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ESTIMATION OF THE ENERGETIC POTENTIAL OF HOUSEHOLD SOLID WASTE BASED ON TWO MANAGEMENT STRATEGIES: LANDFILLING AND THERMAL CONVERSION

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The work presents a comparative analysis of two solutions for municipal solid waste energy potential recovery: as biogas recovered from the landfills and thermal-chemical conversion, both using the advantage of related technologies in the mature stage of development. The work presents estimations of the energetic potential of waste both in gross form and biogas with the quantity and quality calculated using mathematical models. For 2014, in Romania, 4.25Mt municipal waste was generated with a content of about 53% biodegradable material, the content of degradable carbon being of about 0.125 kgC/kg$_{waste}$. The combustible fraction represents around 22.5% whereas the humidity may be up to 49%. The lower calorific value of gross domestic waste is about 6260 kJ/kg. The analysis revealed an energetic potential of biogas generated from the landfill as thermal energy of about 1164 GWh$_t$ whereas the thermal energy recoverable by direct combustion of domestic waste may reach 3553 GWh$_t$.

Keywords: landfill gas, thermal conversion, household waste, energy

1. Introduction

The society faces increasingly high problems related to municipal solid waste, since the quantity produced per capita is higher, as the population increases, as well as the economic development of a country [1, 2]. In 2012, on global level, the estimated quantity of waste reached 1.3 billion tons. The quantity of waste generated per capita of inhabitant increased in the last decade, from 0.64 kg/capita/day to 1.2 kg/capita/day and for the year 2025 it is estimated to reach 1.42 kg/capita/day [3]. Globally, it has been estimated that around 410 million tons of municipal solid waste collected have been directed either towards the landfills or towards garbage dumps, which represents 53.6% of the quantity collected [3, 4]. In Romania, in 2011 3.89 million tons of household wastes were generated out of which 93% were landfilled [5]. It results that the landfilling is

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still the most common method to discharge the solid municipal waste, as it is simple, cheap, but not the most efficient and ecological.

These high quantities of municipal solid waste, besides the negative impact on environment caused by it (pollution of the air, of surface and underground water, of ground), it involves as well the continuous demand of new disposal places.

On the other hand, the content of biodegradable materials (food waste, paper, board, etc.) in the composition of waste, which generally ranges between 30% – 65% [2, 6], is subject to a process of natural decomposition, pursuant to which the gas is being produced with a contents of around 50% methane [6], known as a greenhouse effect gas (GHG). The methane discharged in the atmosphere by the waste deposits represents 5% of all emissions of GHG [7].

Due to these reasons, different alternative processes and technologies (anaerobic digestion, composting, combustion, gasification, pyrolysis, landfilling by recovery of landfill gas) for the disposal of municipal solid waste with energy recovery are to be considered [4, 7, 8], aiming to reduce the quantities meant for storage, as well as the uncontrolled methane emissions. Thus, on global and European level there are protocols, policies and regulations (e.g. Kyoto Protocol, Directive 2008/98/EC – on treatment of waste) being thus encouraged the use of alternative methods of treatment of household waste. In this context, the Directive 2008/98/EC stipulates, among others things, the recovery of gas from landfills to prevent the GHG emissions, this being used as fuel for the production of energy [9, 10] due to its calorific value. Also, to reduce the quantity of municipal waste to be disposed combustion process can be used as alternative method for the energy recovery [8, 11], based on the combustible fraction in the composition of waste that ranges between 15% – 35% [2, 3].

To estimate the methane emissions, several more or less complex mathematical models are presented in the dedicated literature [6, 7, 12, 13]. The application of such models entails, generally, the knowledge of specific information on the characteristics of waste landfilled (quantity, composition, time scale), as well as the landfills management manner and the environment conditions (temperature and annual average precipitations).

This work presents the study made for the estimation of the potential of landfill gas (LFG) generated since the decomposition of organic material of the waste landfilled, based on 6 mathematical models for the estimation of methane emissions as well as a comparative analysis with a view to estimate the energetic potential of waste based on two strategies of management of domestic solid waste namely: landfilling with recovery of LFG and energy conversion in internal engines and combustion coupled with stream turbines.

