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Article

Modelling the Potential Biogas Productivity Range from a MSW Landfill for Its Sustainable Exploitation

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Abstract: A model of biogas generation was modified and applied to the case of a sanitary landfill in Italy. The modifications considered the role of the temperature field normally established within each layer of waste. It must be pointed out the temperature affects the anaerobic biodegradation kinetics. In order to assess the effect of moisture on the waste biodegradation rate, on the bacteria process and then on the methane production, the model was compared with the LandGEM one. Information on the initial water content came from data concerning waste composition. No additional information about the hydrological balance was available. Thus, nine sets of kinetic constants, derived by literature, were adopted for the simulations. Results showed a significant variability of the maximal hourly biogas flows on a yearly basis, with consequences for the collectable amount during the operating period of a hypothetical engine. The approach is a useful tool to assess the lowest and highest biogas productivity in order to analyze the viability of biogas exploitation for energy purposes. This is useful also in countries that must plan for biogas exploitation from old and new landfills, as a consequence of developments in the waste sector.

Keywords: biodegradation; biogas; landfill; methane; modelling; moisture; MSW

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1. Introduction

The high management cost for the treatment of wet waste and the increasing need for reducing the quantity of organic fraction in landfills have increased interest in waste management in Europe. Several studies have demonstrated the increased interest in waste management, environmental legislation and recently, from a public viewpoint [1–11].

Biological processes under anaerobic conditions drive the production of biogas, namely, a gaseous mixture composed almost entirely of methane (CH_4) and carbon dioxide (CO_2) [12–14]. Anaerobic bacterial flora, which is highly specialized and differentiated in strains with a close syntrophic relationship, is responsible of the decomposition of organic material [15–18].

In landfilled waste, the biochemical reactions evolve through three phases: an aerobic phase, an acid phase and the methanogenesis, which is the main source of the CH_4 contained in the final biogas mixture. The landfill gas is produced by microbial anaerobic degradation of the organic fraction in waste. The biodegradable organic material in waste is made up of vegetable and animal matter, paper, garden waste, wood and textile material. The organic carbon is the common element between biodegradable materials that allows the development of methane production. On the basis of the average composition of municipal waste and previous experimental studies [19], some considerations can be expressed: organic carbon is about 50% of organic matter (on dry basis) and the organic carbon potentially leading to biogas formation is about 50% of the total organic carbon. Pre-treatments of the organic waste also decrease the biogas potential: bio-drying and bio-stabilization perform a mineralization of the organic matter, whose carbon content is converted to CO_2 by aerobic bacteria [20,21].

The biogas production in the landfill is influenced by several factors: availability of oxygen, pH, alkalinity, nutrients, inhibitors, temperature and water content. The absence of oxygen is fundamental condition for the growth of anaerobic bacteria: methanogenic bacteria require very low redox potentials (lower than −330 mV) [22]. Another important state is the stability of pH range, since methanogenic bacteria operate with the highest efficiency at a pH between 6 and 8 [23]. These bacteria are very sensitive to pH variation and different operative conditions may lead to low conversion of H_2 and acetic acids, with a consequent accumulation of volatile organic acids and consequently a decrease in pH, which can stop the process. An adequate ratio of nitrogen (N) and phosphorus (P) is also required by the anaerobic ecosystem [24]. If there is interest in exploiting biogas for energy purposes, the presence of inhibitors like sulfates, CO_2, ammonium, sodium, potassium, calcium, magnesium and some organic compounds is to be avoided in a landfill. Additional key factor is the temperature: laboratory experiences demonstrated that increases in temperature from 20–30 and 40 °C raise considerably the CH_4 generation rate [25,26]. It is noted that the temperature is no more influenced by outside at a certain depth of the landfill, but only by the exothermic fermentative reactions of waste. Furthermore, the relationship between temperature and outside is a function of the insulation properties of the layers of waste deposited.

Another factor, which interferes in the generation of methane in a landfill, is the moisture content. In the past, several studies have investigated the effect of different levels of moisture on bacteria activity [27,28]. The moisture content controls methane production, since it stimulates microbial activity by providing closer contact between soluble and insoluble substrates and bacteria [29]. In other words, water allows for bacterial life, offers the maximal solid–liquid interface and, then, permits the hydrolysis of organic matter—the diffusion of bacteria—of the hydrolyzed substrate and of nutrients in the heap of waste.

For these reasons, the biogas generation raises significantly with temperature, as demonstrated by the results of several studies [30]. In one of these, it was observed that an increase of the water content implies a logarithmic increase of the biogas production [31]. In addition, waste samples, if led to saturation, generated an amount of biogas higher than one order of magnitude with respect to unsaturated samples. Also, laboratory studies, carried out on lysimeters, showed that a very low amount is obtained in poor moisture conditions. The water content in the waste disposed of in landfill depends on climatic conditions, on the waste composition and on the techniques of collection [2]. Following the disposal, moisture becomes also a function of the coverage, the sealing of the bottom and sides, rainfall, the presence of aquifers and leachate recirculation. Regarding the leachate recirculation, as reported by Abichou [32], this process decreases the biochemical methane potential, increases the methane yield, the decomposition of solids but also the pollutants' percentage in the final leachate, making it difficult to be treated [33]. However, in order to estimate the biogas generation from landfills, a correct determination of the initial moisture and the hydrological balance is necessary.

