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Master thesis

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ASSESSMENT OF BIOGAS PRODUCTION MODELS FOR MUNICPAL SOLID WASTE LANDFILLS THROUGH A CASE STUDY IN VENETO

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1. INTRODUCTION

The aim of this study is to assess the goodness of two models for biogas production from municipal solid waste landfills; the models are LandGEM, a model developed by U.S. EPA in 2005, and a first order kinetic model developed by Cossu and Andreottola in 1988. Both the models are tested on a MSW landfill in Padua province, managed by S.E.S.A. S.p.A..

In the first chapter a brief description of landfill gas problem is reported to contextualize the study, with a special attention for greenhouse gas issue. The second chapter shows the mechanism of biogas formation, impacts, utilization and modeling. The third regards the inherent legislation, both European and Italian. The fourth chapter offers a description of the surroundings of landfill area, while the fifth a description of the plant, in particular of the treatments prior to landfilling and of the landfill itself. The sixth paragraph describes LandGEM model: the theory, the application to the particular landfill and the results; the same description is presented in chapter eight for the first order kinetic model. In chapter nine the evaluation of models results is done with respect to real data coming from the plant: a critical view on parameters is implemented. Finally in the tenth chapter conclusions of the study are reported.

2. THE LANDFILL GAS PROBLEM

In the last decades the greenhouse gases produced by human activities have been predominating over those of natural origin. Both the United Nations and the European Union have adopted protocols (e.g. Kyoto protocol) with the purpose of evaluating the emissions of the principal gases responsible for greenhouse effect, to keep under control and to reduce their general emissions both in the short-term and long-term periods (Aronica et al., 2008). Municipal solid waste landfills constitute a broad part of these anthropogenic sources and emitted biogas from landfills is one of the objectives foreseen in Kyoto protocol; moreover biogas is composed of about 60% of methane and 40% of carbon dioxide and the first has a 25 times stronger greenhouse gas potential than the second.

Therefore it is obviously important to evaluate these emissions; this can be done through the modeling of landfill gas behavior, i.e. when the production begins, increases and finally ceases. This is important in turn to find the best way to contain emissions and utilize landfill gas: indeed the economical feasibility of biogas utilization depends on the potential production of the same; if it is too low, gas will be burned instead of utilized to produce energy since costs will be greater than the gains from energy selling.

A variety of biogas production models exists and in this study two of them will be implemented on a specific landfill, showing how it is important to know the exact composition of the waste landfilled.

3. WHAT IS LANDFILL GAS?

3.1 Landfill gas generation

Shortly after MSW is landfilled, the organic components start to undergo biochemical reactions. In the presence of atmospheric air, that is near the surface of the landfill, the natural organic compounds are oxidized aerobically. However, the principal bio-reaction in landfills is anaerobic digestion. The phases of this process are five:

- *aerobic degradation*: this phase is due to the residual air present in waste. It lasts few days and the composition of the gas is the same of air: 80% of nitrogen and 20% of oxygen; then the oxygen is depleted and the formation of carbon dioxide starts.
- *Acidogenic/acetogenic phase*: hydrolysis and fermentation lead to the formation of carbon dioxide, hydrogen, volatile fatty acids and dissolved organic matter; elementary nitrogen is turned away by carbon dioxide and hydrogen production.
- *Unstable methanogenic phase*: the production of methane begins, starting both from acetic acid and from hydrogen; therefore carbon dioxide lower its content together with hydrogen whose percentage goes to zero. This phase can last from few months to one or two years.
- *Stable methanogenic phase*: this is the phase, lasting 15-20 years, in which there is the formation of biogas in its most classical composition: indeed methane reaches the value of 55-60% in volume and carbon dioxide is its complementary element.
- *Final aerobic phase*: when all organic matter has been degraded, methane production stops, while nitrogen and oxygen start to appear, after the air diffusion in landfill body, until they reach air composition.

The five stages are showed in the figure 1.

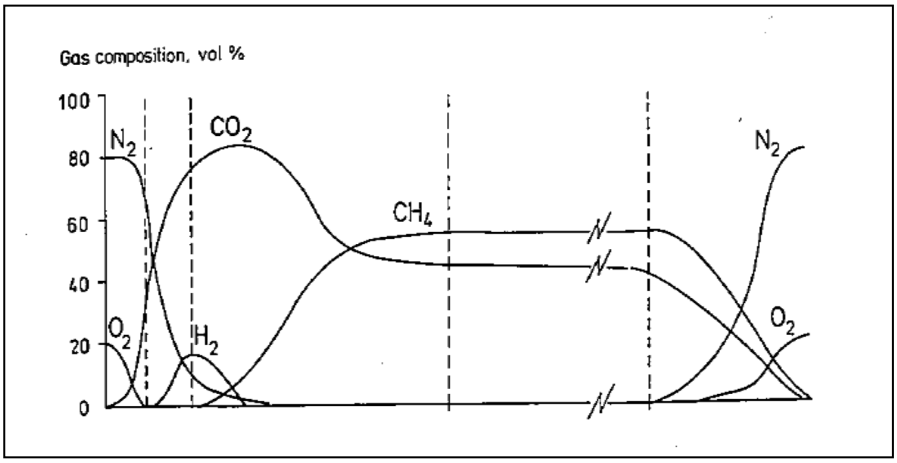


Fig. 1 – Illustration of developments in gas composition in a landfill cell (Christensen and Kjeldsen, 1989).

Some examples of reactions occurring in anaerobic decomposition of waste are shown in table 1 and the whole process is represented in figure 2.

Tab. 1 - Examples of important reactions for four groups of bacteria involved in anaerobic degradation.

Fermentative processes	
$C_6H_{12}O_6 + 2H_2O$	$2CH_3COOH + 4H_2 + 2CO_2$
$C_6H_{12}O_6$	$CH_3C_2H_4COOH + 2H_2 + 2CO_2$
$C_6H_{12}O_6$	$2CH_3CH_2OH + 2CO_2$
Acetogenic processes	
$CH_3CH_2COOH + 2H_2O$	$CH_3COOH + CO_2 + 3H_2$
$CH_3C_2H_4COOH + 2H_2O$	$2CH_3COOH + 2H_2$
$CH_3CH_2OH + H_2O$	$CH_3COOH + 2H_2$
$2C_6H_5COOH + 10H_2O$	$7CH_3COOH + H_2$
Methanogenic processes	
$4H_2 + CO_2$	$CH_4 + 2H_2O$
CH_3COOH	$CH_4 + CO_2$
$HCOOH + 3H_2$	$CH_4 + 2H_2O$
$CH_3OH + H_2$	$CH_4 + H_2O$
Sulphate reducing processes	
$4H_2 + SO_4^{2-} + H^+$	$HS^- + 4H_2O$
$CH_3COOH+ SO_4^{2-}$	$CO_2 + HS^- + HCO_3^- + H_20$
$2CH_3C_2H_4COOH + SO_4^{2-} + H^+$	$4CH_3COOH + HS^-$

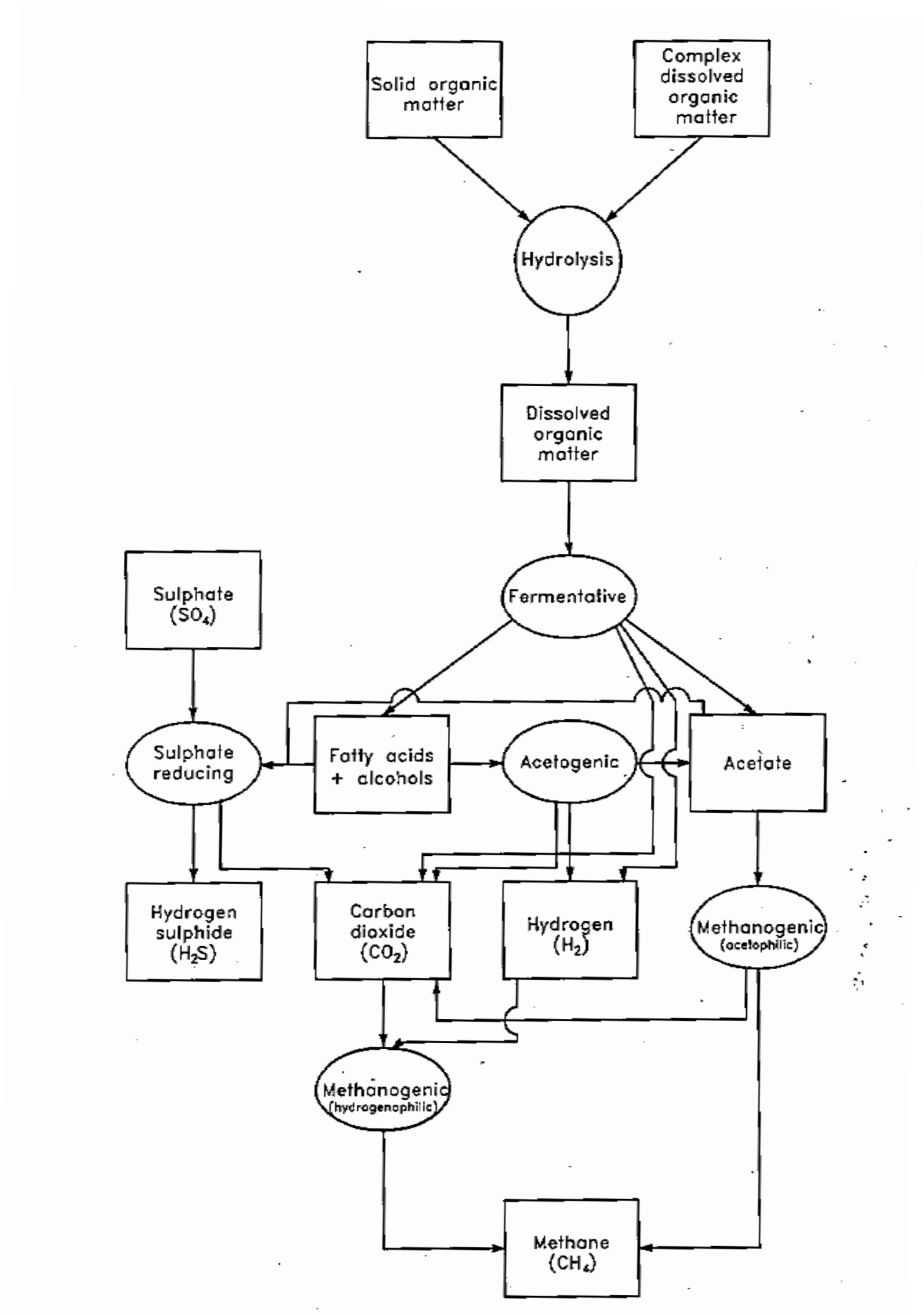


Fig. 2 – Anaerobic degradation of organic matter in landfill (Christensen and Kjeldsen, 1989).

In the stable methanogenic phase, as can be seen from figure 3, the methane content can reach the value of 65% and carbon dioxide is its complementary for the 99%.

The remaining 1% can be divided in several trace compounds, like carbon monoxide, hydrogen, hydrogen sulfide, mercaptans, etc.

GAS	Concentrations Exceptional	Concentrations Typical
methane	(0-45)*	45-65 % vol
CO2	(55-80)*	35-55 % vol
CO	(<1)*	0% vol
hydrogen	(0-30)*	0% vol
H2S		<50 ppm
R-SH		<50 ppm
trichloroethylene		<50 ppm
tetrachlomethylene		<50 ppm
CCl4		<5 ppm
vynilchloride		<20 ppm
steam		2-4 % vol
oxygen	(<20)*	0 % vol
nitrogen	(<80)*	0 % vol
argon		<1% vol
traces		<1% vol

Fig. 3 – Biogas typical composition (**“***Landfill gas management*” lesson of professor Raga, 2011).

3.2 Landfill gas impacts

Landfill gas has different types of impacts on environment, going from the surroundings of the plant to atmospheric level. Here are listed the main impacts of landfill gas:

- *Ozone depletion*: this is the most wide problem of a landfill and it is due to the presence of chlorofluorocarbons in biogas; UV rays can destroy CFC releasing Cl° radicals that, bounding to ozone, destroy it produce oxygen.
- *Greenhouse gas effect*: methane is 25% stronger than carbon dioxide in contributing to greenhouse gas effect.
- *Compounds coming from gas combustion*: once biogas is extracted it can be flared or utilized; in both cases, its combustion produces carbon dioxide, carbon monoxide and other compounds.
- *Explosion*: if methane is present at a concentration of 5-15% mixed with air in a confined place it can explode; this phenomenon can happen even 10 km away from a landfill, due to the migration of biogas under the ground level.

- *Asphyxiation*: this happens when in a confined place, methane begins to replace oxygen.
- *Odour*: as already said biogas contains many trace compounds and the ones coming from the degradation of proteins (therefore containing sulphur and nitrogen) can produce an unpleasant odour; examples of these elements are mercaptans, ammonia, indole and skatole.

3.3 Landfill gas utilization

Given the impacts described before, it is reasonable to collect biogas and to utilize it, if possible, to produce energy; this can be an alternative energy, useful to supply the current fossil fuel depletion.

Biogas is firstly collected thanks to a system of wells and trenches which are collected each other through piping and finally conveyed to a large fan which creates a negative pressure that collects the gas; before utilization it undergoes to some treatments like compression, water, carbon dioxide and hydrogen sulphide removal.

In the figure below it is presented the different possible utilizations of biogas.

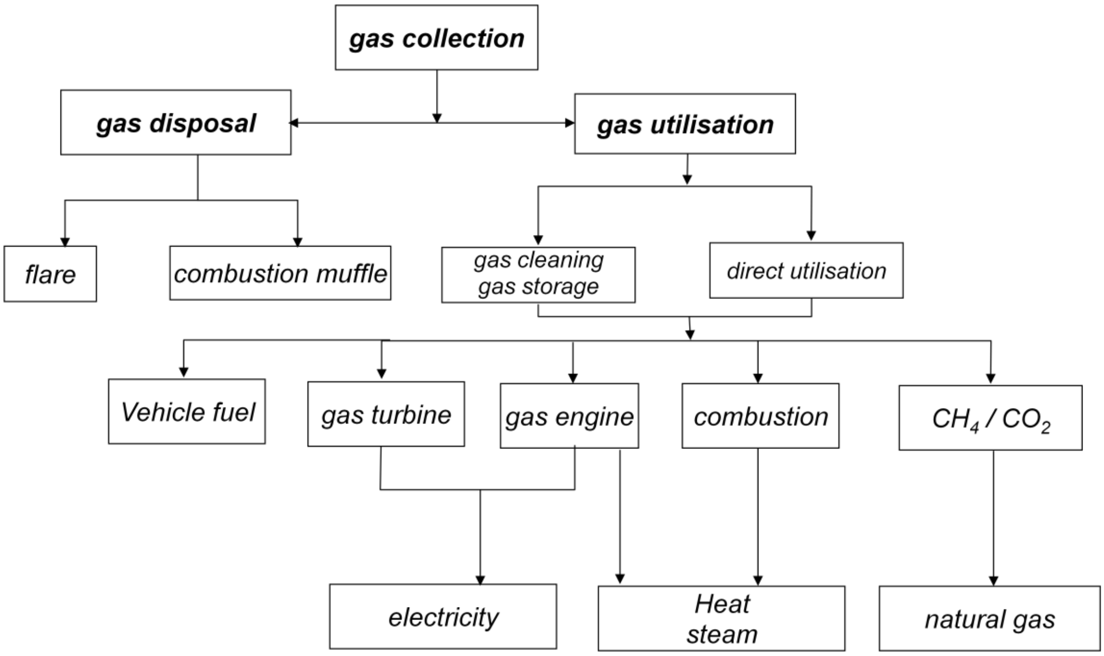


Fig. 4 – Biogas utilizations ("*Landfill gas management*" lesson of professor Raga, 2011).

The most feasible use of biogas is the combustion in engines to produce electricity that can be used in the plant itself, while the surplus of energy can be sold to the public net.

In this case the engine can convert to energy only the 35% of the potential, the rest being dispersed in the form of heat; therefore it has been found the way to use also this different type of energy: cogeneration, the combined production of electricity and heat. Figure 5 presents a general scheme of cogeneration.

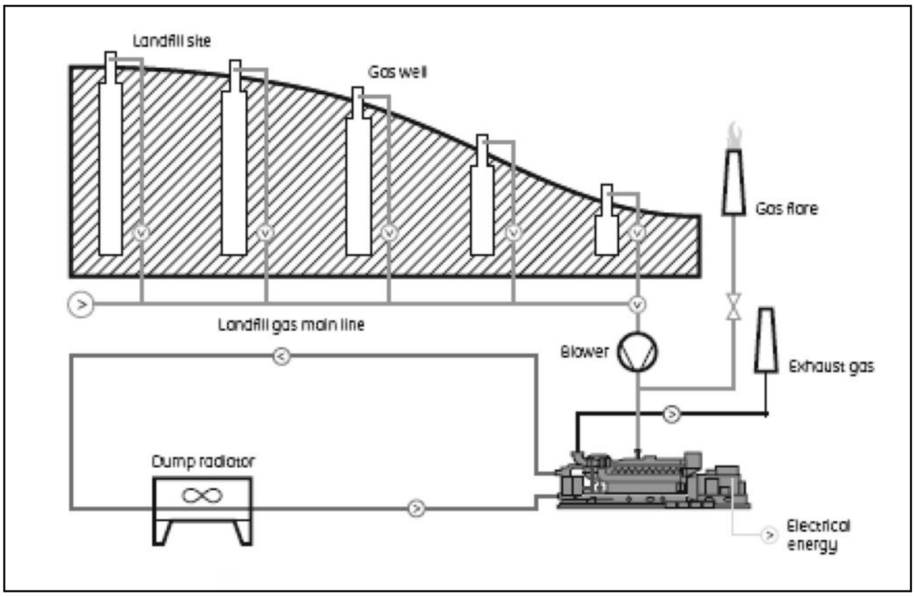


Fig. 5 – Typical cogeneration process **(**www.images.google.it).

This system permits several advantages:

- to save primary energy;
- to safeguard environment;
- to lower carbon dioxide emissions;
- to lower costs;
- to create new job places.

The functioning of the system depends upon a CHP engine which transforms biogas in electricity through combustion; the cooling of the engine and of the smokes of combustion, through heat exchangers, can heat water that can be used in the plant itself or can be sent away to heat public and/or private buildings.

If cogeneration is not feasible for different reasons, like low amounts of biogas produced or initial periods of biogas production, flare is the solution which permits the removal of smell, toxic compounds, methane and ozone depleting substances.

3.4 Modeling landfill gas production

Biogas modeling is a very important issue to understand the possibility of energy recovery and to control landfill status. This is confirmed by the fact that the first models began to be implemented in 70's; there are a lot of models seeking to calculate landfill gas generation and a summary distinction can be made on the basis of the availability of data and state of knowledge of the system:

- *Statistical analysis*: when a large number of data are available, but knowledge of the system is inadequate, and the data collected for different purposes; this kind of model does not assume any cause-effect relation or deal with the temporal dynamics of the system, but presents the general characteristics of the data 'population' and provides correlations;
- *Stochastic model*: describes the temporal trend of data without explaining it; this kind of model is useful for describing the behaviour of a black-box system;
- *Simplified deterministic model*: requires the knowledge of the mechanism governing the system, it is able to describe the behaviour of the system with simplified mathematical equations;
- *Complex deterministic model*: acts in a similar way to the above mentioned model using more complex mathematical equations.

Most models belong to the third type which can be further subdivided into static and dynamic models; in the first type there's an instantaneous relation between input and output, that is to say that the system has no memory of past inputs and outputs and the state of the system is stationary. In the second type the relation between inputs and outputs is not instantaneous and state variables describing temporal evolution should be introduced.

A further distinction can be made in this direction:

- *Empirical models*: dealing with a black-box system (a system characterized by input and output data), these models are distinguished by a mathematical function relating inputs and outputs which is based on a time series of experimental data;
- *Stoichiometric models*: are based on a global stoichiometric reaction and lead to the highest potential yield of biogas;
- *Biochemical models*: they consider the biodegradability of the different components of the waste, and each differs in terms of kinetic expression, number of substrata and parameters;
- *Ecological models*: they deal with the ecosystem on which the process is based and describe the relation between the system components; they are also the more complex models.

Both the models used in the following chapters belong to the category of simplified deterministic model since the mechanism governing the system is well known; the sub-category is that of dynamic models since there is the time variable in functions governing the system. Finally they are both biochemical models since the biodegradability of the different components of the waste are taken into account.

4. LEGISLATION ABOUT LANDFILL GAS

4.1 European legislation

In Europe the legislation about biogas is strictly connected to that consistent with landfills and pollution in general; in the following paragraphs the main directives are presented.

4.1.1 Directive 96/61/EC regarding the integrated prevention and control of pollution

Directive 96/61/CE was passed to prevent and reduce the contamination of the atmosphere, water, and soil produced by industrial activity, and includes the treatment and elimination of urban waste. Salient aspects of this directive are the following:

- Member States of the European Union must take the necessary measures to provide that the competent authorities ensure that installations are operated in such a way that all the appropriate preventive measures are taken against pollution, in particular through application of the best available techniques;

- energy must be used efficiently and necessary measures taken to prevent serious accidents and limit possible negative impacts;

- when an industrial installation is closed down and ceases operation, necessary measures must be taken upon definitive cessation of activities to avoid any pollution risk and return the site of operation to a satisfactory state (post-closure responsibility).

4.1.2 COM (96) 557

The Strategy paper for reducing methane emission aims to "*examine problems and concerns related to atmospheric methane emissions, to identify the main emissions sources and sinks, to introduce some cost-effective means to reduce these emissions* *and to provide a set of potentials measures for incorporating into a Community emissions mitigation strategy. The Communication covers a series of measures that explicitly address the priority sectors, namely agriculture, waste and energy.”*

In particular, regarding waste disposal, the options suggested to reduce methane emissions are:

- anaerobic landfill management: methane recovery and utilization (this is the case of S.E.S.A. landfill);
- aerobic landfill management (semi-aerobic, re-circulatory semi-aerobic and aerobic landfills);
- reduced landfilling of organic waste (this is currently the most preferred option).

4.1.3 Directive 99/31/EC on landfilling of waste

After various proposals, drafts, and discussions to find common ground on environmental protection, Directive 99/31/CE (Legislative Decree no. 36 January 2003, in Italy) was enacted and passed. The overall objective is “ *by way of stringent operational and technical requirements on the waste and landfills, to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill.”*

The directive gives special importance to the biogas for these reasons:

“- whereas further consideration should be given to the issues of incineration of municipal and non-hazardous waste, composting, biomethanisation, and the processing of dredging sludges;

-whereas, like any other type of waste treatment, landfill should be adequately monitored and managed to prevent or reduce potential adverse effects on the environment and risks to human health;

-whereas measures should be taken to reduce the production of methane gas from landfills, inter alia, in order to reduce global warming, through the reduction of the landfill of biodegradable waste and the requirements to introduce landfill gas control.

The directive obliges the operator, once the landfill has been closed, to be responsible for the "*maintenance, monitoring and control in the after-care phase for as long as may be required by the competent authority, taking into account the time during which the landfill could present hazard."*In particular, in this period the operator must monitor and analyze landfill gas and leachate in accordance with Annex III; here the directive imposes to control the potential gaseous emissions (CH_4, CO_2, O_2, H_2S, H_2, etc..) monthly in the operative phase and every six months in the post-operative phase.

In Annex I the directive suggests how to manage biogas:

- *"appropriate measures shall be taken in order to control the accumulation and migration of landfill gas (Annex III);"*
- *"landfill gas shall be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and used. If the gas collected cannot be used to produce energy, it must be flared;"*
- *"the collection, treatment and use of landfill gas under paragraph 4.2 shall be carried on in a manner which minimizes damage to or deterioration of the environment and risk to human health."*

4.1.4 Decision 99/296

It regards the monitoring of CO2 and other greenhouse gases such as methane and affirms that Member States should make an inventory of the sources of gas emissions and their elimination by drainage sites, as well as describe the policies and national regulations adopted to reduce such emissions, and thus facilitate their total elimination.

4.1.5 Directive 2008/1/EC (IPPC Directive)

This Directive repeals the Directive 96/61/EC and requires industrial and agricultural activities with a high pollution potential to have a permit. This permit can only be issued if certain environmental conditions are met, so that the companies themselves bear responsibility for preventing and reducing any pollution they may cause.

In Annex I the activities submitted to the Directive are listed and in particular:

- *"Installations for the disposal of non-hazardous waste as defined in Annex II A to Directive 2006/12/EC under headings D8 and D9, with a capacity exceeding 50 tonnes per day."*
- *"Landfills receiving more than 10 tonnes per day or with a total capacity exceeding 25000 tonnes, excluding landfills of inert waste."*

The permit must contain in particular these information:

- the sources of emissions from the installation;
- the nature and quantities of foreseeable emissions from the installation into each medium as well as identification of significant effects of the emissions on the environment;
- the proposed technology and other techniques for preventing or, where this not possible, reducing emissions from the installation;
- measures planned to monitor emissions into the environment.

Besides the operator must inform the competent authority of the results of the monitoring of releases and without delay of any incident or accident significantly affecting the environment.

4.1.6 Directive 2008/98/EC on waste

This Directive establishes a legal framework for the treatment of waste within the Community. It aims at protecting the environment and human health through the prevention of the harmful effects of waste generation and waste management.

It creates a hierarchy regarding waste, i.e.:

- prevention;
- preparing for reuse;
- recycling;
- other recovery, notably energy recovery;
- disposal.

In particular the directive underlines that *“member States shall take the necessary measures to ensure that waste management is carried out without endangering human health, without harming the environment and, in particular: without risk to water, air, soil, plants or animals.”*

Moreover, it suggests the modality of the permit from the competent authority, which must contain:

“(a) the types and quantities of waste that may be treated;

(b) for each type of operation permitted, the technical and any other requirements relevant to the site concerned;

(c) the safety and precautionary measures to be taken;

(d) the method to be used for each type of operation;

(e) such monitoring and control operations as may be necessary;

(f) such closure and after-care provisions as may be necessary.”

4.1.7 Directive 2009/28/EC on renewable energy

Considering that *“the control of European energy consumption and the increased use of energy from renewable sources, together with energy savings and increased energy efficiency, constitute important parts of the package of measures needed to reduce greenhouse gas emissions and comply with the Kyoto Protocol to the United*

Nations Framework Convention on Climate Change, and with further Community and international greenhouse gas emission reduction commitments beyond 2012."

This Directive establishes a common framework for the production and promotion of energy from renewable sources. This directive comprehends also biogas from landfilling, indeed: " *"energy from renewable sources" means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases"*.

Each Member State has a target calculated according to the share of energy from renewable sources in its gross final consumption for 2020.

4.2 Italian legislation

The Italian legislation about biogas can be connected with the Legislative Decree 36/2003 which gives all the provisions regarding landfill siting, construction, bottom lining, top cover, leachate and biogas drainage and collection, closure and aftercare period.

4.2.1 Legislative Decree 36/2003 on landfill

This legislative decree is the Italian transposition of Directive 99/31/EC and legislates about landfilling; it "*establishes operational and technical requirements for waste and landfills, measures, procedures and guidelines aimed at preventing or reducing the most possible negative effects on the environment, in particular pollution of surface water, groundwater, the soil and air, and on the global environment, including the effect emissions, as well as' the risks to human health arising from the landfilling of waste, during the whole life cycle of the landfill."*

In the second article the definition of landfill gas is given as: *"all the gases generated from the landfilled waste"*.

The most prominent features of the law are given by:

- Art. 8: "*the application for a permit for the construction and operation of a landfill must also contain at least the following data and information*:
  - *the proposed methods for the prevention and reduction pollution, with particular reference to the measures for prevent the infiltration of water inside and the consequent formation of leachate;*
  - *the surveillance and control plan, in which must be given all necessary measures to prevent the risk of accidents caused by the operation of the landfill and to limit their consequences, both in the operational phase and in post-operative, with particular reference to the precautions taken for the protection of waters against pollution caused by infiltration of leachate in the ground and the other measures of prevention and protection against damage to the environment, the parameters to be monitored, the frequency of monitoring and the verification activities' study of the site by the applicant are given in Table 2 of Annex 2;"*
- Art. 12, paragraph 3: *"The landfill, or a part thereof, is considered finally closed only after the competent territorial authority (...) has performed a final inspection on the site, assessed all the reports submitted by the operator pursuant to Article 10, paragraph 1, letter l), and communicated to the operator the approval of the closure. The result of the inspection does not entail, in any case, a lower responsibility for the manager in relation to conditions the permit. Even after the final closure of the landfill, indeed, the manager is responsible for the maintenance, surveillance and control in the management of post-operative phase for all the time during which the landfill can lead risks to the environment."*
- Art.13, paragraph 2: *"The maintenance, supervision and monitoring of the landfill must also be insured during the after-care period, until the competent territorial authority determines that the landfill does not pose a risk to health and the environment. In particular, must be guaranteed checks and analysis on biogas, leachate and groundwater that can be concerned."*
- Art.13, paragraph 5: the monitoring of the landfill must be transmitted to the competent authority and comprehends:

"a) quantity and type of waste disposed of and their seasonal trends;

b) transfer price;

c) the pattern of numbers and volume of leachate and its procedures for the treatment and disposal;

d) amount of biogas produced and extracted and procedures for the treatment and disposal;

e) volume occupied and residual landfill capacity;

f) the results of checks carried out on waste sent in the landfill for their admissibility, as well as on matrices environmental."

5. SITE DESCRIPTION

The area of the study (the S.E.S.A. plant), is located in Veneto region, in the province of Padua and municipality of Este, in a locality named Comuna at the coordinates: latitude 45,22° and longitude 11,62°.

Fig. 6 - Veneto region (www.torri.it).

The plant confines with the western municipality of Ospedaletto Euganeo.

Fig. 7– Plant location with Ospedaletto Euganeo and Este municipalities (www.maps.google.it, modified).

5.1 Geology

The area is inserted, from a geological point of view, in the Veneto-Friuli plain, eastern termination of the Po Valley, bordered to the north and east from the Alpine foothills, to the west from the Lessini and Berici hills and to the south by Adige river and Adriatic Sea.

