other researches of Thomson et al. (2009) revealed that k values varies between 0.023 - 0.056 yr^{-1} and L_o between 90 - 134 m^3_{CH4}/t_{waste}; Machado et al. (2009) has experimentally determined the k constant, the results presents that k constant is 0.2 yr^{-1} and L_o is 70 m^3_{CH4}/t_{waste} for tropical landfills; Aguilar et al. (2012) has calculated for Mexic the k values, the results shows variation between 0.031 - 0.048 yr^{-1} and L_o varies between 60 - 80 m^3_{CH4}/t_{waste}. Measurements performed in several countries such as USA, the UK, the Netherlands, Argentina, New Zealand, Mexico, among others, show that the k constant value is between 0.0286 - 0.3 yr^{-1} (IPCC, 2006). The LFG estimation production of Cell A of the municipal landfill has been performed considering the following input data: the exploitation beginning year - 2005; cell A closure year - 2011; the annual waste quantity landfilled (Fig. 1); the simulation period 2005-2030; methane generation potential (L_o) and decay constant (k) (Table 4); the management landfill factor is 0.8; and no fire has been recorded for the landfill area. At the same time, the methane content of 50% of the LFG volume is taken into consideration.

Consequently, Fig. 3 shows the theoretic annual estimation of LFG production, as well as of GHG emissions. Fig. 3 presents that in the year when Cell A has been covered, the maximum production of LFG (410 m^3_{LFG}/h) and methane, respectively, (205 m^3_{CH4}/h) was achieved, after this it decreases exponentially. In year 2030, the LFG production is 147 m^3_{LFG}/h that represents 36% of the maximum value; therefore, the period of LFG production can go beyond 2030. The LFG production period is similar with other studies under the same weather conditions (Fauor et al., 2007; Kamalan et al., 2011; Scharff and Jacobs, 2006; Thomson et al., 2009). Ferran et al. (2013) used the Mexican model for LFG production estimation for a 32 ha landfill with 5 million tons of waste, the results revealed a maximum production of approximately 3500 m^3_{LFG}/h.

The results are similar if we consider the same waste quantities landfilled. As well Aguilar et al. (2011) obtained similar results in terms of k constant and L_o. One might consider that, between year 2005-2030, the landfill may produce about 1.53 million m^3 of methane (about 3.06 million m^3 of LFG), representing about 416,930 t_{CO2-eq}.

3.2. LFG flow and composition

The results presented in Fig. 3 do not involve the fact that the total quantity of produced LFG can be recovered because it depends on the recovery system efficiency at the moment of LFG extraction (Table 2). LFG recovery from the landfill has started with Cell A closure (year 2011). As mentioned, the quantity of recovered gas is influenced by the landfill seal method (Table 2). Thus, three possible scenarios for landfill gas recovery can be considered based on recovery efficiencies.

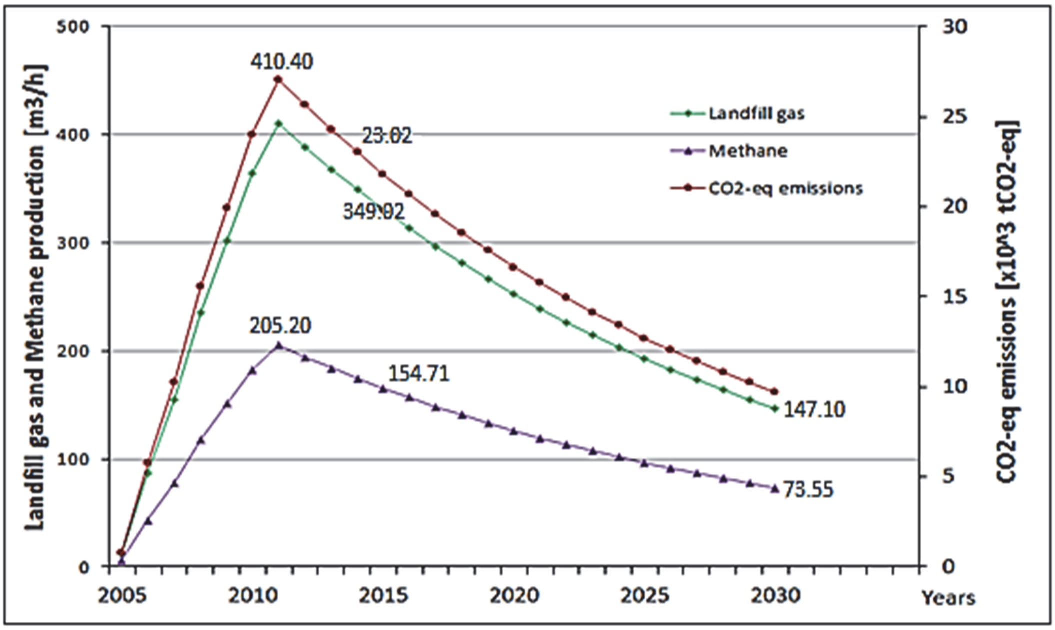

Fig. 2. Landfill gas estimation and methane emissions from the municipal landfill of Oradea City

Fig. 4 presents the variation curves of LFG recovered from Oradea landfill, considering the average values from Table 2 has resulted different recovery efficiencies: low (45%), medium (60%) and high (85%). The measurements of LFG flow were made at the location of the landfill through pumping tests are also presented. These data show that the efficiency of LFG collecting system is improved in time. Also in Fig. 4 are presented the variation curves of LFG production using two mathematical models: LandGEM and SWANA (Faour et al., 2007; Kamalan et al., 2011). The LFG efficiency recovery was considered 45% in order to compare the results with the real data.