In the light of the importance of a correct determination of moisture, the aim of this study is to focus on the problems related to the modelling of biogas generation when insufficient information about the water content and the hydrological balance of a landfill is available. The model developed by Manna *et al.* [34] was modified by the authors in order to evaluate the generation of biogas from an Italian landfill. Data on the waste composition and estimation of its changes for the incoming years, of a municipal landfill located in the North of Italy, chosen as case-study, are the basis for the model. These data provide the only available information about the water content of the incoming waste to be disposed of.

Difficulties in the choice of an appropriate biogas generation rate for modelling purposes will be discussed and, as an attempt to define a range of reasonable results, different scenarios will be simulated, starting from different biogas generation rates suggested by other studies. At the end, a further comparison with the Landfill Gas Emission Model LandGEM version 3.02 [35] was made in order to evaluate the accuracy of the proposed model.

2. Materials and Methods

A useful tool to estimate the generation of biogas from the landfill is biochemical modelling. The biogas estimation from the waste anaerobic digestion can be approximated by the following equation:

$$\frac{dC_{gas,i}}{dt} = K_i\left(C_{gas,i} - C_{gas0,i}\right) \tag{1}$$

where:

- $C_{gas,I}$, which is expressed in kg, is the amount of organic carbon that could be effectively used for energy purpose for the component I of the waste,
- $C_{gas0,I}$, expressed in kg, is the organic carbon that could be effectively used for energy purpose at the time $t = 0$ for the component I,
- K_i is the biodegradation rate for the component i.

A stoichiometric model based on the Arrhenius equation, can calculate the organic carbon that can be effectively used for energy production, whilst K_i depends on the characteristics of the component i of the waste and on the temperature, according to the equation:

$$K_i = k_i\, exp\left[-\frac{E}{RT_0}\left(1-\frac{T_0}{T_w}\right)\right] \tag{2}$$

where

- k_i is the biodegradation rate constant for the component i,
- E is the activation energy (in J mol^{-1}),
- R is ideal gas constant (8.314 J mol^{-1} K^{-1}),
- T_w is the waste absolute temperature and T_0 is equal to 308.15 K [34].

To simplify the biogas generation modelling and on the basis of biodegradability, the waste components can be aggregated into three main fractions: a rapidly biodegradable fraction (RBF), made of food waste; a moderately biodegradable fraction (MBF), made of green waste and under-sieve; and a slowly biodegradable fraction (SBF), that contains paper, cardboard, wood and textiles [30]. A specific biodegradation rate constant (k_i) can be associated to each fraction. The sum of these three contributions, expressed through integration of Equation (1), allows obtaining the cumulative biogas production (G_t, expressed in Nm^3), at the time t:

$$G_t = \sum_{i=1}^{a} g\, C_{gas\,0,i}[1-\exp(-k_i t)] \tag{3}$$

where g is the specific biogas generation (1.867 Nm^3 kg^{-1} of biogasifiable organic carbon, if it is assumed that the mixture is made only of CH_4 and CO_2) [36].

Over the years, different kinds of numerical and mathematical models, of different complexity have been developed and used [37]. Among the most important: the triangular model is a much simplified approach that does not take into account the effect of temperature variation; the two-stage exponential model adopts two biodegradation rate constants, one for the growth stage and one for the decrease phase of the generation rate; the Landfill Gas Emission Model LandGEM is a biochemical model implemented by the U.S. EPA that considers the waste as composed of an only class, thus requiring an only kinetic constant for methane (k) and a potential methane generation per ton of waste (L_o):

$$Q_{CH4} = L_o R[exp(kc) - \exp(kt)] \tag{4}$$

where:

- Q_{CH4} is the volume of methane generated annually,
- R is the mean amount of waste disposed annually,
- c is the number of years from the landfill closure,
- t is the number of years from the first disposal [35].

It is important to highlight that the default values, k and L_o, suggested by the model, are representative of American landfills and, thus, may not be applied directly to European landfills without a calibration on monitored case-studies.

Manna developed a more accurate biochemical model, which considers the temperature variation in time and depth and the landfill settlement. The model describes the behavior of the landfill over three different periods of time. In the first one, the waste is discharged in a test cell and the overall depth of the landfill increases as a function of the time; the cell is divided into an inhibition zone and a reaction zone;

in the inhibition zone no reaction occurs, while the reaction zone is involved in the biogas production. The second period is identified with the end of the cultivation of the landfill and an insulation layer covers the heap. In the third period, the entire column of waste contributes to the production of methane and there is no inhibition zone since each layer of waste has a residence time higher than the inhibition time.

