

TRABAJO DE GRADO

PERFORMANCE EVALUATION AND ANALYSIS OF THE BIOFILTRATION SYSTEM ON MUNICIPAL SOLID WASTE LANDFILLS

Presentado ante la Ilustre
Universidad Central de Venezuela
Por la Br. Redondo T. Yuraima C.
Para optar al Título
de Ingeniera Química

Caracas, 2012

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*To my parents and grandparents
for always believe in me.*

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To God, for guiding me towards the way of my happiness.

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Redondo T. Yuraima C.

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Tutores Académicos: Prof. Giuseppe Genon y Prof. Jaime Hernández

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Resumen. El interés social y científico por el calentamiento global ha generado la búsqueda de tecnologías que permitan reducir las emisiones de los gases con efecto invernadero. Este proyecto se basa en la reacción de oxidación microbológica del metano generado en los rellenos sanitarios, la cual fue estudiada en los sistemas biofiltrantes de cinco sitios de disposición de residuos urbanos localizados en Piemonte, Italia. Buscando evaluar y analizar el rendimiento de los biofiltros, se hizo un análisis con los datos reportados a la "*Provincia di Torino*", desde el 2009 hasta el 2011; siendo los principales valores a considerar: el flujo de alimentación, la concentración de metano a la entrada y salida del sistema, así como la eficiencia calculada a partir de los mismos; los cuales buscaban determinar las características de la corriente de ingreso del gas, que permiten cumplir las regulaciones establecidas en referencia al 1% v/v como valor máximo de metano emitido, y como mínimo un 65% de disminución. Por otra parte, con el objetivo de poder establecer comparación entre los casos de estudio se calcularon el flujo de gas y de metano por volumen de biofiltro; mientras que como información adicional, se presentaron mediciones del 2012 para evaluar las condiciones de los sistemas. Finalmente, se evaluó la inversión al considerar los costos del equipo. Como conclusión se observó que cuando el gas de ingreso contiene menos de 5% de metano y presenta un flujo alrededor de $120 \text{ m}^3/h$, los resultados obtenidos son satisfactorios. Fue también evidenciado que: la disminución interna fue baja, los datos externos no son confiables, el sistema requiere 55000€ de inversión, las mediciones del 2012 no son representativas, y que Collereto Giacosa presento el menor tiempo de residencia y la peor calidad del gas.

CONTENTS

<i>Content</i>	<i>Pag.</i>
INTRODUCTION	1
0.1 General	1
0.2 Thesis outline	3
CHAPTER I. FOUNDATIONS OF THE RESEARCH	5
1.1 Problem statement	5
1.2 Objectives	6
CHAPTER II. BACKGROUND	7
2.1 Methane	7
2.2 Waste Disposal	7
2.3 Methane in the Landfills	10
2.3.1 . Capture system	13
2.3.2 . Energy recovery	14
2.4 Laws	14
2.4.1 . International	14
2.4.2 . European	15
2.4.3 . Italian	15
2.5 Microbial Methane Oxidation	16
2.6 Biofiltration system	19
CHAPTER III. CASE OF STUDY	22
3.1 Landfills	22
3.1.1 . Pinerolo	22
3.1.2 . Grosso	24
3.1.3 . Collegno	25

3.1.4 . Bairo	26
3.1.5 . Collettero Giacosa	26
CHAPTER IV. METHODOLOGY	28
4.1 Performance evaluation and analysis	28
4.2 Comparison between the cases	29
4.3 Field measurements 2012	29
4.4 Costs	29
CHAPTER V. DATA	31
5.1 Measure system	31
5.2 Data Analysis	35
5.2.1 . Comparative factors	60
5.3 Inspections	70
5.4 Costs Analysis	76
CHAPTER VI. CONCLUSIONS AND RECOMMENDATIONS	78
CONCLUSIONs	78
RECOMMENDATIONS	81

INTRODUCTION

0.1 General

On the last decade the global warming has become a matter of concern around the world, encouraging scientists to identify the causes and to develop methods in order to reduce the effects. Nowadays, it is well known that a variety of gases are the main reason of this problem; however, each gas has a particular consequence in the atmosphere, specially the methane (CH_4), which is a greenhouse gas with a high explosion potential, a long life-time in the atmosphere and according to the Intergovernmental Panel on Climate Change[1] has 25 times the global warming potential (GWP) of carbon dioxide over a 100 years period; reason why there is an increasing trend on finding methods that allow the collection and treatment of this particular gas.

There are a variety of sources, natural or not, of methane emissions in the world; in particular, one of the anthropogenics is the decomposition of Municipal Solid Waste (MSW), which is the based of this study. It is important to establish that disposal locations produce methane for a long period of time, starting from the moment when the transfer of waste is allowed (operative phase) and continuing even decades after the landfill is closed (post-operative state); generating diverse amounts and quality of this particular gas according to the conditions of the site, for that reason, in the active period the methane is sent to energy recovery, whilst in those closed the quantity is so low that this is not possible.

The biofiltration is an alternative method for treating the gas currents containing low quantities of methane (poor gas), which is ideal for the landfill in post-operative phase, or those active where due to the conditions of the soil the gas is escaping of the perimeter and must be capture and treated. The system is based on a container covered with a semipermeable material, and contains a biofilter media in which the microbial methane oxidation takes place. This biological process has been studied locally and internationally in recent years due to the high rates of abatement that can be achieved under certain conditions, which must be controlled in other to guarantee the results, some of these factors include: the landfill gas loading, the climatic conditions, the media used in the biofilter, and the moisture content.

This study was conducted in five landfills, two active and three in post-operative

conditions, containing at least one biofilter and located in the region of Piedmont, north east Italy; in the communities of: *Pinerolo, Grosso, Collegno, Bairo and Colletero Giacosa*, as shown on the Fig.1.

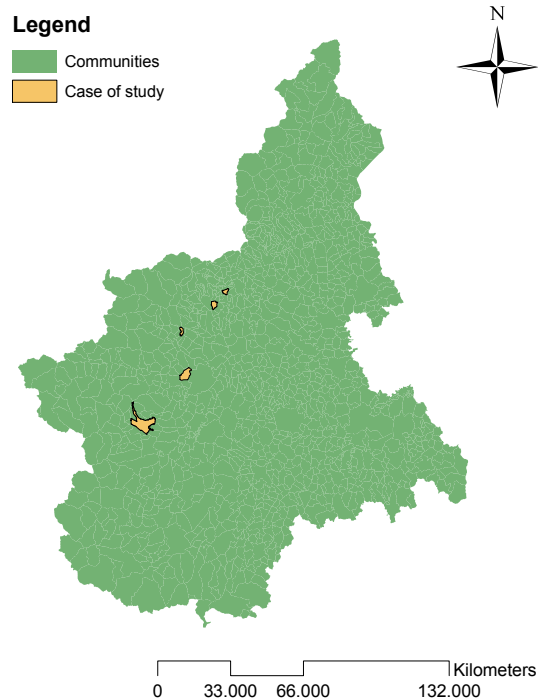


Figure 1: Landfills location

Each landfill under consideration is managed by a certain company (ACEA, SCS, Cidiu, Sia), that in most cases is also responsible for the biofilter and, since 2009, must report to the "*Provincia di Torino*" data measurements taken in the system, such as: the flow of the input current, the percentage of methane, carbon dioxide and oxygen before and after the biofiltration system, the lower explosive limit, temperature, depression applied, and so on.

Using the common data reported, and seeking to determinate if this alternative treatment is reducing the methane emissions into the atmosphere, this study will analyze the flow and the percentage of methane obtained on from 2009 to 2011. Another aspect under consideration was the efficiency of abatement, calculated from the percentage of methane before and after the system.

It was established that the results of the above mentioned analysis, did not allow a

comparison between the cases under study, for that reason two new parameters were calculated: the gas and methane volume per biofilter volume per hour, which indicated the residence time and quality of the fluid in the system, respectively.

Regarding the performance analysis, as additional information, measurements were taken in the late May and early June on the 2012 to evaluate the conditions of the biofilters.

It is important to establish that each landfill measured and reported the data mentioned in different periods of time, for that reason the analyzed data were presented as monthly puntual values in graphs, in order to observe the behaviour and perform the study. However, when the data taken on the 2012 is considered, the previous years are reported as a single average value, in order to compare them plainly, in tables.

The performance analysis of the biofiltration system will be based on determinate de conditions that fulfill the regulations established by the "*Provincia di Torino*", which indicates that methane emission under the 1% of volume, and an abatement above the 65% are considered satisfactory results. However, it is important to establish that this is not the only normative regarding the release of this type of gas, the European Union has set a series of environmental laws seeking to reduce the global warming, and there is also the Kyoto Protocol as the most global law on the subject.

Finally, another aspects to consider in the implementation of this type of equipment, are the initial and maintaining costs involved, which in combination with the perform analysis, determinate if the investment is worth it.

0.2 Thesis outline

Following this introduction, six more chapters will be develop: the **first chapter** identify the bases of this project by establishing the problem statement and the objectives.

The **second chapter** explains all the theoretical information required to understand the content of this thesis, among which will be defined: methane, Municipal Solid Waste landfills, the laws regarding this previous aspects and the biofiltration (from the biological oxidation taking place to the structure of the system).

The detail information of the landfills under consideration are presented in the **third**

chapter, such as: characteristics, management, and so on.

On the **fourth chapter** the methodology required to develop this study is explained.

The data will be presented and analyze on the **fifth chapter**, based on the performance observed since 2009, the comparison factors calculated and the cost of the biofiltration system.

Finally the **sixth chapter** presents the conclusions for determining whether the objectives of this thesis were fulfill, and some recommendations are made to improve any similar study in the future.

CHAPTER I

FOUNDATIONS OF THE RESEARCH

Seeking to establish the bases of this thesis, this chapter will define the reasons why this project was created. On the other hand, the general and specific objectives are going to be presented in detail.

1.1 Problem statement

Since the beginning of the industrial and technological revolution, there was not a concern in the environment, for that reason a great quantity of pollutants was poured into the atmosphere, water and soil. Nowadays, the consequences of the anthropogenic activities is a subject of priority in the society, not only in the matter of solving the damages already caused but also involves the creation of regulations and the research for new technologies with the objective of reduce the levels of contamination that the current way of living generates.

In particular, the atmospheric pollution and its relation with the global warming is the main subject of worries; for that reason, the scientific community has study the sources, in order to determinate the substance causing this effects and their consequences.

It have been noticed that methane is a greenhouse gas with a high warming potential; however, in the last decades there was an excessive increase of its presence in the atmosphere, generating an interest in reducing its emission. It is important to establish that Municipal Solid Waste landfills are one of this gas sources due to the decomposition of waste; for that reason, the public italian entities responsible for these sites proposed this project with the purpose of studyin biofiltration systems, that are based in the microbiological methane oxidation reaction, which are a treatment method for the current of poor gas generated.

1.2 Objectives

Base on the previous information, this thesis seeks as **general objectives**:
Evaluate and analyze the performance of the biofiltration system on Municipal Solid Waste landfills, as well as determine the conditions when the investment required by these type of equipment is worth it.

For which the following **specific objectives** must be fulfilled:

- (a) Determine the conditions under which the output satisfies the italian regulations.
- (b) Analyze the performance of the systems.
- (c) Establish comparisons between the biofilters studied.
- (d) Calculate an approximate cost of a single biofiltration system.

CHAPTER II

BACKGROUND

This chapter defines a serie of concepts required to understand the subject under study, starting with the definition of methane and landfill (even considers how these are related), following by the laws that the disposal sites have to fulfill, and finally the explanation of the biofiltration system and the microbial oxidation taking place in it.

2.1 Methane

Methane is a chemical compound which molecular formula is CH_4 and molecular weight is 16.04 g/mol. It is a colorless, odorless and extremely flammable gas; and as the simplest saturated alphatic hydrocarbon, its very stable at normal temperatures and pressure.[2]

It is the main component in natural gas, which is an alternative fuel less harmful for the environment, reason why, on the past decades its demand has suffered a worldwide increase[3], that is favored by the abundance of it on the planet. However, on the past decade, the scientifics have found that using methane to satisfy the energy requirements has a negative impact in our atmosphere, because generates around 16% of the positive radiative forcing (warming).[4]

The particular interest on global warming showed by the scientific community has led to a serie of investigations in order to identify the sources of atmospheric CH_4 , and it has been discovered that around 60% are caused by human activities, such as waste disposal, agriculture and fossil fuel[5]; for that reason, they are trying to develop methods to reduce the emissions.

2.2 Waste Disposal

From the beginning of the history, humanity has used the Earth resources to improve their way of living, but benefits associated with the development of technology have increased the quantity and types of waste. The disposal sites (also called landfills) represent risks to health, as well as a source of air, soil and water pollution; in order

to reduce these disadvantages, some measures have been taken, such as: regulations about the construction and management of the locations and the type of waste they can contain.[6]

Solid Waste includes all products generated by human and animal activities, which are in solid state and discarded because they are no longer useful or desired. Particularly, this study is based on Municipal Solid Waste (MSW), which is the type of refuse collected by communities, that is generated from offices, shops, households, and so on; reason why there is a great diversity on waste composition. "The management of this type of waste include collection, recycling, solid waste disposal on land, biological and other treatments as well as incineration and upper burning of waste".[7] Being the land disposal the main interest of this study.

The Italian law define landfill as an "area used for disposal of waste by deposit operations on or in the ground, including the internal zone on the place of production of the waste used for disposal of the same by their manufacturer, and any area where the waste is subjected to temporary storage for more than one year."[8] It is important to consider that in Italy there are three types of landfills differentiated by their content as: to hazardous waste, to inert waste and to MSW (or non hazardous waste).

Each landfill has phases characterizing the activities that must be developed; in those containing Municipal Solid Waste these are [6]:

- **Construction of the site**, after the selection of the proper location and once completed the administrative process to obtain the building permit, a series of actions must take place:

Excavation this step involves the movement of large amount of ground, as seen on Fig. 2(a), and also must assure the stability of slopes to prevent the fall of soil into the bottom.

Waterproofing, once the structure of the landfill is finished, the bottom is profiled with certain slope in order to ensure the flow of water towards the points where the lifting systems will be placed. Then, a multilayer barrier is placed covering the bottom and sides of the landfill, as shown in Fig. 2(b), where it is possible to observe that natural (soils with a low hydraulic conductivity) and artificial (geomembrane) materials are used.

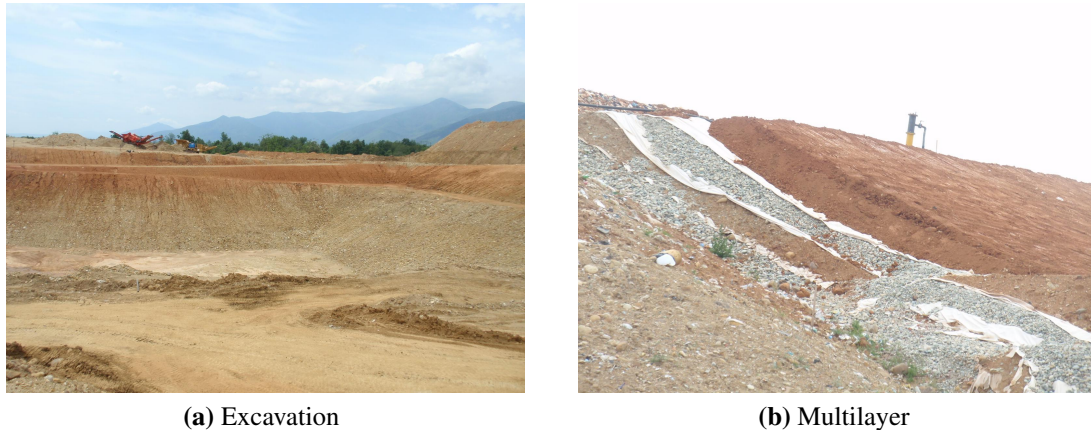


Figure 2: Steps for the construction of a landfill

Drainage, on the top of the multilayer barrier a layer of drainage for the liquid is placed. This is composed by natural granular material with high permeability, inside which are placed the slotted pipes. Nevertheless, the rain water must be drained to avoid the infiltration on the landfill, this is the reason why a concrete groove is build along the entire perimeter, which allows to intercept the water run-off and also performs the function of anchoring the waterproofing geomembrane.