2. Quantity and composition of household solid waste

To establish the energy potential of a specific source of municipal solid waste the quantity and the quality of the waste generated must be known.

The qualitative and quantitative characteristics of solid domestic waste landfilled are heterogeneous and time variable. These depend on the region, life styles of population, economic activities, season, culture and traditions [2, 3, 14].

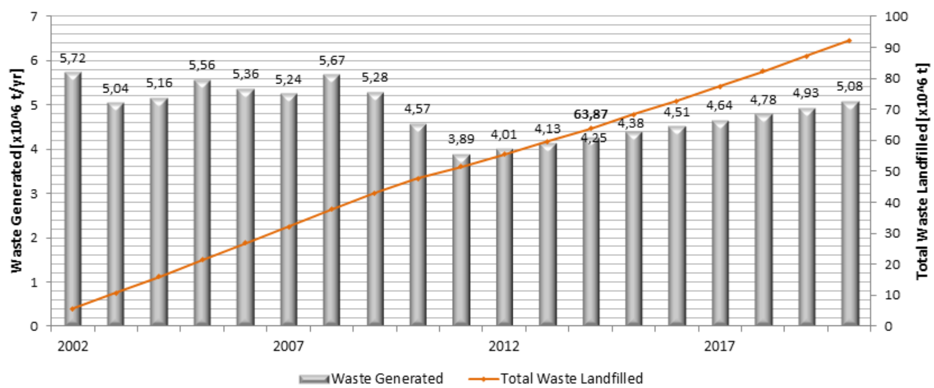

Fig. 1. Quantity of waste landfilled and cumulated between 2002 – 2020 [5]

According to the data of the most recent census performed by the National Institute of Statistics (INS), Romania has a stable population of 19'073767 of people, out of which 52.8% is urban and 47.2% is rural. According to the ANPM (National Agency for Environmental Protection) statistics, it is estimated that in Romania 0.9 kg/capita/day is generated in the urban area, and 0.4 kg/capita/day in the rural area. In Fig. 1 it is presented the quantity of waste landfilled between the years 2002 – 2007 according to the information supplied by ANPM [5]. In the range of 2007 – 2011, the period of global economic crisis, there is a decrease of the quantity of waste generated due to the life styles changings. Based on current data regarding the waste quantities generation, in our analysis we considered an annual increase rate of 3% of the waste collected since 2012 until 2020. Since 2002 there are around 63.87 million tons of wastes landfilled.

Fig. 2 presents the composition of municipal waste in Romania between 2006 and 2010, according to ANPM reports. The content of organic material (biodegradable, paper and cardboard, textile, wood) is about 67.2%, out of which 49.6% is readily degradable (putrescible). Such data shows that domestic waste has a high methane generation potential [7, 15]. Combustible materials (paper, cardboard, textile, wood and plastic materials) represent 23.6%.

Fig. 2. Composition of household solid waste 2006-2010 [5]

It can be also noticed that during 2005 – 2010 the biodegradable fraction presents small variations, whereas the percentage of materials such as paper and cardboard, plastic, mainly metals and glass decreases in time due to the presence of recycling in the urban areas.

3. Technologies of energetic conversion of waste

3.1 Landfilling. Potential of biogas

On global level, the landfilling is the method most accepted economically. Currently, such landfills are built by compaction, impermeabilization and levelling of the land so as to allow the installation of some systems of draining, pumping of leachate, extraction and capture of gas.

Inside landfills natural decomposition of organic fraction (food waste, paper, cardboard, etc.) of household waste, in the absence of oxygen, takes place, obtaining the landfill gas (LFG). The most important biological reactions are performed by aerobe and anaerobe microorganisms and are associated to the organic fraction of waste.

Fig. 3 presents the 4 phases of organic material decomposition. The process starts in the presence of oxygen, caught in the waste upon the storage (aerobe phase – Hydrolysis). This phase lasts several weeks. From the coating waste, the oxygen starts being consumed by the biological activity. During this phase the main gaseous component generated is the carbon dioxide, reaching a maximum concentration at the end (Acitogenesis phase). Once the oxygen is consumed, the degradation of organic fraction is performed in its absence (anaerobic phases). In Acetogenesis phase, the organic material is transformed into LFG.