This model was originally modified adding a sub-model for the calculation of the temperature field within each layer of waste, which implements the equations of energy conservation at finite differences, integrating them according to the boundary conditions that characterize every cell at a certain time. In the revised formulation, the landfill is no longer described as only a column of waste, but as a series of overlapping cells representing the single layers. An Italian municipal landfill was used to calibrate the modified model [37]. The subdivision of the heap in an active and inactive zone, like in Manna model, is no longer needed. This is because each cell is defined active or inactive depending on whether its residence time is higher or lower than the inhibition time (assumed equal to 4 months in this case), which the user can specify before running the code [37]. Furthermore, the proposed model calculates the internal heat generation (*H*) due to the exothermic biodegradation reactions of organic matter (subscript *i* is omitted for simplicity of reading):

$$H = -\rho_w n_g \Delta E_r \quad (5)$$

where:

- ρ_w is the density of waste,
- ΔE_r is the energy released by the biological reaction
- n_g is the volume of gas that can be generated.

$$n_g = g A_k K G_t \quad (6)$$

with A_k inhibition factor due to excessive temperature:

$$A_k = \begin{cases} 0.014(T_w - 273.15) + 0.28 & T_w \leq 340\ K \\ 0 & T_W > 340\ K \end{cases} \quad (7)$$

Because temperature may increase within the layers until values that can inactivate biological activity of the anaerobic bacteria, the internal heat generation is then limited to a temperature not higher than 340 K, over which inhibitory conditions are established. Every single cell provides its own contribution to biogas generation, since every cell generates a specific amount of biogas calculated on the basis of the field of temperature. To take into account the outside temperature variability, the field temperature, used in the model, was made to depend on the boundary conditions and on the evolution of the thermal state, both for the single cell and for the whole configuration.

The user, for each temporal step, can define the depth of every cell (one month in this case). Using data about the area occupied by each lot and data about the annual amount of waste dumped makes the calculation of the depths an easy step. With the modified model, a better approximation of the evolution of the landfill in terms of its annual expansion is possible. In the case study, information about the historical evolution of the landfill, comprehensive of the dates of activation of each lot, were retrieved, in order to simulate the annual growth of each sector as more accurately as possible. In fact, considering the landfill as composed of an only heap of waste, instead of different heaps, may lead to erroneous results: the creation of different confined environments may entail a higher insulation of the heaps from the outside, since the period of exposure of the waste to the atmosphere is reduced. This may imply a shorter duration of the aerobic phase and, then, an anticipation of the acid phase and of the methanogenesis. Furthermore, considering the landfill divided into smaller and multiple sectors would imply a higher biogas generation, since the biogas production is influenced by the waste age [38] and smaller heaps are composed of waste that has been more recently dumped and covered. Indeed, the cultivation of the landfill sector by sector implies that the covering of each heap takes place after a shorter period with respect to the case of considering the landfill as an only heap. The consequent insulation may promote higher temperatures, close to the optimum for methanogenic bacteria, and the presence of more recent waste may enhance the biogas production. The model provides the possibility to realistically define the landfill and the way this is cultivated.

For the presented case study, the waste composition for the incoming years was estimated with the hypothesis of reaching the goal of selective collection established for 2013, which prescribes a minor content of fermentable organic matter in the total amount of waste to be deposited into the landfill [39,40]. Data about the waste composition were collected from 2004 (opening year of the studied part of landfill) to 2011; from 2013–2017 (estimated year of closure) the composition was assumed to be constant and equal to that estimated for 2013; for 2012, a mean composition between 2011 and 2013 was assumed, in terms of amount of waste deposited for each class (Table 1). The classes were grouped according to the three fractions presented above (RBF, MBF and SBF).

Table 1. Percentages of waste composition for the biogas generation modelling adopted for the case-study and annual amount of incoming waste [39].

Waste fractions	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Food waste	32.1%	29.5%	20.4%	15.5%	21.5%	24.2%	19.4%	14.5%	15.6%	17.4%
Green waste	6.8%	5.2%	5.4%	6.7%	4.2%	5.2%	5%	0.4%	3.5%	8.2%
Paper	7.4%	10.7%	10.1%	13.6%	14.6%	10.5%	10%	9.1%	9.1%	9.1%
Cardboard	2.8%	4.6%	5%	11%	6.3%	5.7%	5.8%	4.7%	4.8%	4.9%
Composites	7%	3.2%	4.6%	4.4%	1.4%	0.8%	0.2%	0.9%	1.8%	3.2%
Metals	1.5%	3.4%	2.5%	2.7%	6.2%	4.8%	2.2%	3.8%	2.9%	1.6%
Plastics	13%	9.7%	19.1%	19.8%	13.6%	16.8%	19.4%	18.5%	18.5%	18.7%
Rubber	0.7%	0.1%	0.8%	2.5%	0.7%	0.3%	1.1%	0.4%	0.7%	1.1%
Glass and aggregates	4.7%	12.3%	5%	4%	5.1%	3.6%	5%	10.5%	8.8%	6.3%
Textiles	1.6%	5.1%	4.5%	4.3%	3.6%	2.1%	6%	3.4%	4.4%	5.8%
Diapers	12.4%	6.4%	9.2%	3.1%	11.5%	8.6%	10.9%	14.9%	15.4%	16.3%
Wood	1.4%	2.1%	1.3%	2.5%	1.6%	1.3%	0.9%	3.3%	3.3%	3.3%
Under-sieve	4.8%	3.2%	9.1%	7.2%	8.2%	13.4%	12.8%	15.5%	9.9%	1.7%
Other	3.7%	4.5%	3%	2.9%	1.6%	2.8%	1.6%	0%	1.2%	2.4%
Total (tons)	24809	22440	44568	49432	40128	13966	2607	15990	13321	10653

