LANDFILL GAS ENERGY RECOVERY: ECONOMIC AND ENVIRONMENTAL EVALUATION FOR A STUDY CASE

A. CORTI*, L. LOMBARDI** AND L. FRASSINETTI°

** Dipartimento di Ingegneria dell'Informazione – Università degli Studi di Siena – via Roma, 56, 53100 Siena, Italy*
*** Dipartimento di Energetica "Sergio Stecco" – Università degli Studi di Firenze – via di Santa Marta, 3, 50139 Firenze, Italy*
° Centro Servizi Ambiente Impianti Spa - S.p. 7 di Piantravigne, 52028 Terranuova Bracciolini (AR), Italy

SUMMARY: The present study is concerned with the economic and environmental evaluation of landfill gas exploitation system in reference to an existing study case landfill, located in Tuscany Region (Italy). Landfill gas production, during the different life phases of the study case landfill, has been predicted according to a mathematical model, based on first-order decay equation, considering different behaviours for different types of biodegradable wastes. On the basis of the landfill gas collected yearly it is possible to estimate the appropriate size and number of reciprocating engines required every year for the landfill gas exploitation. As a matter of fact, during the energy recovery time, different combinations of engine sizes and numbers can be adopted to exploit the landfill gas: the selection of the final combination was carried out with the aim of maximising the profits coming from the balance of energy system investment and maintenance costs and electric energy selling earnings. Two scenarios were compared from an economic point of view, highlighting the one with the maximum economic profits. The scenarios were also compared from an environmental point of view, evaluating the overall contribution to Greenhouse Effect from escaped landfill gas, collected and combusted landfill gas and recovered electric energy avoided emissions.

1. INTRODUCTION

Energy recovery from landfill gas (LFG) is strongly recommended by both European and member states regulation as a mean to reduce the environmental impact, in term of Greenhouse Effect (GHE), arising from landfills containing biodegradable wastes. As a matter of fact, biodegradable organic matter contained in municipal solid wastes is degraded by anaerobic biological processes in landfills giving place to a LFG, which is approximately composed by 50% of methane and 50% of carbon dioxide. Hence the LFG has two main features: it is composed by two of the main Greenhouse gases and it has not negligible heating value (approximately 17.000 kJ/Nm^3).

Simple flare combustion of LFG allows reducing landfill GHE contribution converting

Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium
S. Margherita di Pula, Cagliari, Italy; 1 - 5 October 2007

methane to carbon dioxide, since Global Warming Potential (GWP) of methane is twenty-one times larger than GWP of carbon dioxide. When LFG is combusted in a reciprocating engine to recover energy – both thermal and electric energy can be delivered – landfill Greenhouse effect is further reduced, considering the avoided emissions from conventional sources of energy, in place of which LFG is exploited.

The LFG energy recovery by means of reciprocating engines is a quite wide spread practice in modern landfills, but the energy recovery system definition and sizing, also in reference to its economic convenience, is a crucial and tricky issue.

Hence, an appropriate prediction of the LFG production during the different life phases of the landfill is of great importance in order to properly size the energy recovery system.

With this aim, a mathematical model for the prevision of LFG production has been applied, in reference to an existing study case landfill, in order to carry out an economic and environmental evaluation of LFG exploitation system

2. LFG MATHEMATICAL MODELLING

2.1 The model

The applied model is based on the Scholl Canyon Equation (1) which assumes that LFG generation is a function of first-order kinetics. The LFG production rate is assumed to be at its peak upon initial placement after a negligible lag time – in the original version - during which anaerobic conditions are established and decreases exponentially (first-order decay) as the organic content of the waste is consumed (Department of the Army U.S., 1995). Average annual placement rates are used, and the time measurements are in years. The model equation takes the form:

$$Q_{LFG} = R_{avg} \cdot L_0 \cdot (e^{-kc} - e^{-kT}) \quad (1)$$

where:
Q_{LFG}= LFG generation rate at time T [m^3/year]
L_0= waste potential LFG generation capacity [m^3/t]
R_{avg} = average annual acceptance rate of waste [t/year]
k = LFG generation rate constant [1/year]
c = time since landfill closure [year] (c = 0 for active landfills)
T = time since initial waste placement [year]