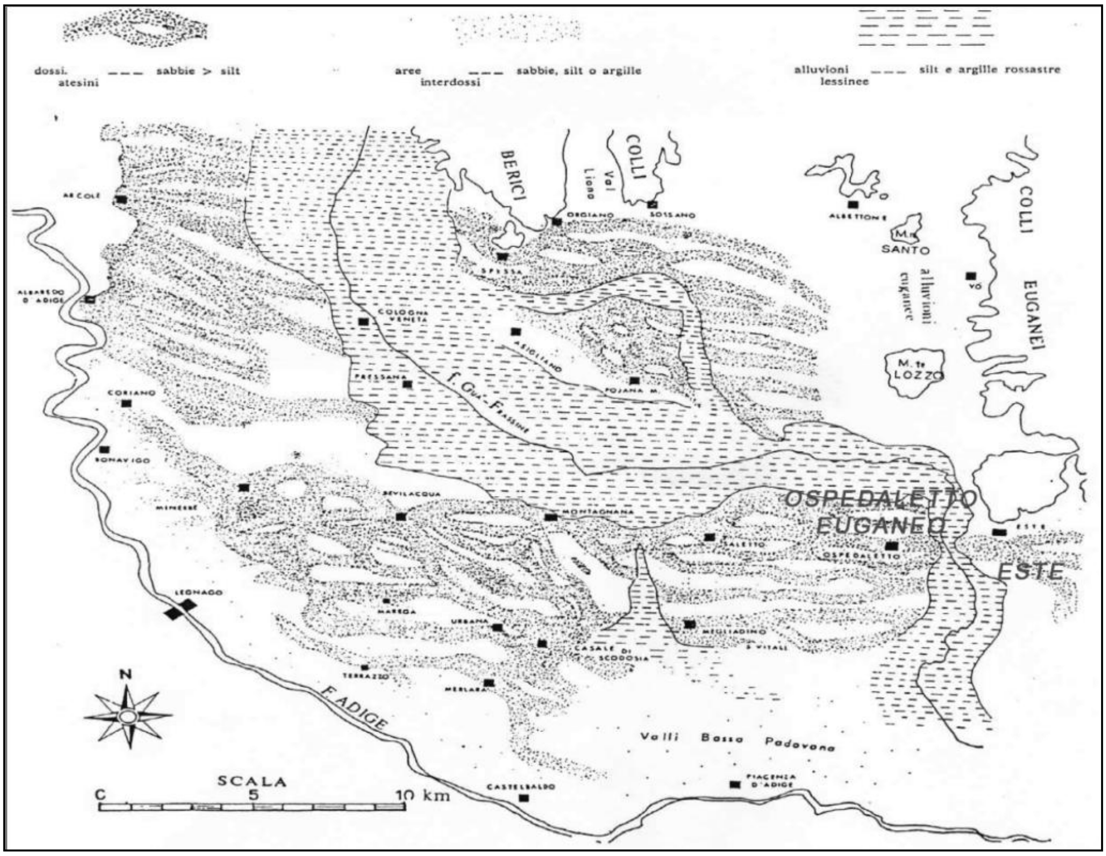


Fig. 8 – Geomorphological map of Este surroundings (Geological relation of estense P.A.T.I.).

The surroundings are characterized mainly by agricultural activities a flat morphology, crossed by a dense irrigation network and terminated by Colli Euganei.

The Veneto plain, formed in relatively short geological time, consists of thick layers of sedimentary materials, due to the succession of glacial and interglacial stages.

From the depositional point of view, the layer is made up of sedimentary incoherent material of fluvial origin in the high plains next to the hills, from alternations of marine and fluvial deposits in the vicinity of the middle zone of the plain and deposits almost exclusively marine in the lowlands.

In 2008 S.E.S.A. commissioned a hydrogeological study (Dal Prà M., *Relazione geologica e idrogeologica*) of the subsoil before starting the project of two new sectors of the landfill and the result can be taken as model for the whole area. The lithological sequence is composed by:

- an alternation of clay and lime layers from the ground plane to 3,60-4,50 metres;
- the first fine sandbank, sometimes weakly lime, from 3,60–4,50 metres to a maximum of 6,90 metres of depth;
- a dense alternation of clay and lime layers beyond 6,90 metres until 14 metres;
- finally, from 14 metres till 20 metres (the ultimate depth investigated) a fine sandbank has been found.

5.2 Hydrography

The surroundings of the plant are characterised by a dense network of canals; Canale Brancaglia flows 800 metres eastern from the landfill and a bit more far flow Scolo Lozzo and Canale Bisatto. In the immediate nearness of the plant are present: Scolo delle Monache (250 metres south-east from the landfill), Scolo Meggiotto next to the west part of the landfill and Scolo Maceratoi (20 metres from Scolo Meggiotto).

These canals are never larger than 4 metres and are 3-5 deep from the ground level. Minor canals are present along north and south sides of landfill, but they are often dry and they do not anyway exceed the depth of 50-80 cm.

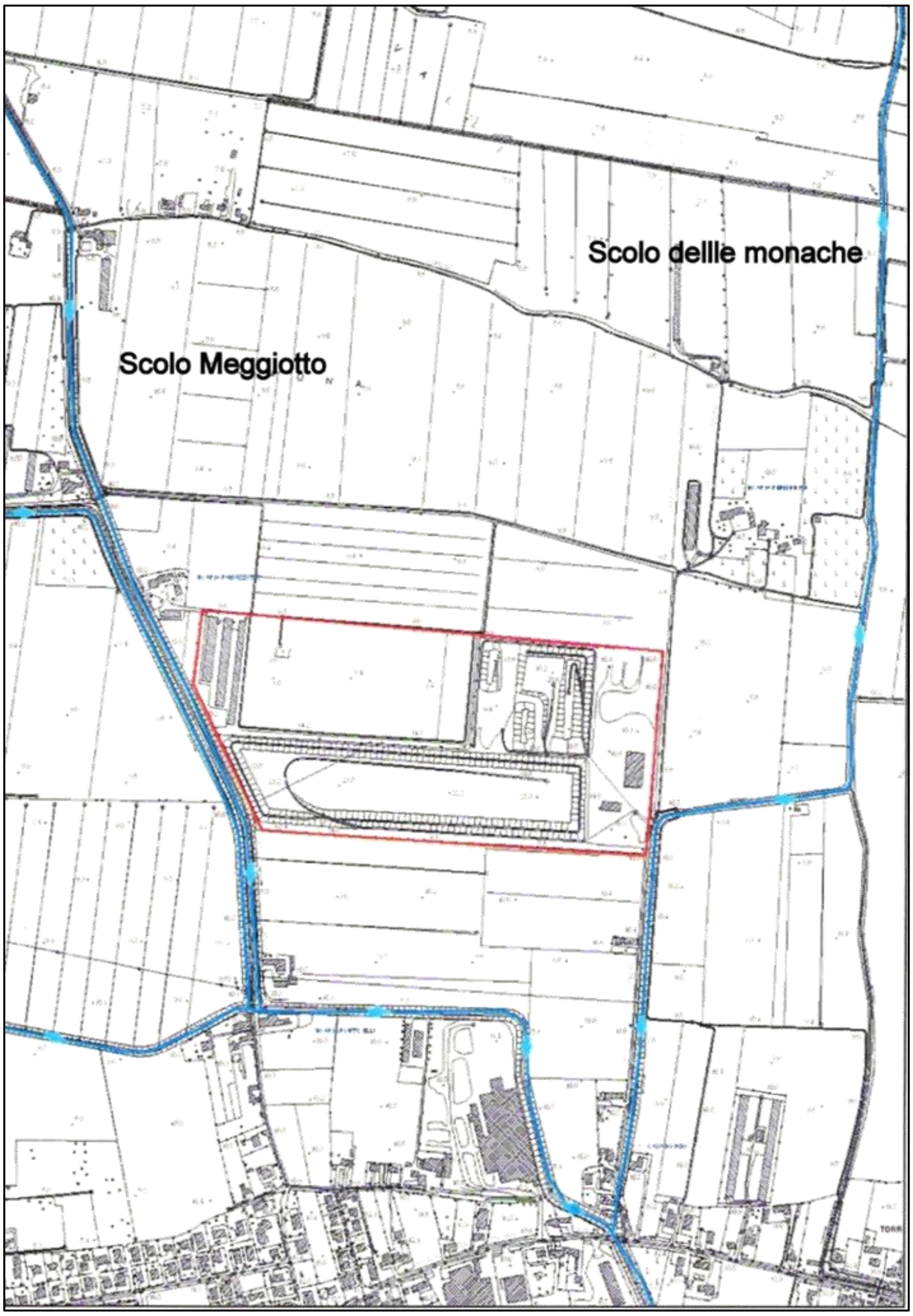


Fig. 9 – Hydrological map of the plant area (*Geological and hydrogeological study for the landfill extension project*, 2008).

In Veneto plain it is possible to distinguish these hydrogeological units:

- *high plain*: it is situated in the foothills and consists of a mattress mainly gravelly coarse, permeable and somewhat due to the activities of the major rivers (Piave, Brenta and Adige Astico), which houses a phreatic aquifer undifferentiated very rich and of good quality and therefore heavily exploited; its upper surface is found at depths decreasing from the foot of the mountains to the south; the water table is fed mainly by losses that occur along particular stretches of waterways, from direct precipitation and man-made irrigation of cultivated land.

- *Average plain:* is a wide band of few kilometres and consists of alternating layers of gravelly-sandy and silty-clay, which divide the undifferentiated aquifer in overlapping layers that determine the well-known phenomenon of the springs. The springs are the come to light of water of the aquifer, which are largely powered by contributions from the water table high plains.
- *Lowland:* are located in the south of the springs zone, they are formed by a dense alternation of sandy lithotypes and clayey-silt lithotypes. This sedimentary structure allows the existence, up to a depth of some tens of meters, of a system of aquifers of different sizes, extremely differentiated both in depth and in extension, generally in hydraulic balance between them. The first of these layers, generally with phreatic characteristics, is located at shallow depth from the ground level and is often influenced by the presence of irrigation channels in the surface. More in-depth, up to about 300-350 meters, there are in pressure groundwaters housed in sandy and/or gravelly layers.

The Este plant is located in the low Veneto plain and the underground scheme is made by an alternation of clay-lime layers and sandy layers, which house the groundwater. Thanks to the geological survey, made before the extension of the landfill area in 2008, the groundwater scheme is known:

- first aquifer: is present in a sandy layer with a variable thick; it starts at a depth of 3,6 – 4,5 metres and continues till 7 metres;
- second aquifer: it is housed in a deeper sandy bank and it is located beyond a depth of 14 metres.

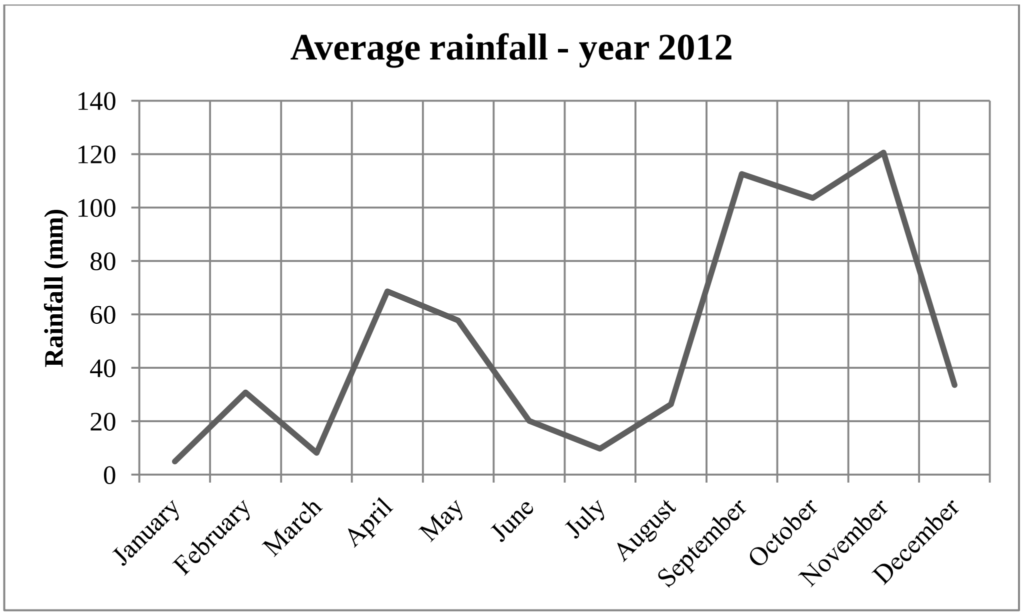
5.3 Climate

The climate of the territory falls under the Mediterranean category with continental characteristics, therefore with cold winters and hot, humid summers. The rainfall is relatively low, with reference values in the range of 600-800 mm/year. In the following table the average precipitation of the last years is shown.

Tab. 2 – Monthly and yearly rainfall in the plant (ARPAV).

Year /Month	**Total rainfall year 2008** [mm]	**Total rainfall year 2009** [mm]	**Total rainfall year 2010** [mm]	**Total rainfall year 2011** [mm]	**Total rainfall year 2012** [mm]
January	9,1	51,5	39,4	13,7	5,0
February	34,2	49,2	40,2	28,2	30,8
March	23,2	71,0	34,6	66,4	8,2
April	24,4	62,0	36,8	6,2	68,6
May	107,2	18,0	160,4	46,6	57,8
June	77,4	42,0	89,8	73,0	20,2
July	180,4	41,6	8,0	44,0	9,8
August	67,0	12,2	35,0	2,8	26,4
September	30,2	74,0	52,8	25,4	112,6
October	101,4	23,6	63,0	71,8	103,6
November	50,8	45,4	153,0	38,2	120,6
December	155,2	66,0	78,8	20,6	33,6
Total	**151,5**	**556,4**	**791,8**	**436,9**	**597,2**

The distribution of rainfall is of bimodal type, with absolute maximum spring (May) and relative maximum autumn (November) while the absolute minimum is in winter (January) and the relative minimum in August, as can be seen from graph 1.



Graph 1 - Monthly rainfall in 2012.

The temperature regime sees a summer maximum in July and a minimum in January. The seasonal maximum temperatures exceed 29°C, with weak circulation continental regimen, while the seasonal minimum stands at - 1.7 °C.

5.4 Environmental bonds

Law 394/91 defines the natural areas classification and institutes the official list of protected areas; in particular, they are classified as follow:

- national parks: they are not present in the nearness of the plant;
- regional or inter-regional parks: in Padua province there are the Natural Park of Sile river and the Regional Park of Colli Euganei; the last comprehends part of Este municipality, it is located anyway at 1500 m from the plant;
- natural reserves: none of the six reserves of Veneto region are in the nearness of the plant;
- protected wetlands: no areas are present in the province of Padua;
- other protected areas: in the Tombolo municipality, 45 km away from the plant, there is a protected area named Parco Palude di Onara; the area is external to Este municipality.

Regarding Natura 2000 net, which imposes to detect ZPS (Zone a Protezione Speciale, deriving from Birds Directive) and SIC (Siti di Importanza Comunitaria, deriving from Habitat Directive), the area of the plant is interested by:

- ZPS IT3260020 “Le Vallette” which is located 700 m away from the plant;
- SIC and ZPS IT3260017 “Colli Euganei–Monte Lozzo–Monte Ricco” which is at 1500 m away from the plant.

Moreover, the area is not interested by hydrogeological or landscape bonds.

Finally the northern part of the plant is considered floodable area from Civil Protection.

6. PLANT DESCRIPTION

S.E.S.A. S.p.A. stands for "Società Estense Servizi Ambientali" and fulfils a variety of environmental services; among these, the company manages the separate collection mainly in the basin number 3 of Padua, but also in other municipalities as reported in table 3.

Tab. 3 – Municipalities interested in waste collection by S.E.S.A. S.p.A. (*Dichiarazione ambientale*, 2011).

Padua 3 Basin	**Padua 4 Basin**	**Treviso 1 Basin**
Battaglia Terme	Bovolenta	Codognè
Baone	Candiana	Cimadolmo
Cinto Euganeo	Conselve	Fontanelle
Este	Due Carrare	Gaiarine
Lozzo Atestino	Piove di Sacco	Mansuè
Montagnana	Sant'Angelo di Piove di Sacco	Meduna di Livenza
Ospedaletto Euganeo	Arre	Oderzo
Pozzonovo	San Pietro Viminario	Ormelle
Sant' Elena		Ponte di Piave
Pernumia		Portobuffolè
Stanghella		Salgareda
		San Paolo di Piave
		Vazzola

The collection comprehends street sweeping, municipal waste, but also bulky and hazardous waste. Once collected waste goes to the plant where is submitted to different treatments, as explained in the following paragraph.

6.1 Waste treatments

The plant configuration is showed in figure 10, where are also indicated the different treatment units,described forward.

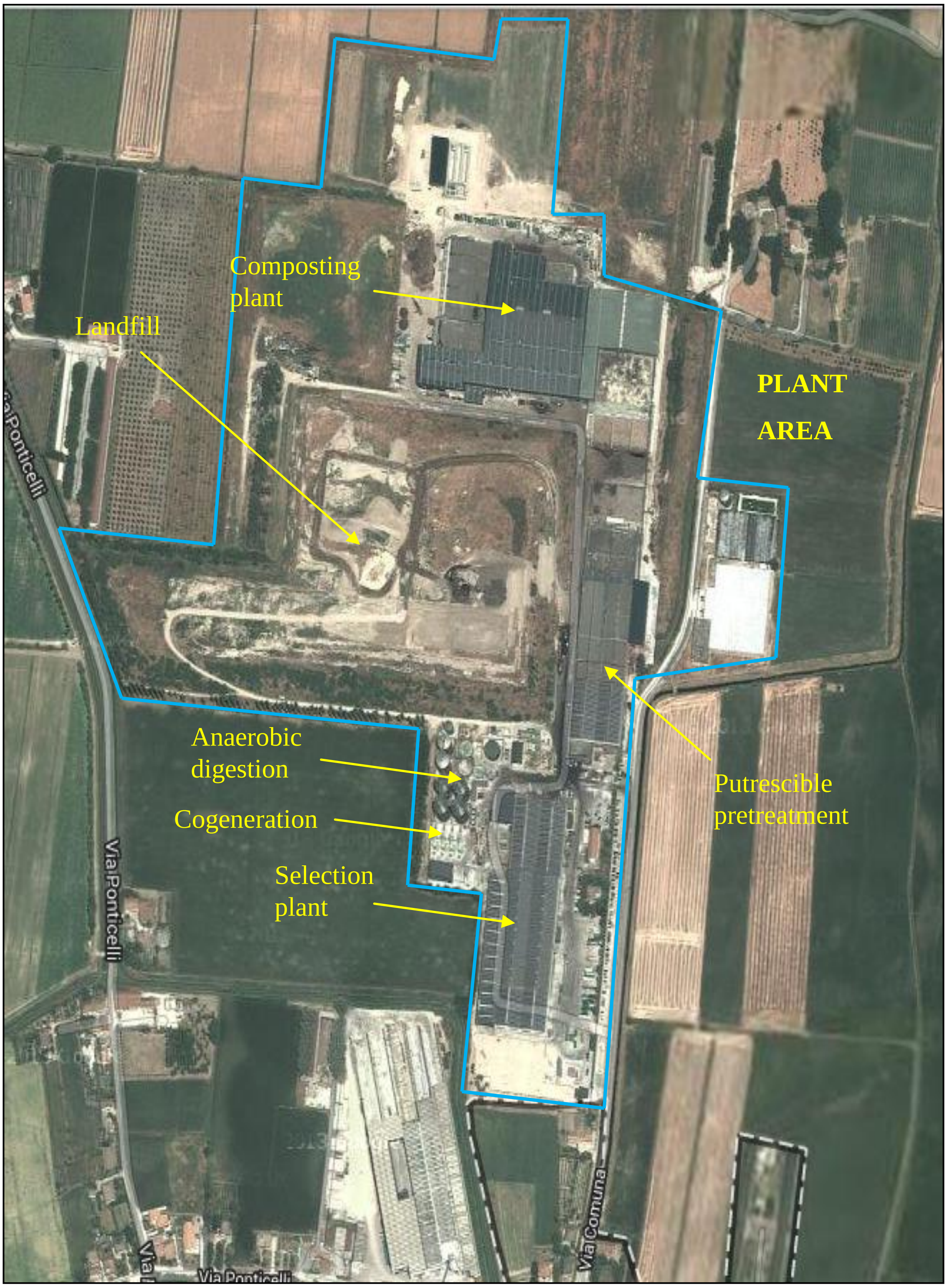


Fig. 10 – Aerial view of plant , with treatment units (www.maps.google.it**,** modified).

- *Selection*: once arrived to the plant waste are transferred in the selection shed; this is sized to treat 98.000 t/y, comprehending waste from separated and non separated fluxes. These are:
  - multimaterial collection waste;
  - monomaterial collection waste;
  - residual waste;
  - waste coming from commercial and industrial activities similar to MSW;
  - market waste;
  - bulky waste;
  - oversieve of composting plant.

  The waste is initially stored and then fed in a bag opener; thanks to a conveyor belt, it passes into a drum screen which produces three different streams. The fine stream is composed of material with granulometry minor than 60/80 mm (inerts and pieces of plastic and paper) mostly non recyclable and therefore sent to landfill disposal. The second fraction, comprehended between 60/80 mm and 180/250 mm (plastic bottles, aluminum and steel containers, newspapers,…), is sent to the automatic selection. Finally the bulky fraction (cardboard, packaging, …) goes to the relative selection.

  The second fraction will be submitted to a magnetic separator and an Eddy current separator, then it goes to a manual/mechanical separation; indeed some conveyor belts are provided with an optical separator to divide different materials, which are finally controlled by operators and then submitted to press.

  The bulky fraction is controlled by operators which separate the recyclable fraction; the residual fraction is sent to the bag opener again.

  S.E.S.A. stores the recyclable materials and relies upon external firms to treat them.

  Regarding bulky and T/F waste, S.E.S.A. has a storage area waiting for external firms.

- *Composting*: putrescible, livestock, sludge and green waste are mixed and undergo to the composting process (bio-oxidation and maturation) and then stored to produce high quality compost. The exceeding green waste is treated apart in biocells to form green compost going to garden centres. The biocells have a capacity of 14.000 t/y of which:
  - 60.000 t/y to be mixed with putrescible waste and producing high quality compost;
  - 80.000 t/y available to produce green compost.

  The oversieve of composting process is sent to the landfill.

- *Anaerobic digestion*: the anaerobic digestion plant is fed with the squeeze of putrescible waste and also with livestock waste; the process is wet and mesophilic with a duration of 20-25 days. The plant is composed by four digesters of 2500 m^3 each and four post-digesters of the same size, with a capacity of 228.000 t/y. The biogas produced is treated thanks to: a water and soda scrubber, a compression and a de-hydratation units; then it is utilized in a cogeneration unit composed of six engines with a capacity of 1415 kW_e and 1345 kW_t; these engines, together with the one serving the landfill, feed the district heating. A centrifuge treats the digestate coming out from digesters: the liquid fraction is sent to the internal MBR waste water treatment plant, while the solid fraction is sent to composting process.

- *District heating*: as already said, biogas is utilized to produce electricity to be used in the plant and to be sold to the public net; moreover the thermal energy realized is used to heat the near public and private users. The line actually covers 5,4 Km, but it is thought to extend toward Este and Ospedaletto Euganeo municipalities.

- *Photovoltaic panels*: the entire area of the plant is covered with panels, located on the shed roofs and produces 110 KWe.

- *Waste water treatment*: this section is composed of three different plants:

  - MBR biological plant, which treats process water from scrubbers, service area waters and exceeding digestate;

  - first flush plant, which treats precipitations falling on the selection service area;

  - chemical-physical plant, which pre-treats leachate from landfill prior to be sent to the public biological waste water treatment plant of Este, managed by S.E.S.A. too.

6.2 Landfill

In figure 11 it is shown an aerial view of landfill site, while in figure 12 is presented the current area of the landfill divided in sectors and basins.

Fig. 11 – Landfill aerial view (www.maps.google.it).

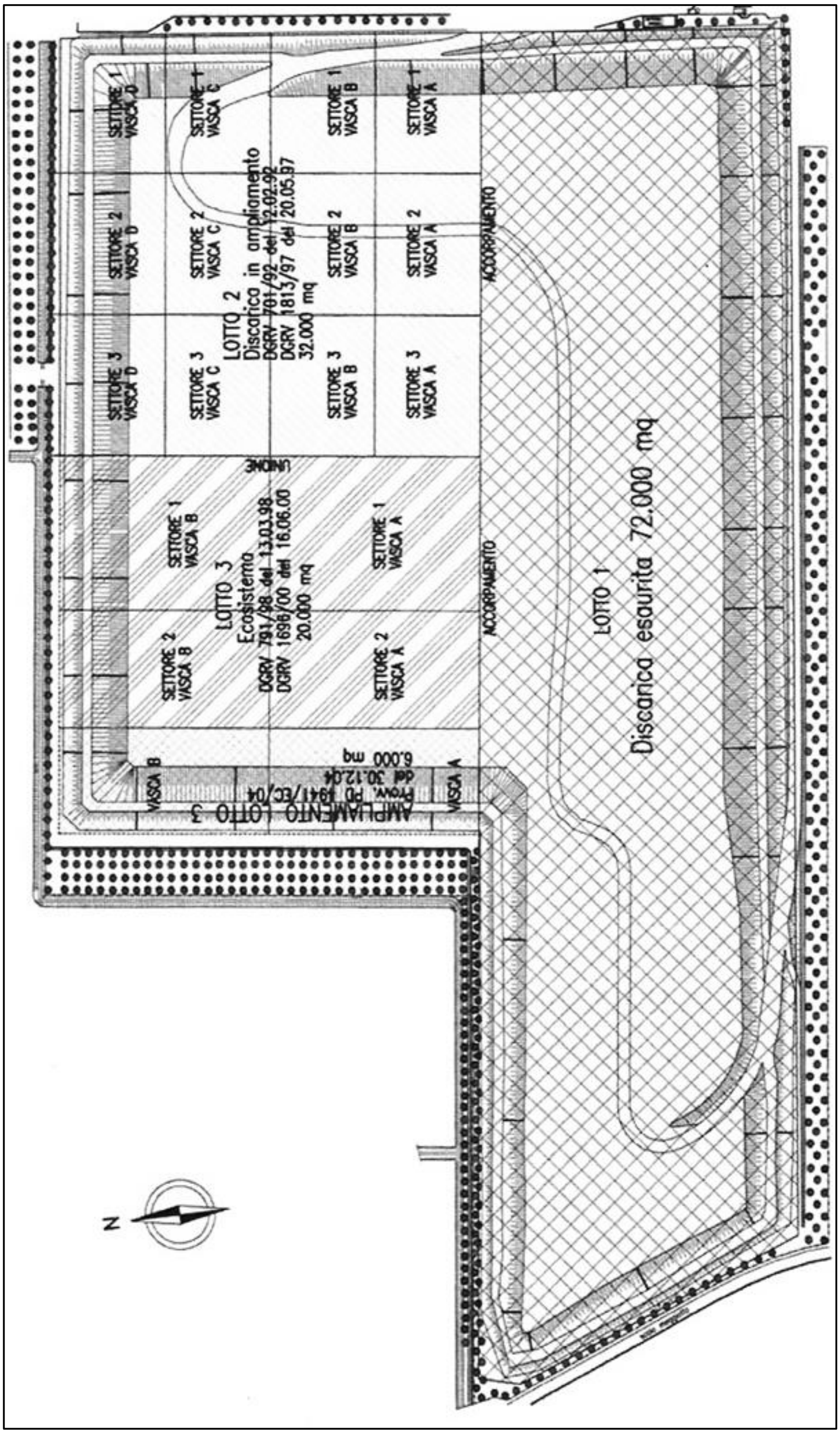


Fig. 12 – Scheme of landfill sectors and area at present day (Technical relation "*Nuovo impianto di selezione e valorizzazione rifiuti urbani da raccolta differenziata con adeguamento impianto di smaltimento rifiuti urbani non pericolosi e opere accessorie*", 2008).

Following figure 12 it is possible to discover landfill history, which starts in the 60's. The landfill was initially managed by Este municipality (until 1995) and the landfill area was limited to Lotto n°1: it has been approved by Veneto Region Decree n°117/AMB on 16/07/1986 and, subsequently, with the Veneto Region Decree n°508 on 22/02/1991 the completion and arrangement of this parcel have been approved. Lotto n°1 has an area of 72.000 m^2 and a volume of 750.000 m^3, a trapezoidal shape and in 1995 has been exhausted.

Tab. 4 - Area and volume of landfill sectors.

Parcel	**Area (m^2)**	**Volume (m^3)**
Lotto 1	72.000	750.000
Lotto 2	32.000	320.300
Lotto 3 (sector 1-2)	20.000	355.000
Lotto 3 (sector 3)	6.000	95.000
Total	**130.000**	**1.520.300**

Lotto n°2 project has been proposed by Este municipality in 1991, it has an area of 32.000 m^2 and it is divided in three sectors with 4 basins each (A, B, C and D), the volume is of 251.000 m^3. It has been approved by Delibera Giunta Regionale of Veneto region n°701 on 12/02/1992 and in August 1995 S.E.S.A. began the works; in november 1995 the disposal in basins A and B started.

With the Delibera Giunta Regionale of Veneto region n°1813/1997 has been approved the project "Variante tecnica", which introduced important environmental protection works like leachate and biogas collection on both the landfill sectors and unification of Lotto n° 1 and n°2, which added 69.300 m^3.

With the Delibera Giunta Regionale of Veneto region n°791/1998 has been approved the project "Ecosistema", or Lotto n°3, which has an area of 20.000 m^2 and a volume of 355.000 m^3 comprehending the unification of Lotto n°1 and n°3. An integration to D.G.R.V. n°791/1998, approved with D.G.R.V. n°1696/00 on 02/02/2000, has lead to several improvements to landfill:

- waterproofing of landfill bottom: from the bottom to the top 50 cm of clay, HPDE geomembrane, another 50 cm clay layer protected with a geotextile;

- daily cover: in alternative to clay or vegetable soil, other materials can be used (listed in D.M. 5/2/98);
- strengthening of leachate drainage system, with new wells;
- strengthening of biogas aspiration system;
- final arrangement: two new layers, the first with low permeability and the second with natural soil.