The proposed model was applied also considering the history of the landfill, following its growth sector by sector and assuming the future opening of more sectors. To perform an appropriate modelling of biogas generation process, an appropriate set of biodegradation rates (k_i) was needed. The choice of these parameters depends strongly on the specific landfill in which the model is applied to and would require a calibration on each landfill, so this represents the main problem for an accurate modelling. In fact, the biodegradation rates are functions of moisture, which represents the most important factor in the anaerobic decomposition. The absence of a well-designed biogas extraction/monitoring system for the landfill made a calibration on this specific case impossible. Due to the impossibility of choosing one specific set of biodegradation rates, nine scenarios were elaborated on the basis of different values for k_i proposed in literature and/or applied to real cases (Table 2). Thus, nine simulations were run by applying the modified model, covering a period between 2004 and 2040.

Table 2. Biodegradation rate constants for the three fractions of waste (RBF, MBF and SBF) adopted for the biogas generation modelling.

Scenario	Model	Reference	Application or case-study	Biodegradation rate (y^{-1})		
				RBF	MBF	SBF
1	GasSim	[39]	arid zones	0.076	0.046	0.013
2	GasSim	[39]	moderately wet zones	0.116	0.076	0.046
3	GasSim	[39]	very wet zones	0.694	0.116	0.076
4	Afvalzorg	[41]	Dutch municipal landfill 1	0.187	0.099	0.030
5	Afvalzorg	[41]	Dutch municipal landfill 2	0.231	0.116	0.030
6	ADEME	[39]	-	0.500	0.100	0.040
7	BIO-7	[42]	-	0.244	-	0.082
8	Manna *et al.*	[34]	Italian municipal landfill	0.2	0.139	0.046
9	Hoeks	[28]	-	0.693	0.139	0.046

With the goal to compare the results obtained from the proposed model, the data were implemented also into the LandGEM model. As mentioned above, the parameters adopted in the first method are only kinetic constant for methane (k) and a potential methane generation per ton of waste (L_o). Since the default values suggested by the model (k and $L_{o,}$) are representative of American landfills, the following equations were used to adapt the model to the case study.

$$k = \sum_{i=1}^{n} (\%r_i * vp) \tag{8}$$

$$L_0 = MCF * DOC * DOC_F * F * \frac{16}{12} \tag{9}$$

where:

- $\%r_i$ is the percentage of waste in each category
- vp is the kinetic constant predetermined by the Mexico LFG model 2.0, as described by Aguilar [36],
- MCF is the correction factor for methane,
- DOC is the degradable organic carbon (fraction),
- DOC_F is the fraction of degradable organic carbon assimilated,
- F is the fraction of CH_4 in the biogas, and the ratio 16:12 is the stoichiometric constant.

These relations are used to modify the parameters into the Mexico LFG model in order to estimate the landfill gas generation in a specific landfill. In the case study the following values were adopted: 1 for MCF, 0.1603 for DOC, 0.5 for F, whilst two default values proposed by Intergovernmental Panel on Climate Change (IPCC) were assumed for DOC_F: 0.77 [43] and 0.50 [44].

In order to evaluate the kinetic constant for methane production, $\%r_i$ were calculated by a weighted average from 2004–2017 for each category of waste (from 2013–2017 the composition was assumed to be constant and equal to that estimated for 2013).

To define the *vp* factor, different kinds of degradation for each waste component were assumed: a very rapid degradation rate for food waste, a moderately rapid one for green waste and paper, a moderately slow one for wood and under-sieve, a very slow one for cardboard, textiles, diapers, whilst the other materials were assumed inert [37]. The final parameters obtained for the specific case of study were: 0.033 for *k*, 82.28 $m^3 t^{-1}$ (with 0.77 DOC_F) and 53.43 $m^3 t^{-1}$ (with 0.50 DOC_F) for L_0.

3. Results and Discussion

By a preliminary analysis of the results of the simulations, three of the nine scenarios (Scenario 1, Scenario 3 and Scenario 9) were excluded from the subsequent step of this study, since their sets of kinetic constants are typical of extreme climatic conditions (dry zones and wet zones), which are far from the ones of the present case study. The other kinetic parameters used for the remaining scenarios could be considered representative of temperate climates.