Gas Capture, as for the liquid generated, a capture system is installed for the gas; however, this is not only based on internal wells, it also involves a serie of extenals points located on the periphery, to verify that biogas is no escaping from the landfill.

Monitoring, as final construction step, the structure must be equipped with control and monitoring systems to assure the continuous supervision of the quantity and quality of the gas and liquid generated; and to verify that there is no pollution of soil, water and air nearby the landfill.

- **Operative**, when all the considerations of landfill construction are taken, it is possible to initiate the transfer of waste. This phase not only covers the disposal of refuse in the area, it also must manages the treatment of the liquid and gas generated.



Figure 3: MSW Operative Landfill

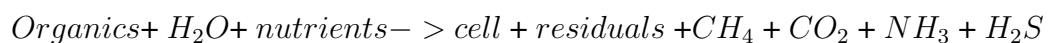
- **Post-Operative**, this phase begins when the final cover system of the landfill is completed, which is also based on a multiplayer barrier. Also in this case, and even when there is not addition of waste, liquid and gas are still under internal and external monitoring.

As mentioned above, landfills not only have to manage waste, there is also gas and liquid (called leachate) generated that must be taken into consideration, this fluids have the following characteristics:

- *Biogas*, this particular fluid is generated by the degradation of waste and, as it is the one under study in this thesis, will be explained in detail in the next section of this chapter.
- Leachate, this liquid is a result of the infiltration of rainwater and the contact of this fluid with the waste. Due to its origin, the leachate is polluted, with a composition that depends on the type and age of waste that generated it.

2.3 Methane in the Landfills

The diverse composition on Municipal Solid Waste landfills, generates a serie of biological reactions, of which is obtained as a key product the biogas, generated by an anaerobic decomposition of waste which can be summarised as follows[9]:



As shown, the process is generated by anaerobic bacteria highly specialized, which in presence of nutrients and water are capable of degrade the organic and biodegradable fraction of waste, such as: food and paper; and has as primary product a gas with a major proportion of methane (46-60% v/v)[10], followed by carbon dioxide as second major component, while oxygen, nitrogen, organic compounds and ammonia are also present but with a low composition.

It is important to stand out that the chemical reaction presented above is a summary of a serie of steps, among this are: **Aerobic phase**, due to the presence of oxygen in the landfill, the degradation of waste takes place. In this step, the chains on the organic substance are demolished by an hydrolysis reaction with water. **Transition phase**, in which the oxygen runs out, reason why the anaerobic conditions are established. In this conditions, the nitrates and sulfates are reduce to gas (nitrogen and hydrogen sulfide) due to the acceptance of electrons of these in the biological reactions. The leachate is also affected by the present of organic acids, which reduce its pH. **Acid phase**, in this case, the quantity of organic acids increase and by hydrolysis the compounds are reduce to their simple form, which are used by the biomass as energy and carbon sources. It is also observed that some of the biological reaction generate intermediate products, due to the conversion of monomers organic compounds. **Anaerobic methane phase**, one of the products previously generated is the acetic acid, which is oxidized to methane and carbon dioxide, through reactions with methane bacterias. On the other hand, hydrogen sulfide and ammonia are also generated. **Maturation phase**, this is reached when the biodegradable substance are converted in methane and carbon dioxide.[9]

The complex process above mentioned, allows to establish the landfill as a biological reactor, in which the reactions that take place can not be controlled or even simulated, however, it is known that some factors affect the generation of biogas, such as [9]:

- **Environmental factors**, such as: the rain or temperature.
- **Waste characteristics**, like: composition, humidity, any pretreatment.
- **Landfill management characteristics**, among which: leachate recycle, mode of waste disposal, barrier materials.

The effect of these factors decrease when the transfer of waste is finished and the landfill is covered by a multilayer barrier, which is reflected on a reduction of methane

generation as shown in Fig. 4; however, it is observed that even when the quantity of methane per year falls, the highest percentage of production of this particular gas takes place more than a decade after the closure of the site, reason why the monitoring phase previously mentioned must continue for a long period of time.

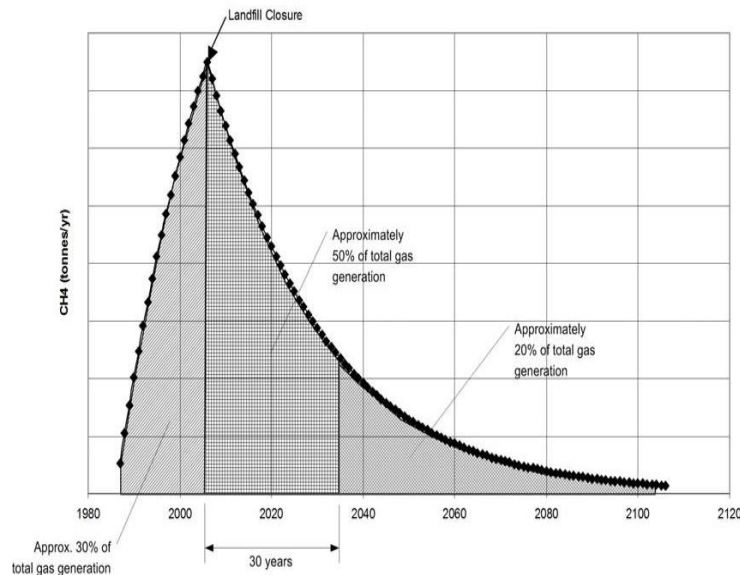


Figure 4: Typical landfill methane generation curve [4]

The Intergovernmental Panel on Climate Change [5] determined that disposal sites generate approximately 10% of global anthropogenic methane emissions, which is caused by the migration of this particular gas through the landfill and its multilayer cover reaching the atmosphere and nearby soil. The biogas transport mechanisms are: molecular diffusion, caused by the concentration gradient between the landfill and the external environment, and convection; these are influenced by the following factors[9]:

- *Characteristics of the gas*, like: diffusivity, viscosity.
- *Landfill characteristics*, such as: permeability, temperature, humidity.
- *Atmospheric conditions*, like: wind velocity, atmospheric pressure, air temperature.
- *Capture system*, the conditions and efficiency of it.

It is important to establish that when the biogas travels through the soil and reach the atmosphere, suffers some transformations due to reactions taking place, such as:

degradation and absorption, which are influenced by the characteristics of the soil and the capacity of reaction between the soil and the gas. However, as it is not possible to know which transformations are going to occur and, due to the effects that the dispersion of methane may cause in the environment and human health, it is considered that the biogas generated must be captured.[9]

2.3.1 Capture system

The capture system, is based on the creation of a series of ducts, with a higher gas permeability than the adjacent areas, which allows the relief of the gas naturally or artificially (applying depression through a system of ventilation). These may have a horizontal (drainage trenches) or vertical (wells) configuration, and can be located in the landfill perimeter or within it.[9]

Wells are the most common configuration of capture system, especially on the internal zone of the landfill, these are around 7 meters deep, with a diameter of at least 80 centimeters, and usually present the following characteristics: the lower zone of the well is perforated and contains gravel, whilst the upper part is surrounded by clay and is not perforated; it is important to establish that the landfill depth determines the distance between wells, which is usually around 10 and 15 meters. To fulfill the capture, all the wells are connected to an aspiration system using pipelines, which on the lower points contains condensate separators to remove the humidity of the current.[9]

For an adequate capture and effective utilization of the gas, it is necessary to ensure that: the installation has a high efficiency, the generation of biogas takes the least number of years possible and that the presence of hazardous components is low.[11]

In most cases, landfills contain two capture systems: the *primary*, which in operative sites represents the current with higher content of methane, and is generally sent to energy recovery; and the *secondary*, capturing the gas on the perimeter, which usually presents poor conditions, and nowadays is sent to the biofiltration system; being the method under study in this thesis, this last treatment will be explained in detail in the last sections of this chapter.

It is important to consider that in previous decades, there was not concern on the environment and after the capture, this gas was dispersed on the atmosphere; however,

the risk was reduced by decreasing the amount of undesirable components (such as carbon dioxide and hydrogen sulfide) in the currents.

2.3.2 Energy recovery

As it was previously mentioned, the captured biogas containing a high percentage of methane, is usually sent to the energy recovery facility on the landfill, in which is used to generate electricity and in some cases, also heat; the difference between these two final destinations is that those producing heat and electricity (cogeneration), uses an exchanger to recover the caloric energy generated on the motor cooling system, whilst on those of only electricity that heat is dispersed on the atmosphere.

This use of the gas is a tempting proposition, because represents benefits from an economical and environmental point of view, due to the fact that a profit can be obtained by the exploitation of a "free fuel", and the emissions of hazardous gases as methane are reduced.[11]

2.4 Laws

From 1750 to 2005 the methane atmospheric concentration has doubled, making a significant contribution to global warming, mainly caused by human activities.[4] Considering the consequences of the anthropogenic greenhouse gas emissions, the various environmental agencies decreed laws to reduce them; being the Kyoto protocol the biggest regulation applied, because it referred to all the countries involved, followed by a series of others scales, as below presented:

2.4.1 International

The Kyoto Protocol, which goal is to reduce overall emissions (measured as the equivalent in carbon dioxide) of the six main greenhouse gases: carbon dioxide (CO_2), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), nitrous oxide (N_2O) and sulphur hexafluoride (SF_6). The Protocol fixed a specific period of time, started in 2008 and ending in 2012, during which the commitment is to achieve the reduction or limitation of the targets, assigned to each country or region. "The system

established by the Protocol is one of the most comprehensive and rigorous to be found in international treaties", in which the parties have to follow a series of specific rules and regulations concerning the reporting of information, to demonstrate that they are meeting their objectives. Italy, as a part of the European Union, has to reduce 8% of its emissions.[12]

2.4.2 European

The European Environment Agency aims to reduce the contamination levels that its countries generate; for that reason, "since the early 1970s Europe has been firmly committed to the environment: protection of air and water quality, conservation of resources and protection of biodiversity, waste management and control of activities which have an adverse impact, are just some of the areas in which the EU is active, at both Member State level and internationally." As member, Italy must follow numerous environmental policies targeting the diverse types and sources of pollution; it is important to establish that, due to the variety of legislations, none will be specified.[13]

2.4.3 Italian

National regulations governing landfills of study, are presented below:

Decreto legislativo 13 gennaio 2003, n. 36 di Attuazione della direttiva 1999/31/CE relativa alle discariche di rifiuti This particular decree was created on January 2003, since then it has been modified, being the last on the 29th december, 2011. "The main objective is to provide operational and technical requirements for waste and landfills, measures, procedures and guidelines designed to prevent or minimize the negative environmental impact, in particular the pollution of surface water, groundwater, soil and air, and on global including the greenhouse effect, and the risks for the human health from the landfilling of waste, during the entire life cycle of the site." [14]

The law provides the classification of the waste as: municipal, hazardous, not hazardous and inert; and the definition of some terms of interest regarding the landfills, such as: their definition and classification, treatment, management, location, closure, the entities responsible of ensuring the correct procedure on the site, as well as the protection required to prevent the contamination of soil, water and air.

On the particular matter of gas produced, the decree establish on the first annex that "the management of the biogas must be conducted in such a way as to minimize the risk for the environment and the human health; the aim is not to perceive the presence of the landfill outside of a narrow buffer zone." Is important to mention that it dictates that methane, oxygen and carbon dioxide must be measured at least monthly when there is transfer of waste and weekly when there is not (non operative phase); also that monitoring wells must be placed inside and outside the site limits in other to determinate if there is any leakage of gas.[8]

Decreto 27 settembre 2010 di Definizione dei criteri di ammissibilità dei rifiuti in discarica This decree replaces the definitions of the criteria for acceptance of waste in landfills, contained in the decree of the ministry of the environment on August 3, 2005. The main objective is to define the criteria and procedures for the acceptance of the types of waste that a disposal site must contain, according to the classification; also the entities responsible.[15]

The decrees previously mentioned are those exercised in Italy; however, it needs to be pointed out that they do not make reference to the biofilter treatment, for that reason, the *Provincia di Torino*, as the only public entity that may consider the need to formally replace the combustion system when it proves unsustainable, has established some regulations on the matter of the output feature such as that methane concentration must be bellow 1% in volume [14], and in exceptional cases this value goes up to 3%; while regardind the abatement, the minimum value desired is 65%.

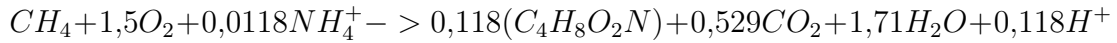
2.5 Microbial Methane Oxidation

Since 1990 the methane oxidation in landfills has been studied and evaluated around the world, with the objective of identify the factors affecting the rates obtained. "The research indicated that this process appeared to be enhanced in a media that: was porous, had good water holding capacity, was stable, and had a high level of organic matter".[4]

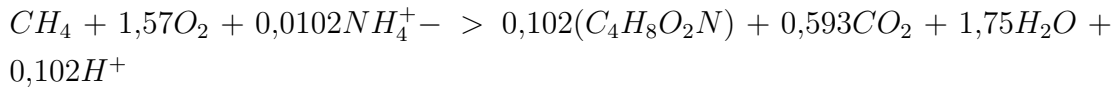
Nowadays, the microbial oxidation is used as a method for treatment of biogas at landfills where the conventional gas management can not be applied; its goal is to reduce the emissions. The oxidation is a very complex exothermic process, and for that

reason involves a series of intermediate steps, in which the bacteria utilises different paths to oxidize methane. According to Hilger and Humer[16] the stoichiometric reaction for the two possible pathways of the process, can be summarised as follows:

Ribulose monophosphate pathway (RuMP):



Serine pathway:



As it is shown above, methanotrophs are able to use methane in presence of oxygen and convert it to energy, carbon dioxide, water and cell material. *Note that $C_4H_8O_2N$ represents microbial biomass.* It is important to establish that "both pathways initiates with the conversion of methane (CH_4) to methanol (CH_3OH), this process occurs by the intervention of the methane monooxygenase enzyme (MMO). Then, the methanol is turned to formaldehyde, which can be used in the electron-transport chain, oxidised to formate, or assimilated by the cell via the RuMP and/or Serine pathway".[17] This particular process is influenced by a number of factors[4], including:

- **The supply of methane and oxygen**, usually methanotrophs are present where methane mixes with atmospheric air, for that reason, it is essential for the oxidation process that the concentration is under control. It is known that the conditions change according to the distance from the gas source, meaning that after a certain point, the oxygen amount will be higher than the methane and this fact declines the oxidation rate. On the other hand, the quantity of oxygen and the rate of oxidation are directly proportional, so a high concentration of methane may also decrease the rate; furthermore, it have been noticed that having at least 0.4-0.5% in volume of oxygen avoid limiting the process.
- **The acidity of the media**, previous studies indicated that the bacteria in which the oxidation is based, prefer neutral pH conditions.
- **Temperature of the media**, in general the methanotrophs are mesophilic[18], and for that reason the optimal conditions are between 25 and 40°C. It is important to consider that this factor may be affected by site conditions, such as rainfall, atmospheric temperature, and so on, that can cool the soil media. On the other hand, even the methanotropic activity might change the media conditions,

due to the exothermic behaviour of the reaction.