In 2000 works relative to Lotto n°3, Sector 1, have been completed.

In 2004, the adjustment to Legislative Decree 13/1/2003 n°36 has been approved with Provvedimento of Province of Padua n°4941/EC/2004 on 30/12/2004. It provides different news regarding daily cover and bottom layer, but also the landfill life extension with a new sector of Lotto n°3 of 6.000 m^2 and a volume of 95.000 m^3.

Tab. 5 - Other data regarding landfill

Landfill characteristics	
Mean depth respect to ground level	3,5 m
Max height respect to ground level	19 m ± 1
Waste density for residual conferment	1 t/m^3
Residual capacity of landfill at 31/12/2008	125.315 m^3

In 2008 a new part of the landfill has been projected and approved, but construction works haven't been started yet. This new portion of landfill will consist in two sectors : Lotto ovest with an area of 10.500 m^2 and Lotto nord with an area of 34.000 m^2, the total extension volume will be of 375.000 m^3. In figure 13 are showed the new portions of landfill with the red line, while yellow line divides sectors nord and ovest.

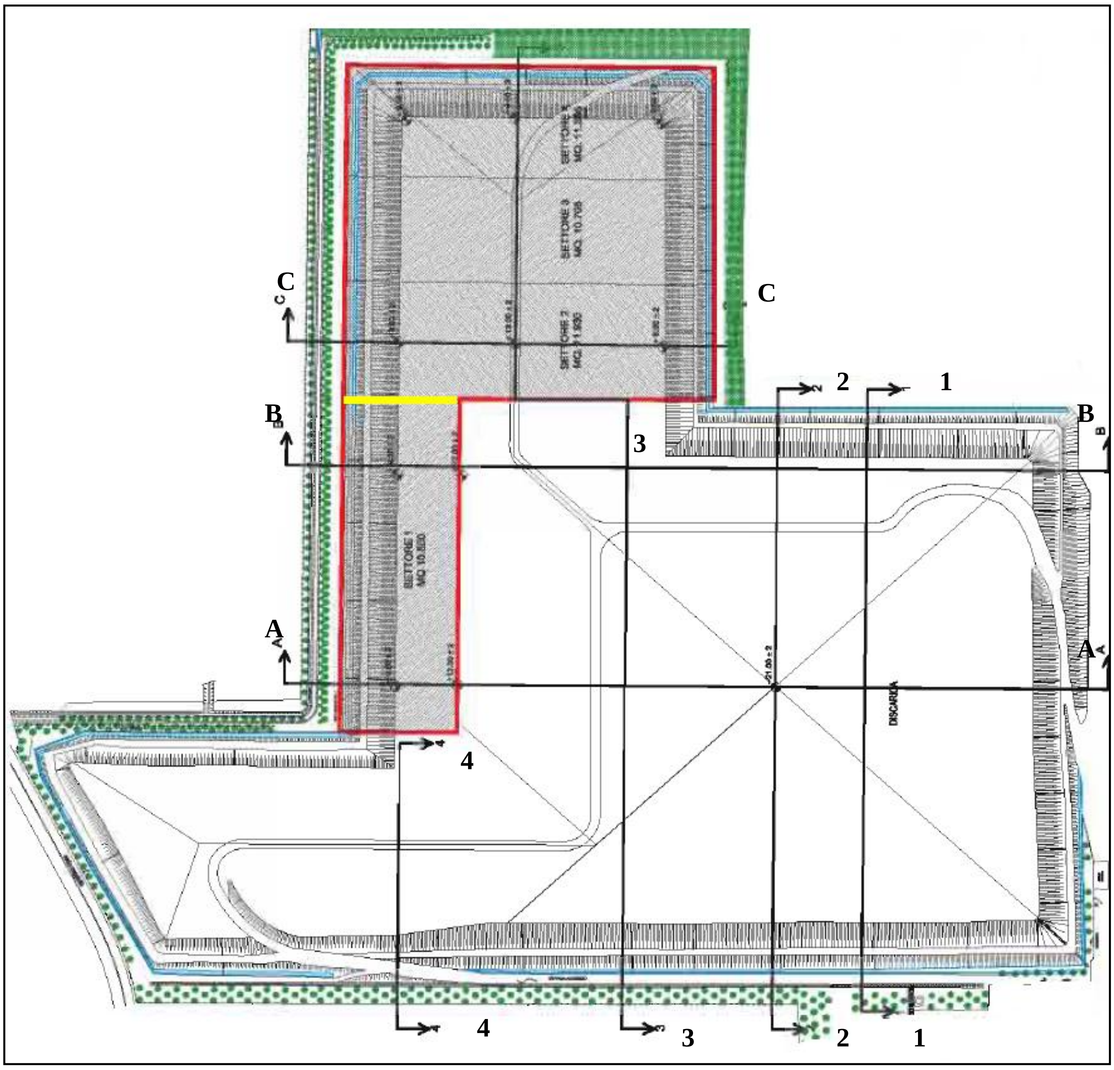


Fig. 13 – Representative plant view for following sections.

The landfill exercise is today regulated by the Provvedimento n°60/IPPC/2008: Integrated Pollution Prevention Control; the operator will follow it during the closure phase. In particular, the morphology compliance of landfill and the capacity of meteoric waters removal must be checked before the closure.

Bottom liner

Since old landfill has been projected in the 60’s, the only layer in the bottom is represented by a compacted clay liner; while the rest of the landfill is provided with a more complex liner following the provisions of Legislative Decree 36/2003.

It is composed, both for Lotto n°2 and n°3, from the bottom to the top by:

- compacted clay liner (50cm) with a permeability k <10^{-9} m/s;
- HDPE geomembrane (2mm) to strengthen the clay protection function;
- compacted clay liner (50cm) with a permeability k <10^{-9} m/s;
- geotextile to separate drainage layer from clay;
- drainage layer (50 cm) with gravel of ø = 30-100 mm to convey and collect leachate;
- waste.

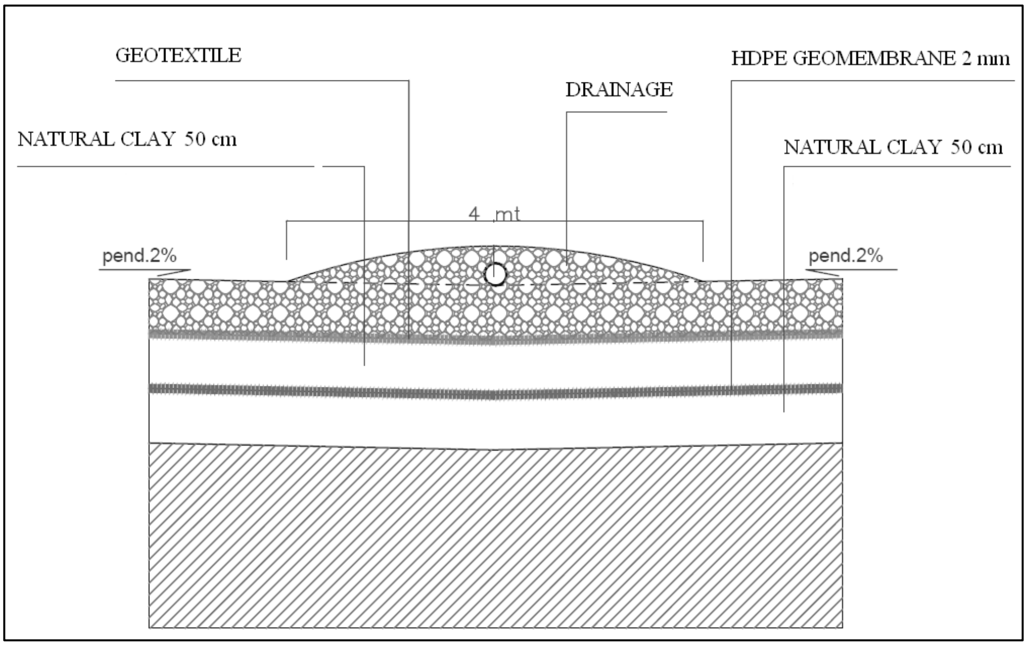


Fig. 14 – Bottom liner of Lotto n°2 and n°3.

Top cover

Landfill cover is different for old landfill and Lotto n°2 and n°3; in particular for old landfill it is composed from the bottom to the top by:

- waste;
- compensation layer (natural soil, compost and/or remediation soil);
- compost layer (50 cm);
- clay layer (50 cm);
- vegetal soil and compost layer (100cm).

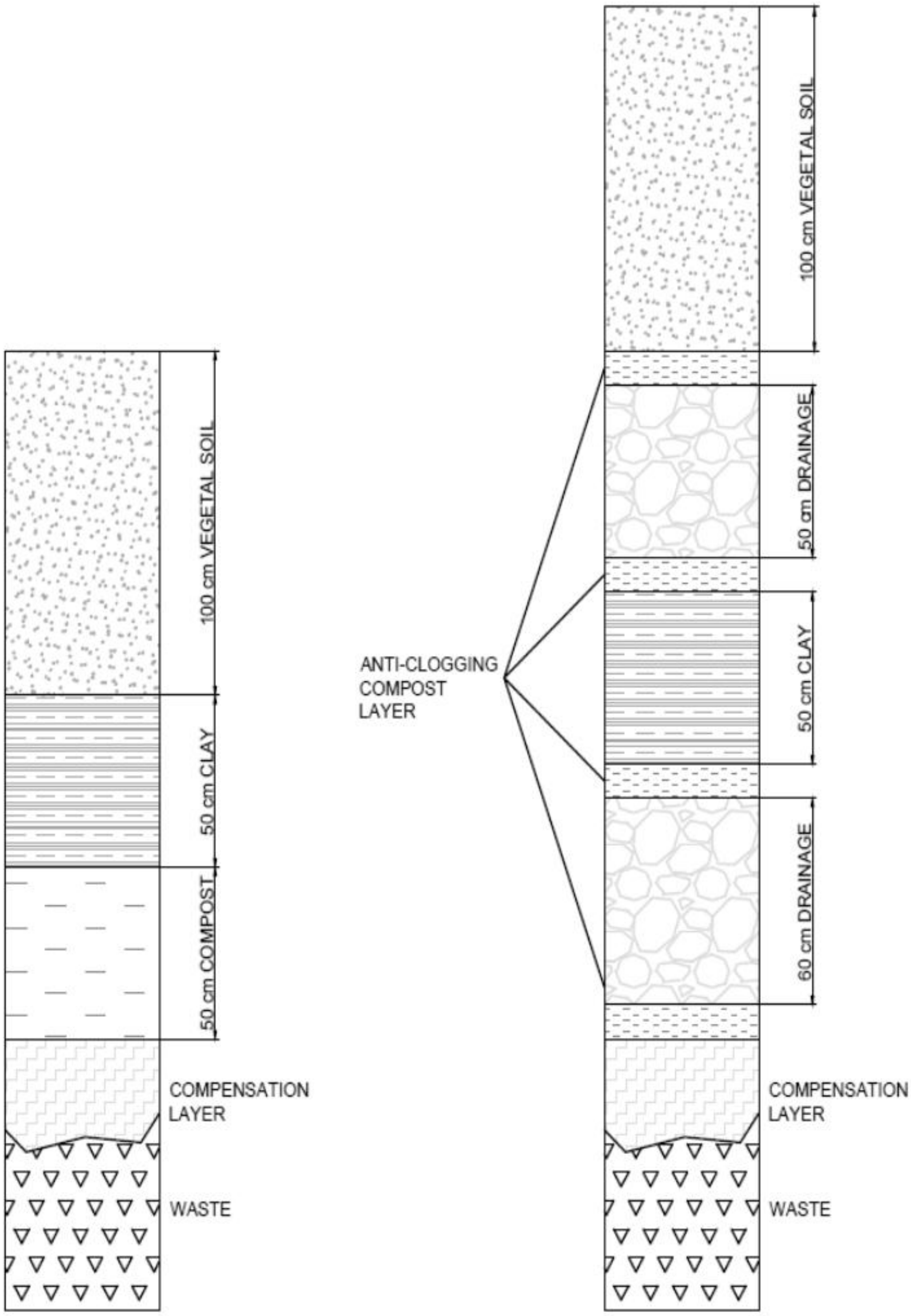


Fig. 15 – Top cover of old landfill (left) and of Lotto n°2 and n°3 (right).

Regarding Lotto n°2 and n°3 top cover (fig.15) is composed from the bottom to the top by:

- waste;
- compensation layer;
- biogas drainage layer (60 cm) made of glass refuse, gravel, compost or other material;
- clay layer (50cm);
- rain water drainage layer (50cm) made of glass refuse, gravel, compost or other material;
- natural soil and compost (100cm);
- between each layer is located an anti-clogging layer of 10-20 cm made of compost with a diameter of more or less 25 mm.

Leachate drainage system

Leachate collection system comprehends a double slope of 1% on the bottom of the landfill along sector length and 1% on the sector transversal section; leachate is collected thanks to PE slotted pipes with 200 mm of external diameter wrapped in a gravel bed; the drainage net is arranged in a fish bone manner. Each sector has two storage tanks in the external parts, provided with submergible pumps starting only when leachate head goes beyond 50 cm level. Once collected leachate goes towards the internal physical/chemical wastewater treatment plant. In figure 16 a detail of vertical system of collection is shown.

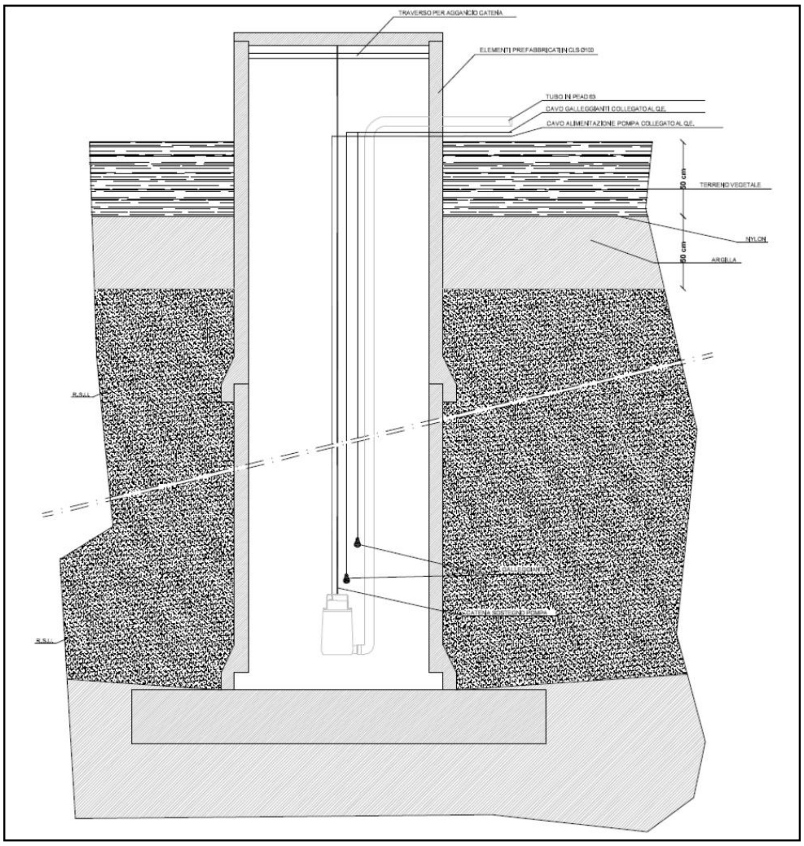


Fig. 16 – Detail of a leachate well, provided of a submergible pump.

<u>Biogas drainage system</u>

Regarding biogas collection system, works started in 1997 with the realization of the shafts for drainage, the capitation net and the energy recovery plant, through the activation of cogeneration plant. The collection net is of vertical-horizontal type, where vertical part is composed by shafts with HDPE head completed with drainage and the horizontal part made by transport pipes, in HDPE, which link shafts with regulation stations. In figure 17 it is shown the net of biogas collection in 2004. Regulation stations are named A and B for the old landfill, while C and E for the recent part (fig.18).

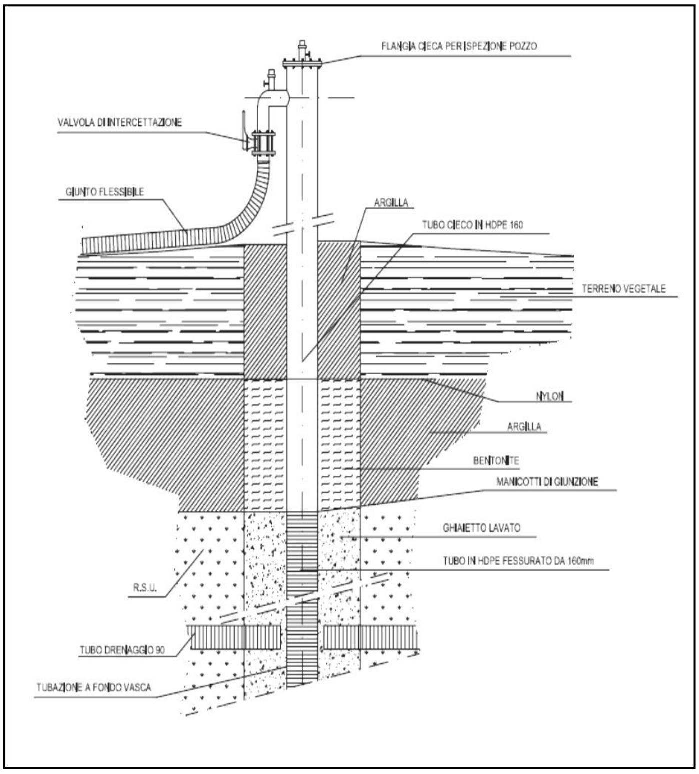


Fig. 17 – Detail of a biogas venting well.

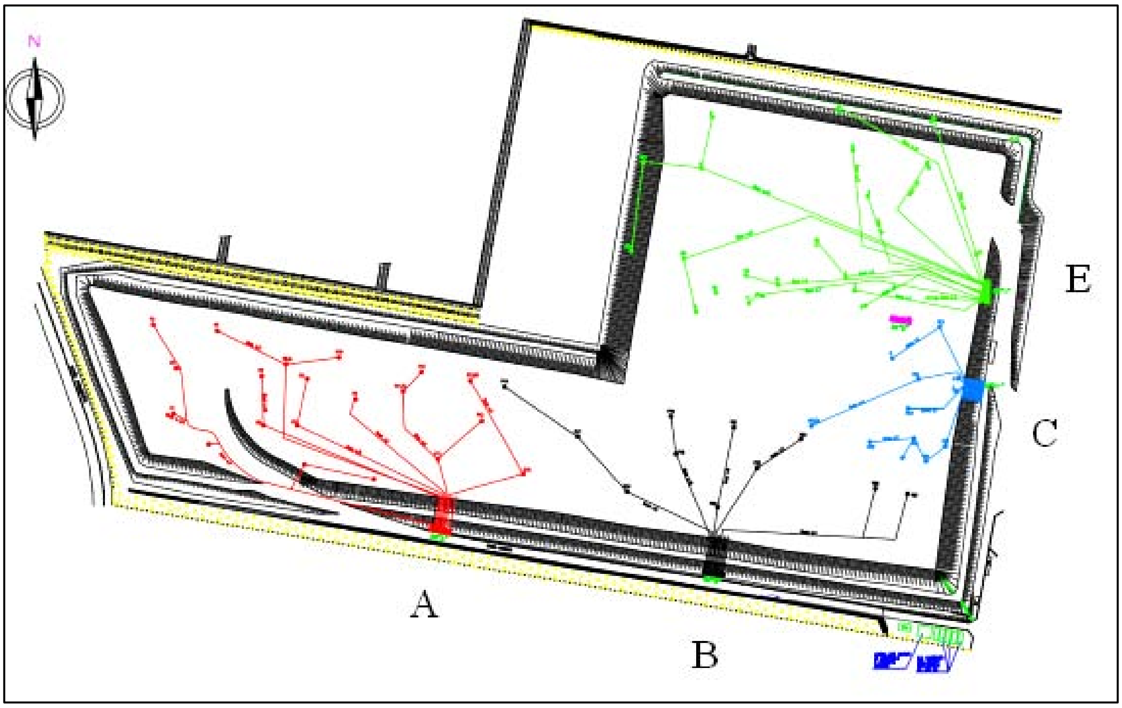


Fig. 18 – Biogas extraction system plant view.

These stations collect all the pipes in the nearness allowing the separate regulation of each shaft or line in function of productive characteristics. From the regulation stations the biogas is conveyed to a cogeneration plant, formed by an engine with a nominal power of 1416 kW/h.

Prior to reach the engine, biogas goes trough different stages, as shown in figure 19:

- an aspirator which creates the right depression to extract biogas from the landfill;
- a depression controller;
- a refrigerator group to decrease gas temperature to extract the condense;
- a condense separator;
- a pressure controller that regulates the pressure of biogas;
- a torch to burn biogas in the case of malfunctioning of cogeneration engine or gas over-production;

The engine is a Jenbacher JGS 416 GS-B.L, named SESA 3, with the characteristics showed in table 6:

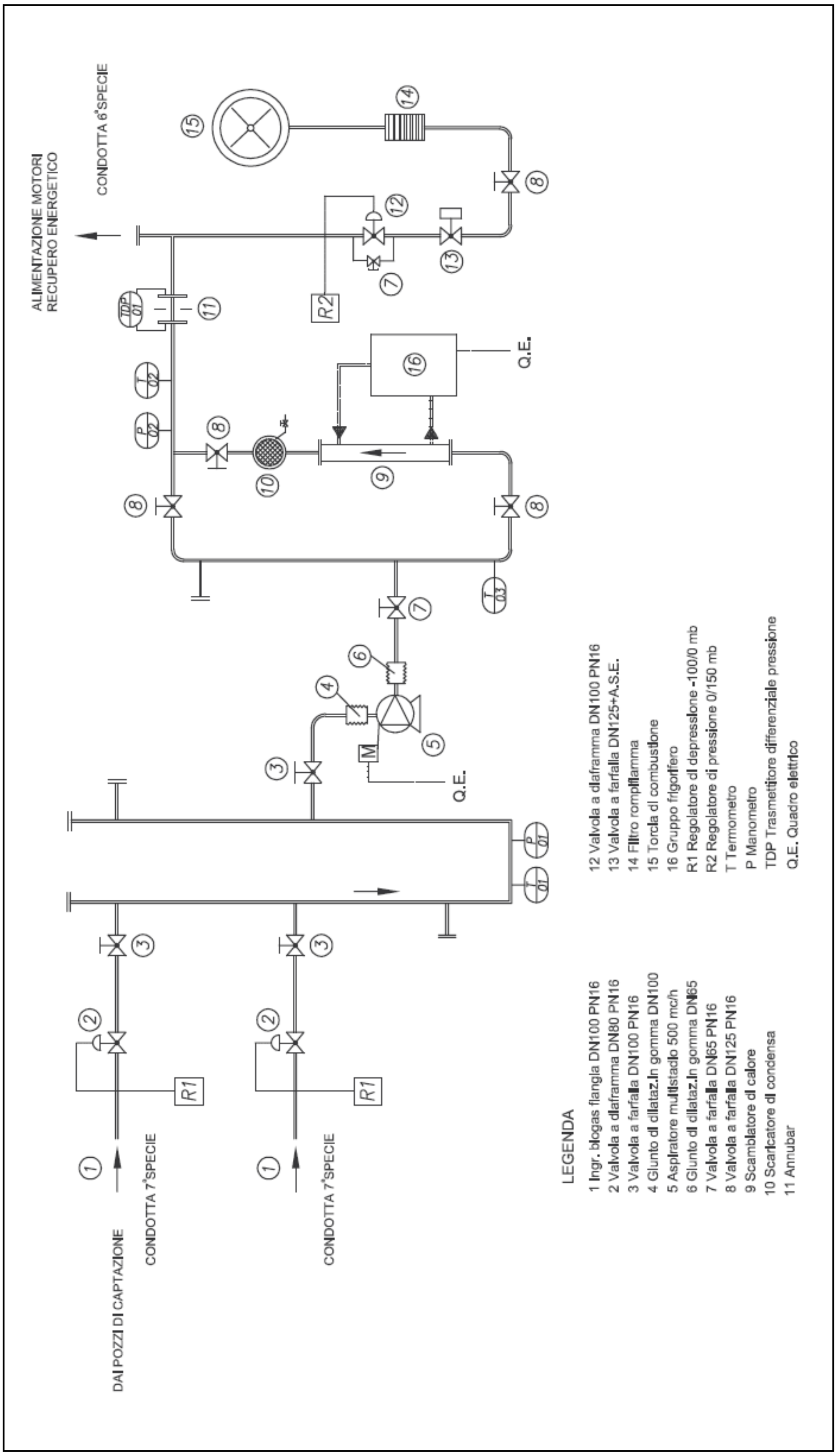


Fig. 19 – Biogas treatment section before going to cogeneration engine.

Tab. 6 - Ge Jecnbacher 416 cogegnerator engine characteristics.

Jenbacher JGS 416 GS-B.L cogenerator engine				
Data with		**Max load**	**Partial load**	
		100%	75%	50%
Gas quantity	Nm^3/h	529	405	281
Mechanical power	kW	1026	770	513
Electrical power	kW	998	747	495
Thermal power to dissipate				
~ Engine cooling water circuit	kW	174		
~ Low temperature circuit	kW	45		
~ Oil cooling water	kW	143		
~ Engine cooling water	kW	195		
~ Superficial heat	kW	71		
~ Residual thermal power	kW	24		
Electric efficiency	%	41,9	41	39,2
Dimensions				
~ Length	mm	6200		
~ Width	mm	1800		
~ Height	mm	2200		
Weight	kg	12500		

The torch is a CONVECO TO 1500 model whose characteristics are listed below:

Tab. 7 – Torch TO 1500 CONVECO characteristics.

CONVECO Torch TO 1500 model		
Flow rate	Nm^3/h	1500
Feeding tension	V	380
Combustion temperature	°C	800-1000
Combustion power	kW	3000-6000
Combustion range (CH_4= 50%)	Nm^3/h	300-1500
Minimum methane percentage	%	20
Height	mm	10000
Diameter	mm	400

7. LANDGEM MODEL

LandGEM is an automated tool for estimating the volume and composition of the generated gas throughout the time as a consequence of the degradation of organic matter, indeed it estimates emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds (NMOCs) and individual air pollutants composing LFG.

The last version (3.02), used in this case, has been released from EPA in 2005 and presents several improvements compared to version 2.01: a better accuracy of emissions estimates over time, since it takes into account a 0,1 year as time increment, rather than an entire year step; it allows to calculate directly total landfill gas, while before it must be calculated apart starting from methane emission rates; it has reduced the reporting of emissions from 200 to 140 years past closure; it can be entered waste also in the landfill closure year, while before not; moreover version 3.02 contains values of k and L_0 also for wet landfills (bioreactors).

7.1 Theory behind LandGEM

The software is based upon a first order decomposition rate equation (Eq. 1) for quantifying emissions from the decomposition of landfilled waste and to estimate annual emissions over a time period based on user specifications.

The model can work both with site-specific data or with two different sets of default parameters:

- *CAA defaults values*: they are based on requirements for MSW landfills laid down by the Clean Air Act (CAA)[1], including the NSPS/EG[2] and NESHAP[3].

[1] The *Clean Air Act* is a United States federal law designed to control air pollution on a national level. It requires the Environmental Protection Agency (EPA) to develop and enforce regulations to protect the public from airborne contaminants known to be hazardous to human health. The 1963 version of the legislation established a research program, expanded in 1967. Major amendments to the law, requiring regulatory controls for air pollution, passed in 1970, 1977, and 1990 (http://epa.gov/oar/caa/index.html).

This set of default parameters yields conservative (maximum) emission estimates and can be used for determining whether a landfill is subject to the control requirements of the NSPS/EG or NESHAP. The applicability is determined by tiers; the first tier is a size cutoff: below 25 million cubic metres of waste landfill is not subject to the regulation. The second tier consists in assessing if the emissions of NMOCs exceed the limit of 50 Mg/y using LandGEM with CAA defaults; in this case it can be decided to install emissions controls or to move to the third tier: i.e. testing landfill for NMOCs concentrations. If the test shows that cut off values is still exceeded, it can be decided to install emissions controls or to go to the fourth tier: performing another test to obtain site-specific k value.

- *Inventory default values*: with the exception of wet landfill defaults, the inventory defaults are based on emission factors in the U.S. Environmental Protection Agency's (EPA's) *Compilation of Air Pollutant Emission Factors* (AP-42)[4]. This set of defaults yields average emission and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data.

Therefore if site-specific values are available it is advisable to use them to obtain the most actual results; in case of lack of data it is recommendable to use inventory default values to have a result respecting typical U.S. landfill emissions. Finally, if

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[2] NSPS/EG (*New Source Performance Standards/emission guidelines*) is one of the four regulatory programs established by the CAA, dictating the level of pollution that a new stationary source/existing source may produce.

[3] NESHAP (*National Emissions Standards for Hazardous Air Pollutants*) is one of the four regulatory programs established by the CAA; they are emissions standards set by the United States EPA for an air pollutant that may cause an increase in fatalities or in serious, irreversible, or incapacitating illness.

[4] AP-42 *Compilation of Air Pollutant Emission Factors*: was first published by the US Public Health Service in 1968. In 1972, it was revised and issued as the second edition by the US Environmental Protection Agency (EPA). Air pollutant emission factors are representative values that attempt to relate the quantity of a pollutant released to the ambient air with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per mega gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages (http://www.epa.gov/ttn/chief/ap42/index.html).

the purpose of the study is to verify if the landfill is subjected to CAA regulation it can be used the set of CAA default values, as specified above.

The first order decomposition rate equation used is:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=1}^{1} k L_0 \left(\frac{M_t}{10}\right) e^{-k t_{i,j}} \qquad \text{(Eq. 1)}$$

Where:

- Q_{CH4} = annual methane generation in the year of calculation [m^3/y];
- i =1 year time increment;
- n = (year of the calculation) – (initial year of waste acceptance);
- j =0,1 deci-year time increment;
- k = methane generation rate constant[y^{-1}], accounting for how quickly the methane generation rate decreases once it reaches its peak rate;
- L_0 = potential methane generation capacity [m^3/t];
- M = 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 (decimal years, e.g. 3,2 years).