Figure 1 presents the maximal hourly biogas flows on yearly average of 6 scenarios, obtained by the proposed model, and of case A (k = 0.033, L_0 = 82.28) and B (k = 0.033, L_0 = 53.43) calculated by the LandGEM model. On the basis of the six scenarios, the calculated biogas flows show a large variability, ranging from 114 $Nm^3 h^{-1}$ to 180 $Nm^3 h^{-1}$. Even without observed values of the methane production, it is possible to state that the LandGEM model underestimates the methane generation when it was used a lower factor of DOC_F, which represents the degradable organic fraction that is converted into biogas. This may be ascribed to the simple hypothesis of the LandGEM model, which assumes the waste as composed of an only class, thus not contemplating the annual change of the waste composition. Indeed, the higher trend of the methane generation after the closure of the landfill is due to a higher presence of organic matter into the waste than the real situation.

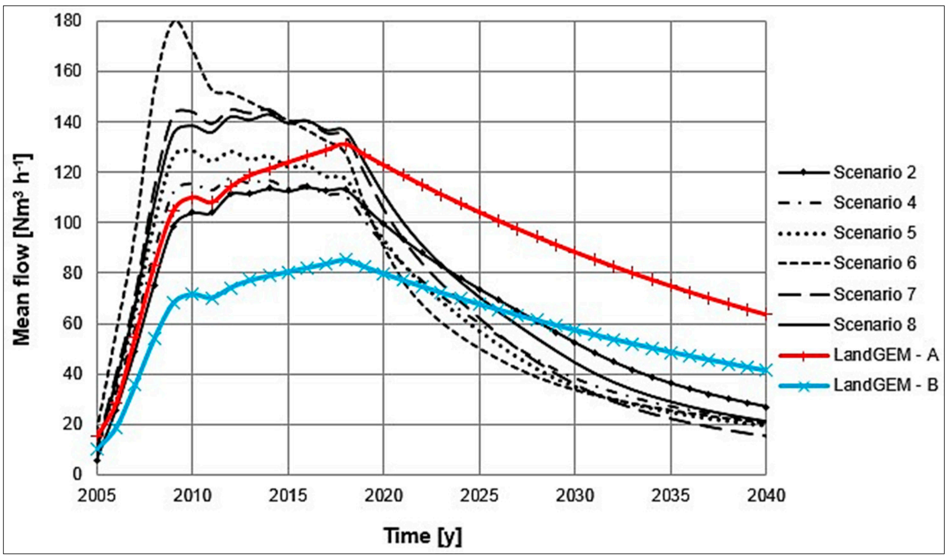

Figure 1. Mean annual biogas flows on yearly average calculated for the case-study on the basis of the six scenarios considered and of case A (red line) and B (blue line); Scenarios 1, 3 and 9 were excluded, since they were considered as extreme situations.

With the goal of simulating the biogas uptake from the extraction system and the transfer to a generator, a set of efficiency coefficients for the whole collecting system was introduced (Table 3). In order to make an economic balance for the exploitation of the whole biogas production also after the landfill closedown, which is expected for 2017, these coefficients simulate a temporal variability of the system efficiency in transferring the biogas to the generator till 2026 (year of its hypothetical end of life).

Table 3. Efficiencies of the collecting system adopted for the simulations.

Year	Efficiency of the collecting system (%)
2008	19
2009	28
2010	32
2011	50
2012	52
2013	55
2014	58
2015	61
2016	64
2017	67
2018	71
2019	75
2020	79
2021	83
2022	80
2023	78
2024	76
2025	73
2026	71
2027	69
2028	67
2029	65
2030	63
2031	61
2032	59
2033	58
2034	56
2035	54
2036	53
2037	51
2038	50
2039	48
2040	47

Figure 2 presents the maximal volume of collectable biogas during the operating period of the generator. However, such calculation is affected by the variability of the results. It is possible to highlight that, for five of the six scenarios, the most convenient year for starting the biogas exploitation is 2011, whilst, for the remaining scenario (Scenario 6), the maximum collectable volume would have been obtained if the biogas exploitation had started in 2009. Therefore, these results suggest that the biogas utilization should start as soon as possible, in order to exploit the maximal available energy.