- **The physical characteristics of the media**, determinate certain factors that can affect the oxidation process, some of these are: porosity, which affects the movement of fluids; water holding capacity, refers to the specific quantity of water that can be hold; the stability of organic matter contain in the media, which affects the availability of oxygen.
- **Moisture content in the media**, the quantity of liquid present is an important parameter that allows the presence of methanotrophs[19], and its value depends on their physical characteristics, previously mentioned; therefore, the optimum conditions of this parameter can not be establish without knowing the media material. However, it should be noted that under the 8% of volume[20], the oxidation rate decrease because the bacteria experience water stress. It must be established that as in the temperature, this factor may be affected by site conditions.
- **The nature and supply of nutrients**, which may affect the microbial activity required for the process, because the bacteria needs them for their survival, among which are: nitrate and ammonium; however, these may result negative to the oxidation reaction, after a certain amount such as: ammonium ($> 14mg,kg^{-1}$), salinity ($> 6mS,cm^{-1}$) and cooper ($> 60mg,kg^{-1}$). Nitrate, on the other hand, do not have inhibitory effects on the process. Finally, there are some compounds that have not significant effects, among which are: phosphate, organic amendments with low C/N ratio.
- **The generation of extracellular polymeric substances (EPS)**, generally the bacteria used in this particular process (methanotrophs) generate EPS in capsule and slime form which include sugars and amino acids[21]; the increase in this substance production is directly linked to the rise of oxidation rate, due to the higher temperature generated by the exothermic reaction, making the soil dryer and solidifying the viscous EPS that move across the pores, as a white compact mass, which may block the biofilter and difficult the process. However, it is important to establish that the unfavorable influence caused by EPS are rather rare, and this problem can be solved maintaining the moisture content with irrigation and with a highly porous media[22].

The previously mentioned factors must be considered in order to guarantee the ideal performance of the methane oxidation process. On the other hand, it is evident that they are all linked in some way, for example: if the moisture content decrease, the gas movement increase and this favors the contact with the bacteria located on the surface of the media, rising the oxidation rate, which elevates the temperature and hence generates EPS.

2.6 Biofiltration system

The concern of reducing methane emissions to the atmosphere leads to the research of methods to convert it in CO_2 ; combustion and biological degradation have been the most applied. The combustion has place when the methane percentage allows the torch to remain on; otherwise, the oxidation is mostly applied on the treatment of biogas with a methane concentration under 15%. [19] It is important to establish that this kind of procedure are used when the conventional methods of energy recovery can not be implemented.

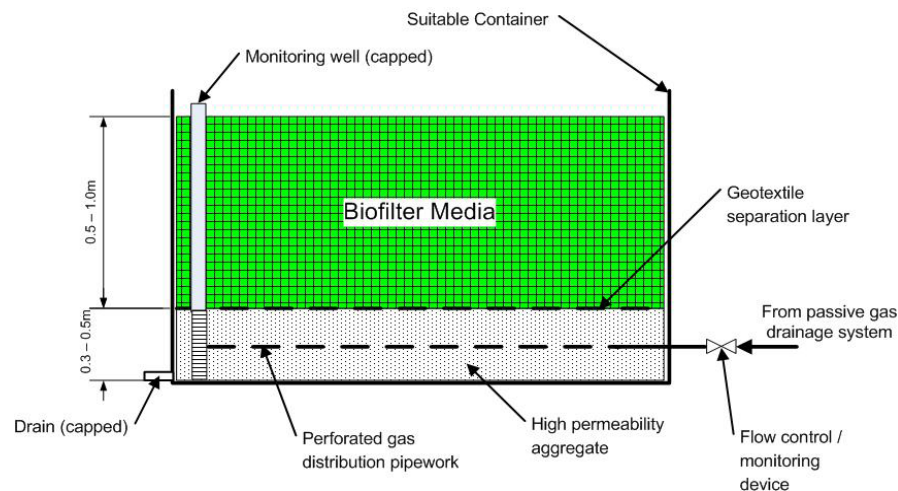


Figure 5: Typical section of a movable passive biofilter [4]

The passive microbial methane oxidation can take place in a variety of configurations such as: biowindows, biocovers or biofilters[4]; however, this last system will be the only one explained in detail, because it is the interest of this study.

This particular equipment consists in a drainage system, located at the bottom of the retaining structure, from which the gas enter and is distributed in that area; then the

pressure difference makes the input gas rise through the separation layer (as shown in Fig. 6) and the biofilter media; finally, the gas must traverse a semi permeable cover in which the final capture of methane is done. Another aspect to take into account is that the liquid generated by the irrigation (leachate) goes down and is drained through the tailgate of the structure.

It must be consider that the biofiltration can take place using two configurations of drainage system:

- *Active*, in which the methane is captured from the landfill using a depression system and sent to the biofilter with a slight pressure.
- *Passive*, in this case the gas is conveyed without the participation of external interventions, making the passage through the biofilter impossible to control.



(a) Empty system



(b) Distribution area

Figure 6: Interior of a biofilter

The Fig. 5 shows a passive biofilter that differs from an active one in the way the gas enters to the system. Extraction systems under pressure are potentially suitable for low gas generation sites, specially old landfills and those where the quantity of degradable organic waste is really small[4], and according to Huber-Humer[23] some of the advantages of this type of systems are: the monitoring that is simple and effective, and the operational conditions that can be manipulated and controlled.

Using biofiltration systems to reduce methane emissions from landfills is inexpensive, because it is based on the bacteria spontaneously cultivated in the unit.[22] For that reason, is very important to select the correct media, in order to ensure the proper

functioning of the system; Rose and Mahler [24], studied the capacity of different materials as a biofilter and concluded that compost achieve in average the highest rate of oxidation, followed by a mixture of compost and soil, and finally the lowest rates were reached by the use of soil; however, it is important to consider that these results depend upon a serie of environmental conditions. The factors affecting the behaviour and performance of a biofiltration system were described on the previous section, linked to the microbial methane oxidation.

Once installed, the biofilters are optimal long term systems that need to comply some main considerations such as the regular and proper maintenance, and in case of passive systems, the properly localization and design according to the gas outlet. Regardless the fact that this type of equipment require a minimum of maintenance, regular testing allows to determinate when the media must be replace.[25]



Figure 7: Biofilter components

On the matter of the biofilters under study, they are all active and use as media, a mixture of natural components that will be specified on the next chapter. However, the structure of the system is a container with similar characteristics in all the cases, some of these are presented below:

Table 1: Container characteristics

<i>Measurement</i>	<i>Value</i>
<i>Length(m)</i>	6
<i>Depth(m)</i>	2.5
<i>High(m)</i>	2.65

CHAPTER III

CASE OF STUDY

The main purpose of this chapter is to identify the different cases studied: their locations, management and other aspects of interest.

3.1 Landfills

The landfills studied, are located in the region of Piedmont, north east Italy; in the communities of: *Pinerolo, Grosso, Collegno, Bairo and Collettero Giacosa*. These are operative or in a post-closure state, and may or not have energy recovery facilities, but they all have in common that at least one active biofilter is present to treat the poor gas (low gas concentration of methane) capture in or outside the landfill perimeter. The specific characteristics of each landfill will be detailed below:

3.1.1 Pinerolo

Situated on the locality of Torrione with a total volume of $1600000m^3$, this landfill started the transfer of waste on 1976 and is currently active[19], and managed by the group "ACEA Pinerolese Industriale S.p.A".



Figure 8: ACEA logo

The Italian Regional Agency for Environmental Protection ("L'Agenzia Regionale per la Protezione dell'Ambiente (ARPA)") classified this landfill as an active MSW landfill which transfer of waste started before the 2003 (A2 type).[19] The particularity of this, is that it was structured according to the criteria prior to the decree of 2003.

Due to the age of the landfill, there were diverse degrees of maturation; therefore the biogas presented different compositions. The internal wells captured a gas with a 40-50% v/v of methane whilst in the externals the value decreased to <15% v/v[19].

Currently the internal gas goes to energy recovery and the poor gas is the input current of the biofiltration system.



Figure 9: Biofilters in Pinerolo

The structure of the biofilter system is based on four biofilters in parallel, as it is shown in Fig.9, that were installed on September 2005. Initially three of them (numbers 1,2 and 3) were discovered to the atmosphere, while the fourth biofilter was cover with a semipermeable material; but in 2007, after months of study, the manager decided to apply the cover in all the biofilters to make the measurements results more reliable. Another aspect to consider is that the media inserted on the system in 2005 was different for each biofilter, as shown in the table 2:

Table 2: Biofilter media initial composition at Pinerolo

	<i>Biofilter1</i>	<i>Biofilter2</i>	<i>Biofilter3</i>	<i>Biofilter4</i>
<i>Compost composition(%w/w)</i>	65	70	75	75
<i>Non reusable fractions(%w/w)</i>	35	30	25	25
<i>High of biofilter material(m)</i>	1	1.05	1.1	1.1

Seeking to maintain the optimal conditions of the system, in February 2010, the media of all four biofilters was changed for a 65% w/w of non reusable materials and 35% w/w of compost. This substitution must be performed approximately every two years, for that reason in February 2012 another mixture of media was inserted, this time the composition was 50% w/w for each material. Another aspect to consider to guarantee the desired conditions is the irrigation system, which in this case is automatic and spends sixty liters of water for three minutes every ten hours on each biofilter during

summer; however, on winter the atmospheric conditions give the system the humidity needed.

On the matter of the biofiltration system, this landfill reported the percentage of volume for: methane, oxygen and carbon dioxide input and output composition; the lower explosive limit of methane, the milibar of depression applied and the barometric pressure for the total input current. Also the temperature of the site was register in degrees Celsius and the velocity of the fluid on the feed pipeline of each biofilter. These measures were taken monthly, and since the beginning of 2010, reported to the "*Provincia di Torino*" every four months.

3.1.2 Grosso

This landfill is located on the locality of Vauda Grande, has a total volume of $592440m^3$, started the transfer of waste in 1992, and is still in the operative phase[19], and as the previous landfill, it is classified as A2 type by the "ARPA". The management of this landfill is carried out by two companies: "Servizi Intercomunali per l'Ambiente (Sia)" which is the responsible for the landfill, and "Società ASJA Ambiente Italia S.p.A" that deals with the biogas energy recovery facility and the biofiltration system.



(a) Sia logo



(b) ASJA logo

Figure 10: Logos at Grosso

There was only one biofilter installed on January 2010 in this landfill, which is currently active and treats the poor gas of the external wells; while the internal gas is sent to energy recovery. Regarding the conditions of the system, on June 2010 the biofiltration media was changed; and the automatic irrigation system works two minutes, twice a day, but if it is raining they do not irrigate it.

The parameters that this landfill reported to the "*Provincia di Torino*" were: methane, oxygen and carbon dioxide composition, and lower explosive limit of methane before and after the biofilter; the milibar of depression applied and the barometric pressure; and the input flow of gas. These measures were taken monthly, and reported every four months.

This particular landfill has failed to be below the 1% set by regulations; however, due to some problems experienced by the system, the authorities increased the allowable limit to 3%, but despite this, the desired results were difficult to achieve; for that reason, the "*Provincia di Torino*" commanded to enforce regulations to avoid any sanction. Another problem that occurred in the system was that during winter the temperature was very low and the atmospheric conditions affect the media and hence, the oxidation rate.

3.1.3 Collegno

On the locality of Cascina Gaj di Collegno is located this MSW landfill with a total volume of $480000m^3$, which is currently close (was active since 1989 until 1993). This landfill was classified by the Italian Regional Agency for Environmental Protection ("L'Agenzia Regionale per la Protezione dell'Ambiente (ARPA)") as a MSW landfill closed before 1997 (B2 type)[19] and the management is the responsibility of the "Cidiu S.p.A."



Figure 11: CIDIU logo

Due to the age of this type of landfills, the generation of biogas is low; however, since 1998 the unsaturated soil has been monitored, making it possible to note that biogas was escaping from the landfill perimeter, reason why technical interventions

took place to prevent and eliminate any risk originated by the possible migration of biogas. On 1999, a second ring of wells was generated, but on 2001 was noticed that biogas was still present on the first system; reason why on the search of new solutions to secure the nearby soil of the landfill, a biofilter was installed on January 2007, to treat the external gas captured by the first ring wells.

The reports to the "*Provincia di Torino*" were made once a year, and based on weekly measurements of: atmospheric pressure, the concentration of oxygen, carbon dioxide and methane before and after the biofilter; it is important to establish that in this case there were two values after the media: under an above the cover and the efficiencies between these were also reported. The input flow was a fixed value equal to $160m^3/h$.

The biofilter contains a preformed mixture consisting of: non-reusable fractions from ligno-cellulosic, with the addition of compost and peat; which have not been changed since the installation of this system. On the other hand, some peaks on the values of methane were registered probably for the malfunction of the aspiration system, and for that reason, looking to reduce the concentration of gas to treat, a second biofilter was installed on May 2012.

3.1.4 Bairo

The locality of Piane Antonione contain this $228460m^3$ closed landfill, which was active since 1996 until 2001, and according to the "ARPA" was classified as closed after 1997 (B1 type). On this landfill the old pipelines are not in used, they were fixed and connected to the biofilter which was activated on June 2008 to treat internal and external gas. However, due to the fact that the external gas did not contain methane, the dilution caused problems on the system, and for that reason on October 2009 the external network was sent to the off torch system and hence released to the atmosphere without any treatment.

3.1.5 Colleretto Giacosa

Closed since 1996 (four years after the beginning of transfer of waste), this landfill has a total volume of $111041m^3$, is located on the locality of Piane del Ribes, was

classified as B2 type and managed by the SCS society.



Figure 12: SCS logo

Originally the capture system was designed to work discontinuously, but the flow was too low for the pumps, meaning that the system was oversized. For that reason, on January 2008, a biofilter was installed as an alternative to the combustion system, to treat the internal and external gas.

These two last landfill are managed by the same company "Società Canavesana Servizi S.p.a (SCS)", reason why have the following characteristics in common: the irrigation is manual and once a week; they do not have an energy recovery system. Measurements were reported once a year and taken once a month, based on: the input flow of biogas, as well as the input and two outputs of methane on the biofiltration unit.

CHAPTER IV

METHODOLOGY

This chapter establish the necessary procedure to accomplish the data analysis, in order to fulfill the objectives of this project. For that reason, four sections will be presented, in order to explain how each type of data was evaluated.

4.1 Performance evaluation and analysis

The first aspect to consider regarding this analysis is that was established that the study would consist of a research method based in gathering information, in particular the reports from the years 2009 to 2011 that the landfills of Pinerolo, Grosso, Collegno, Bairo and Colletterto Giacosa, sent to the "*Provincia di Torino*".

Seeking to obtain the data required to develop this thesis, it was necessary to visit the office of the mentioned italian entity, where was required to read the documents corresponding to each disposal site of interest; from which general information was extracted, as well as the one referring to the biofilter.

Once the system data were known, the next step was to select those of interest for this study, which in this case were: the flow and the methane percentage in the input and output. These were reported graphically seeking to determinate any particular behavior, referring to the period of the year, the relationship between the parameters under consideration and the evaluation of the values reporting less than 1% v/v of methane as output. On the other hand, the efficiencies were calculated to show the measurements where the 65% was exceeded.

It is important to stand out that the analysis of this type of data was based on the knowledge gained from the biographic materials previously reviewed, as well as the observations of the representative values. However, between the different sites just common behaviors were determinate.

4.2 Comparison between the cases

Aiming to complete the performance evaluation and analysis it was required to establish a comparison between the biofiltration systems under study. For that reason, the gas and methane flow per volume of biofilter were calculated as common parameters in all the cases; from which, was possible to determinate the residence time and the quality of the gas, respectively.