To allow for variances in annual acceptance rates, the derivative of Equation 1 with respect to the time can be used to estimate LFG generation from waste landfilled in a single year (R_i) (IPCC, 1996). In this equation, the variable T is replaced with t-i, which represents the number of years the waste has been in the landfill. The resulting equation thus becomes:

$$Q_{LFG,t,i} = L_0 \cdot k \cdot R_i \cdot e^{-k(t-i)} \quad (2)$$

$Q_{LFG,t,i}$ = the amount of LFG generated in the current year (t) by the waste R_i [m^3/year]
R_i = amount of waste disposed in year i [t/year]
i = the year of waste placement [year]
t = current year [year]

In order to estimate the current emissions from waste placed in all years, Equation 2 can be solved for all values of R_i and the results summed:

$$Q_{LFG,t} = \sum_{i=initial\ year}^{t} Q_{LFG,t,i} = \sum_{i=initial\ year}^{t} R_i \cdot L_0 \cdot k \cdot e^{-k(t-i)} \quad (3)$$

Lag time due to the establishment of anaerobic conditions could also be incorporated into the model by replacing "t" by "t + lag time". The lag time before which anaerobic conditions are established may range from two-hundred days to several years (Department of the Army U.S., 1995):

$$Q_{LFG,t,i} = R_i \cdot L_0 \cdot k \cdot e^{-k(t-i-lag)} \quad (4)$$

lag = time to reach anaerobic conditions [year]

The tricky parameters for the first order models are the gas generation rate constant (k) and the waste potential LFG generation capacity (L_0).

The potential for LFG generation capacity, usually expressed as the volume of gas per mass of waste, can be estimated based on theoretical prediction, laboratory experiments or actual gas production data. At present, there is no method for determining gas potential that is without fault (Reinhart and Faour, 2005).

In the present study both L_0 and k have been estimated on theoretical basis, in reference to a component characterization of the waste, specific for the analysed site and reported in Table 1, using a stoichiometric based approach. For each material component the chemical composition, the moisture and the biodegradability coefficients reported in Table 1 have been assumed (Tchobanoglous,1993).

On the basis of component characterisation of waste, chemical composition of each component and biodegradability of each component it is possible to describe the biodegradable fraction, with reference to the unit mass of waste, by the generic formula CaHbOcNdSe.

Table 1. Waste component characterisation for the study case site and assumed values for chemical composition, moisture and biodegradability

	Component characterization %	C %SS	H %SS	O %SS	N %SS	S %SS	Inert %SS	Moisture %	Biodegradability %
Organic fraction	17,53	28,70	3,10	29,20	1,90	0,60	36,50	70,00	82
Paper and cardboard	32,20	44,40	4,40	40,90	0,10	0,30	9,90	5,50	50
Plastics	16,83	70,50	11,50	11,30	0,90	0,90	4,90	2,00	0
Textile	6,20	39,60	6,50	25,30	5,60	0,70	22,30	10,00	54
Pruning scrap	2,46	45,50	8,70	20,10	1,80	0,20	23,70	60,00	60
Wood	6,31	49,50	6,00	42,70	0,20	0,10	1,50	20,00	72
Glass and inert	10,61	0,50	0,10	0,40	0,10	0,00	98,90	2,00	0
Metals	3,86	0,50	0,60	4,30	0,10	0,00	94,50	3,00	0
Sewage sludge	4,00	47,07	6,74	26,43	5,97	2,25	11,54	70,00	57,5

In calculating the biodegradable fraction, it was also considered that not all the biodegradable fraction is available for being converted to LFG according to an efficiency depending on the landfill body temperature as it follows (Tabasaran, 1982):

$$\text{Biodegradable fraction availability} = 0{,}014\ \text{Temp} + 0{,}28 \quad (5)$$

where Temp is the landfill body temperature expressed in °C. Assuming a landfill body temperature of 35°C the biodegradable fraction availability results 0,77.