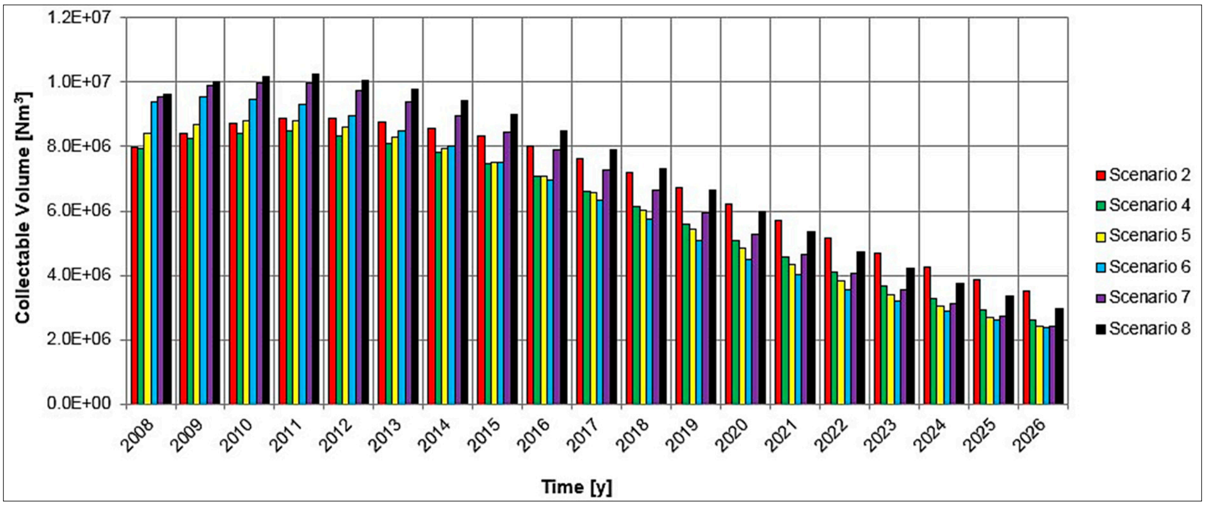

Figure 2. Collectable volume of biogas in 15 years, as a function of the starting year of its exploitation for energy purposes.

Hence, the availability of data about the water content of the landfill is of primary importance, since it has a large influence on the kinetics of biodegradation of the organic matter in the waste and on a consequent correct estimation of the biogas productivity, which is fundamental for a cost-benefit analysis if the biogas utilization for energy purpose is taken into consideration. However, the presented approach is a useful tool to estimate the range of exploitable biogas flows and the lowest biogas productivity, which is important to assess the feasibility of the biogas exploitation. This approach is useful not only in countries with a tradition in waste management, like the old EU members, but also in recent EU entries, where the waste management sector needs a reorganization. In the consequent waste management evolution, landfilling plays a central role for a transient period of years. Indeed, the concept of landfill pre-treatment has been postponed for years in new EU entries in order to allow a viable restructuration of the sector that must move from a landfill-based strategy to a source separation strategy. During this period, the EU accepts that landfills are maintained with conventional methods, where the presence of high contents of food waste and other biodegradable waste will allow the generation of a significant amount of biogas for years. For that reason, it is important to set and adopt methodologies, like the one presented in this paper, in order to collect and organize information useful for decision makers (in spite of its environmental impact, biogas from landfills is a renewable energy source that must be valorized when present).

4. Conclusions

The absence of information on the hydrological balance of a landfill and, consequently, on the water content of the waste entails the inclusion of uncertainties and approximations in the estimation of the biogas potential. The application of the proposed model allowed the generation of a range of biogas potential curves to account for the variability of the expected biogas flows. The proposed model considers the temperature field that is normally established within each layer of waste and that controls, in its turn, the anaerobic biodegradation process, for a more realistic simulation of the biogas production.

The estimation of the potential biogas is particularly important to assess the feasibility of its exploitation for energy purposes. The scenarios created for the simulations differ one from the other for the kinetic constants adopted, which are related to the water content of the waste. As expected, the calculated maximal hourly biogas flows on yearly average, on the basis of the scenarios considered, showed a large variability, ranging from 114 $Nm^3\ h^{-1}$ to 180 $Nm^3\ h^{-1}$. The results were compared with the output of the LandGEM model (version 3.02), a widespread model adopted in the U.S.A. as reference for estimating the methane productivity from landfills. The application of LandGEM showed the tendency to underestimate the results of the model of Manna modified by the DICAM.

To simulate the biogas exploitation by a generator, a set of efficiency coefficients for the biogas collecting system was introduced, assuming a temporal variability till the year of hypothetical disposal of the generator (2026). The variability of the calculated biogas flows showed repercussions for the maximal collectable volume during the operating period. Hence, the availability of data about the water content of the landfill is of primary importance, since it has a large influence on the kinetics of biodegradation of the organic matter in the waste and on a consequent correct estimation of the biogas productivity, which is fundamental for a cost-benefit analysis if biogas utilization for energy purposes is taken into consideration.

A calibration on the landfill would have been needed, for a more accurate application of the model, but the absence of a spatially well-represented biogas monitoring system did not make it possible. However, the described approach represents a useful tool to estimate the lowest and highest biogas productivity in order to assess the feasibility of the biogas exploitation for energy purposes. Furthermore, it can be used also as a first step for the analysis of the environmental impact of a landfill: the dynamics of biogas generation can be coupled with emission data of organic micro-pollutants (as benzene, PCDD/F, *etc.*) taking into account the role of fugitive emissions and flue-gas after combustion of conveyed biogas.

Finally, the proposed approach should be adopted having clear limits in mind that come from the limited information available on the history of those landfills to which it is addressed: it must be used as a preliminary exploratory tool.