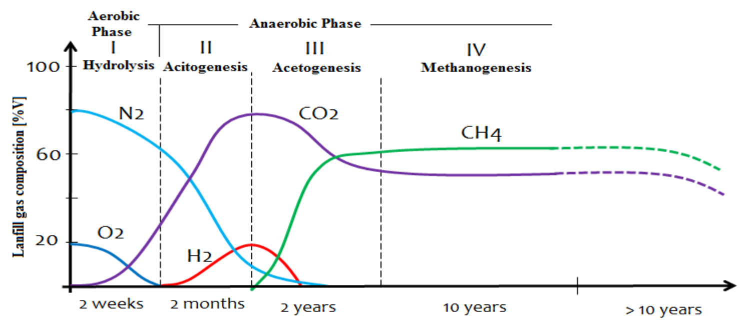

Fig. 3. Phased of formation of biogas in the landfill [6]

During the Methanogenesis phase the methane production reaches the maximum concentration (45%-60%) while the carbon dioxide decreases to 40%-55%.This phase corresponds to the steady state of the process with low variations of gas components concentrations. Other gases are also present (H_2O, H_2S, N_2, C_nH_m) in lower quantities (1 – 5%) [6].

Globally, there are different researches related to the estimation of the quantity of LFG in the waste deposits, based on some mathematical models [6, 7, 12, 13, 16] generally relying on the expression of kinetic process of waste biodegradation, known as the equation of Monod [12]. It is important to know the quantity of methane generated, both during the feasibility projects phase for power generation units, as well as to determine the impact on environment of an uncontrolled landfill, due to the emissions of methane gas [7, 17, 18].

Table 1 presents comparatively 6 mathematical models used both for LFG and methane generation. It can be noticed that these models have the same basic components as input data, slightly different. All models estimate the quantity of LFG based on three entry variables: quantity of waste stored in time, the degradation time (k) and the methane generation potential (Lo). The TNO and Afvalzorg models need besides these parameters the knowledge of the factor of dissimilation (ς) and conversion of carbon in methane (c), also the degradable carbon (C_o, C_{oi}) contained by waste which it is determined in the scientific literature [7, 12, 13, 17].

Methane generation potential (Lo) presents the overall quantity of methane which may be generated per mass unit from the waste landfilled and depends almost entirely on the waste composition, mainly the contents of organic degradable material. Its value is estimated based on the content of degradable carbon (DOC) and the stoichiometric factor (SF) [7].

A higher content of cellulose means a higher value of Lo. The theoretical values of L_o range between 6.2 – 270 Nm^3_{LFG}/t_{waste}, whereas the typical value, used by US EPA, is of 170 Nm^3_{LFG}/t_{waste} [13, 15].

Table 1

Mathematical models for the estimation of the emissions of methane from the landfills [12, 13, 15, 16, 17]

First Order	Consider the following parameters: - age and composition of the waste, - landfill management, - Climatic conditions. The first order models consider that all waste is decomposed with the same speed, and the LFG production decreases depending on the degradation of organic material.	Authors
SWANA[4]	$Q = ML_o k e^{-k(t-t_o)}$ (1) Where: Q – methane produced [m^3/yr]; M – mass of waste landfilled [tons]; Lo – methane generation potential [m^3_{CH4}/$tons_{waste}$]; k – degradation rate constant [1/yr]; t – time [yr], t_o – lag time [yr].	Swana, 1998
LandGEM[5] ver. 3.02	$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$ (2) Where: Q_{CH4} – methane produced [m^3/yr]; M_i – waste landfilled in the i^{th} year [tons/yr]; t_{ij} – age of the j^{th} section of waste mass M_i landfilled in the i^{th} year [yr].	US EPA, 2005
TNO[6]	$\alpha_t = \varsigma c A C_o k_1 e^{-k_1 t}$ (3) Where: α_t – LFG produced [m^3/yr]; ς – dissimilation factor; A – waste landfilled [tons]; c – factor of conversion [m^3_{LFG}/kgC]; C_o–degradable organic carbon [kgC/$tons_{waste}$]	Oonk and Boom, 1995
Mexican v2.0	$Q_{CH_4} = (MCF)(F) \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$ (4) Where: MCF – landfill management factor; F –fire factor	SCS Engineers, 2009
First Order Multi-phase	The organic material is divided in several categories of degradation: rapidly, moderate and slow; and its degradation is deemed independent one of the other.	Authors
SWANA	$Q = ML_o [F_r k_r e^{-k_r (t-t_o)} + F_s k_s e^{-k_s (t-t_o)}]$ (5) Where: F_r, F_s – rapidly respectively slowly degradable fraction; k_r, k_s – rapidly respectively slowly degradation rate constant [1/yr].	Swana, 1998
Afvalzorg	$\alpha_t = \varsigma c \sum_{i=1}^{3} A C_{o,i} k_{1,i} e^{-k_{1,i} t}$ (6) Where: i – fraction of waste with a degradation rate $k_{1,i}$	Afvalzorg, 1996