The biodegradation process of the organic biodegradable fraction to form the LFG can be described by the global stoichiometric reaction (Tchobanoglous,1993):

$$C_aH_bO_cN_dS_e + w \cdot H_2O \rightarrow x \cdot CH_4 + y \cdot CO_2 + z \cdot NH_3 + k \cdot H_2S \quad (6)$$

Applying the stoichiometric balance to the reaction above it is possible to obtain the stoichiometric coefficients w, x, y, z and k as a function of a, b, c, d, e:

$$C_aH_bO_cN_dS_e + \left(\frac{4a-b-2c+3d+2e}{4}\right) \cdot H_2O \rightarrow$$
$$\rightarrow \left(\frac{4a+b-2c-3d-2e}{8}\right) \cdot CH_4 + \left(\frac{4a-b+2c+3d+2e}{8}\right) \cdot CO_2 + dNH_3 + eH_2S \quad (7)$$

Hence, total number of dry kilomoles of LFG will be:

$$LFG_{kmol,dry} = x + y + z + k = \frac{4a+b-2c-3d-2e}{8} + \frac{4a-b+2c+3d+2e}{8} + d + e = a + d + e \ [kmol/t] \quad (8)$$

In order to consider the presence of water vapour in the LFG it has been assumed that the gas is saturated with water vapour. From the total number of kilomoles it is then possible to calculate the potential gas generation capacity (L_0):

$$L_0[Nm^3/t] = LFG_{mol}[kmol/t] \cdot 22{,}414[Nm^3/kmol] \quad (9)$$

Actually, the different components of waste undergo biodegradation according to different degradation rates. The different behaviours have been considered distinguishing the materials in rapidly, moderately and slowly biodegradable, according to (EMCON, 1980). After a literature review (Christensen et al., 1996), (Lifshits and Galueva, 1997), (McBean et al., 2005), different values for LFG generation rate constant have been assumed for each class of materials with different biodegradation velocity, as reported in **Errore. L'origine riferimento non è stata trovata.**Table 2.

Table 2. Values assumed for gas generation rate constant, potential gas generation capacity and lag time of materials with different biodegradation velocity

		k [1/year]	L_0 [Nm^3/t]	Lag Time [year]
Rapidly biodegradable fractions	Organic fraction Pruning scrap	0,36	13,44	0,3
Moderately biodegradable fractions	Paper and cardboard	0,15	29,54	2
Slowly biodegradable fractions	Textile Wood	0,07	29,69	5

Sewage sludge

Also the potential LFG generation capacities (L_0) for each class of material with different biodegradation velocity were calculated separately (calculated values are reported in Table 3) in order to apply the models – when this is allowed by the model itself – in order to proceed with separate calculations and adding up the three contributions of LFG production.

From Equation 7 it is, also, possible to calculate LFG composition, which, in this case, results: CH_4 48,23%; CO_2 47,95%; NH_3 3,39%; H_2S 0,42 %. A main limit of the applied model is the assumption that the composition does not change during the time.

2.2 Application of the model to the study case

The analysed site is the "Casa Rota" landfill, managed by Centro Sevizi Ambiente Impianti S.p.A. (CSAI), which is located in central Italy (Terranuova Bracciolini in the Province of Arezzo – Tuscany Region). The landfill is authorised for an overall capacity of about 3.700.000 m^3 and it can accept non-hazardous waste. The amount of waste landfilled yearly is reported in Table 3. Values until 2005 are real data collected on-site, while values after 2006 are assumed according to the hypothesis of filling up the site authorised capacity within 2009 (last year of operation). Figure 1 shows the results of the model application to the specific study case.