It is important to consider that this new factors were calculated from the same data presented on the previous section and for that reason the analysis was based on the same graphical representation.

4.3 Field measurements 2012

As part of the Italian Regional Agency for Environmental Protection assignments, the representatives of this entity have to visit the disposal sites and take measurements regarding the gas, water and even soil, to guarantee the proper action of the system involves. For that reason, and whereas it is also a way to know better the conditions of work and management, the landfills of Pinerolo, Grosso, Bairo and Collettero Giacosa were visited on the middle of the current year.

In this occasion, the data was measured directly from the biofiltration system and its pipeline. However, as a singular value it was not possible to compare it with the performance data; for that reason, the representation in this case was based on tables were the average results from 2009 and 2011 were put in evaluation with the 2012 measurement, seeking to determinate in each case if the system was or not improving its outcomes.

4.4 Costs

Seeking to fulfill the objective regarding the analysis of the investment that this type of system involves, the economical data of the biofilters were required to each site, but few were provided; for that reason, it was necessary to ask to others sites (beside those under study) the mentioned information; and with all the data obtained an approximation of the cost was made.

Finally, this data and the performance results were used to determine in which cases it is worth the investment.

As it was established, this project base its analysis in data recollected o measured, but is important to stand out that the main information came from bibliographic sources. Another aspect to emphasize is that the study and its results were carried out without following a particular scientific method, since the evaluation of the data was performed using the observations and the bibliographic material.

CHAPTER V

DATA

In order to achieve the goal of this thesis, reference data must be analysed. Particularly, this chapter defines the source and shows the results of the analysis, then presents some comparative factor calculated, the prospective of the current year and finally, the cost analysis of the biofiltration system to determine whether it is worth the investment.

5.1 Measure system

As above mentioned, seeking to fulfill the objectives of this study, this chapter will develop the analysis of more than one type of data. It is important to establish that the performance evaluation was based on bibliographic sources (the reports that each landfill must be sent to the "*Provincia di Torino*"); however, it was considered necessary to understand how the data were obtained, for that reason, the following section will explain on detail the instruments and measurements related.

The previous chapter mentioned the diverse information that all the landfills under study reported; however, seeking to assess the objective regarding the reduction of methane emissions to the atmosphere and selecting the common data presented, these were reduced to: input and output methane concentration, and the input flow. It is important to consider that each type of data required a particular measuring instrument, which are going to be presented on the following paragraphs.

The measurements of methane concentration must be as accurate as possible for the study under consideration; for that reason, a portable gas analyzer of the Geotechnical Instruments (UK) Ltd model GA2000, which is shown on the Fig. 13, was used. This equipment has an internal pump of typically 300 cc/min to capture the gas, and uses a dual wavelength infrared cell with reference channel to measure methane and carbon dioxide percentage in volume; the oxygen, on the other hand, is measured by an internal electrochemical cell. The time response is less than 20 seconds, with a typical accuracy of 0.5%v/v when the gas contains methane from 0 to 5%; about 1%v/v from 5 to 15% CH_4 and 3%v/v when there is more than 15% CH_4 . [26] As final aspect, it is necessary to consider that to ensure the proper performance of the equipment, it must

be serviced at regular 12 monthly intervals by a approved service facility.



Figure 13: Measure equipment

The flow was measured by a flowmeter, based on a mechanical system containing blades rotating due to the movement of the fluid. The performance of this equipment is based on that when the gas travels through the pipeline, the axis moves, accumulating readings that are subsequently translated into data.

Once identified the required instruments, it is necessary to define the locations on the system, where the methane concentration measurements took place:

- Input it was located on the pipeline that feeds the biofilter, before or after the pump. However, a measurement taken just after the flow suffers a dilution with air, as shown in Fig. 14(a), may affect the results; for that reason, this were frequently taken on the most direct point to the system.
- Output, this may refer to two possible measuring locations situated before and after the cover of the biofiltration system, as shown on Fig. 14(b). It is important to establish that unless a distinction is made, in the majority of the cases the information is referring to the one after cover; however, both points are explained below:

Internal, it is based on a pipe positioned in the space between the top of biofilter media and the cover.

External , due to the fact that the cover is semi permeable, the gas escapes through the entire surface. For that reason, to make this measurement possible, a solid structure with a pipe must be placed above the cover.



Figure 14: Measuring points

Although it was established that the structure on the cover allows the determinate the external output values, in some cases it was not fixed to the cover or was not a closed structure, enabling the air to dilute the gas and hence reporting a composition that not corresponds precisely to the real output value of the system; another weakness regarding this particular aspect, is that each landfill uses diverse arrangement and materials to capture this final measurement, so no comparison is possible between the data. Both disadvantage are presented in the following set of photos of Fig. 15(a), (b) and (c).

It is important to establish that the one shown in Fig. 15(d) is considered the best structure because is sealed, closed and made of the same material of the cover, which may reduce the air inlet obtaining results that should be more reliable.



(a) Cone



(b) Bottle



(c) Open cappa



(d) Cappa

Figure 15: External measuring points

To solve this problem, the company that sells the biofilters is developing solutions such as the one shown on Fig. 16, which consist on a close container whose inside contains the media and the cover and as external structure of measurement a campane; however, this system experiences a major disadvantage which is the internal condensation over the cover, for that reason (as it is shown), was required to open the container, allowing the flow of air and hence modifying the results.

It is important to consider that this equipment is not currently present in any of the landfills under study, however seems necessary to stand out the positives and negatives aspects of the biofiltration system, specially when they affect the results of this project.



Figure 16: Improved system

Once known the characteristics and disadvantages of the measurement instruments, the following sections present and interpret the flow and methane percentage obtained by these.

5.2 Data Analysis

The data presented below, as it was previously mention, comes from the reports that each landfill send to the "*Provincia di Torino*", however, it must be consider that since the reports were sent in different periods of time, it was decided to work with the complete data of the last three years (since 2009 to 2011), for the analysis be more reliable.

Due to the large amount of data to be analyzed, it was determined that a graphical approach was the most suitable presentation to evaluate the performance of each system under consideration. For that reason, two types of graphs will be presented throughout the analysis; the first one is base on two scales, each one is represented in a vertical axis of the graph, on the left it is possible to observed the concentration of methane

as a percentage of volume, the right gives the flow of input gas to the system in cubic meters per hour. The second, shows the values of efficiency (as percentage) calculated from the input and output data previously reported. Both types of graphs are based on the months of the year, and are represented by points due to the fact that the values are an average of measurements corresponding to different periods of time.

In view of the diversity of the data, some differences should be considered, such as: where there is more than one biofilter (as in the landfill of Pinerolo), a specific nomenclature must be defined to differentiate each outcome, in this case it will be identified as "b" followed by the number of biofilter of interest; another aspect is when more than one output is reported, in this case will be use "int" and "ext" to identify the internal and external values, respectively.

Once identified how the data will be presented, it is proceeded to develop the analysis of each landfill.

Pinerolo

In contrast with the rest of the cases under study, it is known that during the time period considered this landfill presented more than one active biofilter; however, the analysis will be develop independently for each system. It is important to establish that some considerations must be taken into account for the fourth of them:

1) This was the only disposal site reporting the velocity of the input current, and for that reason, looking to make a comparative analysis of all the landfills data, it was necessary to determinate the flow applying the continuity equation:

$$Q = V * S \tag{1}$$

Where "Q" is the flow of gas in input on cubic meters per hour, "V" is the measure velocity measurement reported on meters by second (which was converted to meters by hour), and "S" is the section of the pipeline that feeds the system on square meters; this last factor is determined using the following formula:

$$S = \pi * 1/4 * D^2 \tag{2}$$

Being "D" the internal diameter of the pipeline where the gas is flowing, which is equal to 79.2 millimeters; resulting a value of section of $4,92 * 10^{-3} m^2$.

2) There were not data reported on February 2011, because there was a problem with the equipment and therefore no measurements were taken.

3) As it was mention on the previous chapter, the measurements of this landfill were usually taken montly, however, due to the fact that a particular studio was develop on the 2010, the data below reported of that year, in particular since February to September, is a media of all the originals which were measured weekly and even daily.

Once these particular aspects are under consideration, the analysis of the four biofilters can be done.

First biofilter

The flow data corresponding to the 2009, as shown on Fig. 17, was relatively stable between 106 and $126 \text{ m}^3/h$. Whilts the range of methane percentage was varying from 2.3 to 8.6% in the input and from 0 to 1.6% in the output.

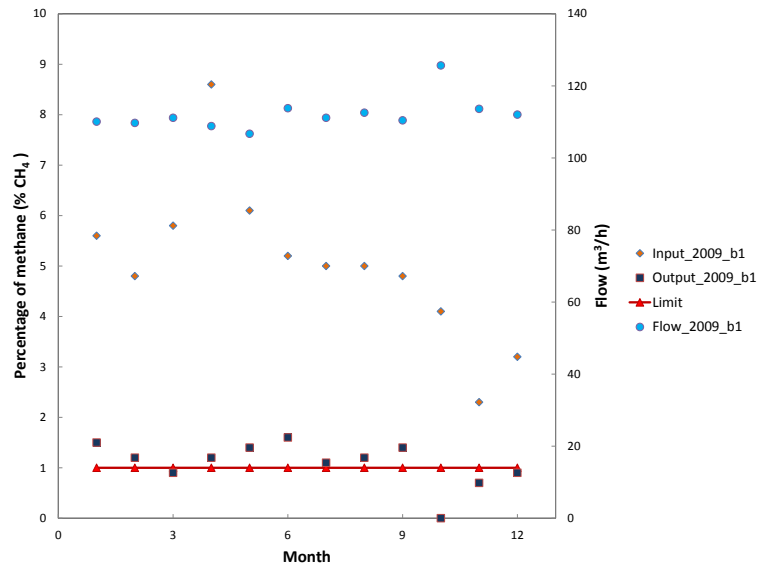


Figure 17: Pinerolo 2009, first biofilter data

The wide flow range observed in Fig. 18, which was fluctuating between 153 and $434 \text{ m}^3/h$, was caused by the study developed on the year 2010, whose objective was to test the efficiency of this system with flows over $430 \text{ m}^3/h$. The evaluation concluded that after reaching the $150 \text{ m}^3/h$ the results were no longer satisfactory[27], which was evident in the graph by the direct relationship between the flow and the output values; however, it is important to highlight that even when the flow range was wide, the external compositions varied only from 0 to 2.8%.

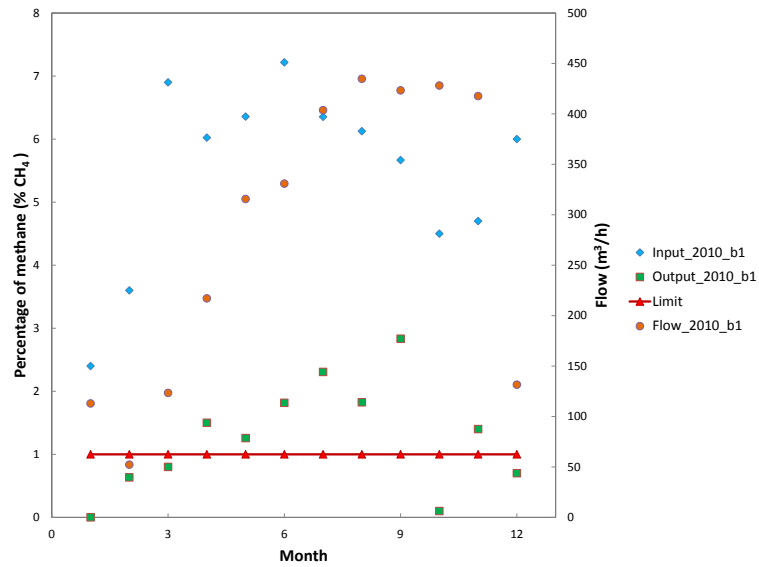


Figure 18: Pinerolo 2010, first biofilter data

On the other hand, the data corresponding to the year 2011 (as shown in Fig.19) presented an irregularity on the output values, which in this particular case were between 1.2 and 5.8%; and a possible cause of this problem is the malfunction of the media. It is important to notice that in the three years under study this particular biofilter reported very few values below the limit of 1% established by the regulations.

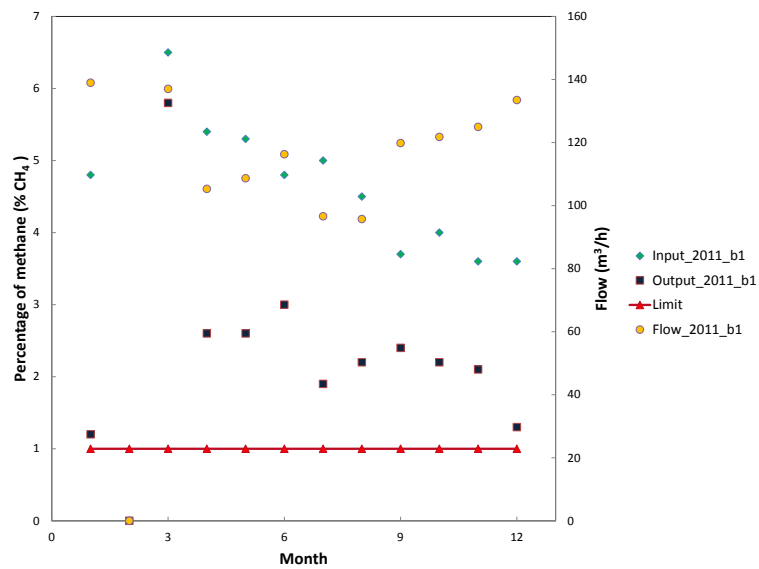


Figure 19: Pinerolo 2011, first biofilter data

Given the diversity of waste present on this landfill, the generation of gas was quite variable, as it can be seen on the stable flow data reported on the 2009, while two years later was varying from 96 to 139 m^3/h (more than twice the fluctuation range obtained on the the first year studied).

The input data was also considerably variable, because in the three years was fluctuating from around 2 to 8%. It is important to establish that as it was expected, the data show no relationship between the flow and the composition in the input.

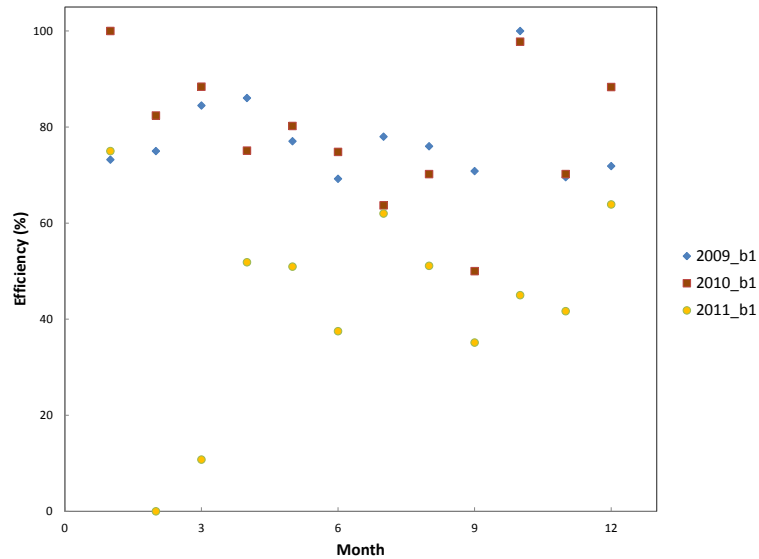


Figure 20: Pinerolo, first biofilter efficiency

Finally, the efficiency was also considered in Fig.20, where was possible to observe even more the particular behavior of the 2011 data; while the previous years were considered satisfactory according to the regulations established by the "*Provincia di Torino*", who seeks to obtain values higher than 65%, being the value of September 2009 the only one out of the desired range.