[4] SWANA – Solid Waste Association of North America
[5] LadGEM – Landfill Gas Model
[6] TNO – Netherlands Organization for Applied Scientific Research

If the landfills exploiting manner is known, this parameter can be determined by using the methodology IPCC [7]:

$$L_o = (MCF)(DOC)(DOC_f)(F)(\frac{16}{12}) \quad (7)$$

The decay rate constant (k) represents the rate at which waste landfilled decays and produces LFG [7]. The value of this constant depends on the waste humidity; the availability of nutrients for the bacteria generating methane; value of acidity (pH); environment temperature. However, these parameters cannot be determined directly inside the deposits, but the estimation is done through the annual average precipitations, [7, 18], according to the following (Eq. 8):

$$k = 0.00013x + 0.019 \quad [yr^{-1}] \quad (8)$$

Where: x – annual precipitations [mm]. The measurements made in a few countries, such as United States, Great Britain, New Zeeland, Canada and Netherlands indicate that the value of the degradation times ranges between 3 – 35 years [7].

3.2. Thermal conversion. Determining the Low Heating Value

Thermal processes such as direct combustion, pyro-combustion, gasification and pyro-gasification of MSW can also be used to recover the energy potential as heat for thermo-dynamic cycles Rankine - Hirn, Brayton or Otto using steam turbines, gas turbine and reciprocating engines [1, 8]. This treatment – recovery – neutralization – disposal process is part of W2E (Waste to Energy) concept and it is an alternative for the integrated waste management, since it reduces the quantity of final residues to landfilling, it requires less space and reduces the fossil fuels consumption for energy generation [1].

In the EU countries, there are 406 units of incineration exploited with a capacity of 54 million tons per year [11]. The countries with a high incineration rate of waste are: Denmark 54.2%, Sweden 48.6% and Germany 37.7%, Luxemburg 35.4%, Netherlands 32.6% reported to the quantity of waste generated [11].

In order to determine the low heating value of household waste for a target location it was used the weighted average of calorific value of waste parts:

$$LHV = \frac{\sum_{i=1}^{n} p_i h_i}{100} \quad (9)$$

Where: LHV – Low Heating Value [kJ/kg]; p_i – percentage of fractions (paper, board, plastic, etc.) of waste [%]; h_i – LHV of every component [kJ/kg].

Nevertheless its importance in estimating the energy potential of a fuel, for the waste case there are also a series of other thermal-physical-chemical properties required for a complete characterisation of a waste in order to be qualified or not for a certain thermal-chemical process treatment.

3.3 Energy potential of waste

The waste energy potential was determined in two ways: by energetic valuation of LFG recovered from landfills and by thermal conversion of waste.

Besides the energetic benefits (production of electric and/or thermal energy) of LFG, its capture allows the reduction of the emissions of GHG, mainly the methane emissions, contributing significantly to the environment preservation (the impact of CH_4 on climate change is over 21 times greater than CO_2) [7].