Table 3. Amount of waste landfilled yearly in the analysed site.

Year	Waste [t]	Year	Waste [t]
1999	171.929	2005	278.634
2000	263.606	2006	240.000
2001	260.453	2007	240.000
2002	315.214	2008	240.000
2003	246.159	2009	240.000
2004	259.896		

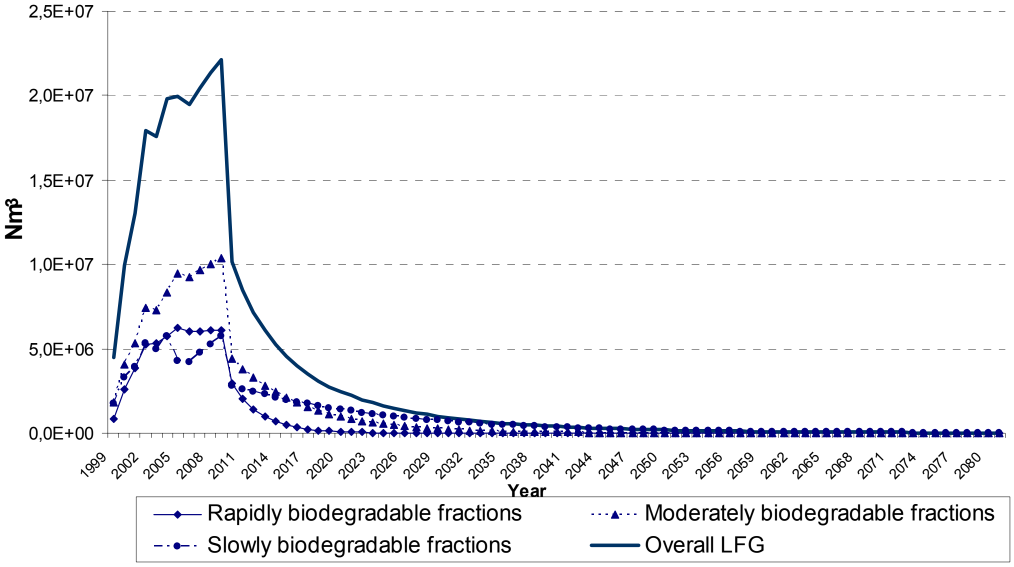

Figure 1. Results of LFG production model, for each group of waste components with different

biodegradation velocity.

Table 3. Collected LFG measured data, estimated escaped LFG at the studied landfill site and estimated collection efficiency.

Year	Collected LFG [Nm^3]	Escaped LFG [Nm^3]	Estimated collection efficiency [%]
2003	7.500.000	-	-
2004	7.707.818	11.713.862	40
2005	11.500.000	-	-

The results obtained from the model have been compared with the measured data of collected LFG at the landfill site during three years of operation, which are reported in Table 4. For the analysed landfill site, the estimated escaped LFG from the landfill surface, is available from a measuring campaign previously carried out, by means of the accumulation chamber method (Raco et al., 2005) during 2004. The specific carbon dioxide emission resulting from those previous measurements is 350 g/(m^2 · day). Assuming a composition of LFG of 50% CH_4 and 50% CO_2 and an overall landfill surface of about 90.000 m^2 (at 2004), the amount escaped LFG is about 11.713.862 Nm^3 in 2004. This allows the estimation of the LFG collection efficiency, as shown in Table 3.

Applying the estimated collection efficiency to the model results, it is possible to estimate the collected LFG from the model results and compare it with the collected LFG measured data available for the years 2003, 2004 and 2005, as shown in Figure 2. On the basis of these results, it has been assumed a collection efficiency coefficient equal to 40% for the years 2003, 2004 and 2005, 60% for the following years (on the basis of the designed improved collection network in the plant).