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Author Contributions

Elena Cristina Rada and Marco Ragazzi designed the research and performed preliminary considerations; Marco Schiavon developed the modeling and wrote the paper supported by Paolo Stefani. All authors contributed to a deeper data analysis, read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Liamsanguan, C.; Gheewala, S.H. LCA: A decision support tool for environmental assessment of MSW management systems. *J. Environ. Monitor.* **2008**, *87*, 132–138.
2. Rada, E.C.; Istrate, I.A.; Ragazzi, M. Trends in the management of residual municipal solid waste. *Environ. Technol.* **2009**, *30*, 651–661.
3. Tarabella, A.; Burchi, B. Systematic review of sustainable waste management systems. *Q. Access Success* **2011**, *12*, 47–55.
4. Ragazzi, M.; Rada, E.C. RDF/SRF evolution and bio-drying. *WIT Trans. Ecol. Environ.* **2012**, *163*, 199–208.
5. Ionescu, G.; Rada, E.C.; Ragazzi, M.; Marculescu, C.; Badea, A.; Apostol, T. Integrated municipal solid waste model using advanced pretreatment and waste to energy processes. *Energ. Convers. Manag.* **2013**, *76*, 1083–1092.
6. Albu, A.; Ivan, P. Waste management between authorities policies and residents perception. *Q. Access Success* **2013**, *14*, 441–447.
7. Vaccari, M.; Torretta, V.; Collivignarelli, C. Effect of Improving Environmental Sustainability in Developing Countries by Upgrading Solid Waste Management Techniques: A Case Study. *Sustainability* **2012**, *4*, 2852–2861.
8. Castagna, A.; Casagrande, M.; Zeni, A.; Girelli, E.; Rada, E.C.; Ragazzi, M.; Apostol, T. 3R'S from citizens point of view and their proposal from a case-study. *UPB Sci. Bull.* **2013**, *75*, 253–264.
9. Ionescu, G.; Mărculescu, C.; Badea, A. Alternative solutions for MSW to energy conversion. *UPB Sci. Bull.* **2010**, *73*, 243–254.
10. Ragazzi, M.; Torretta, V.; Ionescu, G.; Istrate, I.A. Maintenance strategies and local impact of MSW incinerators. *WIT Trans. Ecol. Environ.* **2013**, *176*, 235–244.
11. Torretta, V.; Ionescu, G.; Raboni, M.; Merler, G. The mass and energy balance of an integrated solution for municipal solid waste treatment. *WIT Trans. Ecol. Environ.* **2014**, *180*, 151–161.
12. Andreottola, G.; Ragazzi, M.; Foladori, P.; Villa, R.; Langone, M.; Rada, E.C. The unit integrated approach for OFMSW treatment. *UPB Sci. Bull.* **2012**, *74*, 19–26.
13. Trulli, E.; Torretta, V.; Raboni, M.; Masi, S. Incineration of pre-treated municipal solid waste (MSW) for energy co-generation in a non-densely populated area. *Sustainability* **2013**, *5*, 5333–5346.
14. Grosser, A.; Worwag, M.; Neczaj, E.; Kamizela, T. Co-digestion of organic fraction of municipal solid waste with different organic wastes: A review. In *Environmental Engineering IV*; Pawlowski, A., Dudzinska, R.M., Pawlowski, V., Eds.; CRC Press-Taylor & Francis Group: London, UK, 2013.
15. Chanakya, H.N.; Sharma, I.; Ramachandra, T.V. Micro-scale anaerobic digestion of point source components of organic fraction of municipal solid waste. *Waste Manag.* **2009**, *29*, 1306–1312.
16. Rada, E.C.; Ragazzi, M.; Torretta, V. Laboratory-scale anaerobic sequencing batch reactor for treatment of stillage from fruit distillation. *Water Sci. Technol.* **2013**, *67*, 1068–1074.