It is important to notice that without considering the 2011 particular data, and even with the experimentation of 2010, the first two years under consideration reached the 100% efficiency.

Second biofilter

On this case the data of 2009 showed an input concentration fluctuating between 2.2 and 8.7%, while the flow was stable within 107 and 124 m^3/h , as it is shown on Fig. 21. The output, on the other hand, varied from 0 and 1.9%, and as observed, in

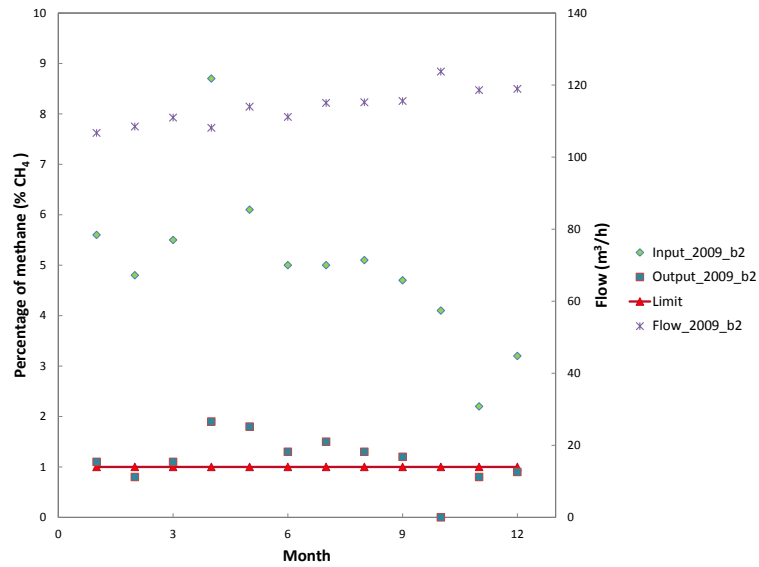


Figure 21: Pinerolo 2009, second biofilter data

this particular case, in the winter months reported a methane percentage under the limit and from spring to fall, the output went up above the 1%.

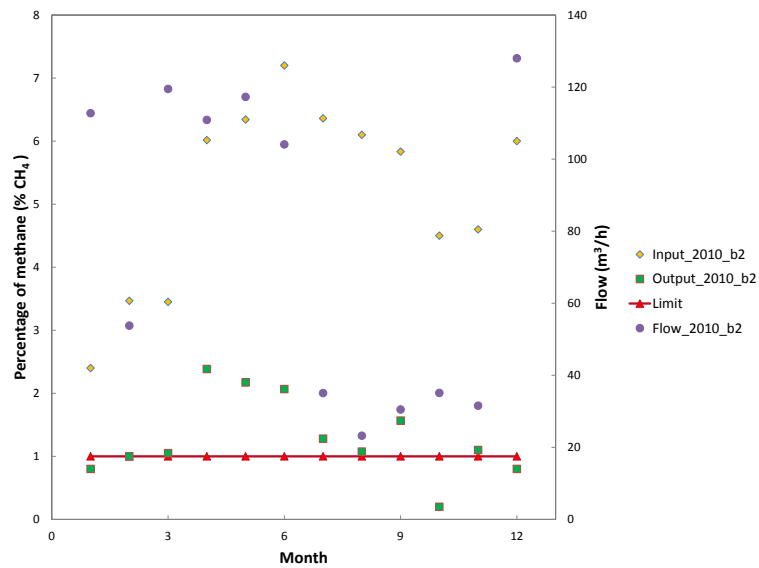


Figure 22: Pinerolo 2010, second biofilter data

In contrast with the first biofilter, the 2010 study of this system (as the rest of them) was not exposed to flows over the $150 \text{ m}^3/h$; however, some low values were evaluated, as it is shown in Fig. 22, where the minimum value of flow was $23 \text{ m}^3/h$ on August,

which increased slightly in the coming months, and finally on December went up to the higher value reported ($130 \text{ m}^3/h$).

Another aspect to consider was the input, varying from 2.4 to 7.2% of methane, while the output was between from 0.2 and 2.4%, presenting few values under the limit. Also in this case, the experimentation on the flow showed the higher output values when the flow increases.

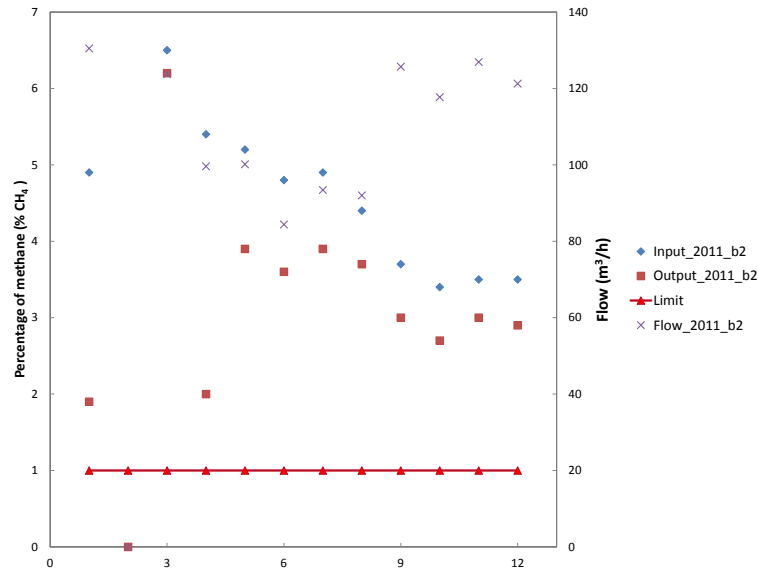


Figure 23: Pinerolo 2011, second biofilter data

As in the first biofilter, the Fig. 23 referring to the year 2011, showed a output data reporting methane percentages well above the limit, varying from 2 to 6.2%. It becomes possible to observe that in comparison to the Fig. 19, this biofilter had output values relatively close to those of input, which was fluctuating from 3.4 to 6.5%. The flow, on the other hand, stated with a maximum value of $130 \text{ m}^3/h$ on January, then gradually descended until it reached a minimum of $84 \text{ m}^3/h$ on June, after which increased once again ending the year around the $120 \text{ m}^3/h$.

The efficiency on this biofilter was slightly lower than the previous one, because the 2009 values were between 64 and 100%, whilst those of 2010 were varying from 60 to 95%, being higher the quantity of values out of the range established, as it is shown on the Fig. 24. Another common aspect with the previous biofilter, is that the data of 2011 reflected a problem with the system, because the majority of the values were really low.

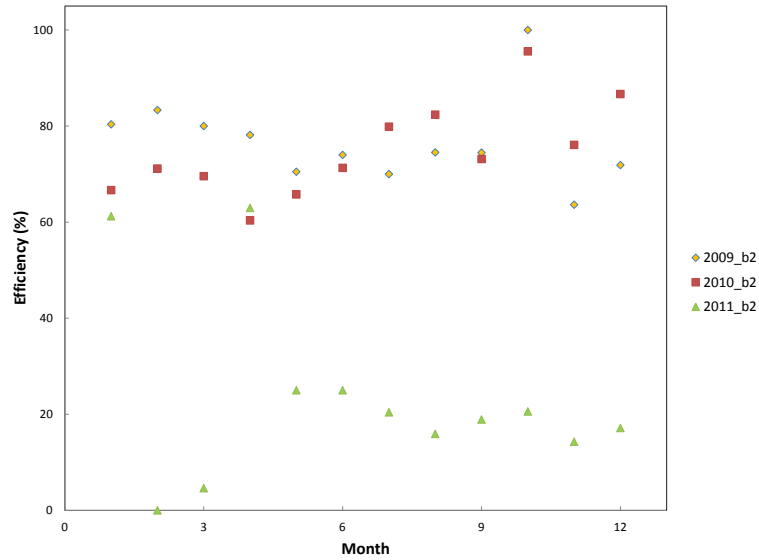


Figure 24: Pinerolo, second biofilter efficiency

Third biofilter

The 2009 data of this biofilter reported on Fig. 25, showed a very stable flow that was varying from 111 and 128 m^3/h ; on the other hand, the methane percentage was fluctuating between 2.2 and 8.6% in the input, and from 0 to 2.1% in the output. As in previous cases, just a few values were under the limit established by the "Provincia di Torino", being most of them obtained during the winter.

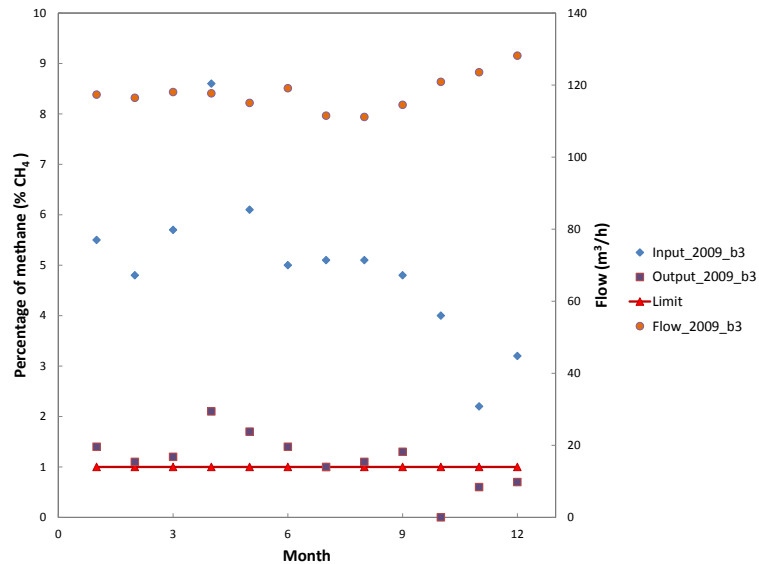


Figure 25: Pinerolo 2009, third biofilter data

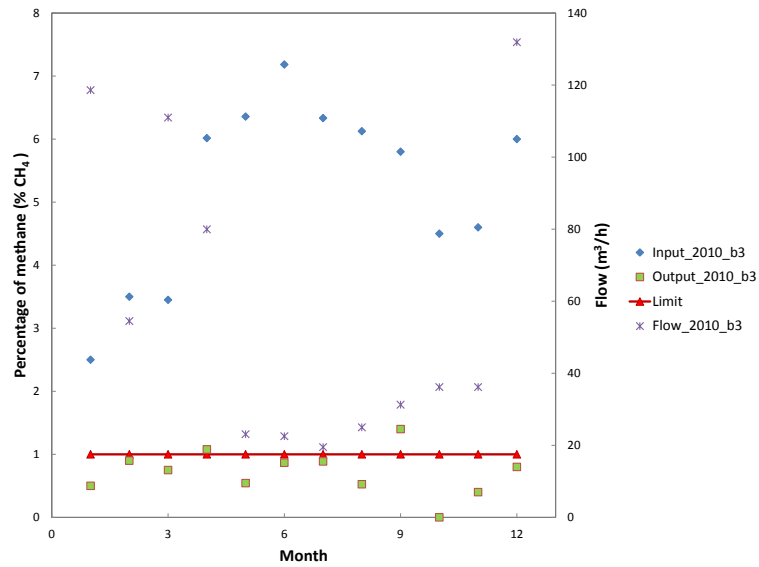


Figure 26: Pinerolo 2010, third biofilter data

As on the second biofilter, 2010 data reported on Fig. 26, had a wide range of flow values (from 19 to $131 \text{ m}^3/h$) where the lowest were within May and November, followed by the maximum on the last month of the year. Referring to the methane percentage, the input was between 2.5 and 7.2%; while that the output was varying from 0 to 1.4%, being this maximum value the only obtained above the limit of 1%.

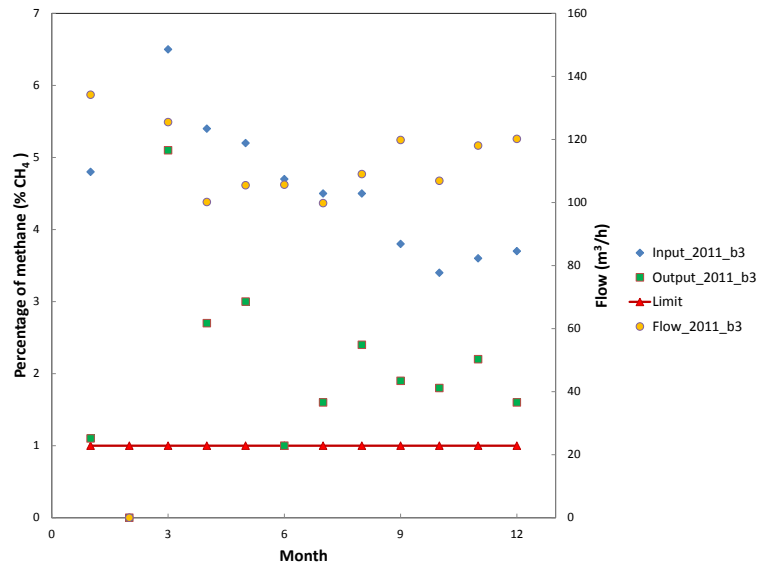


Figure 27: Pinerolo 2011, third biofilter data

Regarding the data of 2011, Fig.27 reported the same irregularity on the output data, which was varying from 1 to 5.1%. The input, on the other hand, was between 3.4 and 6.5 %, while the flow was fluctuating from 100 to 134 m^3/h .

Without regarding the last year data, because reflected a malfunction on the system; the results obtained on 2009 and 2010 were considered satisfactory because their lowest efficiencies were 72 and 74% respectively, being both above the 65% requirement, as reported in Fig.28.

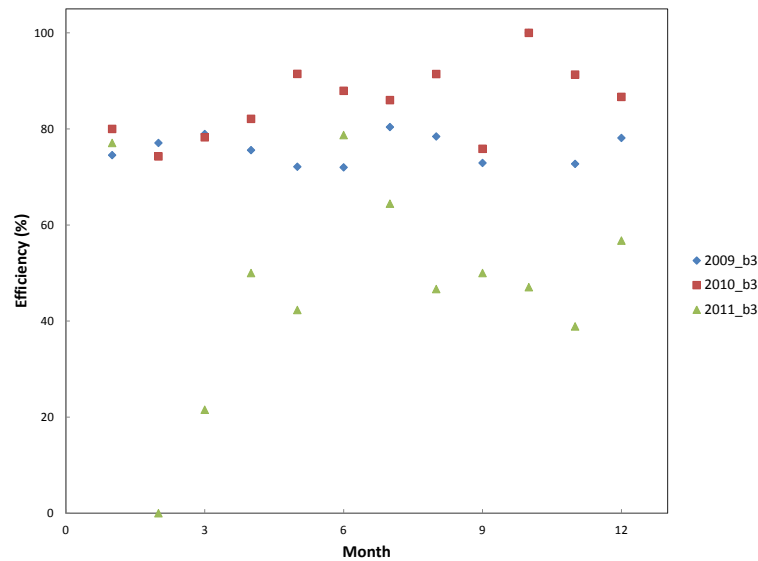


Figure 28: Pinerolo, third biofilter efficiency

Fourth biofilter

On the 2009, this biofilter presented a wide range of percentage of methane in the input, which was varying from 2.3 to 8.4%, as it is shown in the Fig.29. The flow was fluctuating from 116 to 150 m^3/h , while the output was between 0 and 2.6%. It is important to establish that, on the contrary to the previous mentioned results of the 2010 study, in this particular case, when the maximum flow was reached, the output did not show any relationship.