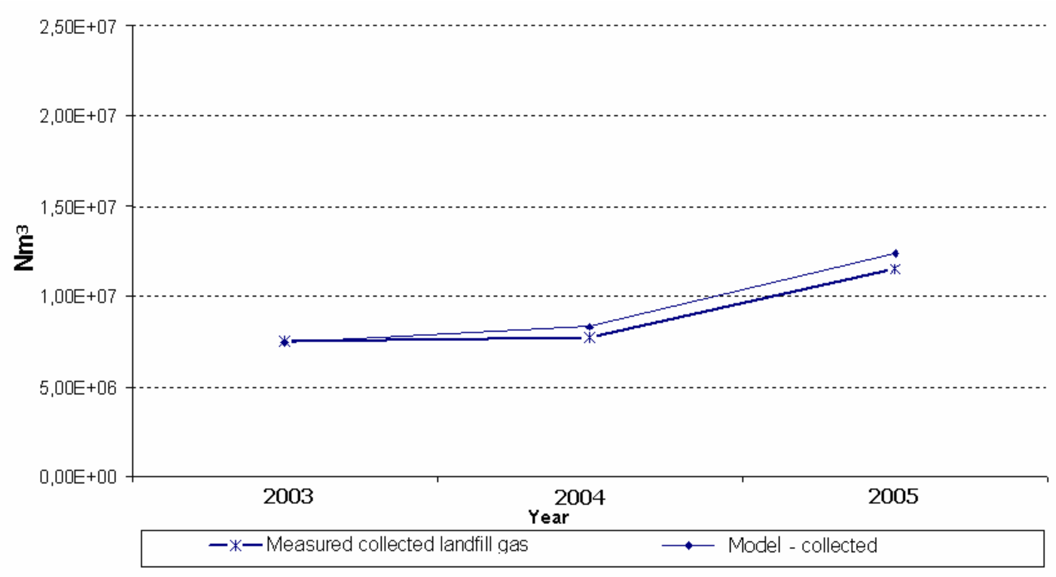

Figure 2. Comparison of results obtained from the applied model with the measured data of collected LFG.

3. ENERGY RECOVERY AND ECONOMIC EVALUATION

Reciprocating engines were considered for energy recovery purpose, selecting the engine configuration along the time with the aim of obtaining the maximum profits from selling the produced electric energy.

Several sizes of engine have been considered with reference to existing Jenbacher engines (kWe 143, kWe 330, kWe 511, kWe 625, kWe 836, kWe 1048, kWe 1413, kWe 1698). The amount of potential electric energy has been calculated according to:

$$EE = \eta_{el} \cdot LHV_{LFG} \cdot V_{LFG} \quad (10)$$

where:
EE = electric energy [kW]
η_{el} = engine electric energy conversion efficiency
V_{LFG} = LFG flow rate [Nm^3/h]
LHV_{LFG} = LFG low heating value [kWh/Nm^3]

The values of engine maximum LFG flow rate and energy conversion efficiency were retrieved from Jenbacher engine technical forms. Energy conversion efficiency was considered dependant on the engine load (i.e. decreasing when load decreases) according to the indications on Jenbacher engine technical forms.

On the basis of the LFG collected yearly, obtained from the applied model, it is possible to estimate the appropriate size and number of reciprocating engines required every year for the LFG exploitation, considering as constraints the maximum load (i.e. maximum LFG flow rate) for each engine and 90.000 hours as maximum amount of operating hours for each engine (about ten years). A 88% availability of the engines was assumed.

Two scenarios were considered: for both of them energy recovery is assumed to start in 2004, the year in which two 625 kWe and two 836kWe engines were actually installed at the studied site. The first one is based on the assumption to use the four actually installed engines until their end-of-life (ten years) and then adding other engines to exploit LFG in the later period (constrained scenario). The second scenario does not consider the constraint of using the existing engines, arranging a configuration for maximum LFG exploitation since 2004 (non-constrained scenario).