The quantity of energy recovered from LFG, is provided by the following (Eq. 10) [8, 9].

$$W = \dot{m}(\%V_{CH4})(Et)R\eta \tag{10}$$

Where: $\dot{m}$ – LFG quantity [m^3], V_{CH4} – methane fraction in LFG [%], Et – equivalent energy content of methane [kWh_t/m^3], R – efficiency of the recovery system [%], η - efficiency of the installation of conversion in energy [%], which generally on cogeneration ranges between 80 – 85% [9, 10].

On the other hand, the energy recovered by waste combustion depends on the waste mass M[kg]; low heating value of waste LVH [kJ/kg]; performance of incineration assembly – recovery boiler η_{CR}=(0.5 – 0.8) [8]

$$W = M(LHV)\eta_{CR} \tag{11}$$

4. Results and discussions

4.1 Estimation of landfill gas potential

On national wide, there are 31 landfills and 106 garbage dumps [5] therefore the value of landfill management factor (MCF) was selected 0.8. Considering the waste composition (see Table 1), and that Romania has a temperate-continental climate with annual average precipitations countrywide of 637 mm [5], the value of methane generation potential Lo, according to IPCC methodology [7] is presented in table 2.

Table 2

Potential of generating the methane

Parameter	MCF	DOC	DOCf	F	SF	Lo	Lo
Unit	--	gC/g_{waste}	--	--	g_{CH4}/gC	m^3_{CH4}/t_{waste}	m^3_{LFG}/t_{waste}
Value	0.8	0.125	0.77	0.5	16/12	76.7	153.4

As it may be seen, the value for methane generation potential is 76.7

m^3_{CH4}/t_{waste} and the LFG flow rate about 153.4 m^3_{LFG}/t_{waste}. According to IPCC (2006), the value for LFG is in the range of (100-200)m^3_{LFG}/t_{waste}. Thus, it may be stated that the estimation of the production of biogas is within acceptable limits.

Table 3 presents the values of the input data for first order models and multi-phase models (SWANA amended and Afvalzorg) based on the scientific literature [6, 15, 17], and according to waste composition, the repository management, and the environment conditions of Romania.

Table 3

Values of parameters applied for every model

Parameter		First order models	Multi-phase models
$k_{RD(r)}$	[an^{-1}]	-	0.10
k_{MD}	[an^{-1}]	-	0.0645
$K_{LD(s)}$	[an^{-1}]	-	0.03
$k_{(1)}$	[an^{-1}]	0.0648	-
L_o	[m^3_{CH4}/t_{waste}]	76.7	-
C_0	[kgC/t_{waste}]	108	-
C_{01}	[kgC/t_{waste}]	-	182
C_{02}	[kgC/t_{waste}]	-	118
C_{03}	[kgC/t_{waste}]	-	36
ζ	[-]	0.77	0.77
Methane	[%]	50	50

Note: RD(r) – rapidly degradable; MD – moderate degradable; LD(s) – slowly degradable

It may be noticed that the degradation interval of waste is about 7 years for the rapidly degradable components (food waste, vegetables, etc.); 11 years for those moderate degradable (paper, cardboard, textile) and 23 years for those slowly degradable (wood, straw, leaves, etc.).

The LFG production was estimated for the period 2002-2020. Fig. 5 shows the results of the estimation of LFG production by applying the methods described above (see Table 1).

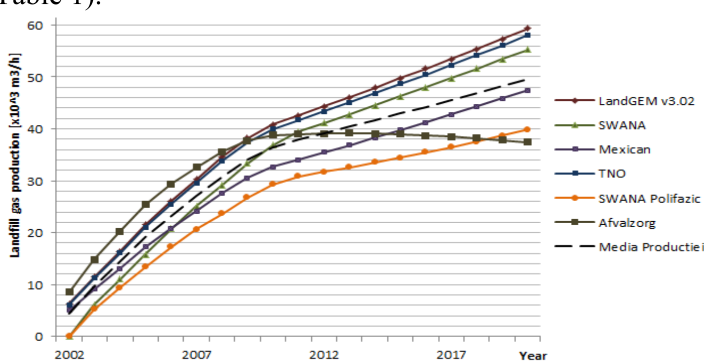

Fig. 4. Estimation of landfill gas potential

The results differ from one model to the other, which may be explained by different approaches used for every model (see Table 1). It may be noticed as well that, for 2014, the LFG flow estimated with the first order models LandGEM (47900 m^3/h); SWANA (44480 m^3/h) and TNO (46800 m^3/h) overestimate the gas production opposite to the average (41690 m^3/h); whereas the Mexican models (38320 m^3/h); SWANA modified (34000 m^3/h) and Afvalzorg (38080 m^3/h) underestimate the biogas production. This difference is given by the contents of degradable carbon considered for every model.