It can be observed that the results obtained by the LandGEM model are overestimated while the SWANA model is underestimated. Therefore, the comparison of theoretical results with real data (Fig. 4) obtained through measurements, shows that the Mexican model is the most suitable for landfill gas estimations in our case. The data from Fig. 4 shows that the current efficiency of recovery system is close to 45%. This also comes from the fact that Cell A of the landfill is temporarily covered with a 0.5 meters layer of soil. As established in literature data for landfill exploitation the final coverage has to be represented by a protection layer made of geotextile and a 2 meters layer of soil. Consequently, the efficiency of gas collection system will be improved in the future. The LFG quantity which can be recovered, according to the final closure of Cell A and the recovery efficiencies, would be: 45% - 157 m^3_{LFG}/h; 60% - 209 m^3_{LFG}/h; and 85% - 297m^3_{LFG}/h, respectively.

On the other hand, LFG extracted from landfills can be used to generation energy, only if it contains CH_4 between 45% - 50% and O_2 content is less than 1% (Table 3). Variations on LFG composition are due to several factors, such as: nutrient contained in waste composition; waste compacting; water precipitation penetration influencing the internal humidity of the landfill; internal temperature of the landfill; waste landfill life time (ATSDR, 2001). Measurements of LFG composition through 45 wells (21 samples during three months) have been performed in order to highlight possible variations of the composition. Fig. 5 presents the average LFG composition (content of CH_4, CO_2 and O_2). Methane concentration varies between 67% and 40% based on the well depth and the quantity of organic matter in that extraction point, resulting in an average of methane content of about 53%. As for the concentration of oxygen, it is majorly under 1%. The average of oxygen concentration is about 0.72%. As for the CO2 content in the LGF composition it is around 40%.

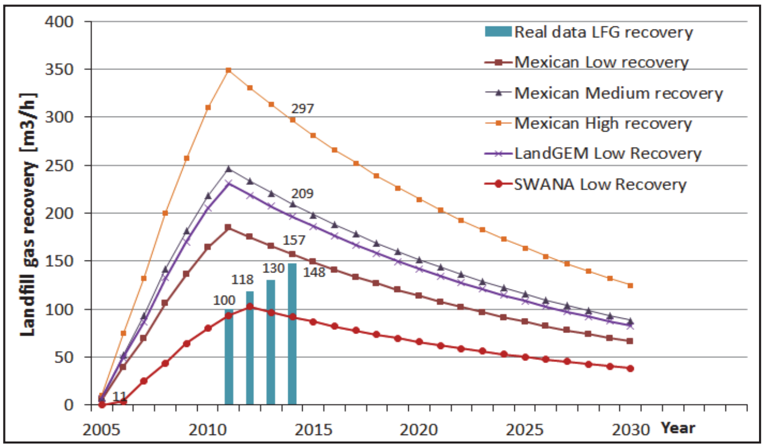

Fig. 3. Quantities estimation of recovered landfill gas

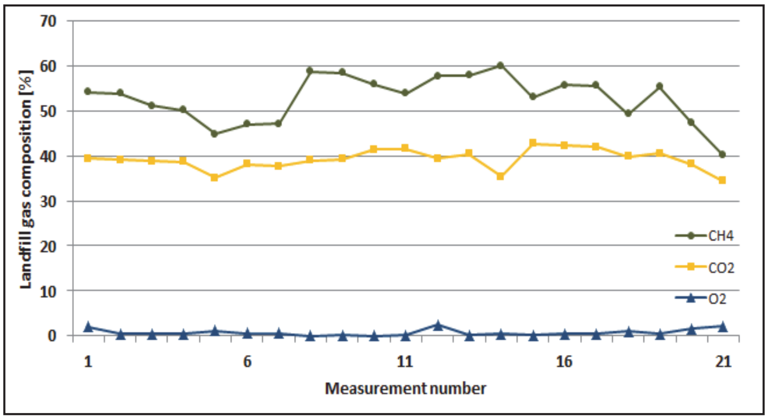

Fig. 4. Main LFG components

With respect to the H2S content, it has not been measured because the motor-generator group is equipped with an active carbon filter for safety issues. Consequently, the foregoing results show that the LFG composition extracted from cell A of the landfill makes it appropriate for being used in energy conversion units for electricity generation with internal combustion engines.

3.3. Electric energy generation

The efficiency of an internal combustion engine in co-generation is about 85%, of which about 35% is electric and 50% is thermal energy. Thermal energy can be mainly used for domestic heating as well as for other energetic purposes.