As a matter of fact, different duration of energy recovery time, different combinations of engine sizes and numbers can be adopted to exploit the LFG: the selection of the final combination, for the two scenarios, was carried out – after several combination tries - with the aim of maximising the profits coming from the balance of energy system investment and maintenance costs and electric energy selling earnings.

The economic evaluation was carried out considering the depreciation annual cost for the engine investment (considering 6,5% interest rate and 10 years investment time), the maintenance costs (assumed 0,03 €/kWh for programmed maintenance plus 3% for non programmed maintenance), the earnings for electric energy (EE) selling assuming a selling price equal to 0,13 €/kWh. Table 4 reports the engine costs.

Table 4. Investment costs and depreciation cost for the engines.

Engine size	Engine cost [€]	Additional cost [€]	Total investment cost [€]	Depreciation [€/year]
kWe 143	252.000	282.500	534.500	74.351
kWe 625	377.000	282.500	659.500	91.740
kWe 836	435.000	282.500	717.500	99.808
kWe 1413	689.300	282.500	971.800	135.182

The final configurations for energy recovery – for each scenario - were evaluated also from an environmental point of view, estimating the overall GHE produced, considering the contribution due to the presence of both CO_2 and CH_4 in the escaped LFG and considering the contribution due to CO_2 (originally present in LFG and obtained from CH_4 combustion) in collected and combusted LFG.

Moreover, it is possible to consider that the amount of electric energy produced by the engines fed with LFG, is no more produced by conventional energy system, this term can be considered as an avoided effect of GHE emissions and then subtracted from the overall balance. Being the specific emission of about 0,551 kg of equivalent CO_2/kWh for electric energy production (with reference to the Italian situation (ENEL, 1999)) the overall avoided effect can be calculated.

4. RESULTS AND DISCUSSION

Concerning the constrained scenario, the energy recovery starts in 2004 and finishes in 2036. After the use of two 625 kWe and two 836kWe engines – already installed at the landfill site – until 2015, a combination of engines which maximises the profit was found, based on the use of one 143 kWe engine and one 625 kWe engines, distributed as shown in Figure 3.

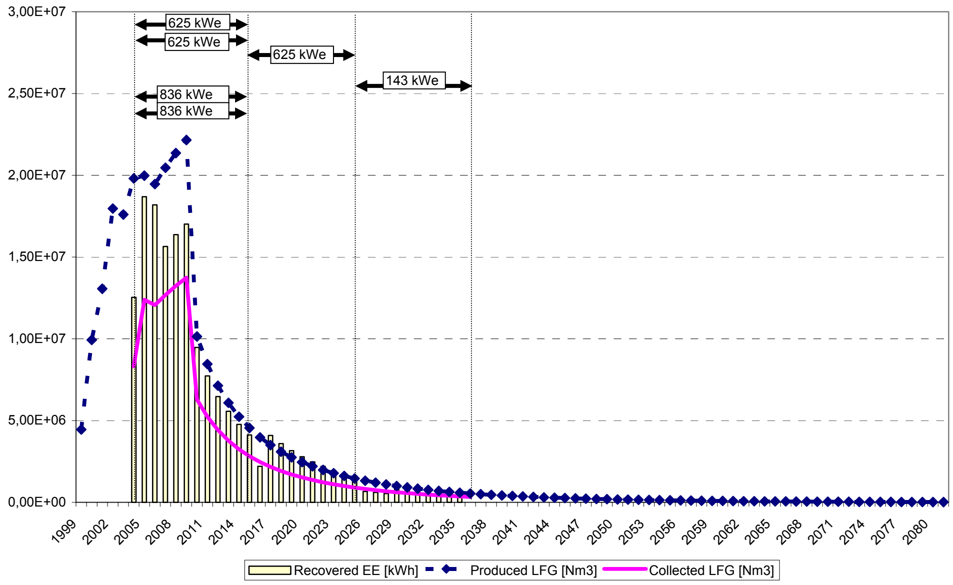

Figure 3 – Results of produced LFG, collected LFG and recovered electric energy, with the indication of the time during which engines have been used (Constrained scenario).