The total landfill gas emissions are calculated by estimating methane generation (Q_{CH4}) and doubling it, since landfill gas is assumed to be composed roughly 50% of methane and 50% of carbon dioxide; nevertheless this proportion can be changed with site-specific values.

As can be seen from (Eq.1), methane generation is function mainly of two parameters, apart from waste mass and time:

- *CH_4 generation rate constant* (k) determines the rate of CH_4 generation for each sub-mass of waste in the landfill. The higher the value of k, the faster CH_4 generation rate increases and then decays over time (fig. 20). The value of k is function of waste moisture content, availability of the nutrients for methanogens, pH and temperature and it ranges between 0,003 and 0,21 y^{-1}.

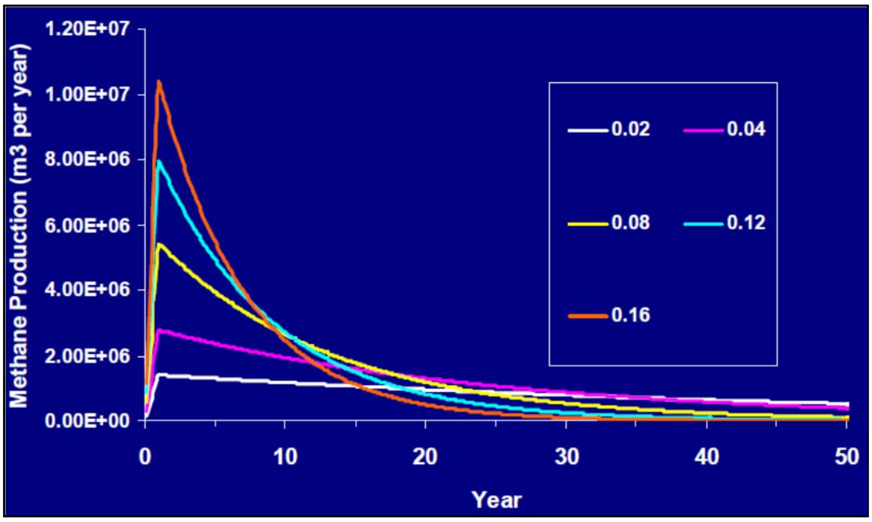


Fig. 20 – Effect of k increase in methane production (Barlaz et al).

- *Potential CH_4 generation capacity* (L_0) depends only on the type of waste landfilled; the higher the cellulose content of the waste, the higher the value of L_0 and the higher the value of methane production (fig. 21). It ranges between 6,2 and 270 m^3/t_{waste}.

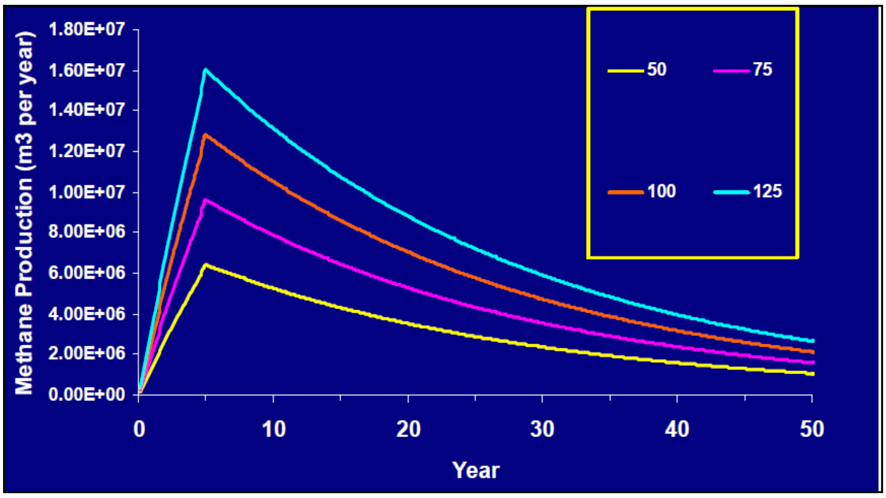


Fig. 21 – Effect of L_0 increase in methane production (Barlaz et al).

Apart from methane, carbon dioxide and total landfill gas, LandGEM calculates also a list of air pollutants present in LFG in low concentration due to the leaching and composition of waste. This calculation is based on concentration measure in LFG, but if this data are not available, the program proposes standard concentrations advised in AP-42 Inventory; moreover the default air pollutants included are designated as hazardous air pollutant (HAP) or volatile organic compound (VOC). Since some air pollutants concentration are higher in case of hazardous landfill disposal, in the model can be selected “co-disposal” (in case of landfills with disposal of hazardous together with non-hazardous waste) and “no or unknown co-disposal”.

So the NMOC (volatile compounds present in LFG, apart from methane) concentration in LFG is function of the type of waste and the extent of reactions that produce various compounds from the anaerobic decomposition of waste. This concentration in field data of 23 landfills ranged from 240 to 14.300 ppmv as hexane and three choices can be done in LandGEM: the default CAA value of 4.000 ppmv and two inventory default options, 2.400 ppmv for co-disposal and 600 ppmv for no or unknown co-disposal.

7.2 How LandGEM works

Providing landfill characteristics

LandGEM is composed by Excel spreadsheets and in the first sheet, named “user inputs”, are requested the following information:

- *Landfill name*;
- *Landfill open year*;
- *Landfill closure year* (with the option for the model calculating closure year);
- *Waste design capacity*.

LandGEM requires *closure year*, but if this is unknown the model will calculate it thanks to *waste design capacity* (t); in any case a *closure year* major than 80 years from the landfill opening is no accepted.

The program will proceed to calculate it starting from landfill *open year*, *waste design capacity* and *waste acceptance rate* in this way:

$$Closure\ year = \frac{Waste\ design\ capacity - \Sigma(waste\ acceptance\ rates)}{Final\ waste\ acceptance\ rate} + Year\ of\ the\ final\ acceptance\ rate$$

Waste design capacity represents the total amount of waste that can be disposed in the landfill, or the amount of waste-in-place upon closure. The value entered should be the amount of decomposable material landfilled, subtracting from the entire *waste design capacity* the portion of inert material present in waste; however, since very often the real composition of waste is unknown, the guide advises to enter the total waste input to reach a more conservative value of methane emissions.

Also *waste acceptance rate* (t/y) must be entered in the model and it makes these assumptions:

- if you enter acceptance rates beyond the landfill closure year you have imposed, the program ignores the acceptance rates past the closure year;
- if you enter acceptance rates through the current year but not up to the landfill closure year you have imposed, LandGEM applies the final acceptance rate between the current year and the closure year;
- if you enter acceptance rates through the current year and choose the model to calculate the landfill closure year, applies the final acceptance rate to each successive year until the waste design capacity is reached.

Also in the case of *waste acceptance rate*, it should be subtracted the amount of inert material, but this is not recommendable if the landfill is a MSW landfill: it will be difficult to verify the exact composition of waste and biogas production could be under estimated.

Determining model parameters

The model, as said before, presents a set of default values (fig.22) that can be chosen or can be changed with site specific parameters.

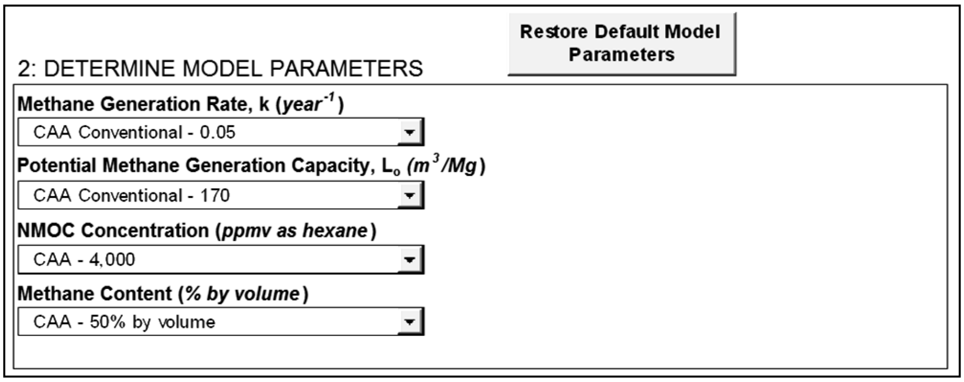


Fig. 22 – Default model parameters of LandGEM (*U.S. EPA, Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide*, 2005).

These parameters are:

- *Methane generation rate constant* (k) [y^{-1}]: the values that can be chosen from the default options are those in table 8, but if a site-specific value is available, it should be used.

Tab. 8 – Default options for k value.

Default type	Landfill type	k value [y^{-1}]
CAA	Conventional	0,05
CAA	Arid area	0,02
Inventory	Conventional	0,04
Inventory	Arid area	0,02
Inventory	Wet (bioreactor)	0,7

Determining the site-specific values is not so simple, as demonstrated by the numerous literature material; following the method proposed by Conestoga-Rovers and Associates (*Landfill gas generation assessment procedure guidelines*, written to support the Ministry of Environment of British Columbia in the Landfill Gas Management Regulation drafting, 2009), the exact waste composition is needed to divide waste in relatively inert, moderately decomposable and decomposable. This subdivision is needed to assign a different value of k to each waste fraction and to find the weight average of the *methane generation rate constants*; the value depends also from the annual precipitation of the site as can be seen from table 9.

Tab. 9 – Methane generation rate constant values (Conestoga-Rovers and Associates, 2009).

	Methane generation rate constant (k) value		
Annual precipitation	**Relatively inert**	**Moderately decomposable**	**Decomposable**
< 200 mm	0,01	0,01	0,03
> 250 to < 500 mm	0,01	0,02	0,05
>500 mm to < 1000 mm	0,02	0,04	0,09
> 1000 mm to < 2000 mm	0,02	0,06	0,11
> 2000 mm to < 3000 mm	0,03	0,07	0,12
> 3000 mm	0,03	0,08	0,13

Furthermore, k value has to be corrected with a water addition factor that accounts for the infiltration of water in the landfill: indeed the higher the water content in waste the higher will be the rate of degradation and the higher will be the methane production (tab. 10).

Tab. 10 – Water addiction factor (Conestoga-Rovers and Associates, 2009).

Landfill conditions	**Water addition factor**
Low to negligible water addition to the waste mass "dry tomb type landfill"	0,9
Partial infiltration or water addition to the waste mass	1,0
Addition of water into the waste mass "bioreactor type landfill"	1,1

- *Potential methane generation capacity* (L_0) [m^3/t]: as for k, the values that can be chosen from the default options are those in table 11, but if a site-specific value is available, it should be used.

Tab. 11 – Default options for L_0 value.

Default type	**Landfill type**	**L_0 value [m^3/t]**
CAA	Conventional	170
CAA	Arid area	170
Inventory	Conventional	100
Inventory	Arid area	100
Inventory	Wet (bioreactor)	96

Following the method proposed by Conestoga-Rovers and Associates, also potential methane generation capacity depends on degradable fraction as showed in table 12:

Tab. 12 – Potential methane generation capacity values (Conestoga-Rovers and Associates, 2009).

Waste characterization	**Methane generation potential L_0 (m^3/t)**
Relatively inert	20
Moderately decomposable	120
Decomposable	160

- *Non methane organic compound concentration* (NMOC) [ppmv as hexane]: as said before, it is function of waste types and must be measured in site for a site-specific values, otherwise a default value should be used.
- *Methane content* [%CH_4]: this value in default parameter correspond to 50% and the range valid for the software is that of 40-60%; if there is a site-specific value it should be entered. The methane content is used to calculate the methane production through (Eq.1) and then it serves for the calculation of carbon dioxide production by:

$$Q_{TOTAL} = Q_{CH_4} + Q_{CO_2}$$

$$Q_{CH_4} = Q_{TOTAL} \times (P_{CH_4}/100)$$

$$Q_{CO_2} = Q_{TOTAL} - Q_{CH_4} = [Q_{CH_4}/(P_{CH_4}/100)] - Q_{CH_4}$$

$$Q_{CO_2} = Q_{CH_4} \times \{[1/(P_{CH_4}/100)] - 1\}$$

Where:

- Q_{TOTAL} is the total production of landfill gas;

- P_{CH4} is the methane percentage in landfill gas.

Selecting gases and pollutants

This option is present in the "*User inputs*" Excel spreadsheet and allows the user to select the most relevant compounds to be modeled by the software.

LandGEM proposes as default options total landfill gas, methane, carbon dioxide and the non methane organic compounds, but there are also 46 pollutants (like benzene, toluene,..) which can be chosen, from the list coming from Ap-42 Inventory. Anyway, even if the user selects these four options, in the "*Inventory*" spreadsheet all the pollutants emissions rates are reported, year by year. While, for the pollutant selected, apart from emission rates, in the "*Graphs*" spreadsheet a graph reporting all the pollutants rates is showed, in three different units.
Besides, it is possible to enter new pollutants, other than the 46 present, setting their concentration in landfill gas and their molecular weight.

7.3 Este landfill case

Data on waste conferment in Este landfill are available from 2005 to 2012 and are reported in table 13.

Tab. 13 – Yearly waste conferment from 2005 to 2012 (data available from S.E.S.A.).

Year	2005	2006	2007	2008	2009	2010	2011	2012
Waste (t)	43.785	32.172	32.395	26.678	22.571	22.380	20.848	15.947

The waste entrance will be useful to derive the waste acceptance rates, that will be calculated thanks to other information regarding the volume and the completion of sectors.

Landfill characteristics

The landfill will be referred to as "S.E.S.A. Este landfill", while the *open year* selected is the 1965, since landfill started to be filled around that year. The *closure year* is 2015; anyway, it is interesting to calculate it through the software. Therefore, residual waste design capacity calculated in 2008 was of about 1.520.300 m^3 corresponding to 1.520.300 t, imposing a waste density in landfill of about $1t/m^3$, and 2012 is the last available year of conferment; LandGEM has calculated 2014 as closure year and this is acceptable.

Determining model parameters

- Regarding *methane generation rate constant* (k), the method described before has been implemented (*Conestoga-Rovers and Associates*); therefore starting from the available merceological analysis of years 2006 and 2007 (table 14 and 15), a weighted average of k value has been calculated. As can be seen, waste are divided by European Waste Catalogue schematization:

200301	Co-mingled material
200303	Street cleaning
200307	Bulky waste
200138	Wood different from 200137
200203	Other non biodegradable waste
200306	Sewage cleaning waste
040222	Waste from unprocessed textile fibres
150106	Mixed packaging
170203	Plastics
170802	gypsum-based construction materials other than 17 08 01
190801	Screenings
191212	Waste produced from mechanical treatment other than 191211
200108	Kitchen and canteen biodegradable waste
200111	Textiles
200139	Plastics
200199	Other fractions non otherwise specified
200201	Biodegradable waste
190805	Sludge from treatment of urban waste water
190812	Sludge from biological treatment of industrial waste water
190814	Sludge from other treatment of industrial waste water

Tab. 14 and15 – Composition of 2006 and 2007 waste at Este landfill (data available from S.E.S.A.).

2006	RSU (residual waste from separate selection)			RSA													SLUDGE	
C.E.R.	200301	200303	200307	40222	150106	170203	170802	190801	191212	200108	200111	200139	200199	200201	200301	200307	190805	190812
JENUARY	1.559,74	92,62	58,96	0,00	0,00	0,94	0,00	88,70	1.090,08	1,50	1,95	2,74	36,18	0,00	4,80	20,84	196,04	0,00
FEBRUARY	1.443,37	148,04	59,38	0,00	0,00	0,00	0,00	118,42	933,68	0,00	3,70	0,00	26,04	0,00	3,26	0,00	183,80	0,00
MARCH	1.712,76	123,80	105,36	0,00	0,00	0,00	3,72	90,14	437,08	0,00	2,74	13,86	56,32	0,00	1,26	0,00	208,12	0,00
APRIL	1.582,64	151,52	80,74	0,00	0,00	0,00	0,00	71,48	227,56	0,00	2,34	3,44	17,78	0,00	11,72	0,00	149,68	13,84
MAY	1.804,28	116,22	104,82	0,00	4,08	33,72	0,00	104,28	297,58	0,00	3,52	23,98	41,80	0,00	0,86	7,36	185,62	0,00
JUNE	1.601,40	116,22	115,06	0,00	6,96	0,00	0,00	120,58	318,58	0,00	1,92	8,38	34,98	7,98	0,98	0,00	196,86	12,52
JULY	1.561,56	83,24	70,78	0,00	4,76	0,00	0,00	76,92	257,92	0,00	2,12	2,56	29,44	0,00	0,86	0,00	247,40	0,00
AUGUST	1.620,68	65,10	136,76	0,00	0,00	0,00	0,00	87,08	238,18	0,00	2,10	0,00	28,96	0,00	5,06	0,00	261,90	10,48
SEPTEMBER	1.690,66	85,86	99,90	0,00	8,68	0,00	0,00	83,30	281,32	0,00	2,92	6,24	31,86	0,00	0,60	0,00	205,74	11,76
OCTOBER	1.712,68	100,80	132,10	0,00	11,08	0,00	0,00	120,24	236,62	0,00	2,12	8,48	34,26	0,00	4,92	0,00	260,36	0,00
NOVEMBER	1.615,44	85,98	103,06	0,00	11,92	0,00	0,00	127,04	628,72	0,00	3,96	5,44	57,10	0,00	0,56	0,00	69,00	13,98
DECEMBER	1.595,40	76,18	130,84	5,24	15,42	0,00	0,00	112,72	1.040,12	0,00	2,14	0,00	20,78	0,00	5,64	0,00	95,00	10,92
TOTAL	**19.500,61**	**1.245,58**	**1.197,76**	**5,24**	**62,90**	**34,66**	**3,72**	**1.200,90**	**5.987,44**	**1,50**	**31,53**	**75,12**	**415,50**	**7,98**	**40,52**	**28,20**	**2.259,52**	**73,50**
ANNUAL TOTAL	**32.172,18**																	

2007	RSU (residual waste from separate selection)				RSA								SLUDGE		
C.E.R.	200301	200303	200307	200138	150106	190801	170802	191212	200111	200139	200199	200301	190805	190812	190814
JENUARY	1.654,24	44,72	81,78	0,00	11,50	165,18	0,00	389,90	2,54	42,28	32,20	0,94	102,50	7,82	0,00
FEBRUARY	1.455,58	63,28	100,08	0,00	14,22	171,64	0,00	237,80	1,56	27,78	19,56	2,54	296,38	0,00	0,00
MARCH	1.756,38	90,82	137,75	0,00	7,24	222,58	8,84	285,10	1,46	6,68	42,24	0,68	399,66	11,06	0,00
APRIL	1.582,54	75,94	102,98	0,00	8,68	137,58	0,00	257,10	2,68	4,24	12,94	6,44	316,44	11,36	0,00
MAY	1.673,80	74,20	143,40	0,00	8,28	159,00	0,00	324,20	0,00	9,84	65,50	1,02	386,92	9,64	0,00
JUNE	1.749,06	77,26	109,22	0,00	9,76	9,48	0,00	412,99	2,96	20,38	27,02	1,12	240,30	0,00	26,62
JULY	1.513,38	41,52	120,98	0,50	7,86	0,92	0,00	616,98	0,00	2,36	30,32	2,82	212,78	12,90	122,56
AUGUST	1.526,62	49,96	136,04	1,14	8,04	46,06	0,00	1.144,60	1,96	0,90	32,04	5,76	283,40	0,00	49,32
SEPTEMBER	1.531,92	52,70	92,54	0,00	7,68	31,66	0,00	493,56	0,00	8,00	37,64	0,80	120,36	0,00	111,76
OCTOBER	1.692,92	54,80	103,80	0,00	14,68	64,18	0,00	545,16	2,92	6,54	44,92	1,02	256,96	25,74	132,90
NOVEMBER	1.606,90	77,82	82,84	0,00	5,28	64,48	0,00	391,38	0,00	3,14	41,22	2,78	249,52	8,78	141,76
DECEMBER	1.487,46	60,38	71,02	0,00	7,52	42,80	0,00	389,04	2,34	0,90	19,14	4,92	159,40	10,40	99,58
TOTAL	**19.230,80**	**763,40**	**1.282,43**	**1,64**	**110,74**	**1.115,56**	**8,84**	**5.487,81**	**18,42**	**133,04**	**404,74**	**30,84**	**3.024,62**	**97,70**	**684,50**
ANNUAL TOTAL	**32.395,08**														

Each waste category has been catalogued with a different degree of biodegradability: relatively inert , moderately decomposable or decomposable; for municipal solid waste has been imposed a composition of 28% of inert waste, 52% of moderately decomposable and 20% of decomposable waste (*Conestoga-Rovers and Associates*, 2009). While for road sweeping a composition of 70% of inert waste, 10% of moderately decomposable and 20% of decomposable waste (*Esposito E.*, 2008). An example of this scheme is reported in table 16 for year 2006.

Tab. 16 – Waste fractioning for year 2006.

Year 2006			**WASTE CATEGORY**		
C.E.R.	**Tons of waste**	**%**	**Relatively inert (t)**	**Moderately decomposable (t)**	**Decomposable (t)**
200301	19.500,61	60,61	5.460,17	10.140,32	3.900,12
200303	1.245,58	3,87	871,91	124,56	249,12
200307	1.197,76	3,72	-	1.197,76	-
040222	5,24	0,02	-	5,24	-
150106	62,90	0,20	62,90	-	-
170203	34,66	0,11	34,66	-	-
170802	3,72	0,01	-	3,72	-
190801	1.200,90	3,73	240,18	-	960,72
191212	5.987,44	18,61	-	5.987,44	-
200108	1,50	0,00	-	-	1,50
200111	31,53	0,10	-	31,53	-
200139	75,12	0,23	75,12	-	-
200199	415,50	1,29	-	415,50	-
200201	7,98	0,02	-	-	7,98
200301	40,52	0,13	11,35	21,07	8,10
200307	28,20	0,09	-	28,20	-
190805	2.259,52	7,02	-	-	2.259,52
190812	73,50	0,23	-	-	73,50
TOTAL	**32.172,18**	**100,00**	**6.756,28**	**17.955,34**	**7.460,56**

Then the fractions have been multiplied for the k value reported in table 10, selecting the range of annual precipitation comprised between 500 and 1000 mm. The average weighted k value for year 2006 resulted to be of 0,05 y^{-1} and 0,049 for year 2007. These results lead to the conclusion that a value of 0,05 y^{-1} is acceptable, also because waste composition for previous years is not available and the most conservative value suggested by LandGEM is the same.

- With the same method has been calculated also the value of *potential methane generation* (m^3/t_{WASTE}), which resulted to be around 100 m^3/t_{WASTE}; this value is consistent with that suggested by AP-42 and so this has been selected.
- The *NMOC concentration* (ppmv as hexane) is not essential for the purpose of this study and there are not available data from the site, for these reasons the default and more conservative value of 4.000 ppmv as hexane has been selected.
- The *methane content* (%CH_4) has been calculated as average value found from available data of stations A, B, C and E; for year 2012 it corresponds to 50%, but S.E.S.A. suggested the value of 49% and this will be used (*Dichiarazione Ambientale*, 2011). Regarding CO_2 content it is estimated to be around 33% from field measurement; nevertheless the program will insert the complementary value of 51% and this must be remembered when discussing final results.

Selecting gases and pollutants

As said before, four different gases or pollutants can be selected to obtain the modeling of their production [m^3/y] and graphs. In this case the default options have been maintained, since the scope of the study is to model landfill gas. The "*Input review*" spreadsheet is that in figure 23.

INPUT REVIEW	**Landfill Name or Identifier:**	S.E.S.A. Este landfill
LANDFILL CHARACTERISTICS		
Landfill Open Year	**1965**	
Landfill Closure Year (with 80-year limit)	**2014**	
Actual Closure Year (without limit)	***2014***	
Have Model Calculate Closure Year?	**Yes**	
Waste Design Capacity	**1.520.300**	*megagrams*
MODEL PARAMETERS		
Methane Generation Rate, k	**0,050**	*year^{-1}*
Potential Methane Generation Capacity, L_o	**100**	*m^3/Mg*
NMOC Concentration	**4.000**	*ppmv as hexane*
Methane Content	**49**	*% by volume*
GASES / POLLUTANTS SELECTED		
Gas / Pollutant #1:	**Total landfill gas**	
Gas / Pollutant #2:	**Methane**	
Gas / Pollutant #3:	**Carbon dioxide**	
Gas / Pollutant #4:	**NMOC**	

Fig. 23 – Input review Excel spreadsheet.

Waste acceptance rates

In table 14 the *waste acceptance rates* of years 2005-2012 are showed and these have been inserted in the program. When the exact yearly waste acceptance rate is unknown, LandGEM suggests to divide the entire tonnage for the years of conferment. Therefore, regarding Lotto n°1, the volume is of 750.000 m^3 and supposing a waste density of 1 t/m^3, 750.000 t of waste have been conferred from 1965 to 1995. So, an average acceptance rate of 24.194 t/y has been entered over 31 years.

Regarding years from 1996 to 2004, the same reasoning has been done: knowing that at 31.12.2007 the residual waste capacity of the landfill was of 125.315 m^3 (125.315 t) and that overall landfill capacity of Lotto n°2 and n° 3 is of 770.300 m^3, the calculation has been:

Capacity (‘96) – Capacity (‘07) = Capacity (‘96-‘07) = 644.985 m^3
Capacity (‘96-‘07) – Waste acceptance rates of years (‘05-‘06-‘07) = 536.633 m^3
536.633 m^3 / 9 (years ‘96-‘04) = 59.626 m^3 ~ 59.626 t

For years 2013 and 2014 the program repeats the last *waste acceptance rate* entered, until the entire waste design capacity is reached, and so the waste acceptance rate for 2013 is of 15.947 t and for 2014 is of 929 t.

The entire sequence of *waste acceptance rates* is shown in table 17.

Tab. 17 – Waste acceptance rates entered in LandGEM.

Year	***(Mg/year)***
1965	24.194
1966	24.194
1967	24.194
1968	24.194
1969	24.194
1970	24.194
1971	24.194
1972	24.194
1973	24.194

1974	24.194
1975	24.194
1976	24.194
1977	24.194
1978	24.194
1979	24.194
1980	24.194
1981	24.194
1982	24.194
1983	24.194
1984	24.194
1985	24.194
1986	24.194
1987	24.194
1988	24.194
1989	24.194
1990	24.194
1991	24.194
1992	24.194
1993	24.194
1994	24.194
1995	24.194
1996	59.626
1997	59.626
1998	59.626
1999	59.626
2000	59.626
2001	59.626
2002	59.626
2003	59.626
2004	59.626
2005	43.785
2006	32.172
2007	32.395
2008	26.678
2009	22.571
2010	22.380
2011	20.848
2012	15.947
2013	15.947
2014	929
2015	0

7.4 Results

In this paragraph will be shown and commented the outputs coming from LandGEM which are divided in "*Methane*", "*Results*", "*Graphs*" and "*Inventory*" Excel spreadsheet.

In the "*Methane*" spreadsheet all the calculations, using (Eq.1) are reported, until year 2105, i.e. for 140 years. For the purpose of this study value going from 2006 to 2012 are interesting since available biogas production regards those years.

In the "*Results*" spreadsheet emissions from 1965 to 2105 are showed, for total landfill gas, methane, carbon dioxide and NMOC, all expressed in t/y (Mg/y), m^3/y and av ft^3/min. In table 18 and 19 emissions from 1965 to 2014 (open to closure years) are showed, as they are the most interesting values.

Tab. 18 – Total landfill gas and methane emissions calculated by LandGEM for years 1965-2014.