Net electricity has been determined by taking into account some assumptions as: the three scenarios regarding the efficiency of LFG recovery, the 55% methane content of LFG composition; the low heating value of methane of 35.8 MJ/m^3; the simulation period 2010 – 2030; the efficiency of the motor-generator group of 35%. In Fig. 6 are presented the comparison between theoretical and real data for net electric energy generation.

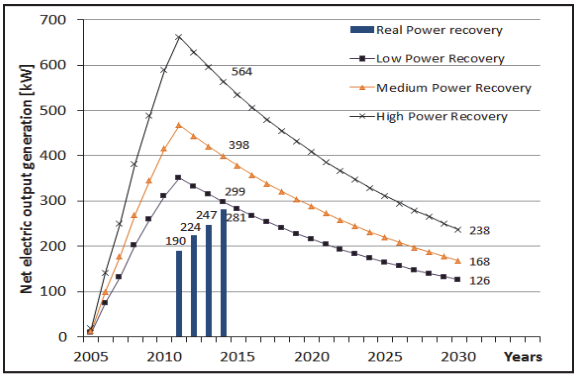

Fig. 5. Net electric output generation

Fig. 6 shows that, in 2014, the energy generated by considering the three theoretical scenarios for LFG recovery would be 299 kW$_e$, 398 kW$_e$, and 564 kW$_e$, respectively. The real quantity of recovered gas is about 148 m^3$_{LFG}$/h (Table 5). By this quantity, 281 kW$_e$ can be obtained. Also, it can be estimated that in 2030 could theoretically generate about 238 kW$_e$ (about 36% of the maximum value of 663 kW$_e$), if the efficiency of recovery system reaches 85%, so the exploitation period for Cell A can be extended up to 2030.

On the other hand, considering that energy generation units can be operated in average 7,446 hours, for the three scenarios, the net electric output for the year 2014 is 2,226 MWh$_e$, 2,964 MWh$_e$ and, 4,200 MWh$_e$, respectively.

For the total simulation period, energy produced for each LFG recovery scenario would be: 40,222 MWh$_e$; 53,630 MWh$_e$; and, 75,975 MWh$_e$, respectively.

It is worth mentioning the fact that, if the exploitation requirements for the landfill for all the period simulations are the same, each cell would contribute same quantity of energy for every 6 years (i.e. each cell is closed at the end of the 6th year), so, in 2017, about 420 kW$_e$ will be generated; and in 2023, it would be about 550 kW$_e$, reaching a maximum of 880 kW$_e$ in 2030.

4. Conclusions

It is important to know the organic matter content of MSW because it is one of the most important factors which determine the quantity of LFG production and the gas composition. MSW in Bihor County has organic matter content of about 60% (putrescible, paper and cardboard, textile, sanitary textile and wood), from which the dominant fraction of about 46% is putrescible materials (food waste, vegetables, agricultural waste). These values influence the results of L$_o$ and k constant compared with other worldwide data. Based on waste composition from Bihor County the results of L$_o$ are 142.56 m^3$_{LFG}$/t$_{waste}$ and k is 0.054 yr^{-1}. Consequently, MSW in Bihor County has a high potential for LFG production.

LFG production of cell A reaches the maximum value in 2011, at 410 m^3$_{LFG}$/h. In year 2030, the LFG production will be 147 m^3$_{LFG}$/h that represents 36% of the maximum value; therefore, the period of LFG production can go beyond 2030.The three considered LFG recovery scenarios estimates a gas flow of 157 m^3$_{LFG}$/h; 209 m^3$_{LFG}$/h; and 297 m^3$_{LFG}$/h, respectively. The comparison between the theoretical results and the real data obtained through measurements suggests that the Mexican model reflects more accurate the LFG production for the specific studied landfill. It also shows that the efficiency of LFG collection facility is currently of about 45%.

Also, it has been determined that in the landfill gas composition the content of methane is 55% and oxygen is 0.72%, which provides good combustion properties for electric energy generation using internal combustion engines. Based on the total LFG flows, the energy generation is about 299 kW$_e$; 398 kW$_e$; and 564 kW$_e$, respectively. By considering that the motor-generator system operates 7,446 h/yr with 35% efficiency, the energy estimation through the three LFG recovery scenarios is about 2,226 MWh$_e$, 2,964 MWh$_e$, and 4,200 MWh$_e$, respectively. For the total measured flow the net electric output would be 2,092 MWh$_e$. For the total simulation period, energy produced for each LFG recovery scenario would be: 40,222 MWh$_e$; 53,630 MWh$_e$; and, 75,975 MWh$_e$, respectively.

On the other site, the methane emissions between years 2005 – 2030 have been determined for about 1.53 million m^3 of methane, which represent 416.93 thousand t$_{CO2\text{-}eq}$, and which can be avoided through methane energy conversion unit. For total life time of the landfill (25 years) the energy that could be generated is 40,222 MWh_e; 53,630 MWh_e, and 75,975 MWh_e, respectively based on different recovery efficiency.

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