As in the previous year, 2010 data did not show any correlation between the flow and the output methane percentage, especially for those low values observed from May to September on the Fig.30, where the output was always above the 1%; it was noticed that in October both parameter reached the minimum value reported, 15 m^3/h and 0.1%, respectively, while the maximum were observed in different months, 139 m^3/h

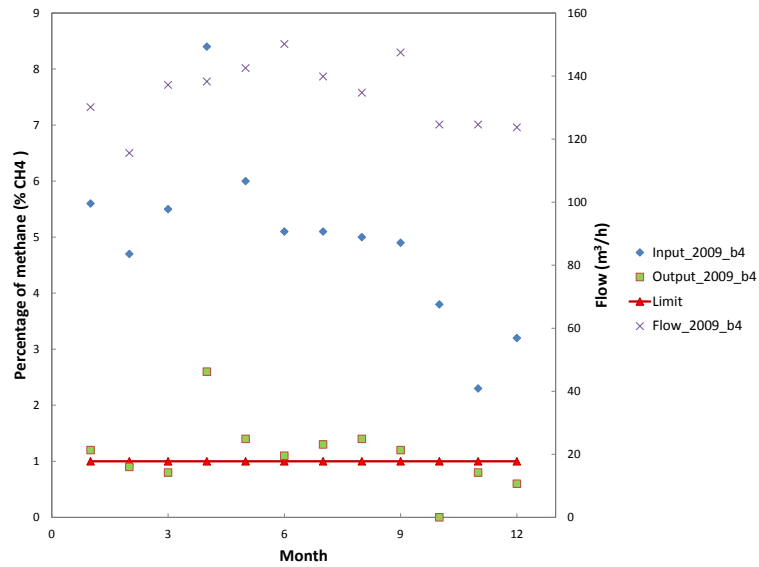


Figure 29: Pinerolo 2009, fourth biofilter data

in December and 1.7% of methane in the output of April.

The input, on the other hand, had a wide range because it fluctuates between 2.5 and 7.2 %, and it is important to notice that from April to September this parameter showed its higher values.

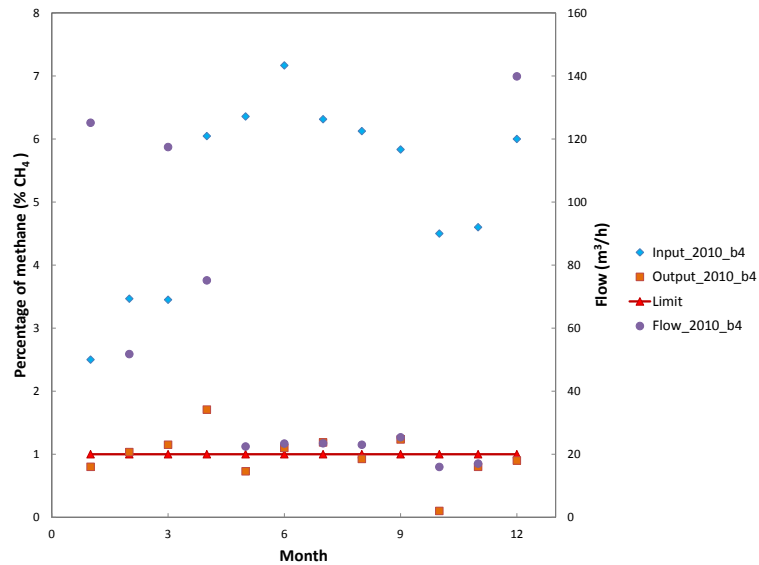


Figure 30: Pinerolo 2010, fourth biofilter data

The 2011 results observed in Fig. 31, in contrast with the previous biofilters,

showed an output data closer to the 1% limit, which even on December went under it with a 0.8%. The flow was oscillating from 96 to 130 m^3/h ; whilst the input methane percentage, reached a maximum on March, progressively decreasing to 3.4% on October.

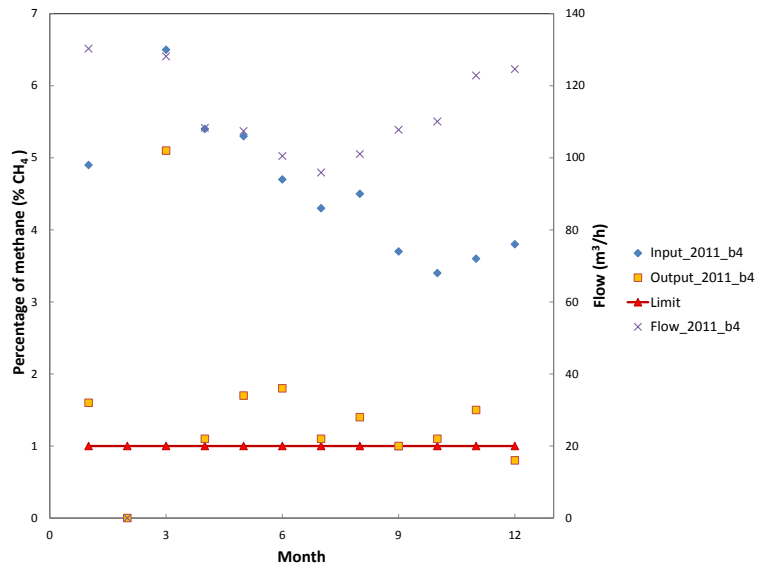


Figure 31: Pinerolo 2011, fourth biofilter data

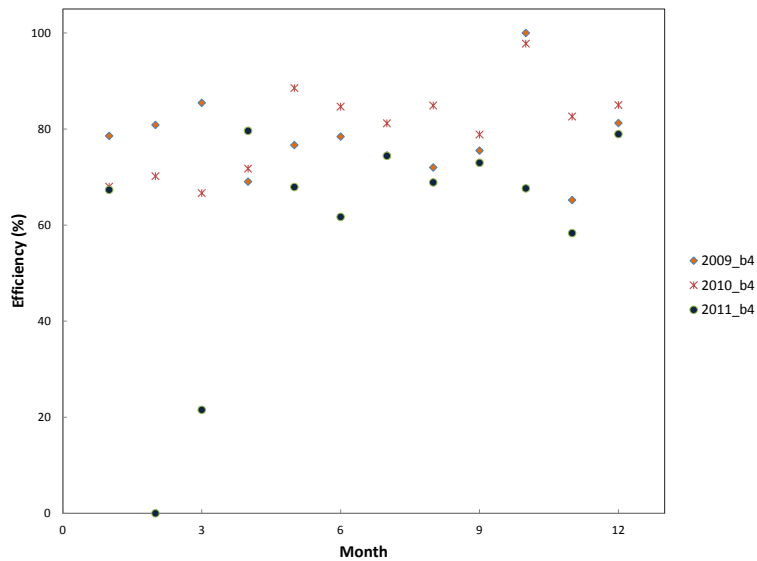


Figure 32: Pinerolo, fourth biofilter efficiency

Without considering the data corresponding to March, and recalling the consideration made referring to February 2011, this particular biofilter showed on last year an

efficiency tendency closer to the results obtained on 2009 and 2010; but, it was still evident a malfunction in the system, because the values were low, being the maximum reached equal to 80%. On the other hand, the previous year showed satisfactory data, because both had as minimum a 65%, as reported on the Fig. 32.

Once the analysis of each biofilter was concluded, some common aspects were taken into account:

- Each year, the input values of the four biofilters exhibited a common tendency that was expected since all were feed by the same current. These are: on 2009 a maximum around 8.5% on April and a minimum of 2.2% on November; on 2010 the data went from 2.5% on January to a 7.2 on June, while in 2011, was observed a trend of maximum 6.5% and minimum of 3.4% on March and October, respectively; however, the first biofiler presented a different behavior, as its minimum of 3.6% was located on December.
- From the previous statement it is observed that the values of methane decreased over the years, which did not correspond with the behavior of a typical landfill presented on a previous chapter; because as an operative landfill it was expected an increase.
- On the four biofilters, the methane percentage data reported on March 2011, indicated that on that month there was still a malfunction on the measurement instrument, as on the previous month, because the values obtained were always out of the range observed on the others month of the year.
- Without considering the irregularities of the 2011 output data, in most cases was observed that during the fall and winter months the output values were lower, which corresponds with the theory, because in those months where the temperature decrease, the moisture level increase and this favors the oxidation rate.
- The flow presented no specific behavior considering neither the years or biofilters under study.

In most cases was noticed that when the percentage of input was under the 5% and the flow between 100 and 130 m^3/h , the objective of an output value under 1% was reached and therefore the 65 % of efficiency was exceeded. However, the data of the third biofilter corresponding to the year 2010, reported in Fig. 26, showed a peculiar

aspect: when the flow was low and the input values were high, the output was low; which may indicate that there was a major contact surface between the gas and the media.

Grosso

Due to the fact that the starting date of the only biofilter present in this landfill refers to January 2010, only two years will be considered.

In the beginning of 2010, the measurement of flow was out of range in comparison with the data on the remainder of the year, this could be caused by an error in the parameter estimation. It is possible to observe in Fig. 33, that by not considering the first value, a relatively stable flow was varying from 119 to 144 m^3/h ; while the methane percentage was fluctuating between 3.1 and 11.7% in the input, and from 1.8 to 8.6% as output.

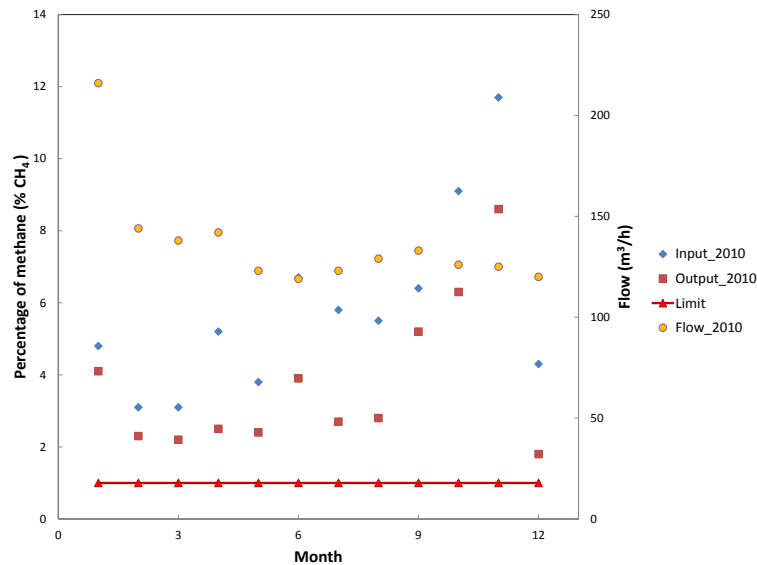


Figure 33: Grosso 2010

In the 2011 data displayed in Fig. 34, was reported that the flow was varying from 47 to 129 m^3/h , the input data was fluctuating between 3.5 and 15.7% and the output from 1.6 to 10.9%. It was possible to observe in the values of August 2011, that the flow and input methane percentage were high, and for that reason a peak in the output was obtained, on the other hand, in that particular month but on 2010, all the data was really low; which allows to establish that, in contrast with the observations

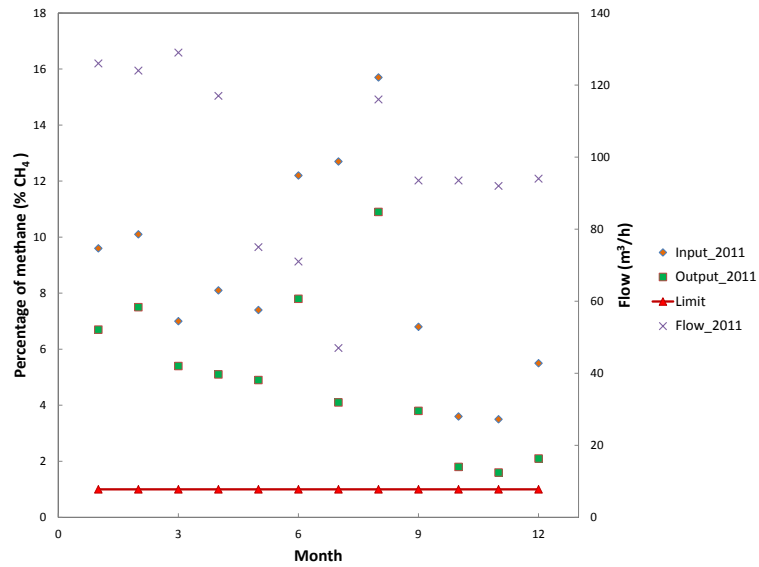


Figure 34: Grosso 2011

on the landfill located in Pinerolo, there was not any particular behavior related with the period of the year, it is possible to observed in the 2010 data that the maximums of methane percentage were obtained since September to November, whilst on the 2011 the highest value was in the summer months, indicating that each site has particular conditions to considerer.

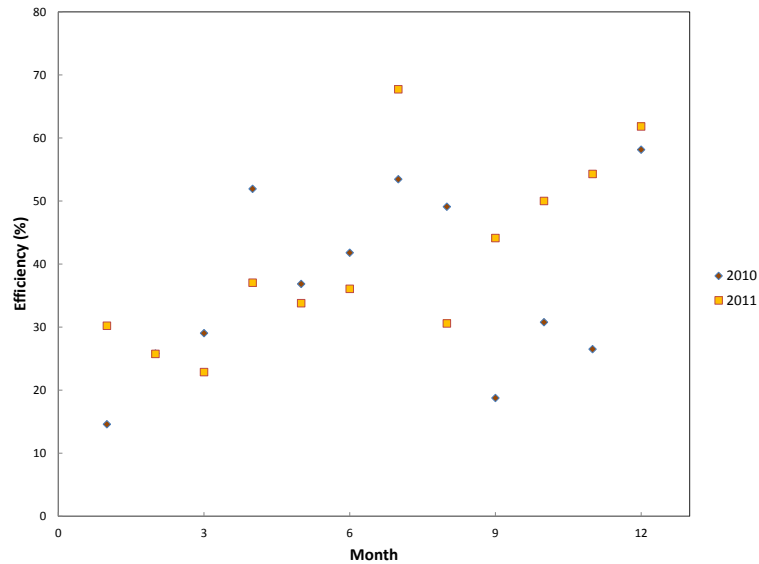


Figure 35: Grosso efficiency

Another diverse aspect to consider is that this operative landfill behaves as expected, because over the years the amount of methane increases, as reported.

It can be seen in the two years that all the output values were above the allowed limit, and in most cases these were relatively close to those reported in the input. These negative aspects were reflected on the low efficiencies reported, as shown in Fig. 35, where the maximum is 68% for 2010 and 58% for 2011; being almost all under the 65% which was the minimum desired result set by the "*Provincia di Torino*".

Collegno

As in the landfill of Pinerolo, to perform the analysis in the only biofilter present on this site, some considerations must be taken into account:

1) The flow was fixed on $160 \text{ m}^3/h$ since the beginning, for that reason, the graphs presented below do not have the double axis, and hence no consideration will be developed regarding this parameter.

2) The measurements of this landfill were taken and reported weekly, therefore each value considered was the average of all the originals.

3) From here onwards, the landfills under consideration will report two outputs (internal and external).

Once these particular aspects are under consideration, the analysis of the biofilter can be done.

The first year studied was 2009, which data is displayed in Fig. 36, where it is observed that the input was varying from 1.5 to 3.9%; whilst the internal output was fluctuating from 0.4 to 1.9%, and the external from 0 to 0.6%. It is important to notice that the maximum input values of methane percentage were reported on May and October, while those of output were obtained on June and November.

Looking at Fig. 37, it is observed that on May 2010, a peak that seems to be out of range was reached on the input and both output data, with values of 5.5, 2.5 and 0.6%, respectively; while the minimum values were obtained in the first months of the year, as 0.5, 0.1 and 0% respectively.