Year	Total landfill gas		Methane	
	(Mg/year)	(m^3/year)	(Mg/year)	(m^3/year)
1965	0	0	0	0
1966	2,999E+02	2,414E+05	7,892E+01	1,183E+05
1967	5,851E+02	4,710E+05	1,540E+02	2,308E+05
1968	8,564E+02	6,895E+05	2,254E+02	3,378E+05
1969	1,115E+03	8,973E+05	2,933E+02	4,397E+05
1970	1,360E+03	1,095E+06	3,579E+02	5,365E+05
1971	1,594E+03	1,283E+06	4,194E+02	6,286E+05
1972	1,816E+03	1,462E+06	4,779E+02	7,163E+05
1973	2,027E+03	1,632E+06	5,335E+02	7,996E+05
1974	2,228E+03	1,794E+06	5,864E+02	8,789E+05
1975	2,419E+03	1,948E+06	6,367E+02	9,543E+05
1976	2,601E+03	2,094E+06	6,846E+02	1,026E+06
1977	2,774E+03	2,233E+06	7,301E+02	1,094E+06
1978	2,939E+03	2,366E+06	7,734E+02	1,159E+06
1979	3,095E+03	2,492E+06	8,146E+02	1,221E+06
1980	3,244E+03	2,612E+06	8,538E+02	1,280E+06
1981	3,386E+03	2,726E+06	8,911E+02	1,336E+06
1982	3,521E+03	2,834E+06	9,265E+02	1,389E+06
1983	3,649E+03	2,937E+06	9,603E+02	1,439E+06
1984	3,771E+03	3,036E+06	9,923E+02	1,487E+06
1985	3,887E+03	3,129E+06	1,023E+03	1,533E+06
1986	3,997E+03	3,218E+06	1,052E+03	1,577E+06
1987	4,102E+03	3,302E+06	1,080E+03	1,618E+06
1988	4,202E+03	3,383E+06	1,106E+03	1,657E+06

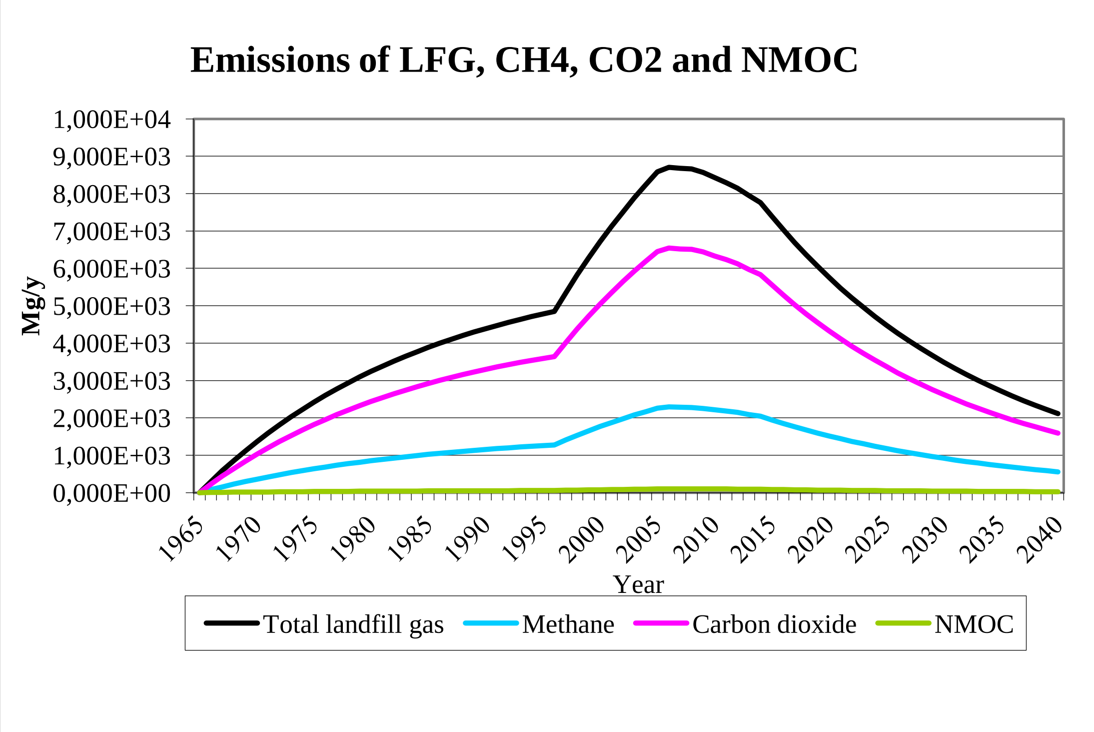
Year	Total landfill gas		Methane	
	(Mg/year)	(m^3/year)	(Mg/year)	(m^3/year)
1989	4,297E+03	3,459E+06	1,131E+03	1,695E+06
1990	4,387E+03	3,532E+06	1,155E+03	1,731E+06
1991	4,473E+03	3,601E+06	1,177E+03	1,764E+06
1992	4,555E+03	3,667E+06	1,199E+03	1,797E+06
1993	4,632E+03	3,729E+06	1,219E+03	1,827E+06
1994	4,706E+03	3,789E+06	1,239E+03	1,857E+06
1995	4,777E+03	3,845E+06	1,257E+03	1,884E+06
1996	4,844E+03	3,899E+06	1,275E+03	1,911E+06
1997	5,346E+03	4,304E+06	1,407E+03	2,109E+06
1998	5,825E+03	4,689E+06	1,533E+03	2,298E+06
1999	6,280E+03	5,055E+06	1,653E+03	2,477E+06
2000	6,712E+03	5,404E+06	1,767E+03	2,648E+06
2001	7,124E+03	5,735E+06	1,875E+03	2,810E+06
2002	7,516E+03	6,050E+06	1,978E+03	2,965E+06
2003	7,888E+03	6,350E+06	2,076E+03	3,112E+06
2004	8,242E+03	6,636E+06	2,169E+03	3,251E+06
2005	8,579E+03	6,907E+06	2,258E+03	3,384E+06
2006	8,704E+03	7,007E+06	2,291E+03	3,433E+06
2007	8,678E+03	6,986E+06	2,284E+03	3,423E+06
2008	8,656E+03	6,969E+06	2,278E+03	3,415E+06
2009	8,565E+03	6,895E+06	2,254E+03	3,379E+06
2010	8,427E+03	6,784E+06	2,218E+03	3,324E+06
2011	8,293E+03	6,676E+06	2,183E+03	3,271E+06
2012	8,147E+03	6,559E+06	2,144E+03	3,214E+06
2013	7,947E+03	6,398E+06	2,092E+03	3,135E+06
2014	7,757E+03	6,245E+06	2,042E+03	3,060E+06

Tab. 19 – Carbon dioxide and NMOC emissions calculated by LandGEM for years 1965-2014.

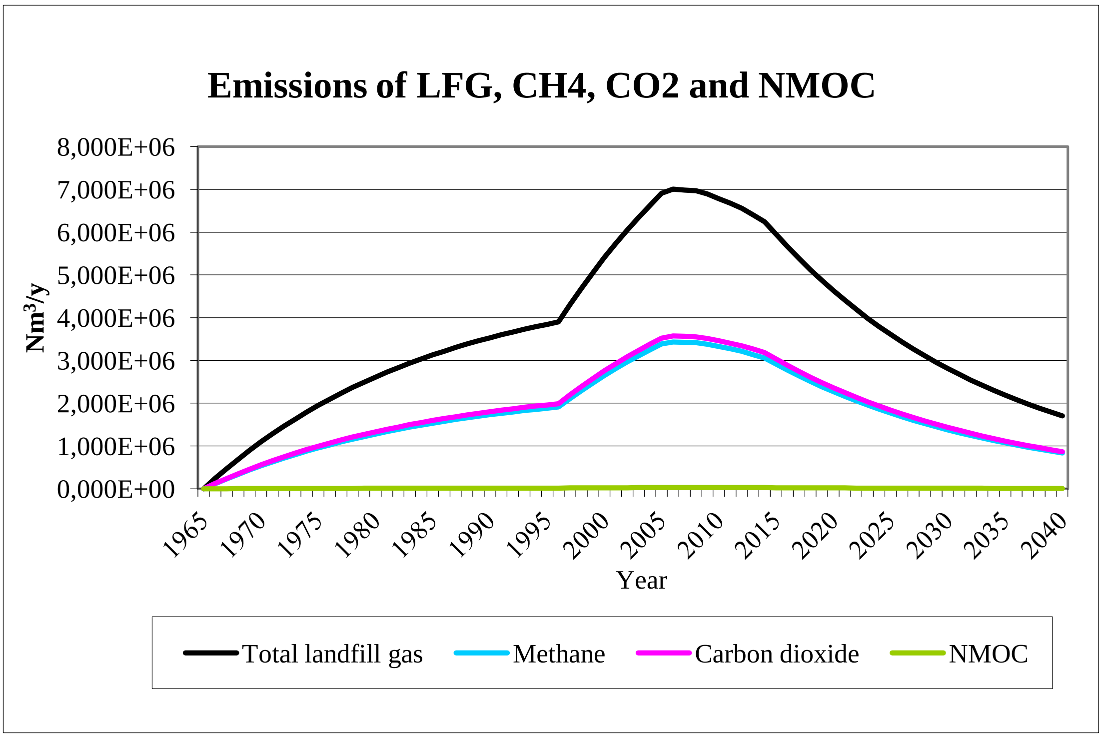
Year	Carbon dioxide		NMOC	
	(Mg/year)	(m^3/year)	(Mg/year)	(m^3/year)
1965	0	0	0	0
1966	2,254E+02	1,231E+05	3,461E+00	9,656E+02
1967	4,397E+02	2,402E+05	6,754E+00	1,884E+03
1968	6,437E+02	3,516E+05	9,886E+00	2,758E+03
1969	8,376E+02	4,576E+05	1,286E+01	3,589E+03
1970	1,022E+03	5,584E+05	1,570E+01	4,380E+03
1971	1,198E+03	6,543E+05	1,839E+01	5,132E+03
1972	1,365E+03	7,455E+05	2,096E+01	5,847E+03
1973	1,523E+03	8,323E+05	2,340E+01	6,528E+03
1974	1,675E+03	9,148E+05	2,572E+01	7,175E+03
1975	1,818E+03	9,933E+05	2,792E+01	7,791E+03
1976	1,955E+03	1,068E+06	3,002E+01	8,376E+03
1977	2,085E+03	1,139E+06	3,202E+01	8,933E+03
1978	2,209E+03	1,207E+06	3,392E+01	9,463E+03
1979	2,326E+03	1,271E+06	3,573E+01	9,967E+03
1980	2,438E+03	1,332E+06	3,745E+01	1,045E+04

Year	Carbon dioxide		NMOC	
	(Mg/year)	(m^3/year)	(Mg/year)	(m^3/year)
1981	2,545E+03	1,390E+06	3,908E+01	1,090E+04
1982	2,646E+03	1,445E+06	4,064E+01	1,134E+04
1983	2,742E+03	1,498E+06	4,212E+01	1,175E+04
1984	2,834E+03	1,548E+06	4,352E+01	1,214E+04
1985	2,921E+03	1,596E+06	4,486E+01	1,252E+04
1986	3,004E+03	1,641E+06	4,614E+01	1,287E+04
1987	3,083E+03	1,684E+06	4,735E+01	1,321E+04
1988	3,158E+03	1,725E+06	4,850E+01	1,353E+04
1989	3,229E+03	1,764E+06	4,960E+01	1,384E+04
1990	3,297E+03	1,801E+06	5,064E+01	1,413E+04
1991	3,362E+03	1,836E+06	5,163E+01	1,440E+04
1992	3,423E+03	1,870E+06	5,257E+01	1,467E+04
1993	3,481E+03	1,902E+06	5,347E+01	1,492E+04
1994	3,537E+03	1,932E+06	5,432E+01	1,516E+04
1995	3,590E+03	1,961E+06	5,514E+01	1,538E+04
1996	3,640E+03	1,989E+06	5,591E+01	1,560E+04
1997	4,018E+03	2,195E+06	6,171E+01	1,722E+04
1998	4,378E+03	2,391E+06	6,723E+01	1,876E+04
1999	4,719E+03	2,578E+06	7,248E+01	2,022E+04
2000	5,045E+03	2,756E+06	7,748E+01	2,162E+04
2001	5,354E+03	2,925E+06	8,223E+01	2,294E+04
2002	5,648E+03	3,086E+06	8,675E+01	2,420E+04
2003	5,928E+03	3,239E+06	9,105E+01	2,540E+04
2004	6,195E+03	3,384E+06	9,514E+01	2,654E+04
2005	6,448E+03	3,523E+06	9,903E+01	2,763E+04
2006	6,541E+03	3,574E+06	1,005E+02	2,803E+04
2007	6,522E+03	3,563E+06	1,002E+02	2,794E+04
2008	6,506E+03	3,554E+06	9,992E+01	2,787E+04
2009	6,437E+03	3,516E+06	9,886E+01	2,758E+04
2010	6,333E+03	3,460E+06	9,727E+01	2,714E+04
2011	6,233E+03	3,405E+06	9,573E+01	2,671E+04
2012	6,123E+03	3,345E+06	9,404E+01	2,624E+04
2013	5,973E+03	3,263E+06	9,173E+01	2,559E+04
2014	5,830E+03	3,185E+06	8,954E+01	2,498E+04

In the "*Graphs*" spreadsheet the overall progress of each different gas is showed with three graphs for the different three units. In this case the most important graphs are that expressed in Mg/y and m^3/y which are reported below.



Graph 2 – Emissions of landfill gas, methane, carbon dioxide and NMOC calculated from LandGEM (Mg/y).



Graph 3 - Emissions of landfill gas, methane, carbon dioxide and NMOC calculated from LandGEM (Nm^3/y).

As can be seen, the trend of the two graphs is similar as expected, apart from the separation of methane and carbon dioxide in graph 2: this is due to the fact that on volume basis the two gases are both more or less 50% of the total gas, while on mass basis carbon dioxide is three times heavier than methane and this is reflected in the graph.

All the gases follow the same trend since they are calculated starting from methane emissions multiplied for the right coefficient. Obviously since the concentration of NMOC is 4000 ppmv the emissions are very low compared to the other.

Regarding the general trend of each compound, it reflects the *waste acceptance rates* entered: from 1965 to 1995 (24.194 t/y) there's a constant increment, then from 1996 to 2004 (59.626 t/y) the increment is constant but it increases more rapidly; from 2005 to 2014 the trend is no more constant since waste acceptance rates are different for each year but always decreasing. Finally, from 2015 to 2105 the trend decreases since the waste conferment stops and biogas production is constant but always decreasing.

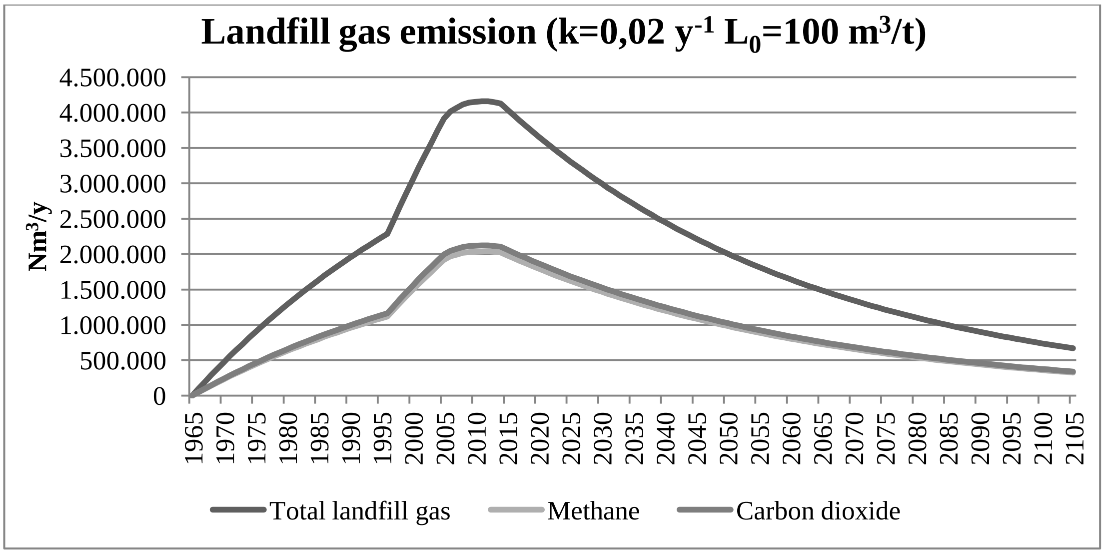
These results will be compared to the actual data coming from S.E.S.A. in chapter 7.

7.5 Effects of parameters variation

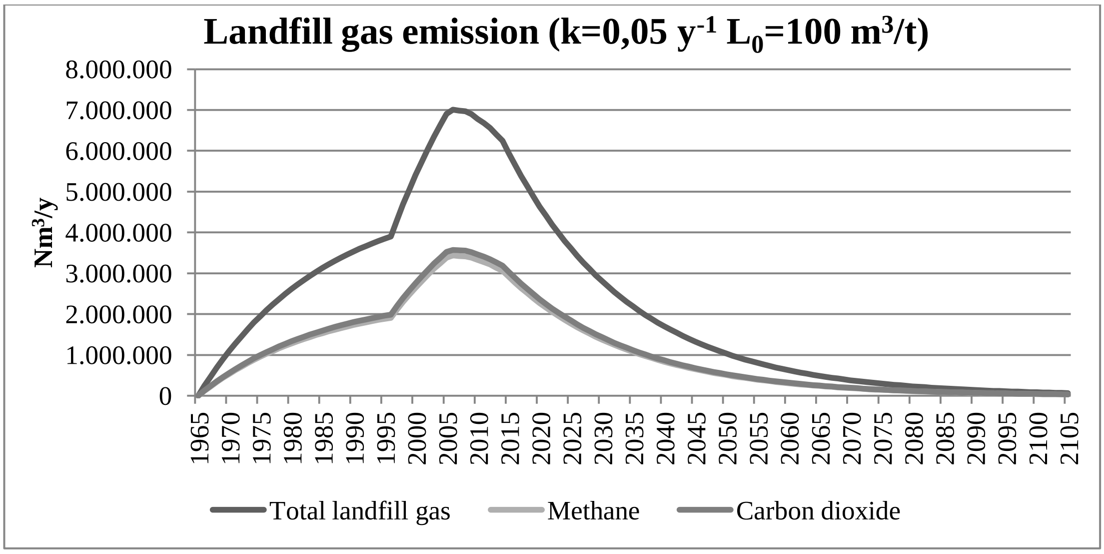
In this paragraph will be shown the changes in results due to the variations in model parameters, in particular *methane generation rate constant* (k) and *potential methane generation capacity* (L_0) will be altered starting from the values chosen in the previous part .

K variations

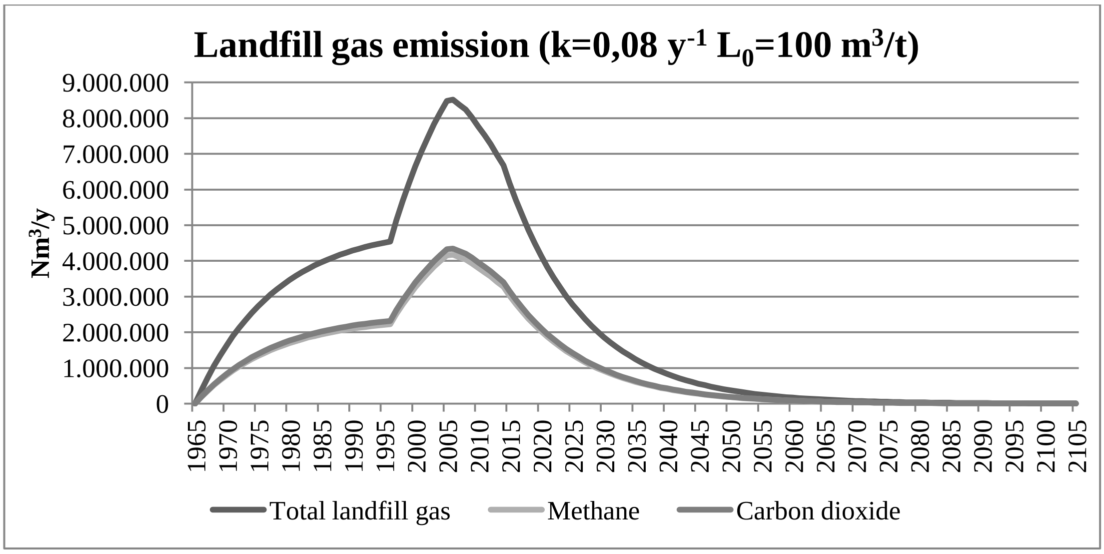
Potential methane capacity has been considered constant at the value of 100 m^3/t_{WASTE}, while the k value has been changed from 0,02 y^{-1} to 0,16 y^{-1} and the results are showed in the following graphs.



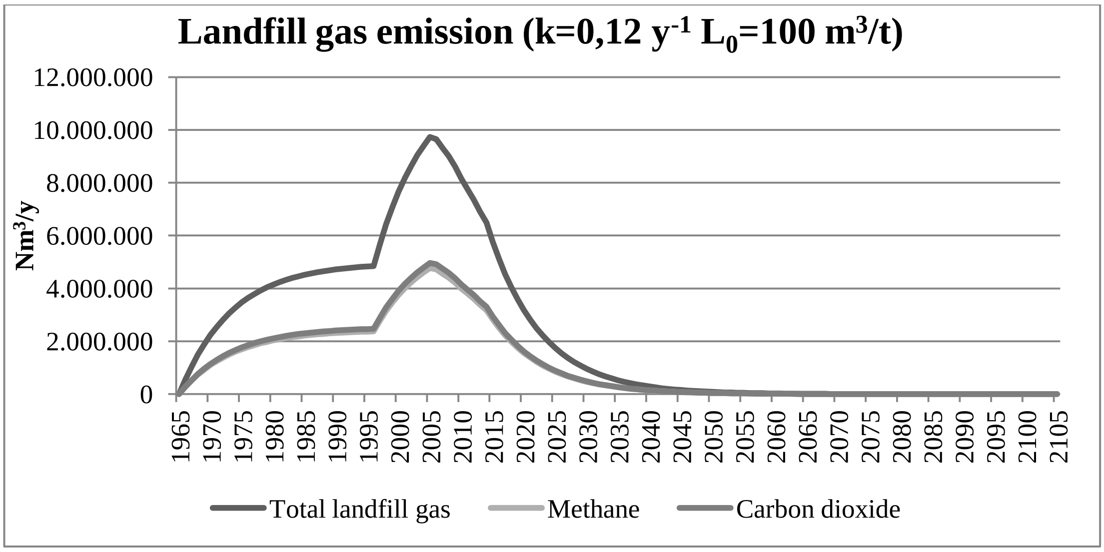
Graph 4 - Emissions of landfill gas, methane, carbon dioxide [Nm^3/y] calculated from LandGEM with k=0,02 y^{-1} and L_0= 100 m^3/t.



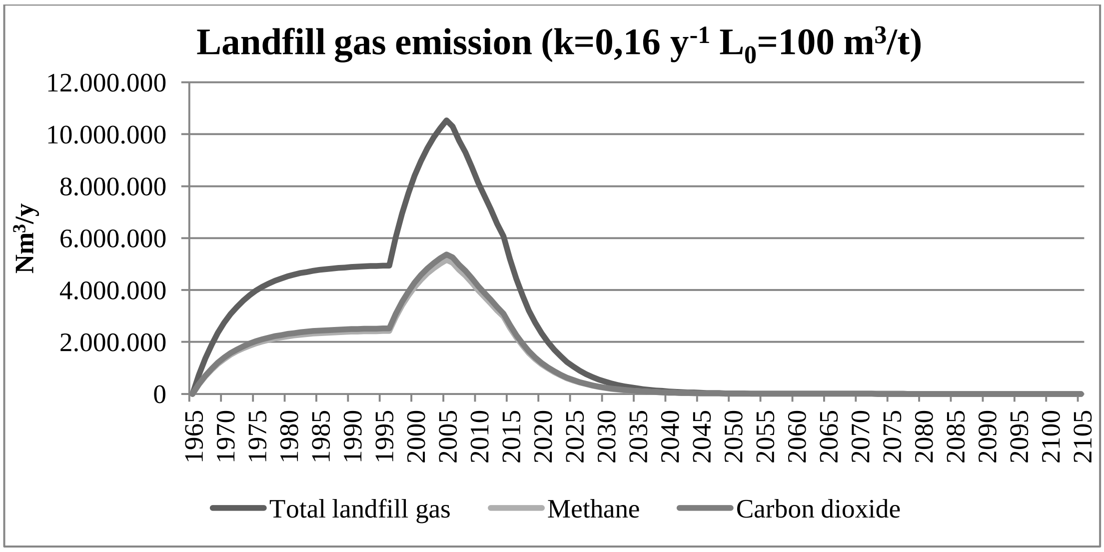
Graph 5 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 100 m^3/t.



Graph 6 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,08 y^{-1} and L_0= 100 m^3/t.

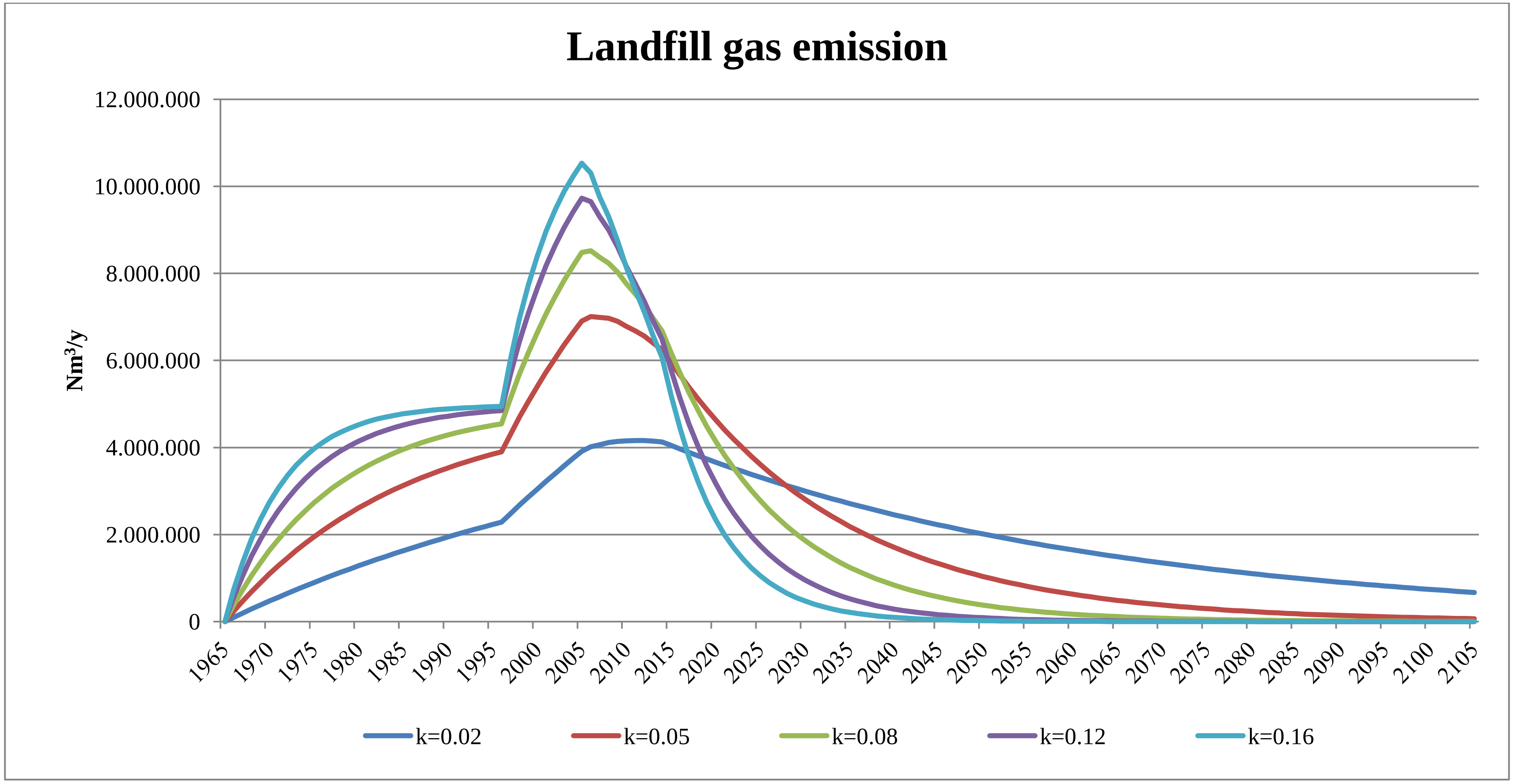


Graph 7 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,12 y^{-1} and L_0= 100 m^3/t.



Graph 8 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with $k=0,16\ y^{-1}$ and $L_0= 100\ m^3/t$.

As can be seen the values of methane, carbon dioxide and landfill gas change together since each compound is calculated starting from methane production. The most interesting thing is how each compound varies from a graph to another as showed in graph 9 for total landfill gas, chosen as example.



Graph 9 - Emissions of landfill gas (Nm^3/y) calculated from LandGEM with L_0= 100 m^3/t and changing the value of k.

Given Eq.1, it easily understandable the reason of the alterations in graph 8.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=1}^{1} kL_0 \left(\frac{M_t}{10}\right) e^{-kt_{i,j}} \qquad \text{(Eq. 1)}$$

However the biochemical reasons behind the changes are more interesting: as said before, the *methane generation rate constant* is function of waste moisture content, nutrients, pH and temperature. An increasing in k value means that one or more of the parameters just mentioned is changed; in particular:

- if moisture content of waste increases also k increases, since water in waste is the transport mean for bacteria and nutrients, it limits the entry of oxygen in the waste mass and it dilutes the inhibitor substances. Anyway if it reaches values greater than 50% it inhibits methanogenesis due to the excessive acid formation and consequently low pH. In figure 24 it is shown the correlation between waste moisture content and biogas generation.

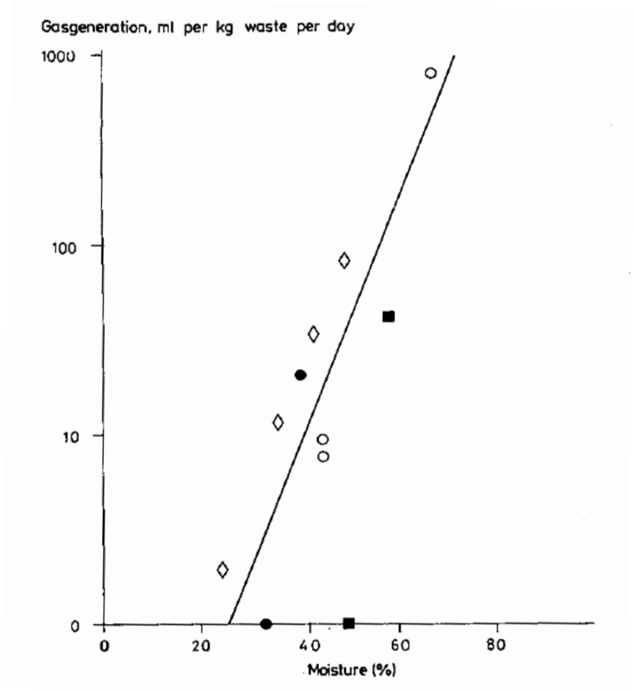


Fig. 24 – Biogas generation in function of waste moisture content (Christensen et al., 1989).

- Also an increase in nutrients content leads to an increase in k value; the most important nutrients are nitrogen, phosphorous and micronutrients as calcium, magnesium, potassium, iron, zinc, copper. The optimum ratio between carbon, nitrogen and phosphorous is 100:0,44:0,08, which means that carbon and nitrogen are needed in very low amounts; indeed the reduce biomass production compared to aerobic process needs much less nutrients.