17. Callegari, A.; Torretta, V.; Capodaglio, A.G. Preliminary trial application of biological desulfonation in anaerobic digestors from pig farms. *Environ. Eng. Manag. J.* **2013**, *12*, 815–819.
18. Martinez, S.; Torretta, V.; Minguela, J.; Siñeriz, F.; Raboni, M.; Copelli, S.; Rada, E.C.; Ragazzi, M. Treatment of slaughterhouse wastewaters using anaerobic filters. *Environ. Technol.* **2014**, *35*, 322–332.
19. Pfeffer, J.T. *Reclamation of Energy from Organic Wastes*; EPA-670/2-74-016; Environmental Protection Agency: Cincinnati, OH, USA, 1974.
20. Ragazzi, M.; Rada, E.C.; Panaitescu, V. Municipal solid waste pre-treatment: A comparison between two dewatering options. *WIT Trans. Ecol. Environ.* **2008**, *102*, 943–949.
21. Rada, E.C.; Ragazzi, M.; Badea, A. MSW Bio-drying: Design criteria from a 10 years research. *UPB Sci. Bull.* **2012**, *74*, 209–216.
22. Cossu, R.; Andreottola, G.; Muntoni, A. *Modelling Landfill Gas Production*; Christenses, T.H.R., Cossu, R., Stegmann, R., Eds.; E & FN Spon: London, UK, 1996.
23. Zehnder, A.J.; Ingvorsen, K.; Marti, T. *Microbiology of Methane Bacteria*; Hughes, D.E., Stafford, D.A., Wheatley, B.I., Baader, W., Lettinga, G., Nyns, E.J., Verstraete, W., Wentworth, R.L., Eds.; Elsevier Biomedical: New York, NY, USA, 1982.
24. Zhang, C.; Su, H.; Baeyens, J.; Tan, T. Reviewing the anaerobic difestion of food waste for biogas production. *Renew. Sustain. Energ. Rev.* **2014**, *38*, 383–392.
25. Buivid, M.J. *Laboratory Simulation of Fuel Gas Production Enhancement from Municipal Solid Waste Landfills*; Dynatech R&D Company: Cambridge, MA, USA, 1980.
26. Ehrig, H.J. Treatment of sanitary landfill leachate: Biological treatment. *Waste Manag. Res.* **1984**, *2*, 131–152.
27. Park, S.; Brown, K.; Thomas, J. The effect of various environmental and design parameters on methane oxidation in a model biofilter. *Waste Manag. Res.* **2002**, *20*, 434–444.
28. Scheutz, C.; Kjeldsen, P. Environmental factors influencing attenuation of methane and hydrochlorofluorocarbons in landfill cover soils. *J. Environ. Qual.* **2004**, *33*, 72–79.
29. Machado, S.L.; Carvalho, M.F.; Gourc, J.P.; Vilar, O.M.; Do Nascimento, J.C.F. Methane generation in tropical landfills: Simplified methods and field results. *Waste Manag.* **2009**, *29*, 153–161.
30. Andreottola, G.; Cossu, R. Modello matematico di produzione del biogas in uno scarico controllato. *Rifiuti Solidi* **1998**, *2*, 473–483.
31. Rees, J.F. Major factors affecting methane production in landfills. In Proceedings of the Landfill Gas Symposium, Harwell, UK, 6 May 1981.
32. Abichou, T.; Barlaz, M.A.; Green, R.; Hater, G. Liquid balance monitoring inside conventional, Retrofit, and bio-reactor landfill cells. *Waste Manag.* **2013**, *33*, 2006–2014.
33. Rada, E.C.; Istrate, I.A.; Ragazzi, M.; Andreottola, G.; Torretta, V. Analysis of electro-oxidation suitability for landfill leachate treatment through an experimental study. *Sustainability* **2013**, *5*, 3960–3975.
34. Manna, L.; Zanetti, M.C.; Genon, G. Modelling biogas production at landfill site. *Resour. Conserv. Recy.* **1999**, *26*, 1–14.
35. US-EPA. Available online: http://www.epa.gov/nrmrl/appcd/combustion/cec_models_dbases.html (accessed on 10 June 2014).

36. Auguilar-Virgen, Q.; Taboada-González, P.; Ojeda-Benítez, S.; Cruz-Sotelo, S. Power generation with biogas from municipal solid waste: Prediction of gas generation with *in situ* parameters. *Renew. Sustain. Energ. Rev.* **2014**, *30*, 412–419.
37. Autonomous Province of Trento (PAT). *Concessione di Lavori per la Progettazione, Realizzazione e Gestione Dell'impianto di Combustione o Altro Trattamento Termico con Recupero Energetico per Rifiuti Urbani e Speciali Assimilabili in Località Ischia Podetti, nel Comune di Trento—Studio di fattibilità*; PAT: Trento, Italy, 2009.
38. Hanson, J.L.; Yeşiller, N.; Onnen, M.T.; Liu, W.-L.; Oettle, N.K.; Marinos, J.A. Development of numerical model for predicting heat generation and temperatures in MSW landfills. *Waste Manag.* **2013**, *33*, 1993–2000.
39. Previdi, M. Analisi Critica Della Modellistica Applicata alla Generazione di Biogas da Discarica di Rifiuti. Master's Thesis, University of Trento, Trento, Italy, March 2005.
40. Rada, E.C. Effects of MSW selective collection on waste-to-energy strategies. *WIT Trans. Ecol. Environ.* **2013**, *176*, 215–223.
41. Afvalzorg. Available online: http://www.afvalzorg.nl/ (accessed on 12 June 2014).
42. Kamalan, H.; Sabour, M.; Shariatmadari, N. A review on landfill gas models. *J. Environ. Sci. Technol.* **2011**, *4*, 79–92.
43. Intergovernmental Panel on Climate Change (IPPC). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Available online: http://www.ipcc-nggip.iges.or.jp/public/gp/english/5_Waste.pdf (accessed on 10 June 2014).
44. Intergovernmental Panel on Climate Change (IPPC). IPCC Guidelines for National Greenhouse Gas Inventories. Available online: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm (accessed on 10 June 2014).