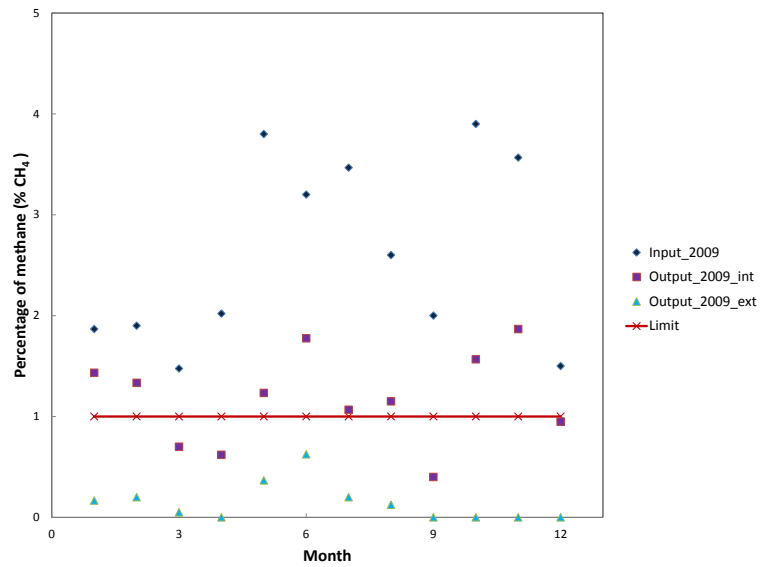


Figure 36: Collegno 2009

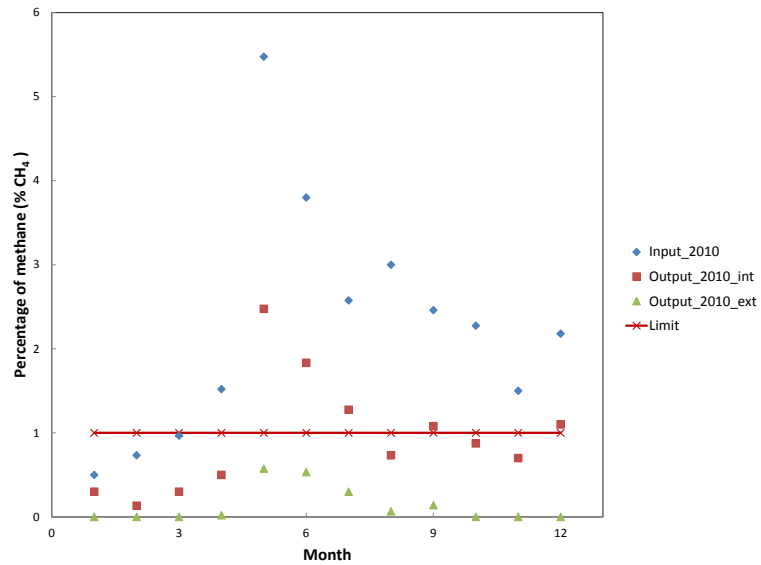


Figure 37: Collegno 2010

The same oscillating behavior observed on the year 2009 is reported on the 2011 data, as shown in Fig. 38, where it is observed that the maximum was obtained on May and the minimum on December. The range of variation of these parameters was: from 0.8 to 3.4% for the input, from 0.4 to 2.4% for the internal output and from 0 to 0.2% for the external.

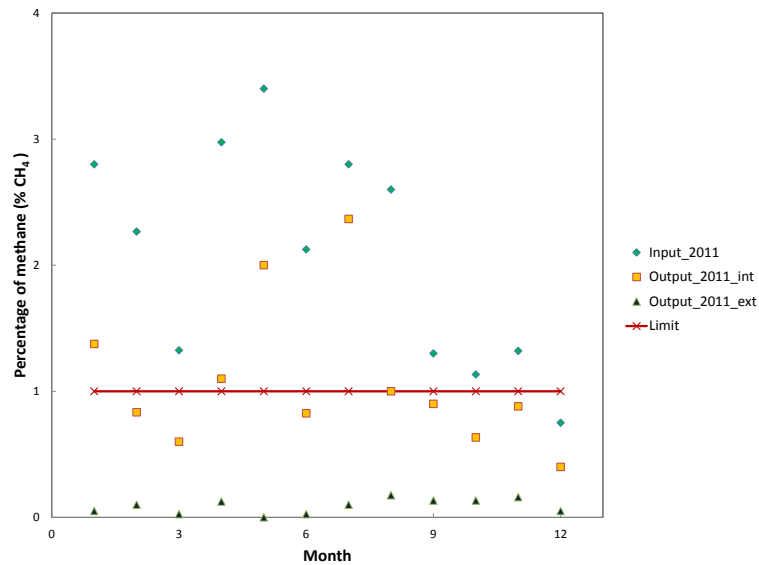


Figure 38: Collegno 2011

It is important to notice that as in the landfill of Grosso, there was not any particular behavior related with the year period; however, a constant peak in the month of May was present in all the cases, which seems to indicate that the conditions of the area in this particular month favor the methane generation on this landfill.

Another aspect that was noticed was the relationship between the input and internal output values; that was consistent with the theoretically established, referring to the influence of the input supply of methane with the oxidation rate.

On the matter of efficiency, Fig. 39 shows the results obtained from the input methane percentage and both output, from which a considerable difference between the two values was reported, being the internal efficiency lower than the external, due to the fact that the cover itself has an ability to filter the methane.

Some of the efficiency values that may be observed on the Fig.39 were: for the year 2009, the internal was varying from 23 to 80%, while the external from 80 to 100%; those of 2010 were fluctuating between 40 and 81% in the internal and between 85 and 100% in the external; finally, the 2011 data showed the widest range, varying from 15 to 63% internally and from 87 to 100% externally. The fall in the internal values observed on the year 2011, seems to indicate that the biofiltration media efficiency started to decrease, so a replacement has to be done soon.

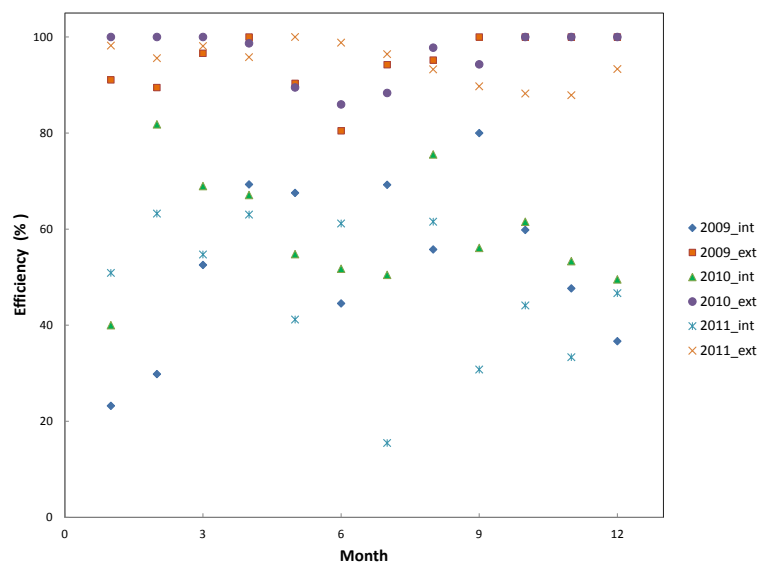


Figure 39: Collegno efficiency

The efficiency data presented above showed satisfactory results to the "Provincia di Torino", because the methane percentage currently emitted to the atmosphere fulfill the objective of the efficiency above the 65 % of abatement.

Referring to the 1% limit of emissions, it was observed that during the three years under consideration the external output values were always under it; while the internal measurements, reported just a few results under this condition, most of them being reached when the input was under the 2% of methane.

Bairo

As stated above, this landfill contains one biofilter that in 2009 started treating internal and external gas; however, as observed in Fig. 40, there was a large difference in the behavior of the trend between the internal input, which was varying from 3.9 to 6.2%, and the average values (identified as "ave") varying from 1 to 5.7%; caused by the dilution of the gas, because the external wells did not captured methane.

The internal output data was also influenced because the increase in the amount of gas flowing through the biofilter media disfavors the oxidation rate, which was reflected on the high values observed, varying from 2.6 to 5.7%. The external output, on the other hand, during most of the month was under the 1% limit; however, on August and September reached a peak around 3.5%. The flow, was not measured on January and

February, and during the rest of the year had a stable behavior varying from 235 and 268 m^3/h .

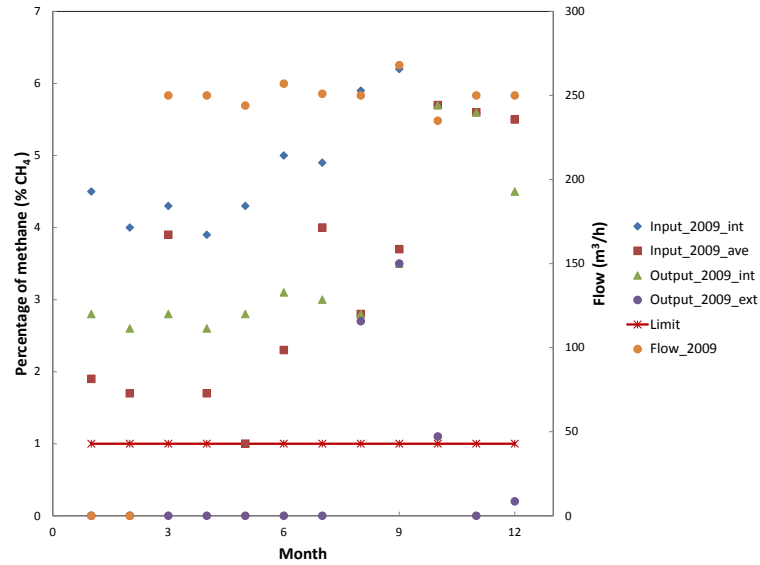


Figure 40: Bairo 2009

Once the external gas was excluded from the feeding line of the biofiltration system, the only input to report was the internal one, as shown in Fig. 41, in which the methane percentage was fluctuating from 3 to 5.7%, whilst the internal output data, had a similar behavior varying between 2.8 and 5.5%; it is important to note that in both parameters the maximum value was observed on September while the minimum was in different months. The external output data, in the majority of the 2010 months, was under the limit established by the "Provincia di Torino"; only on January, September, November and August were above it, presenting in this last month a peak of 2.8%. The flow, on the other hand, was constant at 250-251 m^3/h .

In contrast with the behavior observed in the previous years, where the majority of the external output data were under the 1% limit, the values obtained on the year 2011, reported in Fig. 42, showed a 0.8 % on January as only satisfactory result, whilst the rest is above the desired value, reaching a maximum of 3.1% on December. The input and internal output data presented a similar behavior varying from 3.1 to 6.2%, and 2.6 to 5.8%, respectively.

On the other hand, the flow values were around 250 m^3/h in almost every month, except on the minimum of 187 m^3/h reported in January and the peak of 429 m^3/h

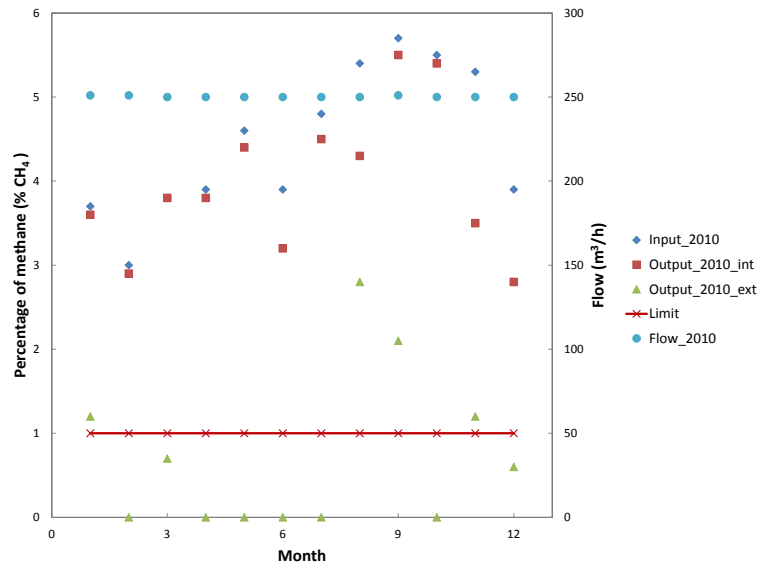


Figure 41: Bairo 2010

reached in October. It is consider important to set down that the behavior of the external output data did not correspond with the one observed in the landfill of Pinerolo, where was clearly observed that with flows above the $150 \text{ m}^3/\text{h}$ the output data increase; whilst in this particular case, in the maximum flow a decrease on the output was reported.

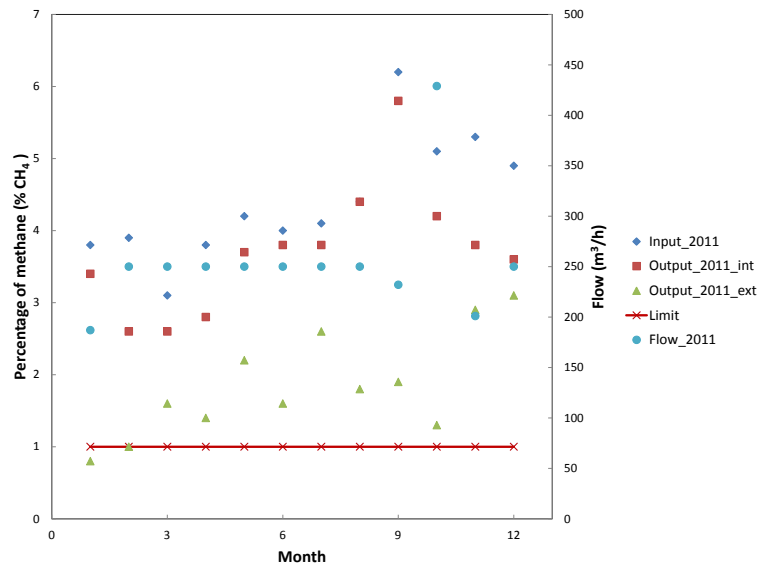


Figure 42: Bairo 2011

The efficiencies of this biofilter reported in Fig. 43, showed a wide range on the 2009 values, varying from 4 to 100%, which highlight what was previous mentioned referring that there was an error in this data due to the presence of the external gas; it was also possible to note that some of the 2009 internal efficiency values obtained were not reported due to they were negatives.

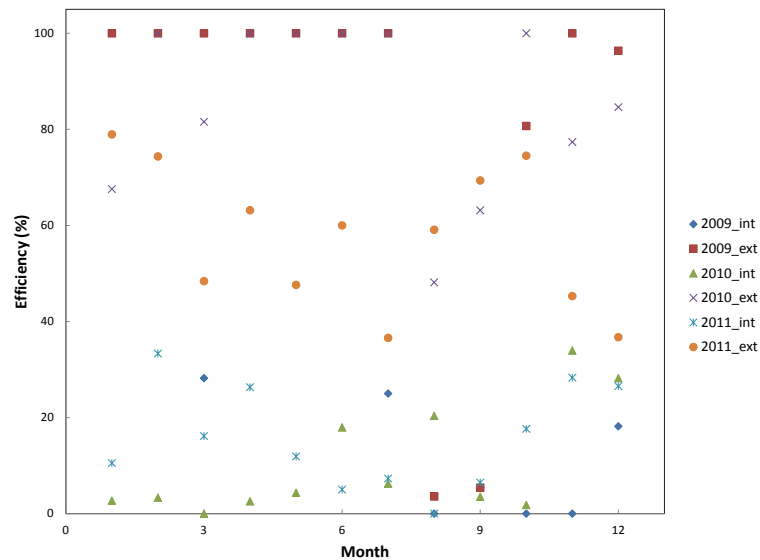


Figure 43: Bairo efficiency

The 2010 internal efficiency was varying from 0 to 28%, while the external was between 48 and 100%. It is important to stand out that in this year, as on the previous one, the efficiencies obtained on August and September seems to indicated an irregularity on the system, because the values fell out of range to the minimum observed, while in the rest of the year were fluctuating closer to the 100%; so by not considering these, could be declare that the expectation of an abatement above 65% was fulfilled.