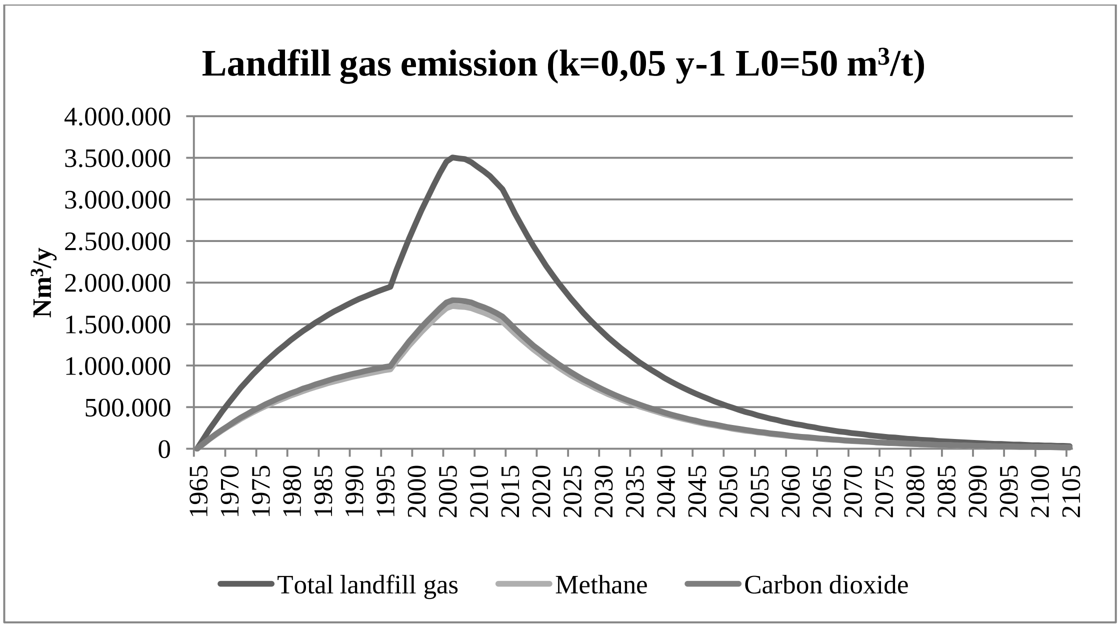
- If temperature grows also k value increases since methanogenesis is a mesophilic process; the minimum temperature for this type of bacteria is 15°C, but an increase to 30°C has demonstrated an increase in biogas production (Christensen et al., 1989).

All these factors modify the k value and as can be seen an increase from 0,02 to 0,16 y^{-1} has several effects on biogas production:

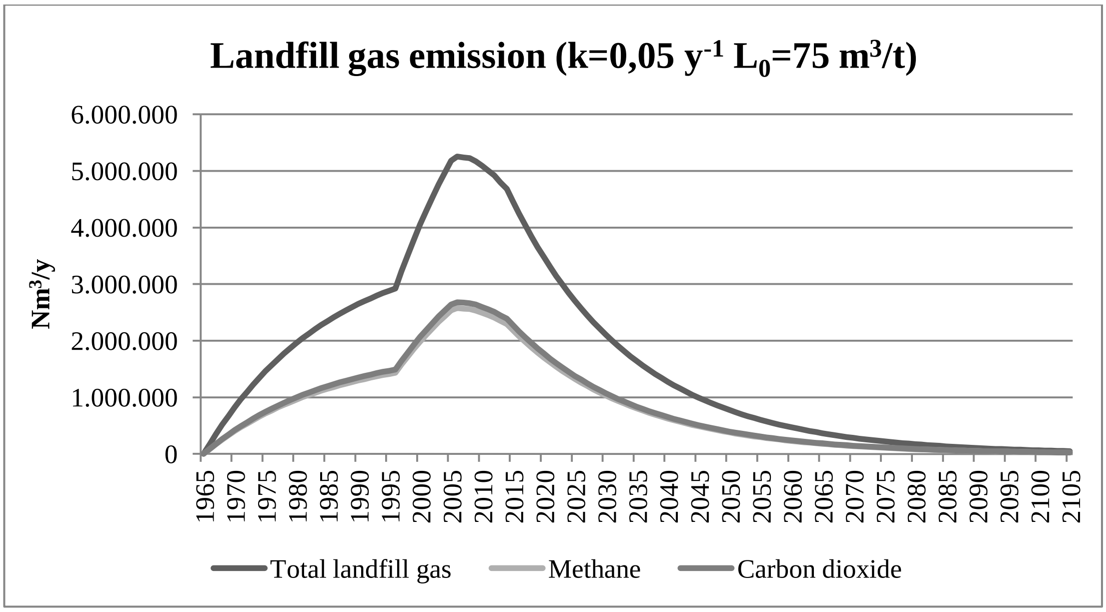
- it increases more rapidly;
- it decreases and ceases more rapidly too, since the substrate ends more rapidly;
- and the change in substrate quantity (from 24.194 t/y o 59.626 t/y) gives more impulse to biogas production when k=0,16 y^{-1} rather than k=0,02 y^{-1}.

L_0 variations

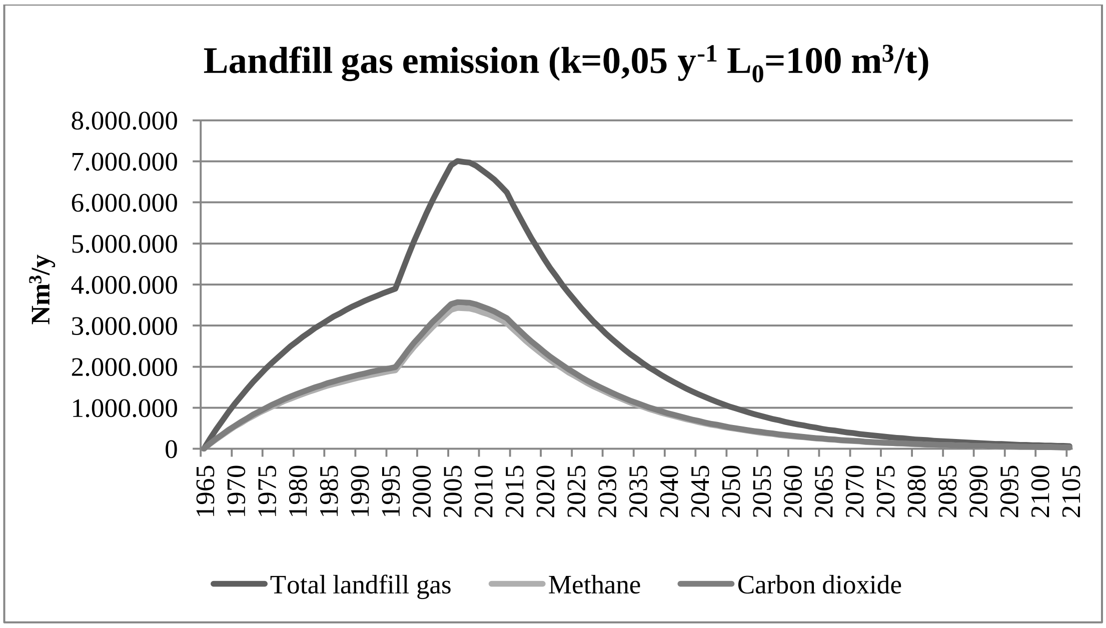
On the other hand, keeping the value of *methane generation rate constant* (k) at 0,05 y^{-1}, the L_0 value has been changed from 50 m^3/t_{WASTE} to 150 m^3/t_{WASTE} and the results are showed in the following graphs.



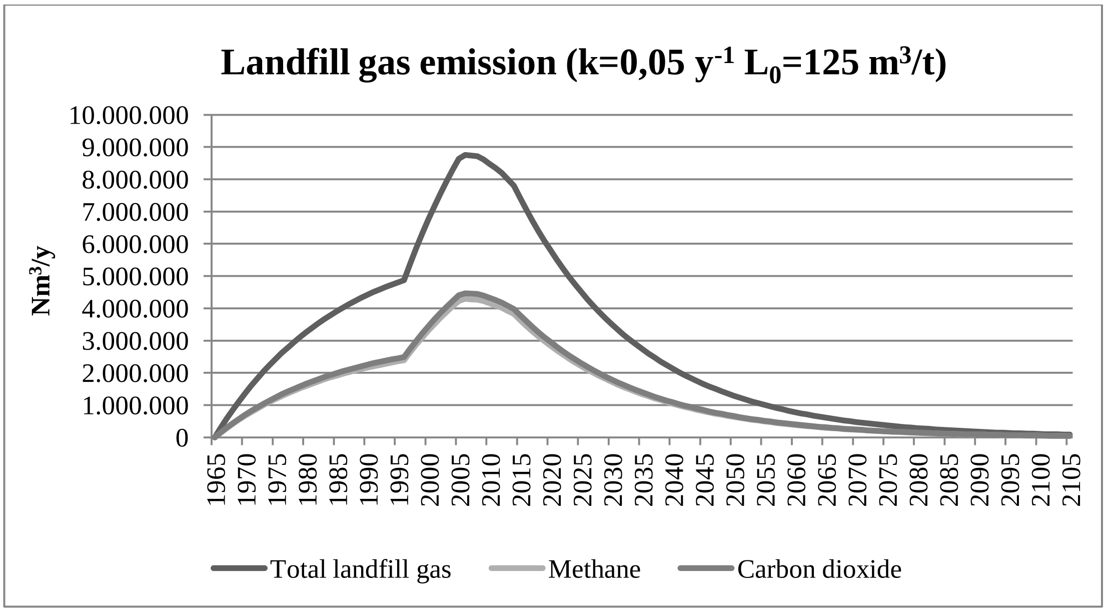
Graph 10 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 50 m^3/t.



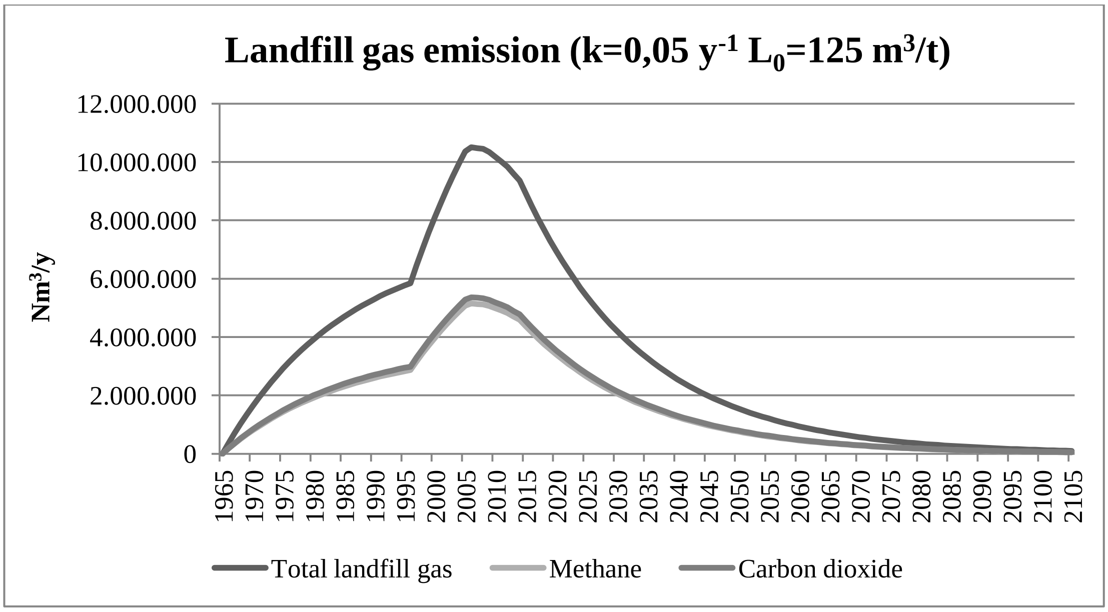
Graph 11 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 75 m^3/t.



Graph 12 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 100 m^3/t.

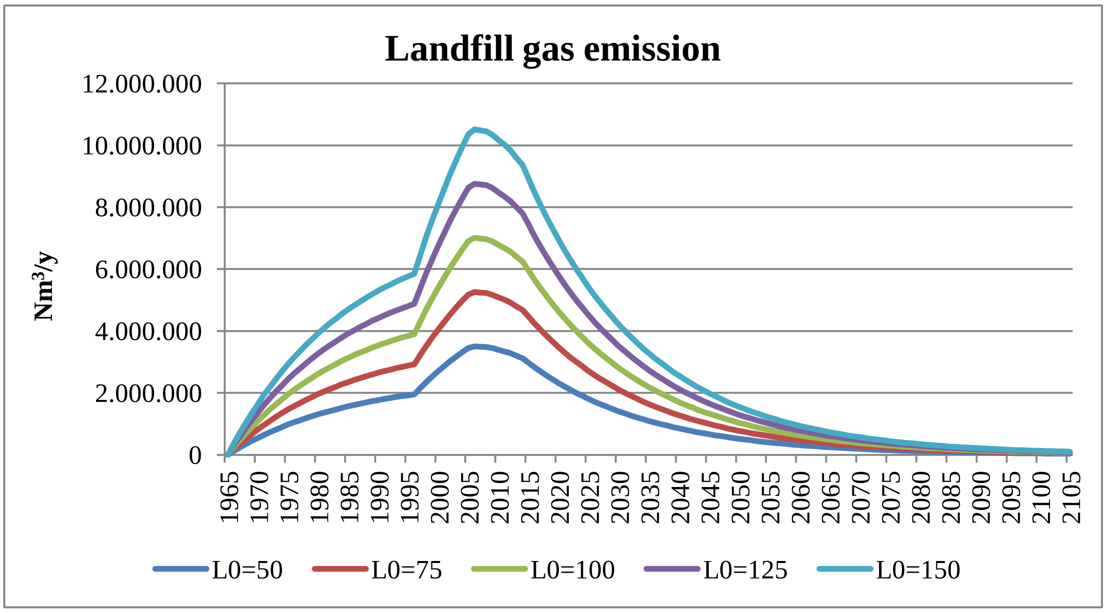


Graph 13 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 125 m^3/t.



Graph 14 - Emissions of landfill gas, methane, carbon dioxide (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and L_0= 150 m^3/t.

Also in the case of potential methane generation variation all the compounds vary in the same way; in the following graph the changes in landfill gas through the variation of L_0 are showed.



Graph 15 - Emissions of landfill gas (Nm^3/y) calculated from LandGEM with k=0,05 y^{-1} and changing the value of L_0.

As said before, *potential methane generation capacity* depends only on the type of waste conferred; this is reflected on graph 15: if L_0 increases biogas generation do the same, while the process maintains the same tendency. The higher the presence of decomposable material in the waste, the higher L_0, the higher the biogas production.

In the paragraph "field data against model data" the graph that fits best the real data will be shown and discussed.

8. FIRST ORDER KINETIC MODEL

The model that is going to be presented has been developed by Cossu and Andreottola in 1988, starting from previous studies. It is subdivided into three submodels: a stoichiometric model, that uses Buswell equation to achieve a quantitative and qualitative estimation of biogas production, a biochemical model that estimates the biodegradable organic carbon content for each category of waste and the maximum theoretical yield of biogas; finally kinetic model that gives the temporal variation of biogas production in cumulative and specific terms.

Stoichiometric model

This submodel suggests the Buswell equation (1952) to represent the overall methane fermentation process for organics in solid waste; this equation (Eq. 2) is based on the knowledge of waste composition and makes some assumptions (Williams et al.):

- does not take into account the solubility of gasses;
- assumes all volatile solids to be available for conversion;
- does not account for any inhibition.

$$C_aH_bO_cN_d + nH_2O \rightarrow xCH_4 + yCO_2 + wNH_3 + zC_5H_7NO_2 + Energy \quad (Eq.2)$$

where:

- $C_aH_bO_cN_d$ is the biodegradable fraction of waste, which is impossible to know exactly;
- nH_2O is the amount of water needed to sustain the reaction;
- xCH_4 are the moles of methane produced;
- yCO_2 are the moles of carbon dioxide produced;
- wNH_3 are the moles of ammonia produced;
- $zC_5H_7NO_2$ is the biomass growth during the process, produced converting organic carbon, which is much lower than that coming from an aerobic reaction and amounts to 4% of degradable organic matter (EMCON, 1980).

From the last point it can be said that biomass can be neglected since it is a very little percentage; therefore (Eq. 2) becomes:

$$C_aH_bO_cN_d + (4a\text{-}b\text{-}2c\text{+}3d)/4\ H_2O \rightarrow$$

$$(4a\text{+}b\text{-}2c\text{-}3d)/8\ CH_4 + (4a\text{-}b\text{+}2c\text{+}3d)/8\ CO_2 + dNH_3 \quad \text{(Eq.3)}$$

Given this equation, once the elementary composition of the waste is known it is easy to calculate both quantity and quality of biogas produced; in any case ammonia production is often neglected since it is present only in trace in biogas. In table 20 it is shown an example of elementary composition of waste:

Tab. 20 – Typical data on elementary composition of MSW organic fraction (Tchobanoglous et al., 1993).

Component	Wet weight	Dry weight	Elementary composition					
	(%)	(%)	C	H	O	N	S	Ash
Food waste	11,4	4,6	4,7	4,7	4,4	13,0	10,0	4,0
Paper	42,8	55,0	50,8	53,0	61,3	18,5	60,0	55,2
Cardboard	7,5	9,8	9,2	9,4	11,1	3,7	10,0	8,0
Plastics	8,8	11,9	15,1	13,8	6,8	-	-	19,8
Textiles	2,5	3,1	3,6	3,3	2,4	14,8	-	1,4
Rubber	0,6	0,9	1,4	1,4	-	1,9	-	1,4
Leather	0,6	0,7	0,9	0,8	0,2	7,4	-	1,1
Yard waste	23,3	11,2	11,4	10,8	10,8	40,7	20,0	8,3
Wood	2,5	2,8	2,9	2,8	3,0	-	-	0,6
TOTAL	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

Moreover, under the hypothesis that all carbon is transformed in biogas, this equation states that:

$$1 \text{ mol C} = 1 \text{ mol } (CH_4 + CO_2)$$

And since at 0°C and 1 atm, a mole of gas corresponds to 22,414 l:

$$1 \text{ mol}_{\text{BIOGAS}} = 22{,}414 \text{ l}$$

And then

$$1 \text{ mol C} = 22{,}414 \text{ l}$$

Therefore knowing that 1 mol of carbon corresponds on weight basis to 12 g C, it can be written:

$$12 \text{ g C} = 22{,}414 \text{ l } (CH_4 + CO_2)$$

Finally:

$$1\text{g C} \rightarrow 1{,}867 \text{ l } (CH_4 + CO_2) \qquad \text{(Eq.4)}$$

Moreover it is assumed that methane content in biogas is in the range of 55-60%.

This is an important result that will be used in the following submodel to calculate the maximum theoretical yield of biogas.

Biochemical model

In the previous model all calculations have been implemented without taking into account biodegradability of waste; therefore Andreottola and Cossu (1988) proposed (Eq.5) to evaluate the content of biodegradable organic carbon in waste, for each subcategory present in it:

$$(OC_b)_i = OC_i \, (f_b)_i \, (1\text{-}u_i) \, p_i \qquad [kgC_{bio}/kgMSW_{WET}] \quad \text{(Eq.5)}$$

where:

- $(OC_b)_i$ is the biodegradable organic carbon in the i^{th} component of wet waste $[kgC_{bio}/kgMSW_{WET}]$;
- OC_i is the organic carbon content in the dry i^{th} component of waste $[kgC_{tot}/kgTS]$;
- $(f_b)_i$ is the biodegradable carbon fraction $[kgC_{bio}/kgC_{tot}]$;
- u_i is the moisture in i^{th} component [% of wet weight] = $[kgwater/kg_{iWET}]$;
- p_i is the wet weight of the i^{th} component $[kg_{iwet}/kgMSW]$.

In table 21 the characteristics of the most significant municipal solid waste components are showed.

Tab. 21 – Moisture content, organic carbon content and biodegradable organic fraction in different waste components (Andreottola and Cossu, 1988).

Waste component	$\mathbf{u_i}$	$\mathbf{Oc_i}$	$\mathbf{(fb)_i}$
	(KgH_2O/Kg wet component)	(KgC/Kg dry component)	(Kg C_{bio}/KgC)
Food waste	0,60	0,48	0,8
Yard waste	0,50	0,48	0,7
Paper and cardboard	0,08	0,44	0,5
Plastic and rubber	0,02	0,70	0,0
Textiles	0,10	0,55	0,2
Wood	0,20	0,50	0,5
Glass	0,03	0,0	0,0
Metals	0,03	0,0	0,0

The biodegradability of these components (f_b) can be estimated also through the lignin content of the waste through Eq.6 (Tchobanoglous et al., 1993):

$$f_{b_i} = 0{,}83 - 0.028\, LC \qquad \text{(Eq.6)}$$

where $(f_b)_i$ is expressed on a volatile solids basis and LC is the lignin content of the volatile solids expressed in percentage of dry weight; therefore higher is the lignin content lower is the biodegradability of a compound; values of biodegradability have been reported in table 22.

Tab. 22 – Biodegradability of some organic compounds found in MSW, based on lignin content (LC) (Tchobanoglous et al., 1993).

Waste component	**Volatile solids (VS) as percentage of total solids (TS)**	**Lignin content (LC) as percentage of VS**	**Biodegradable fraction**
Food waste	7-15	0,40	0,82
Paper			
Newsprint	94,00	21,90	0,22
Office paper	96,40	0,40	0,82
Cardboard	94,00	12,90	0,47
Yard waste	50-90	4,10	0,72

Even if in (Eq.5) landfill inner temperature has been not taken into account, it is really important, as said before, for biological activity connected with anaerobic digestion. Therefore (Eq.7) has been implemented by Tabarasan to improve (Eq.5):

$$(OC_{b_e})_i = (OC_b)_i\,(0.014\,T + 0.28) \qquad \text{(Eq.7)}$$

Where T (°C) is the landfill temperature.

Therefore from (Eq.4) and (Eq.5) it is possible to write:

$$Y_{LFG} = 1.867\ \mathrm{OC_i}\ \mathrm{f_{b_i}}(1 - \mathrm{u_i})\mathrm{p_i} \qquad [\frac{\mathrm{l_{gas}}}{\mathrm{Kg_{MSW}}}] \text{ or } [\frac{\mathrm{m^3{}_{gas}}}{\mathrm{t_{MSW}}}] \qquad \text{(Eq.8)}$$

Kinetic model

The third submodel finds the temporal evolution of biogas generation rate [Nm^3/t_{MSW}] and specific generation rate [$Nm^3/t_{MSW}\ y$].

There is a general equation that governs biogas production in function of the substrate available and time:

$$\frac{dC}{dt} = f(t, C^n) \qquad \text{(Eq.9)}$$

Where:

- *t* is the time;

- *C* is the amount of biodegradable organics or methane, indeed it can express both the rate of substrate degradation or landfill gas production;

- *n* is the order of the model.

This equation is usually applied to a single layer of waste or to a single year of disposal and the global landfill gas production is obtained from the sum of the contributions.

Different authors suggest different model order:

- Zero order kinetic: this means that a small change in the substrate does not affect the rate of biogas production, i.e. methane generation is independent from the amount of substrate remaining or the amount of biogas already produced. For some authors other factors are what really influences the process (moisture content, nutrients, …), while substrate is not the limiting factor.

- First order kinetic: in this case the substrate is the limiting factor, while moisture content and nutrients are not. The choice of a first order kinetic seems to be supported by the fact that biogas production decays over time.

In figure 25 several examples of biogas production equations are showed.

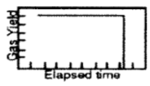
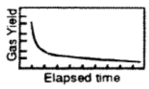
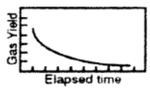
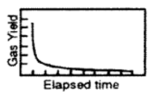
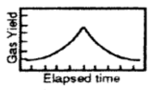
Model	*Integrated form*	*Order*	*Remarks*	*General yield curve*
1. $\frac{dC_i}{dt} = -k$	$C_2 = C_1 - k(t_2 - t_1)$	0	Constant substrate consumption; methane yield rate constant.	
2. $\frac{dC_i}{dt} = -kt$	$C_2 = C_1 - k.\ \ln\frac{t_2}{t_1}$	0	Decay rate declines over time; declining methane production rate.	
3. $\frac{dC_i}{dt} = -kC$	$C_2 = C_1 \cdot \exp[k(t_2 - t_1)]$	1	Exponential decay of substrate.	
4. $\frac{dC_i}{dt} = -\frac{kC}{t}$	$C_2 = C_1 \cdot \exp(k\frac{t_2}{t_1})$	1	Combination of models 2 and 3.	
5. $\frac{dG_i}{dt} = -k_1G$ $\frac{dL_i}{dt} = -k_2L$	$G = \frac{L_0}{2} \cdot \exp[-k_1(t_h - t)]$ $L = \frac{L_0}{2} \cdot \exp[-k_2(t - t_h)]$	1	Two-stage model. Gas generation rate increases then decreases; maximal gas production rate occurs at time t_h.	

Fig. 25 – Examples of zero and first order kinetic equations for biogas production (Zison, 1990).

The most interesting example is that of model 3 which is the typical, simple first order model, where the availability of substrate is the limiting factor. The rate constant (*k*) is the rate at which substrate decays and biogas is produced. Each waste fraction, as said before, has its own degradation rate; this is why in many models substrate is split in several classes with different k values: the readily biodegradable fraction (represented by food waste), the moderately degradable fraction (yard waste) and the slowly biodegradable fraction (paper, cardboard, wood and textiles).

In Andreottola and Cossu model the equation representing biogas production is the following:

$$\frac{dOC_{gi}}{(OC_{bei} - OC_{gi})} = k_i dt \qquad \text{(Eq.10)}$$

where:

- OC_{gi} = gassified carbon (ith component of wet organic waste), representing biogas already produced;
- $(OC_{be})_i$ = biodegradable carbon (ith component of organic waste), representing the amount of landfill gas that has still to be produced;
- k_i = global decay rate (ith component of organic waste).

The global decay rate (k_i) is related to the $t_{1/2}$ as states the equation below:

$$k_i = \ln(2)/t_{1/2} \qquad \text{(Eq.11)}$$

Where $t_{1/2}$ is the half time, i.e. the time over which the gas generation equals half of the estimated yield (fig. 26).

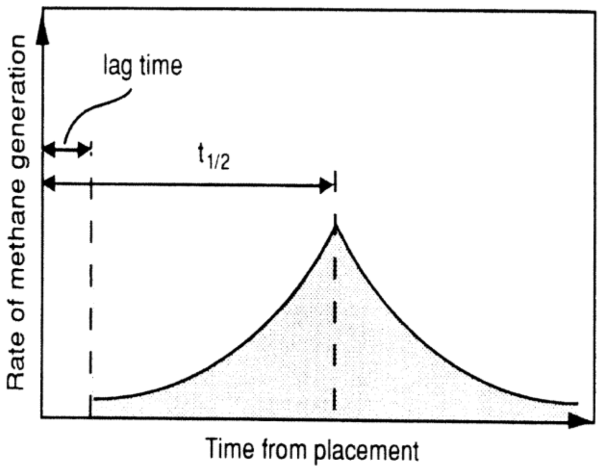


Fig. 26 – General gas-generation curve (Cossu et al., 1996).

Assumed $t_{1/2}$ and k_i values are reported in table 23.

Tab. 23 – $T_{1/2}$ and k_i values (Andreottola and Cossu, 1988).

Biodegradability	$t_{1/2}$ **(y)**	k_i **(y^{-1})**
Ready	1	0,693
Moderate	5	0,139
Slow	15	0,046

Since the rate at which substrate decays is dependent also from moisture and density of the waste, as explained in paragraph 6.5, *k* value can be corrected through two parameters to obtain a effective constant decay rate (k_{ei}) for each component (Eq.12).

$$k_{ei} = \alpha \beta k_i \ [d^{-1}] \qquad \text{(Eq.12)}$$

with:

- $\alpha = u_i/FC_i$
- $\beta = SR_i/SR_{MAXi}$

Where:

- u_i is the actual moisture of i^{th} component;
- FC_i is the field capacity, i.e. the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased;
- SR_i is the actual active surface of i^{th} component;
- SR_{MAXi} is the maximum active surface.

Table 24 reports parameter values for some kind of waste.

Tab. 24 - Biochemical submodel parameters values.

Material	$t_{1/2}$	**k**	**α**	**β**	k_{ei}
Putrescible	1	0,6931	0,7	0,2	0,0970
Textiles	15	0,0462	1,0	0,3	0,0139
Cellulosic material	15	0,0462	1,0	0,3	0,0139

Finally, reorganizing (Eq.10), it is possible to obtain (Eq.13):

$$\frac{dOC_{gi}}{dt} = k_{ei}(OC_{bei} - OC_{gi}) \qquad \text{(Eq.13)}$$

This is easily resolvable in this way:

$$OC_{gi} = OC_{bei}(1 - e^{-k_{ei}t}) \qquad \text{(Eq.14)}$$

Therefore using information in (Eq.8) and (Eq.14) can be derived (Eq.15):

$$G_t = \sum_{i=1}^{n} 1{,}867\, OC_{bei}(1 - e^{-k_{ei}t}) \qquad \text{(Eq.15)}$$

where:

- G_t is the biogas production [Nm^3/t_{MSW}];
- i is the waste category;
- OC_{bei} is the biodegradable carbon in the i^{th} waste category, found in the biochemical model.

The maximum theoretic biogas production [Nm^3/t_{MSW}] is found through (Eq. 16):

$$G_t = \sum_{i=1}^{n} 1{,}867\, OC_{bei} \qquad \text{(Eq.16)}$$

Furthermore, deriving (Eq.15) with respect to time, it is possible to know the specific biogas production [Nm^3/t_{MSW} y], i.e. the production for each year of waste conferment:

$$g = \frac{dG_t}{dt} = \sum_{i=1}^{n} 1{,}867\, OC_{bei}\, k_{ei}\, e^{-k_{ei}t} \qquad \text{(Eq.17)}$$

8.1 Este landfill case

For the purpose of this study, landfill body has been divided in two main sectors at which will be applied the first order kinetic model; in particular LOTTO 1 (*old landfill*) constitutes the first sector and LOTTO 2 and 3 (*new landfill*) together represent the second main sector (fig. 27).