Thus, on first order models, generally, the quantity of degradable carbon is higher (unique potential Lo and constant k) than on multi-phase models where the organic material is divided in two (SWANA amended) or three (Afvalzorg) subcategories depending on their degradation, generating a lower quantity of degradable carbon.

In 2014, the average production of LFG (see Fig. 4), is of 41690 m^3_{LFG}/h (182.6 Mm^3_{CH4}/yr). It must be notified as well that, the gas production in 2020 is the highest, being in average of 49570 m^3/h.

Based on Fig. 4 it may be mentioned that the Mexican Model is the one reflecting the best the gas production countrywide.

4.2 Energy recovery

Based on the data presented above, the energy to be recovered both as biogas and heat of combustion was calculated. Considering an average methane content of 50%, the equivalent energy content of methane *Et*=10kWh/m3, the recovery system efficiency R=75% and the efficiency of the installation of conversion of LFG in energy □=85% (for combined heat and power plant); the energy to be recovered via LFG from the landfills is about 1164 GWh_t (Fig. 5). Of course this estimation is purely theoretical. For real scale applications there are additional variables to be considered such as: power generation unit type, capacity, cogeneration option, etc. that affects the global efficiency estimation and value and, consequently the energy generation output.

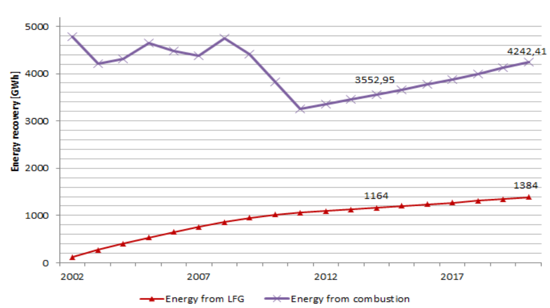

Fig. 5. Energy recovery from waste

For the combustion processing as well as for any thermal-chemical conversion chain the main input data is the low heating value of the product. Based on each waste component LHV the MSW average low heating value was calculated to be about 6260.86 kJ/kg (1.74 kWh_t/kg). The average humidity content was considered 50% [8], that represent the upper limit for the house hold waste to be utilized via combustion [20]. The calorific value of waste from EU is in average of 8360 kJ/kg [8, 19].

Based on these assumptions the energy to be recovered by waste combustion, in 2014 could be about 3553 GWh_t.

Table 4

Energy recovery, year 2014

Technology	Capacity [GWh_t]
Landfill gas	1164
Combustion	3553

Generally, it may be noticed in Fig. 5 that the energy recovered as thermal power by combustion of waste is superior to that obtained from the recovery of LFG from landfills. Nevertheless for power or combined heat and power generation there are many parameters to be considered starting with plant capacity and type, global energy efficiency, electricity vs. heat ratio. All these variables may shift the balance between solutions and case studies are required for a certain application. Additionally the investment costs, the environmental impact analysis and the economic analysis will decide the optimum energy conversion chain.

5. Conclusions

The Romanian energy potential from municipal solid waste was investigated using two different conversion chains (bio-chemical and thermal). The study revealed sensitive differences between the computation results for biogas flow generation as well as for the CH_4 content when using different mathematical models. In 2014, the average production of LFG in Romania was estimated at 41690 m^3_{LFG}/h, with an annual methane production of about 183 Mm^3_{CH4}/yr . The gas production in 2020 will be the highest with about 49570 m^3/h . The Mexican Model proved to be the most accurate for the gas production estimation countrywide. The analysis covered a period of 18 years. For 2014, the energetic potential estimated as thermal power is about 1164 GWh_t via biogas capture from the landfills and about 3553 GWh_t via thermal conversion.

Acknowledgements

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