Concerning the non-constrained scenario, energy recovery starts in 2004 and finishes in 2036, too. A combination of engines which maximises the profit was found, based on the use of one 143 kWe engine, three 625 kWe engines and two 1413 kWe engines, distributed as shown in Figure 4. Table 5 reports costs and earnings for the two scenarios.

From an economical point of view, results for the two scenarios are not so different, with a slight improvement for the non-constrained scenario.

As a matter of fact, comparing the two scenarios, an higher cost of about 14% is required for the second one (non-constrained scenario), which at the same time allows an increase of about 11% in energy recovery and about 10% in profits.

From an environmental point of view (Table 6), the higher amount of energy recovery in the second scenario (non-constrained scenario) offers the possibility of further decrease in GHE of a very small percentage (less than 1%).

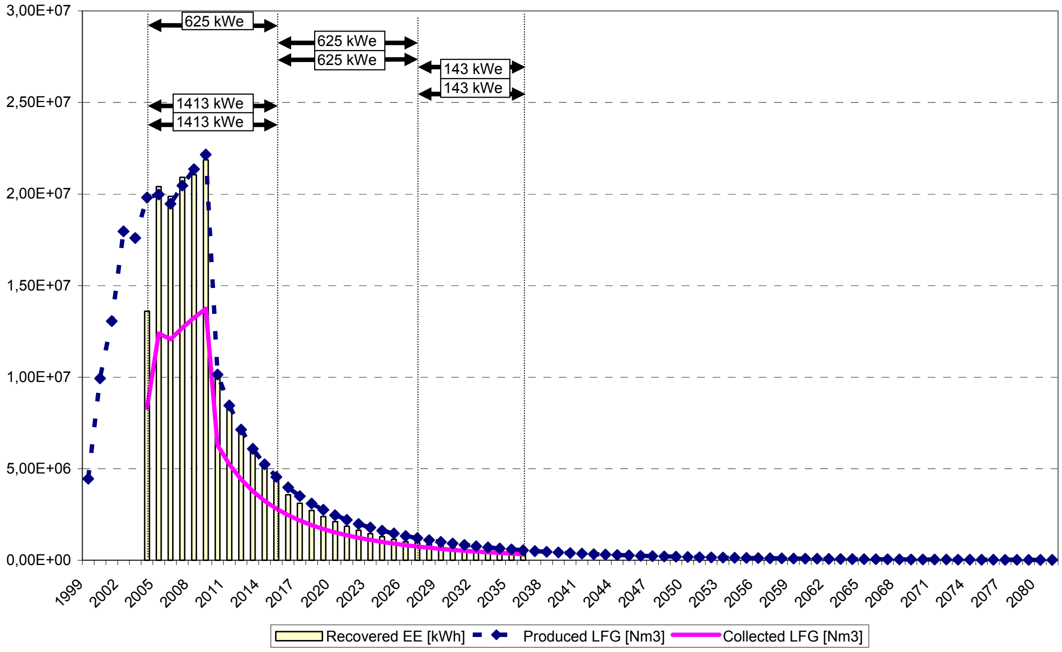

Figure 4. Results of produced LFG, collected LFG and recovered electric energy, with the indication of the time during which engines have been used (Non-constrained scenario)

Table 5. Costs and earnings for the LFG energy recovery system.

	Constrained scenario			Non-constrained scenario		
	kWe143	**kWe625**	**kWe836**	**kWe143**	**kWe625**	**kWe1413**
Produced EE [kWh]	7.445.949	85.701.446	76.666.740	6.513.868	42.315.774	139.652.646
Total produced EE [kWh]		169.814.135			188.678.178	
EE selling earnings [€]	967.973	11.141.188	9.966.676	846.803	5.501.051	18.154.844
Engine + maintenance [€]	751.249	2.872.620	2.088.805	751.249	2.927.351	2.826.306
Net profit [€]	216.724	8.268.568	7.877.871	95.553	2.573.700	15.328.538
Total net profit [€]		16.363.163			17.997.791	

Table 6. Contributions to GHE during the landfill life time.