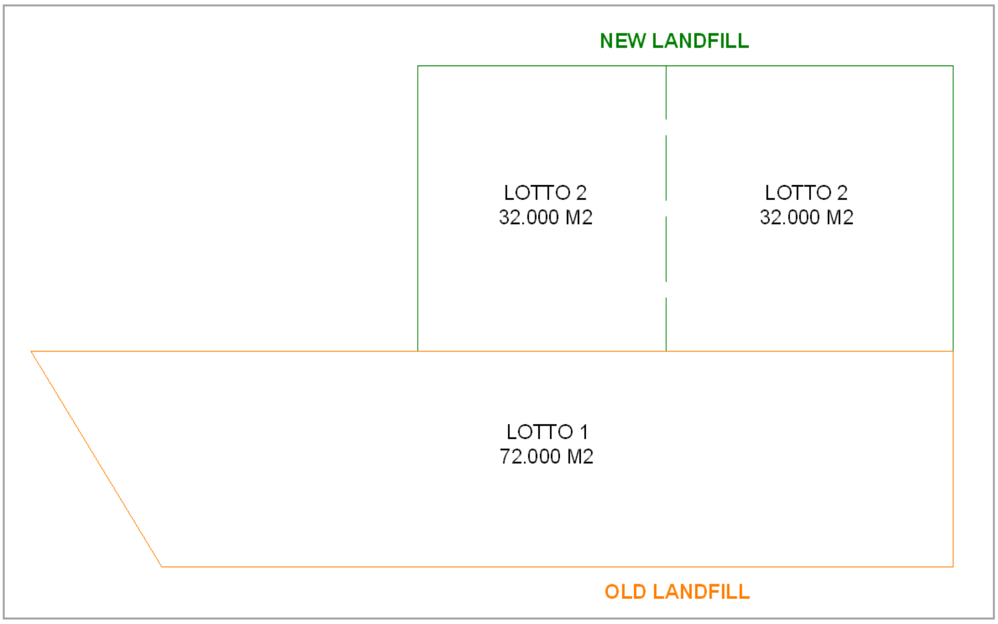


Fig. 27 – Old and new landfill sectors.

The choice has been done given the following considerations:

- conferment in LOTTO 1 started in 60s and ceased in 1995 under the supervision of Este municipality; the waste conferred in these years has different compositions (changing with time), but it is constituted mainly by household waste not differentiated and without any treatment before disposal; moreover there are no data about waste composition.
- LOTTO n°2 and n°3 conferment started when S.E.S.A. took the management of the area and waste in place comes from separate collection.

In the following paragraphs the main characteristics of the two sectors will be presented, i.e. waste quality and quantity; furthermore the model parameters selection and implementation and finally the result will be showed.

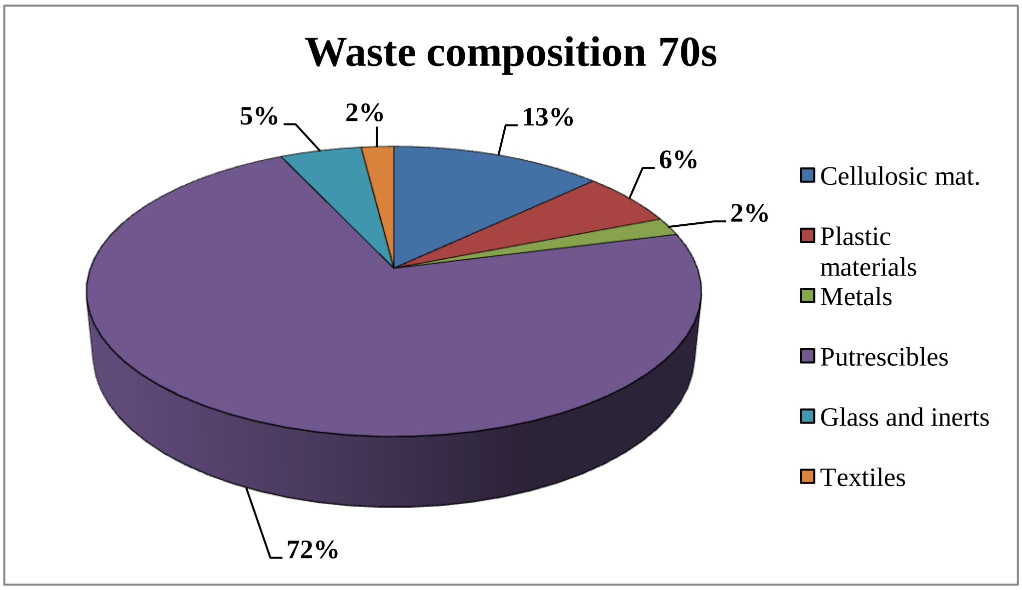
8.1.1 Waste quality and quantity

Given the previous assumptions and the lack of specific data already mentioned, waste composition has to be assumed following some reasoning.

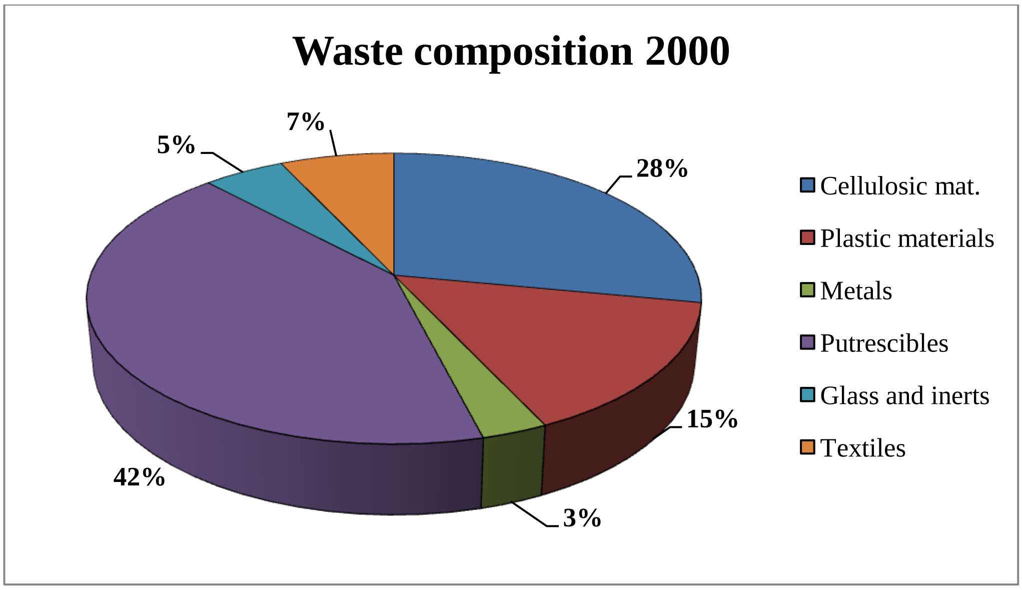
<u>Old landfill waste</u>

The old landfill sector has been filled since 1965 till 1995; obviously the composition of waste in these years has changed a lot. In the model it will be assumed to have changed each ten years, remaining more or less the same for a decade.

Therefore starting from a general waste composition of 70s in Italy (graph 16) and of years 2000 (graph 17), the composition has been assumed to be distributed over these 30 years.

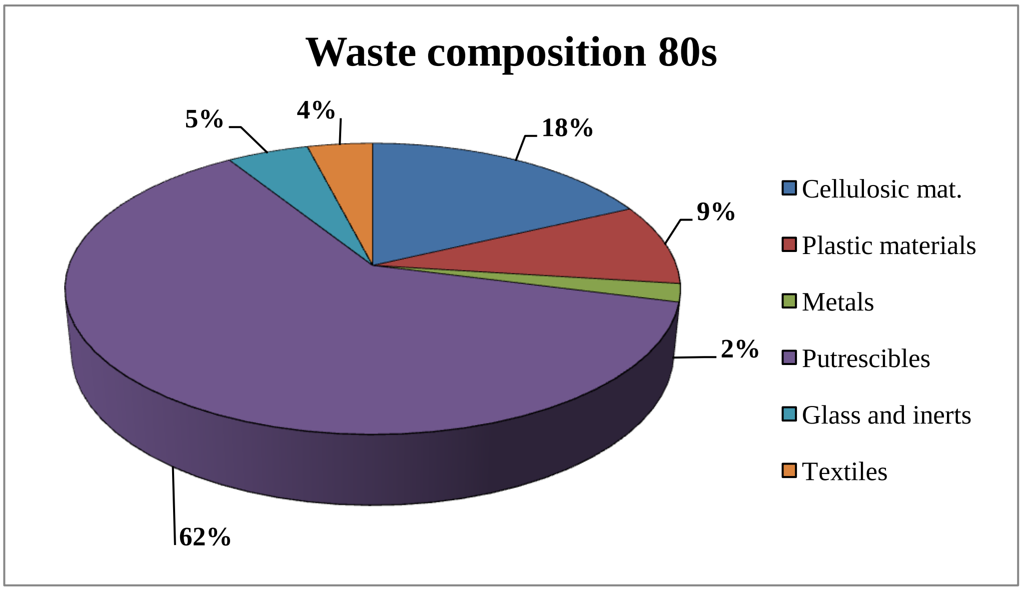


Graph 16 – Waste composition in 70s, Italy (Raga R., *Strategie di gestione dei rifiuti*, 2007, IMAGE, Padova).

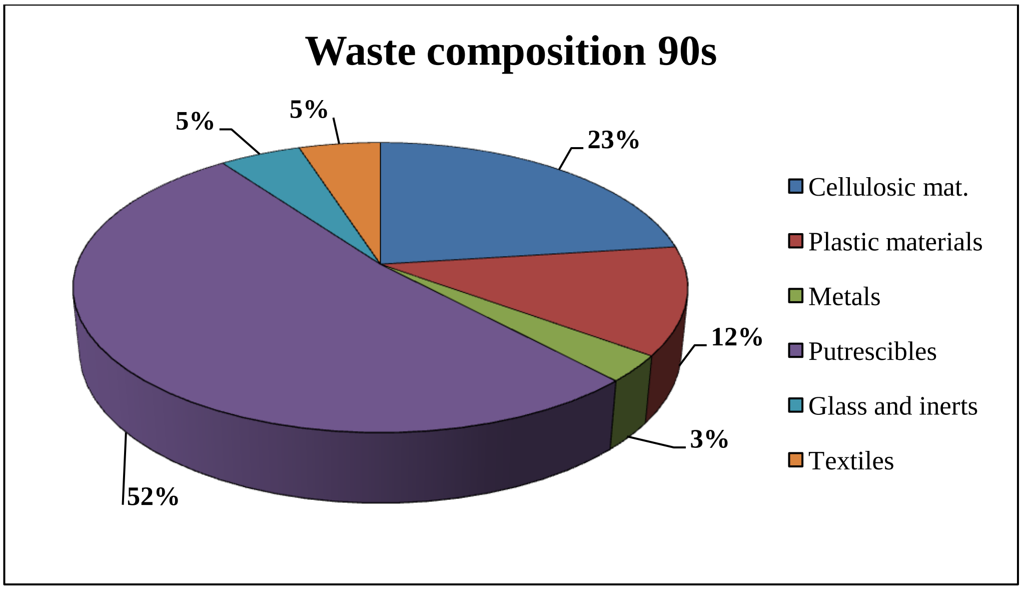


Graph 17 – Waste composition in year 2000, Italy (Raga, *Strategie di gestione dei rifiuti*, 2007, IMAGE, Padova).

In other words, regarding for example putrescible waste, in 70s it amounted to 72% of the total waste, while in 2000 it amounted to 42%; therefore a decrease of 10% each ten years is assumed. The same reasoning has been done for other waste categories (graphs 18 and 19).



Graph 18 – Waste composition in 80s, Italy.



Graph 19 – Waste composition in 90s, Italy.

The trend reflects the reality, indeed from 70s to 2000 the usage of paper and plastic increased a lot making the percentage of these fractions more relevant compared to the others.

Regarding waste quantity in old landfill the same reasoning done for LandGEM model has been implemented: the entire tonnage of waste present in the landfill has been divided for the years of conferment, knowing the volume of the sector. In particular, the volume of old landfill is 750.000 m^3 and supposing a waste density of 1 t/m^3, 750.000 t of waste have been conferred from 1965 to 1995. So an average conferment rate of 24.194 t/y has been calculated.

New landfill waste

For the new landfill sector the composition is partially known; indeed the composition of years 2006 and 2007 are shown in table 15 and 16, subdivided by mean of European Waste Catalogue codes. Moreover is available also the composition of years 2005 and 2008, even if it is divided for macro categories as showed in table 25. In particular MSW, waste coming from commercial and industrial activities, but similar to MSW in composition, and waste water sludge.

Tab. 25 – Waste composition for macro categories for years 2005-2008 (data available from S.E.S.A.).

WASTE COMPOSITION (t/y)				
Year	**MSW**	**Waste similar to MSW**	**WW sludge**	**Total**
2005	22.834	16.873	4.078	43.785
2006	21.944	7.895	2.333	32.172
2007	21.278	7.310	3.807	32.395
2008	20.227	4.627	1.824	26.678

PERCENTAGES (%)				
Year	**MSW**	**Waste similar to MSW**	**WW sludge**	**Total**
2005	52,2%	38,5%	9,3%	100,0%
2006	68,2%	24,5%	7,3%	100,0%
2007	65,7%	22,6%	11,8%	100,0%
2008	75,8%	17,3%	6,8%	100,0%

As can be seen, percentages are quite different, therefore an assumption has to be made; the most representative year, taking into account percentages, is 2006 and its detailed composition is showed in table 26.

Tab. 26 – Waste fractioning for year 2006.

Category	C.E.R.	t/y	%
MSW	200301	19.500,61	60,61
	200303	1.245,58	3,87
	200307	1.197,76	3,72
Waste similar to MSW	040222	5,24	0,02
	150106	62,90	0,20
	170203	34,66	0,11
	170802	3,72	0,01
	190801	1.200,90	3,73
	191212	5.987,44	18,61
	200108	1,50	0,00
	200111	31,53	0,10
	200139	75,12	0,23
	200199	415,50	1,29
	200201	7,98	0,02
	200301	40,52	0,13
	200307	28,20	0,09
WW sludge	190805	2.259,52	7,02
	190812	73,50	0,23
TOTAL		**32.172,18**	**100,00**

Regarding the quantity of waste from 1996 to 2014, the same reasoning done for LandGEM model has been followed and the results are showed in table 27.

Tab. 27 – Waste quantity entered in new landfill for years 1996-2014.

Year	Waste (t/y)
1996	59.626
1997	59.626
1998	59.626
1999	59.626
2000	59.626
2001	59.626
2002	59.626
2003	59.626
2004	59.626
2005	43.785
2006	32.172
2007	32.395
2008	26.678
2009	22.571
2010	22.380
2011	20.848
2012	15.947
2013	15.947
2014	929

8.1.2 Model parameters

Once waste quantity and quality have been ascertained, it is important to evaluate which are the values of $t_{1/2}$, k, u, OC_i, f_b, α and β to attribute to categories that compose waste. Also in this case a different approach will be used for old and new landfill sectors.

Old landfill

The categories in which the waste has been characterized (graphs 16-19) are: cellulosic materials, plastic materials, metals, putrescibles, glass and inerts and textiles; as already said biogas is produced by the anaerobic decomposition of material which has a medium or high degradability, therefore the categories of plastic materials, metals and inerts will not be taken into account since they have a very slow degradability.

Referring to table 23, the remaining classes will be considered as follows: cellulosic material and textiles as slowly degradable, while putrescible material as readily degradable.

For these reasons and referring to tables 21 and 24, the values attributed to the three waste fractions are showed in table 28. Values for k_{ei} can be found in table 24.

Tab. 28 - Main parameters for different fractions (old landfill).

Material	$t_{1/2}$	k	p	u	OCi	f_b	OC_{bi}	OC_{bei}
Cellulosic material	15	0,0462	0,130	0,08	0,44	0,5	0,0263	0,0203
Putrescible	1	0,6931	0,720	0,60	0,48	0,8	0,1106	0,0852
Textiles	15	0,0462	0,020	0,10	0,55	0,2	0,0020	0,0015

The values of p reflect the composition of waste found in graph 14 - 17 and are different for each decade; in table 28 is showed the 70s decade where cellulosic materials, putrescibles and textiles amount respectively to 13%, 72% and 2%. The value of OC_{bei} has been found imposing a landfill inner temperature of 35°C.

New landfill

For the new landfill sector the reference year will be 2006, as already specified. Since it is not possible to subdivide waste in the same categories of old landfill, it will be characterized with reference to degradability degree making some assumption as showed in table 16, reported below.

Tab. 16 – Waste fractioning for year 2006.

Year 2006			WASTE CATEGORY		
C.E.R.	**Tons of waste**	**%**	**Relatively inert (t)**	**Moderately decomposable (t)**	**Decomposable (t)**
200301	19.500,61	60,61	5.460,17	10.140,32	3.900,12
200303	1.245,58	3,87	871,91	124,56	249,12
200307	1.197,76	3,72	-	1.197,76	-
040222	5,24	0,02	-	5,24	-
150106	62,90	0,20	62,90	-	-
170203	34,66	0,11	34,66	-	-
170802	3,72	0,01	-	3,72	-
190801	1.200,90	3,73	240,18	-	960,72
191212	5.987,44	18,61	-	5.987,44	-
200108	1,50	0,00	-	-	1,50
200111	31,53	0,10	-	31,53	-
200139	75,12	0,23	75,12	-	-
200199	415,50	1,29	-	415,50	-
200201	7,98	0,02	-	-	7,98

200301	40,52	0,13	11,35	21,07	8,10
200307	28,20	0,09	-	28,20	-
190805	2.259,52	7,02	-	-	2.259,52
190812	73,50	0,23	-	-	73,50
TOTAL	**32.172,18**	**100,00**	**6.756,28**	**17.955,34**	**7.460,56**

As can be seen, percentage of relatively inert, moderately decomposable and decomposable waste is respectively of 21%, 56% and 23%. These categories can be assimilated to putrescible waste for decomposable fraction, cellulosic material and textiles for moderately decomposable fraction and glass and metals for inert fraction. Therefore the parameters used in the model will be that found in table 29.

Tab. 29 - Main parameters for different fractions (new landfill).

Material	**$t_{1/2}$**	**k**	**p**	**u**	**OCi**	**f_b**	**OC_{bi}**	**OC_{bei}**
Moderately decomposable	15	0,0462	0,560	0,08	0,44	0,5	0,1133	0,0873
Decomposable	1	0,6931	0,230	0,60	0,48	0,8	0,0353	0,0272

Also in this case the landfill inner temperature is supposed to be 35°C.

8.1.3 Model implementation

Obviously also the model implementation is different for old and new landfill.

<u>*Old landfill*</u>

In tables 28, 30 and 31 are reported the parameters for 70s, 80s and 90s years.

Tab. 28 - Main parameters for different fractions (old landfill, 70s).

Material	**$t_{1/2}$**	**k**	**p**	**u**	**OCi**	**f_b**	**OC_{bi}**	**OC_{bei}**
Cellulosic material	15	0,0462	0,130	0,08	0,44	0,5	0,0263	0,0203
Putrescible	1	0,6931	0,720	0,60	0,48	0,8	0,1106	0,0852
Textiles	15	0,0462	0,020	0,10	0,55	0,2	0,0020	0,0015

Tab. 30 - Main parameters for different fractions (old landfill, 80s).

Material	$t_{1/2}$	k	p	u	OCi	f_b	OC_{bi}	OC_{bei}
Cellulosic material	15	0,0462	0,180	0,08	0,44	0,5	0,0364	0,0281
Putrescible	1	0,6931	0,620	0,60	0,48	0,8	0,0952	0,0733
Textiles	15	0,0462	0,040	0,10	0,55	0,2	0,0040	0,0030

Tab. 31 - Main parameters for different fractions (old landfill, 90s).

Material	$t_{1/2}$	k	p	u	OCi	f_b	OC_{bi}	OC_{bei}
Cellulosic material	15	0,0462	0,230	0,08	0,44	0,5	0,0466	0,0358
Putrescible	1	0,6931	0,520	0,60	0,48	0,8	0,0799	0,0615
Textiles	15	0,0462	0,050	0,10	0,55	0,2	0,0050	0,0038

Starting from these data and from those in table 24, the cumulative biogas production G_t [Nm^3/t_{waste}], the specific biogas production g_t [$Nm^3/t_{waste}y$] and the maximum biogas production $G_{t,\ max}$ [Nm^3/t_{waste}] have been calculated for each semester from 1965 to 2105 (to reflect LandGEM model).

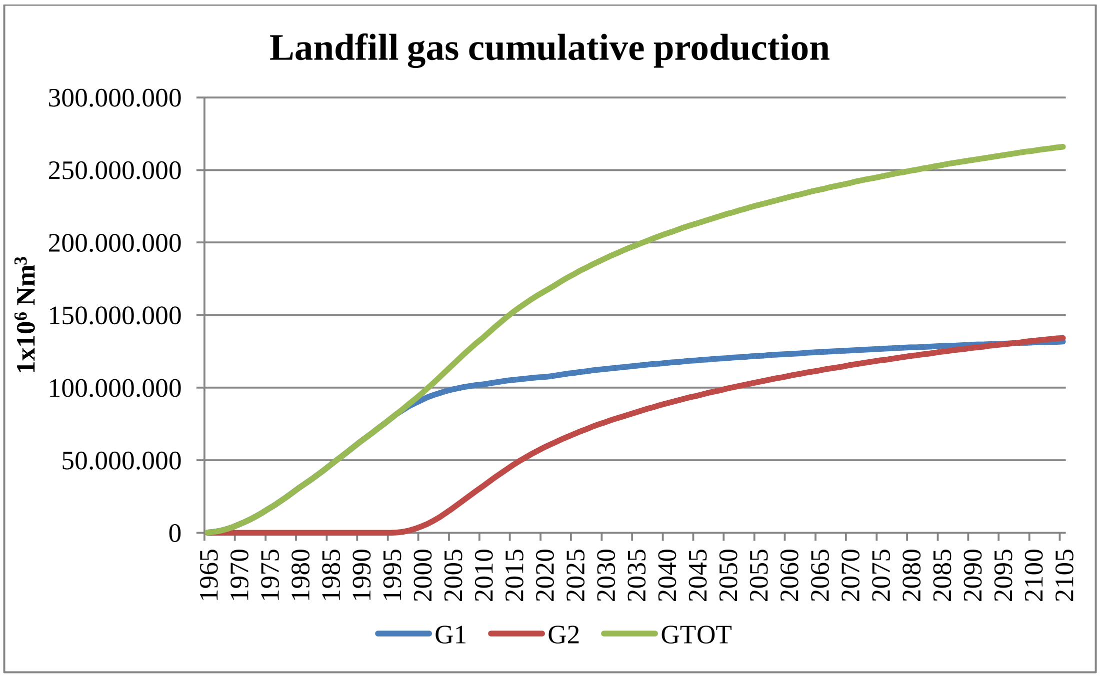
As already said, these values are specific for each year, but don't take into account the waste already landfilled. Therefore each value has been multiplied for the waste tonnage conferred each semester (12.096 t/semester); moreover for each semester the sum of biogas production (cumulative and specific) of each waste tonnage has been done, to find the overall values.

New landfill

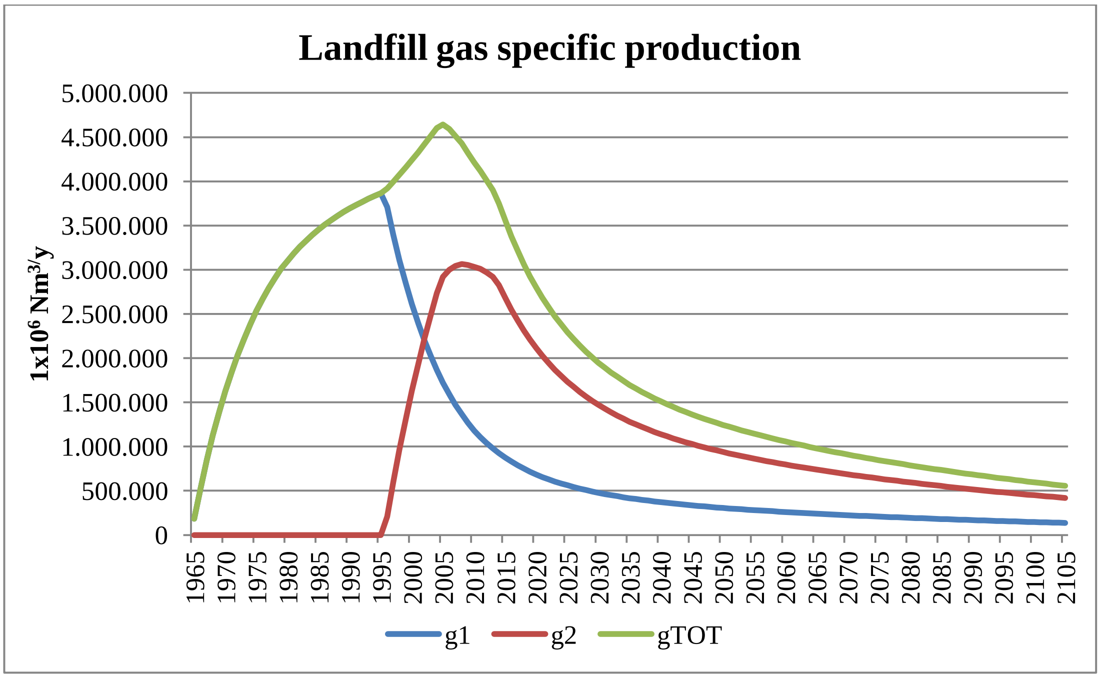
Regarding new landfill sector, the parameter chosen have already been presented and are those of table 29. The same procedure used for old landfill has been implemented with two differences: biogas production starts in 1995 and the waste tonnage is the same from 1995 to 2004 (29.813 t/semester) and from 2005 to 2014 it varies.

8.2 Results

In graphs 20 and 21 model results are showed.



Graph 20 – Landfill gas cumulative production.



Graph 21 – Landfill gas specific production.

In the graphs the blue line describes the old landfill production, the red line the production of new landfill sector, while the green line represents the sum of the two components.

As can be seen the cumulative and specific production behave both as expected. regarding cumulative production of old landfill, it starts in 1965 and increases till 1995, year of sector closure; this is reflected in the graph of specific production, indeed the cubic meters per year produced increase too and this is due to the sum of specific productions of the more and more tons of waste conferred. After 1995 the specific production decreases since no waste is added anymore and at the same time the cumulative production increases again but at a lower rate and stabilize around the value of 130.000.000 m^3.

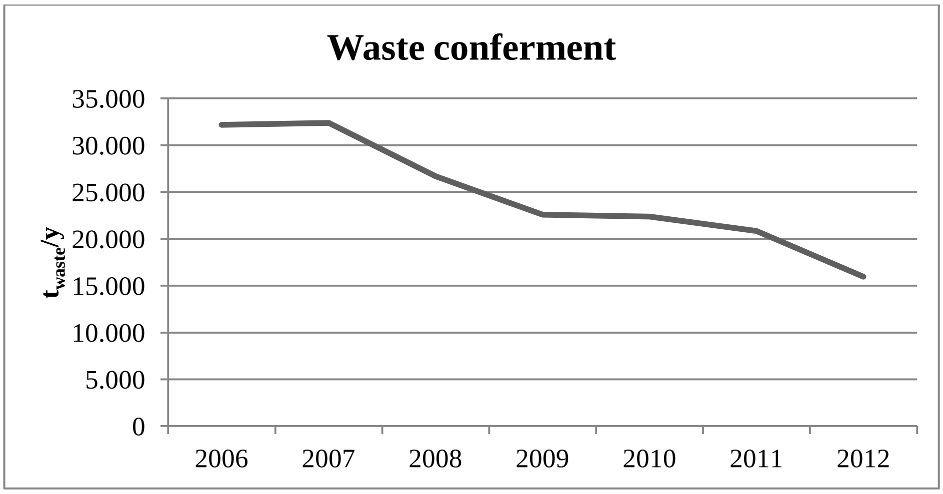
Regarding the new landfill sector, the same reasoning can be done but with a delay of thirty years: indeed the conferment started in 1995. Anyway some differences with respect to old landfill sector can be detected: the specific production has a more rounded shape on the peak of the curve and this is due to the lower and lower waste disposal of the last years with respect to the previous ones; the conferment last less years in the new landfill sector (20 y, rather than 30 y) and this is the reason for a peak reaching only about 3.000.000 Nm^3/y rather than the 4.700.000 Nm^3/y of the old landfill sector. The cumulative production curve of new landfill sector has a shape slight different with respect to old landfill sector one: this is again due to the waste conferment change in the last years.

Finally regarding the green curve, sum of the two just examined, it reflects perfectly the sum of the curves.

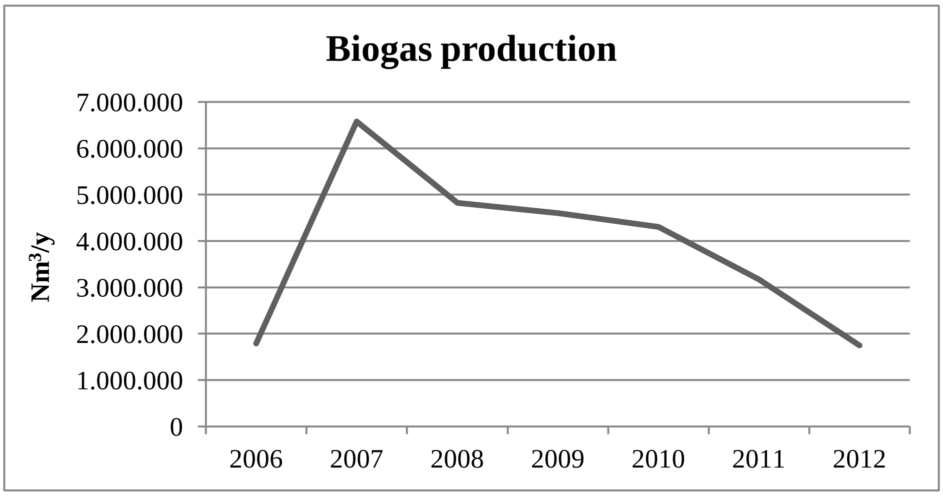
9. FIELD DATA AGAINST MODEL DATA

Data available on biogas production go from year 2006 to year 2012, therefore a comparison in these years with models' results will be done.

In the graph below it is showed waste conferment regarding the interested years; and in graph 23 the biogas production per year is presented (all data available from S.E.S.A.).



Graph 22 – Waste conferment in Este landfill, years 2006-2012.



Graph 23 – Biogas production from Este landfill, years 2006-2012.

Biogas production, as can be seen from the second graph, has a not linear shape; this is due to various factors and some explanations must be given:

- in 2006 the production has been of 1.754.501 Nm^3 which is less than the mean value of other years since the cogeneration engine has been substituted and biogas has been flared rather than utilized;
- in the following years the production has been relatively constant, even if decreasing since waste conferment has dropped too: indeed the new selection plant has been implemented and also a better quality waste has been entered in the landfill (lower biodegradability);
- in 2012 the engine has been submitted to two stops for reparation, therefore biogas production has dropped down to a value 1.747.621 Nm^3; furthermore a lower quantity of waste has been conferred.

These considerations lead to a conclusion: biogas production fits well with waste conferment, apart from engine stops in 2006 and 2012. This is sustained also by the specific biogas production [Nm^3_{biogas}/t_{waste}] showed in table below: indeed the value is almost the same from year 2007 to 2010 and it is around 190-200 Nm^3_{biogas}/t_{waste}.

Tab. 32 - Main parameters for different fractions (new landfill).

Year	Waste (t)	Biogas (Nm^3/y)	Nm^3_{biogas}/t_{waste}
2006	32.172	1.784.501	55,5
2007	32.395	6.573.811	202,9
2008	26.678	4.821.831	180,7
2009	22.571	4.601.021	203,8
2010	22.380	4.303.262	192,3
2011	20.848	3.172.361	152,2
2012	15.947	1.747.621	109,6

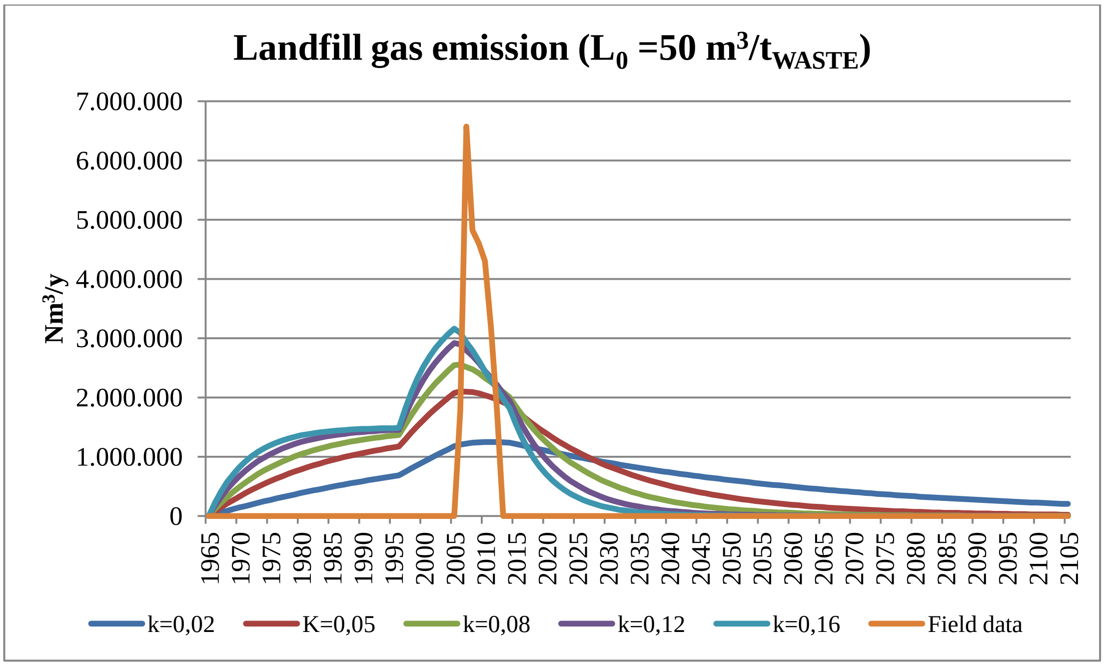
For this reason and for the explanations given before it is reasonable to say that the most reliable years to compare are those from 2008 to 2011, whose data follow the same trend.

Moreover data from the models will be diminished of the 40% since S.E.S.A. has estimated that 60% of biogas production is captured, while the remaining 40% is released in the atmosphere (*Dichiarazione ambientale*, 2012 and 2013). In the following paragraphs field data will be compared to model data through a critical point of view.

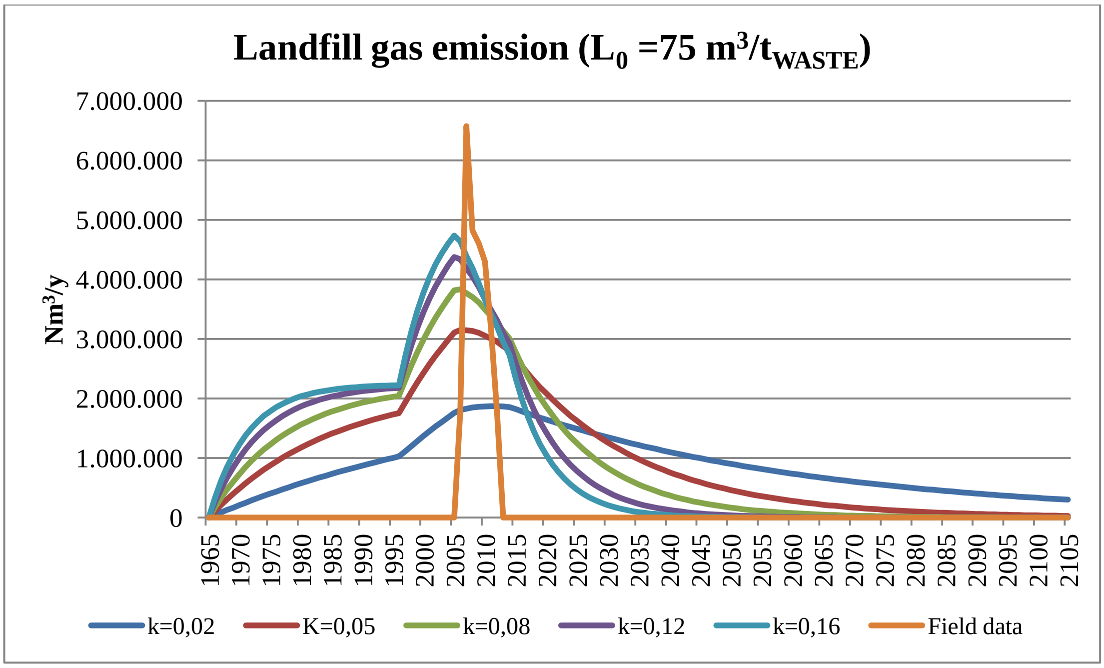
9.1 LandGEM model

Concerning LandGEM model, in this section a validation will be done: changing the values of *methane generation rate constant* (k) and *potential methane generation capacity* (L_0) it will be seen what are the values the reflect better real data.

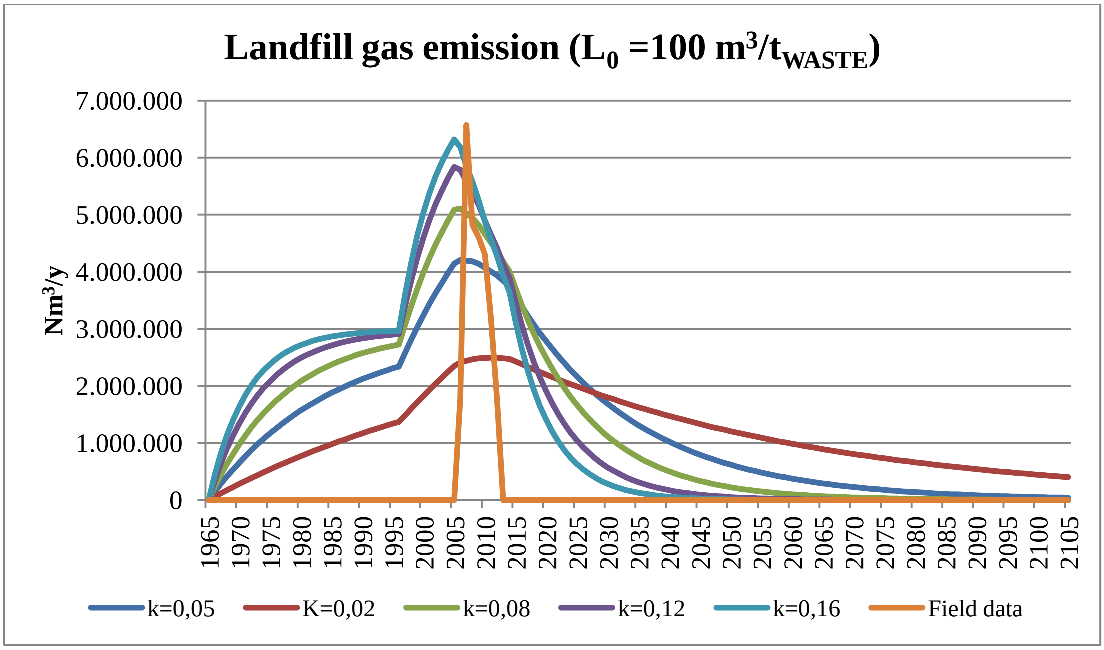
Potential methane generation capacity has been changed of a value of 25 m^3/t starting from 50 m^3/t and going to 150 m^3/t, as advised by Conestoga-Rovers and Associates. Here a graph for each L_0 value will be presented with a change in k value from 0,02 to 0,16 y^{-1}. In the graphs will also be presented the comparison with field data.



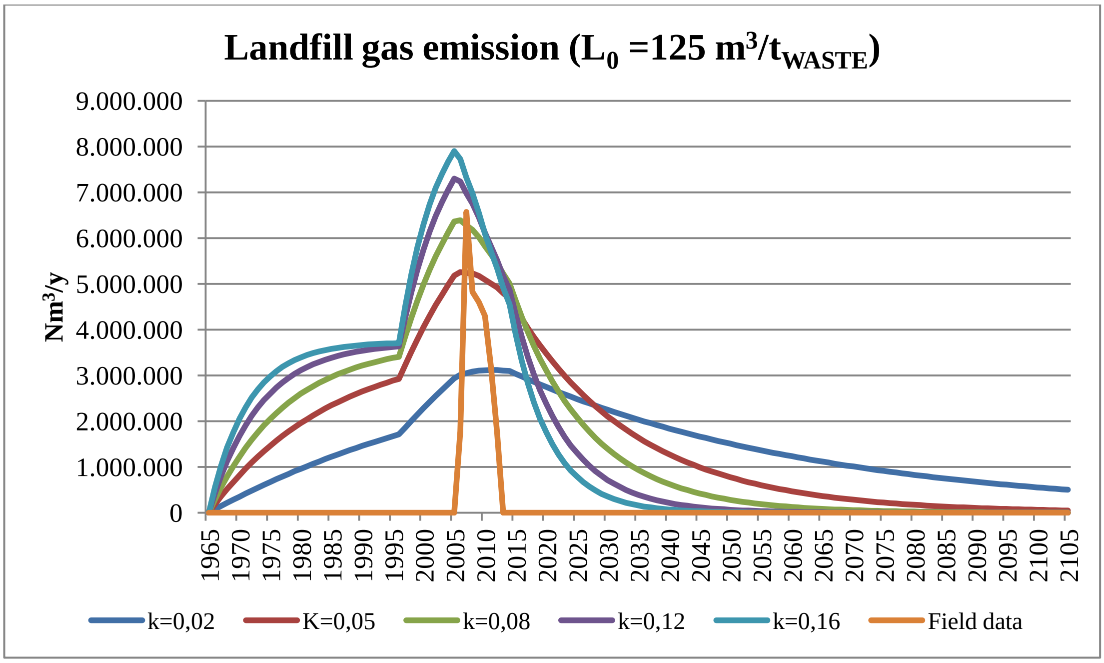
Graph 24 – Biogas production from Este landfill (L_0 = 50 m^3/t_{WASTE}).



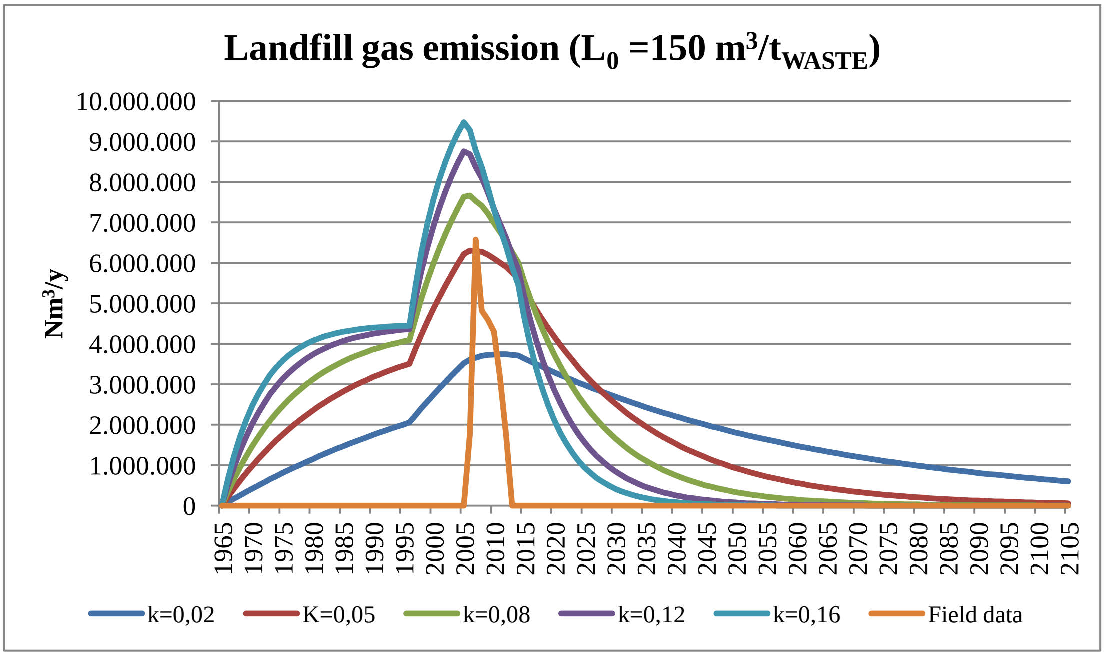
Graph 25 – Biogas production from Este landfill (L_0 = 75 m^3/t_{WASTE}).



Graph 26 – Biogas production from Este landfill (L_0 = 100 m^3/t_{WASTE}).

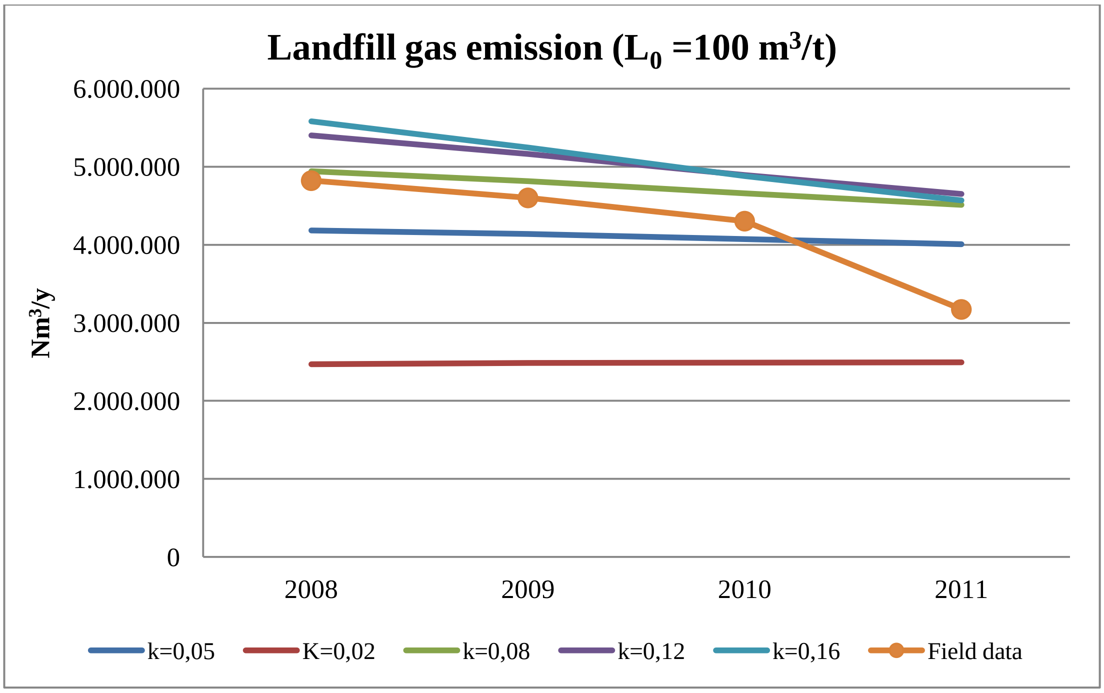


Graph 27 – Biogas production from Este landfill (L_0 = 125 m^3/t_{WASTE}).



Graph 28 – Biogas production from Este landfill (L_0 = 150 m^3/t_{WASTE}).

As can be seen the most reliable graph is that with a *potential generation capacity* of 100 m^3/t, since data from 2008 to 2011 are the nearest to field data; regarding the value of k, from graph 29 it is clear that a value of 0,08 y^{-1} is the most suitable.



Graph 29 – Biogas production from Este landfill (L_0 = 100 m^3/t_{WASTE}), years 2008-2011.

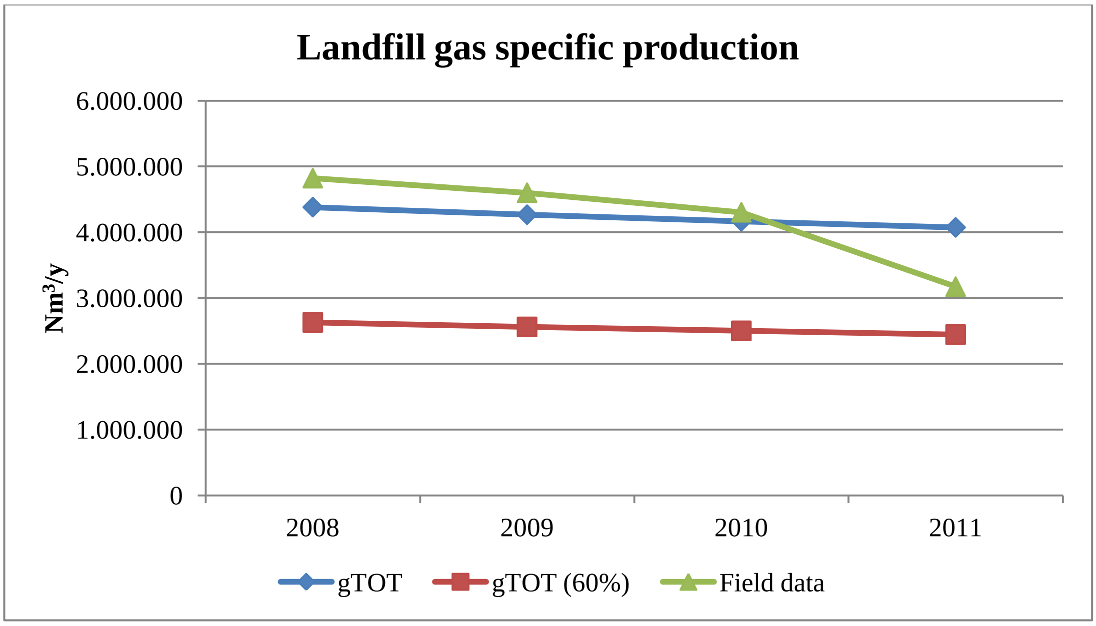
The value chosen in chapter 6.3 was of 0,05 y^{-1} and this difference can be explained through some reasons:

- in LandGEM the landfill has been considered as a whole body, while it is composed of different sectors with different parameters values.
- k value has been chosen as mean value of different components of waste; the composition chosen (year 2006, the most reliable one) is certainly representative for the last years, but regarding Lotto n°1 surely it present some differences; therefore the value of k chosen reflects mainly the new part of landfill. Indeed the composition of waste changes each year and a perfect knowledge of waste composition would have helped in having a most reliable result.
- Besides the uncertainties related to old landfill are a lot and it could be useful to have biogas production separated for Lotto n°1 and Lotto n°2 and n°3; in this way the model could be set applied only on Lotto n°2 and n°3, whose composition is better known.

9.2 First order kinetic model

In graph 30 real data of graph 23 (green line) have been reported together with biogas production calculated by the model (blue line) and the same diminished of the 40% (under the advice of S.E.S.A.). As can be seen, calculated data don't fit very well field data, on the contrary model data are much lower than real ones.

In particular, as already done for LandGEM model, in graph 31 are reported data for years 2008, 2009, 2010 and 2011, the most representative.

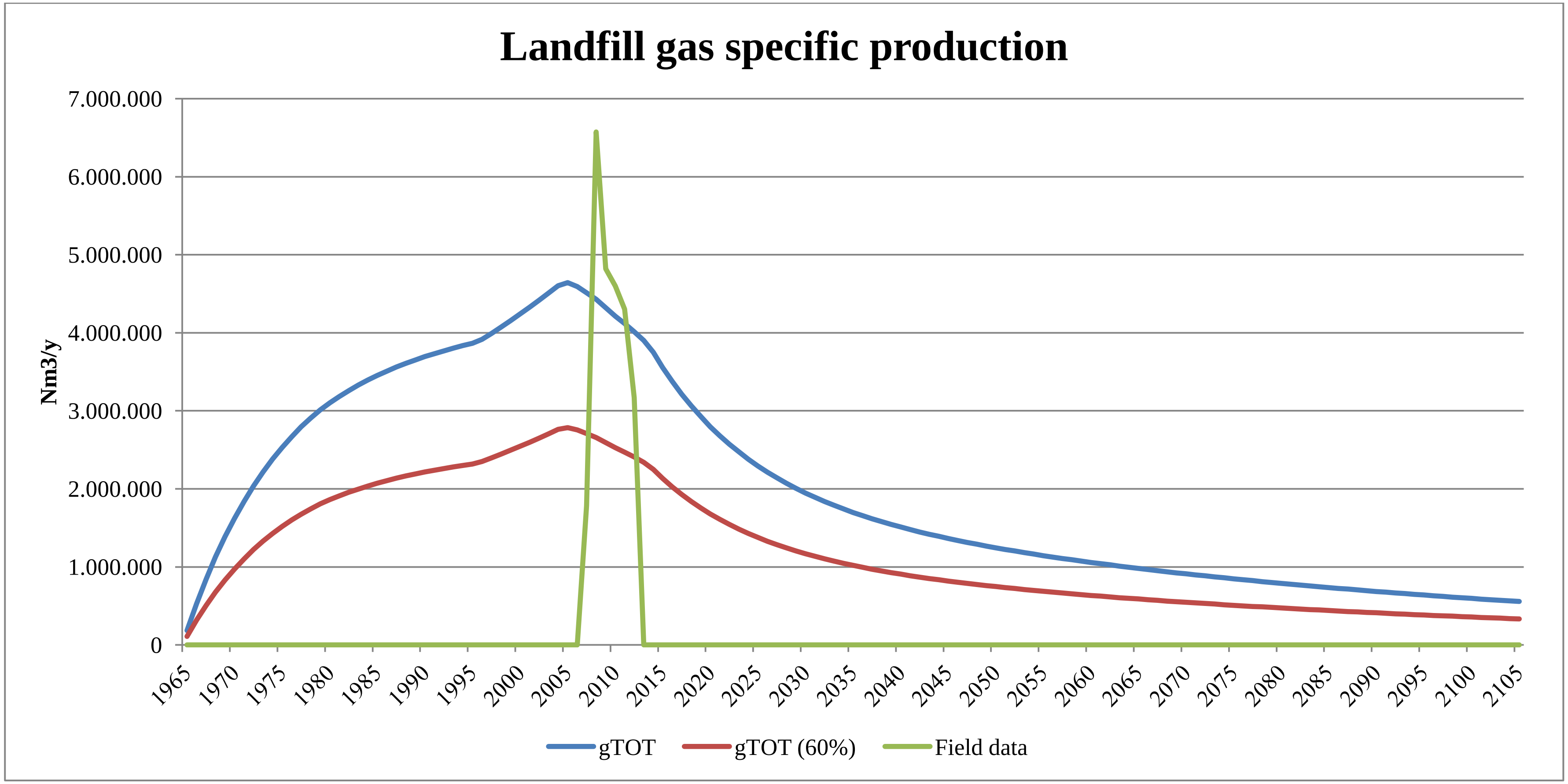


Graph 30 – Landfill gas specific production for years 2008-2011.

To find the reasons of this discrepancy it is useful to examine Eq. 17, reported below:

$$g = \frac{dG_t}{dt} = \sum_{i=1}^{n} 1{,}867\, OC_{bei}\, k_{ei}\, e^{-k_{ei}t} \qquad \text{(Eq.17)}$$

The value of specific production depends mainly on OC_{bei}, k_{ei} and time.



Graph 30 – Landfill gas specific production from Este landfill.

OC_{bei} depends in turn on OC_i which is the organic carbon content of the dry ith component of waste; as already said, this value can be found in literature for each waste category, but in the new landfill sector waste was not categorized and some assumptions have been done. The organic biodegradable carbon content depends also on humidity and biodegradable fraction for which the same reasoning can be done, regarding old and new landfill sectors. Moreover, even if in the old landfill the categorization has been done and values are almost certain, the composition has been merely supposed, rendering the uncertainty even more high. OC_{bei} depends also on waste tonnage and this value has been obtained, rather than known; this can lead to a delay or anticipation in the curve of production which could not fit anymore field data. The organic biodegradable carbon content relies also on temperature: this datum was unknown and has been supposed to be around 35°C; in reality this is a very sensitive data since temperature can change widely in landfill body, due to the different stages of anaerobic decomposition of different waste.
The other sensitive datum is k_{ei} depending on half time and relative density and moisture of the waste; the same reasoning done for other parameters can be applied to it.

Apart from the previous considerations, other site-specific and more general speculations can be added:

- Waste composition of old landfill sector has been supposed starting from a general national datum, but the area is rural, specially till 80s; therefore it is reasonable to say that a higher putrescible component (and so an higher landfill gas production) is probably present in waste of those years.
- Obviously the composition of year 2006 is representative of new landfill sector, but it can differ a lot from year to year.
- Old landfill sector was not managed as a modern sanitary landfill; indeed leachate and biogas collection were not implemented and the capping of the area was very poor. This means that leachate and biogas production could have been accelerated by air and rain infiltrations, resulting in a lower current production with respect to that expected nowadays.

- As already said for LandGEM model if the subdivision of landfill output in sub stations could have helped to adjust model parameters in a better way, both for old and new landfill sector.
- S.E.S.A. advises that biogas captured is around the 60% of the total production, but also this data can differ from year to year and depends on several factors. Moreover the biogas capitation layer o old landfill has been implemented after the closure in 1997 and this can lead to difficulties in reaching all the part of landfill body.

In the following chapter conclusions regarding both models will be presented.

10.CONCLUSIONS

The modeling of biogas production is a very important issue to predict and reduce greenhouse gas emissions from municipal solid waste landfills, one of the most relevant anthropogenic sources.

In particular, in this study two models have been implemented on a landfill in province of Padua, in Veneto region. The landfill in question is a municipal solid waste landfill opened in 1965 and has been managed by Este municipality till 1995; it then passed under the control of S.E.S.A., who started a new part of the landfill and updated it: waste coming from separate collection, new capping, leachate and biogas collection and treatment have been implemented.

The models utilized belong both to the first order kinetic category, since this kinetic is believed to better describe the process of anaerobic digestion, occurring in the landfill body. The first model is LandGEM, developed in its first version by U.S. E.P.A. in 2005; it considers landfill as a whole and requires two main parameters for the modeling of landfill gas production: potential methane generation capacity and methane generation rate constant, which are needed to insert information about waste composition. Moreover the model requires also waste tonnage and methane percentage in biogas.

The results of this model are quite good: indeed the biogas generation is reflected very well in years 2008–2011; parameters have been selected through a waste composition of year 2006 since it was the most representative and data of previous years was not available. Potential methane generation capacity has been supposed to be 100 m^3/t and methane generation rate of 0,05 y^{-1}; at the end a model validation has been implemented to verify if data chosen were the most reliable, changing both the parameters. Potential methane generation capacity chosen confirmed to be the most suitable value; while methane generation rate constant that better responds to field data is 0,08 y^{1}.

The reasons of this variance have to be searched mainly in waste composition: landfill has been considered as a whole body and 2006 waste characterization has been chosen; anyway it can be representative for the last years, but surely waste of previous years, when separate collection was not applied, had an higher putrescible component, explaining the higher value of methane generation rate constant. Obviously a more accurate knowledge of the waste composition could have lead to model results more near to real data.

The second model implement has been called first order kinetic model and was developed by Cossu and Andreottola in 1988 starting from Buswell equation and considerations of other authors. The model takes into account waste tonnage, humidity, but mainly the organic biodegradable content of waste; values for these parameters can be found in literature, diverse for different waste fractions. Model outputs are specific biogas production, cumulative biogas production and maximum theoretic production; the first output have been analyzed since data from Este landfill are specified on annual basis. It is important to underline that field data are not divided on substations, rather the total production of old and new landfill is given. The landfill, on the contrary of LandGEM, has been divided in two main sectors called old and new sectors and different parameters have been adopted, on the basis of a change in composition of waste; for old landfill these changes have supposed to be each decade and for new landfill the 2006 data available.

Results of the model do not fit field data very well, rather they are almost the double; also in this case the main reason can be found in waste composition since it has been assumed starting from national data. Moreover a significant specification to do is that old landfill was not a modern sanitary landfill, indeed capping of the landfill consisted in a layer of soil and this could have caused an acceleration in waste decomposition and in landfill gas production, lowering the actual values. Finally, S.E.S.A. suggests that about the 40% of biogas is dispersed in the atmosphere, but this datum can change widely in years and parts of the landfill changing biogas production.

As can be seen, the main issue in implementing landfill gas production models is the composition of waste: only a very accurate knowledge of these data can lead to significant and reliable results. However, in this specific case, the two models behave in a different way: LandGEM reports results more near to field data with respect to first order decay model. The motive can be searched in the different number of parameters: LandGEM requires only two parameters to be inserted, while the other model has a lot of assumptions to be made; this introduces a higher uncertainty starting from the same number of data. Furthermore, it has been seen how a small variation in parameters of LandGEM leads to very different results; therefore a change in parameters of the second model will produce a huger change given the higher number of parameters.

Surely having field data separated for new and old landfill would have helped in adjusting the parameters values; moreover an accurate knowledge of waste composition would have been useful too.

In conclusion, for the reasons explained before when data on waste composition is not very accurate, only indications can be achieved by models; furthermore models with a lower number of parameters result to be more reliable since the uncertainty due to the lack of data is partially covered.

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