	Constrained scenario	Non-constrained scenario
GHE from escaped LFG [t_{CO2eq}]	1.221.175	1.221.175
GHE from collected LFG [t_{CO2eq}]	234.839	234.839
Total produced GHE [t_{CO2eq}]	**1.456.014**	**1.456.014**
Avoided GHE form EE production [t_{CO2eq}]	-93.568	- 103.962
Net produced GHE [t_{CO2eq}]	**1.362.446**	**1.352.052**

5. CONCLUSIONS

The energy recovery system in a case study landfill located in Tuscany was studied. A mathematical model for landfill gas production prevision was applied, applying an appropriate collection efficiency coefficient in order to estimate the collected amount of landfill gas.

On the basis of the predicted landfill gas production and collection, the combination of engines which maximise the profits was found, in reference to two different scenarios: the first one based on the constraint of using only the already installed engines for their life time (ten years) and then adding an appropriate combination of other engines; the second one aimed to find the combination which maximises the profits without considering any constraint related to already existing engines.

The comparison of the results for the two scenarios showed a slight difference in the final profits of about 10% more – and 11% more in energy recovery - in the non-constrained scenario, in spite of an increase of about 14% of costs.

The higher energy recovery rate contributes a little to the further reduction of Greenhouse Effect from the landfill.

In conclusion the not large difference in the potential profits of the two scenarios suggests that the actual energy recovery system in the case study landfill is quite properly sized for the next years, but it will require an up-grade at the end of life of the installed engines.

Of course a more accurate design of the energy recovery system, based since the beginning on the use of landfill gas prediction models, could have offered the possibility of higher energy recovery and profits.

REFERENCES

Department of the Army U.S. Army Corps of Engineers Washington (1995). Engineering and Design - Landfill Off-Gas Collection and Treatment Systems, da Environmental Technical Letter, ETL 1110-1-160

EMCON Associates (1980). “Methane generation and recovery from landfills”. Ann Arbour Science Publisher Inc., Ann Arbour, USA

ENEL “Rapporto Ambientale 1999” (in Italian)

IPCC (1996), “Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories”. Workbook (Volume 2).

Lifshits A.and Galueva T. (1997), "Gas production modelling based on the field gas emissions measurements", in Sardinia 1997, Sixth International Waste Management and Landfill Symposium, CISA Environmental Sanitary Engineering Centre, Cagliari, Italy.

McBean E., Ritchie S. and Gidda T. (2005), "Landfill gas collection for greenhouse gas credits: an Argentinian case study", Sardinia 2005 Tenth International Waste Management and Landfill Symposium, CISA Environmental Sanitary Engineering Centre, Cagliari, Italy.

Raco B., Scozzari A., Guidi M., Lelli M. and Lippo G., (2005). Comparison of two non invasive methodologies to monitor diffuse biogas emissions from MSW landfills soil: a case study. Sardinia 2005 Tenth International Waste Management and Landfill Symposium, CISA Environmental Sanitary Engineering Centre, Cagliari, Italy.

Reinhart D., Faour A. (2005), First-Order Kinetic Gas Generation Model Parameters for Wet Landfills, EPA-600/R-05/072

Christensen T.H., Cossu R., Stegmann R., (1996) "Landfilling of waste: Biogas", Th. Christensen, E & FN SPON, 237-268.

Tabasaran O. (1981) "Gas production from landfill, in Household Waste Management in Europe, Economics and Techniques", A.V. Bridgewater and Lidgren, K. (eds.), Van Nostrand Reinhold Co., New York, USA, pp. 159-175.

Tchobanoglous G., Theisen H., Vigil S., (1993), Integrated solid waste management – Engineering principles and management issues. McGraw-Hill, Inc.