Referring to the 2011 data, it was possible to observe that the internal efficiency was varying from 5 to 28%, whilst the external, in comparison with the previous years, presented the lowest values, fluctuating between 37 and 79%, which indicated that the desired reduction of methane in the system was not reached.

Due to the fact that 2009 data was considered non reliable and the one from 2011 seems to indicated a malfunction in the system, the 2010 values will allow to determine the optimal conditions of this system to guarantee the 1% limit; which apparently were: a flow of $250 \text{ m}^3/h$ and a methane percentage in the input lower than 5%.

Finally, it is important to highlight that under the years studied the only particular behavior with the period of the year was the peak of input reported around August and September.

Colleretto Giacosa

The biofilter located in this landfill treated internal and external gas, and in contrast to what was previous mentioned regarding Bairo, no problem was observed, even if the gas captured by the external wells contained low concentrations of methane, as shown in Fig. 44, in which the percentage of this particular gas was varying from 0 to 1.1%, while the internal input data was fluctuating in a wide range from 1.3 to 15%. The combination of both capture systems (internal and external), called average input, oscillated between 1.3 and 7.6% of methane.

The output, on the other hand, was varying from 1.1 to 5.9% in the internal measurement, whilst the external was relatively constant at 0%.

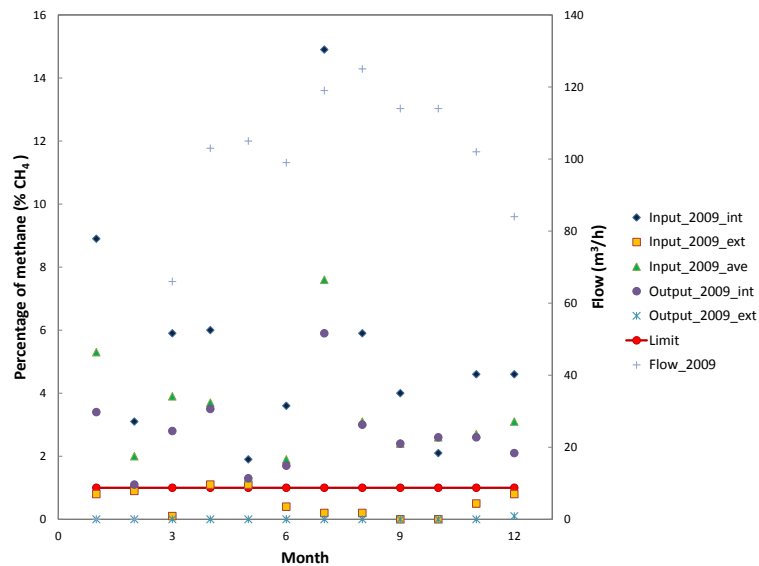


Figure 44: Colleretto 2009

As shown, in the year 2009, on the first two months no flow measurement were taken, while the rest of the year was varying from 66 to 125 m^3/h . It seems important to highlight that the peaks reported in the internal input and output, as well as in the input media, were obtained on August.

The data from the year 2010 shown in Fig. 45, allows to observe that the input data was varying from 2.3 to 6.5% in the internal system and from 0 to 0.7% in the external, reporting an average between 1.3 and 5.1%; it was noticed that the maximum values were reached in the first months of the year. The output was fluctuating between 1.1 and 4.2% internally, and from 0 to 1.8% externally; in this case the peaks were observed on January and August, respectively. Finally, the flow was varying from 50 reached on May to 118 m^3/h on August.

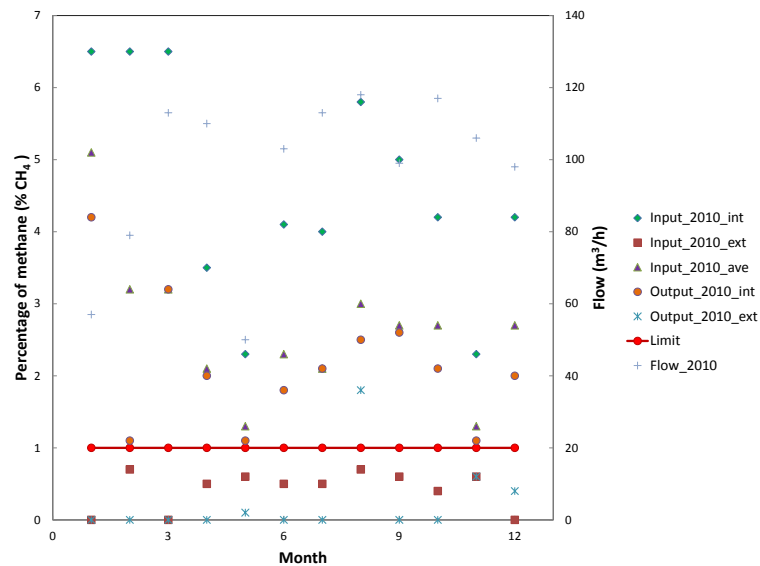


Figure 45: Colletterto 2010

In the 2011 data, reported in Fig.46, the external input was varying from 0 to 0.8%, while the gas captured by the internal wells system contained a methane percentage that was fluctuating between 1.8 and 5.2%, reaching the maximum value on August; the average of the two inputs leads to obtained a gas having a content of methane that was varying from 1.1 on October to 2.8% on January. The internal output was oscillating between 1.1 and 4.2 %, whilst the flow range was within 103 and 157 m^3/h .

In contrast with the previous years, on 2011 higher values of external output were obtained, varying between 0 and 1.6%; however, it is important to stand out that only on December the 0% was reached, while on the previous years this was a recurrent value for this parameter.

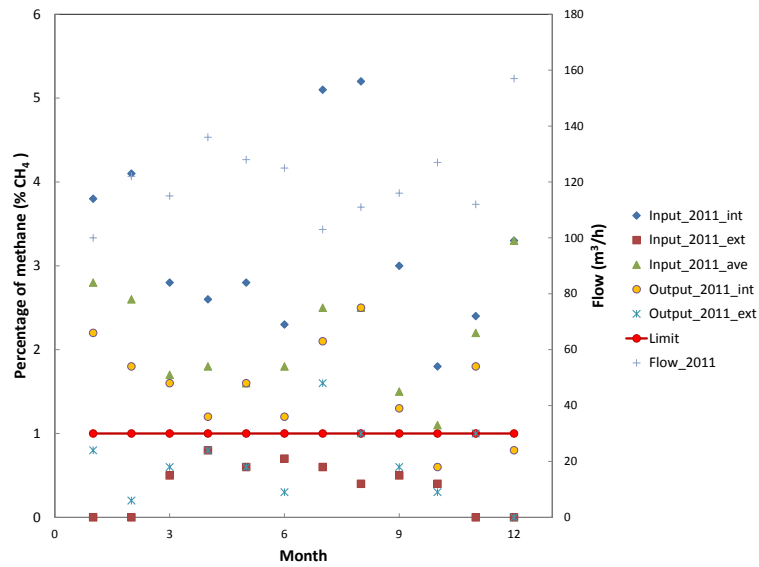


Figure 46: Colletterto 2011

Regarding the previous information, Fig. 47 reported a decrease on the external efficiency results, which were varying from 36 to 100%; whilst the previous years, in most cases, these were closer to the 100%, except on August and November 2010, where minimum values were observed.

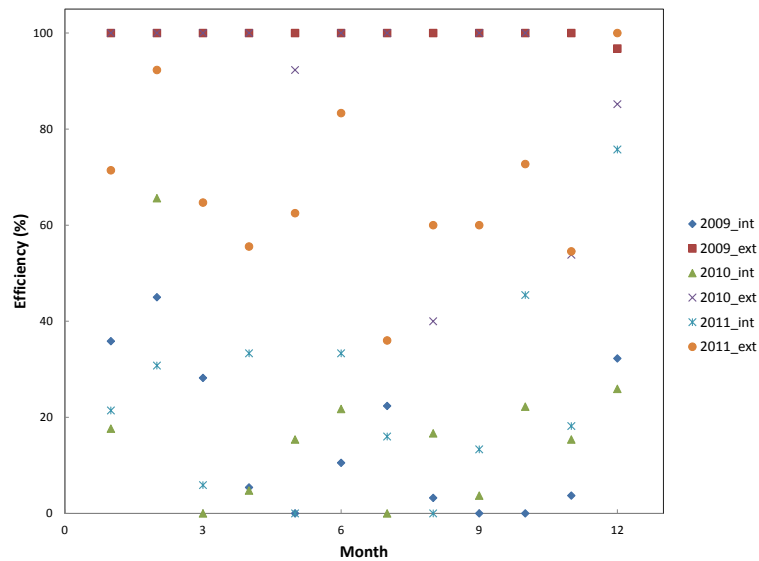


Figure 47: Colletterto efficiency

The efficiency values of the internal measurement points were varying from 0 to

45% in 2009, from 0 to 66% in 2010 and from 0 to 76% in 2011. It is important to establish that all the efficiencies were calculated from the average input, which showed a similar behavior with the internal input, but presented lower values due to the dilution caused by the external current.

The data previously presented shows that the three years under consideration fulfill the regulations of the "*Provincia di Torino*" regarding the 1% limit, while the 65% abatement was also exceeded most cases during 2009 and 2010, but on 2011 the system efficiency decreased.

Seeking to determine the optimal conditions of this landfill, the data from 2009 indicated that in the range of work, even high values of internal input as 15% were diluted by the external current to a point under which the external emissions did not exceed the limit. However, based on the values reported by the average input, because this is real current feeding the system, it was observed that under the 5% of methane and maintaining a flow between 100 and 120 m^3/h the results were satisfactory.

It is considered important to establish that the reported input data equal to zero, seems to indicate an equipment error. On the other hand, due to the fact that the last three landfills analyzed were closed, it was expected a decrease in the quantity of methane over the years, however, this behavior was not observed, which could be caused by the fact that the period of time under consideration was too short to notice a significant change.

Once the data was analyzed, it was noticed that some new factors needed to be calculated to improve this study.

5.2.1 Comparative factors

The data previously presented regards the performance of the biofiltration system in the five landfills under consideration; however, due to the conditions affecting each location and the diversity in management, was not possible to establish a major comparison between all the biofilters. For that reason, seeking to determine a common factor, it was noticed, as reported on the second chapter of this thesis, that all the sites studied contain structures with similar characteristics.

Being the biofilter total volume of 39,8 m^3 constant in all cases, two additional parameters were calculated, regarding the flow of gas and methane treated for cubic meter

of biofilter, respectively; which allows to establish differences between the residence time of the gas and the quality of the flow, referring to the amount of methane.

The specific calculations required to determine the new parameters were:

First

$$P_1 = Q/V_{bio} \quad (3)$$

Where "Q" is the flow of gas in input on cubic meters per hour, " V_{bio} " is the volume of the biofilter on cubic meters.

Second

$$P_2 = P_1 * \%CH_4 \quad (4)$$

Being the methane percentage referred to the input flow, as cubic meters of methane per cubic meters of gas flow.

As a section of the data analysis, the presentation of the results continue to be graphical, based on points referred to the months of the year and indicated for each biofilter.

Pinerolo

First biofilter

As it was established, the first parameter calculated (P_1) allows to determinate an estimate on the inverse of the residence time, because refers to the total amount of gas treated. In this particular biofilter, it was possible to observed a stable behavior in 2009 and 2011, around the 2.8 and 3 $m^3_{gas}/m^3_{bio} * h$, respectively; while the 2010 data, presented a wider range, due to the experimentation in the flow rate previously mentioned, varying from 1 to 11 $m^3_{gas}/m^3_{bio} * h$, as shown in Fig. 48.

The quality of the gas, on the other hand, was reported by the second parameter (P_2), which was fluctuating from 6 to 66 $m^3CH_4/m^3_{bio} * h$, as shown on Fig. 49, where is possible to observed that the irregular behavior of 2010 data continued to be reported, caused by the direct relationship between the flow rate and the parameter under consideration. However, the results of 2009 and 2011 showed slightly constants values around 14 and 12 $m^3CH_4/m^3_{bio} * h$, respectively.

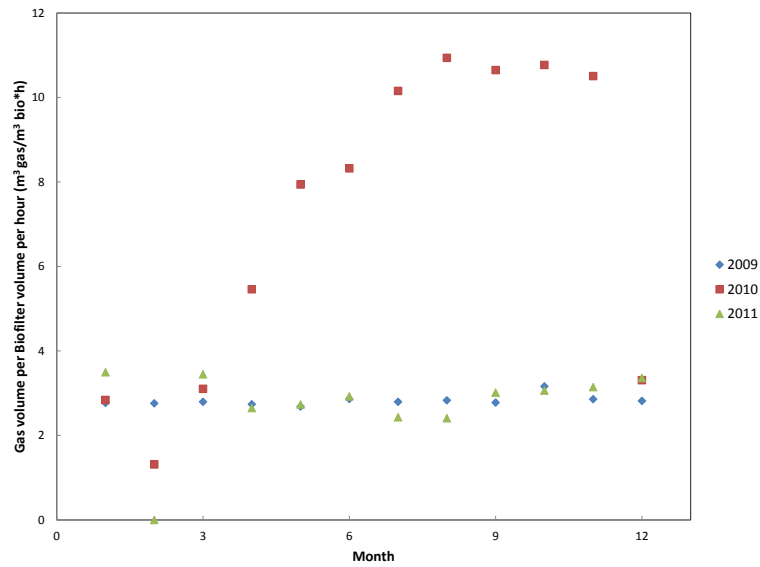


Figure 48: Pinerolo, First parameter, first biofilter

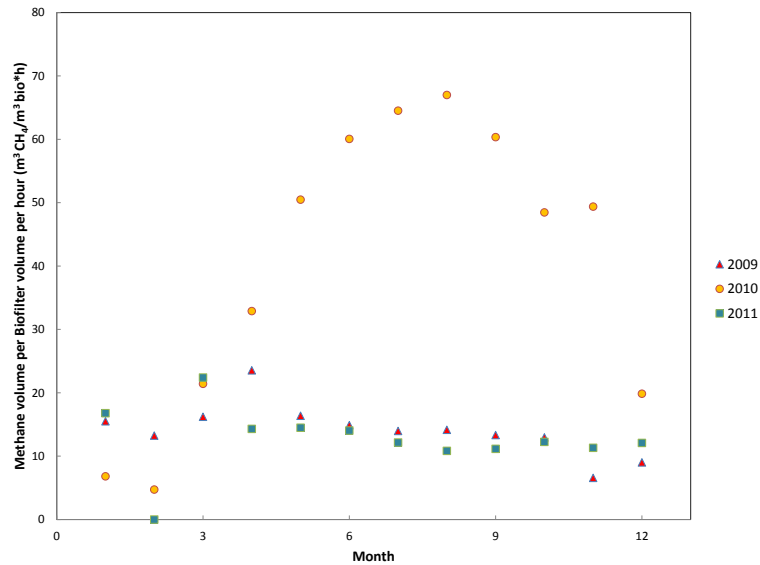


Figure 49: Pinerolo, Second parameter, first biofilter

Second biofilter

Due to the mentioned experimentation referring the flow rate of this landfill that took place in 2010, this biofilter showed for that particular year a serie of low values, which were reflected on the moderate first parameter results obtained, as shown in Fig. 50. On the other hand, the other two years under consideration were more stables varing

from 2.5 to $3 \text{ m}^3_{\text{gas}}/\text{m}^3_{\text{bio}} * \text{h}$.

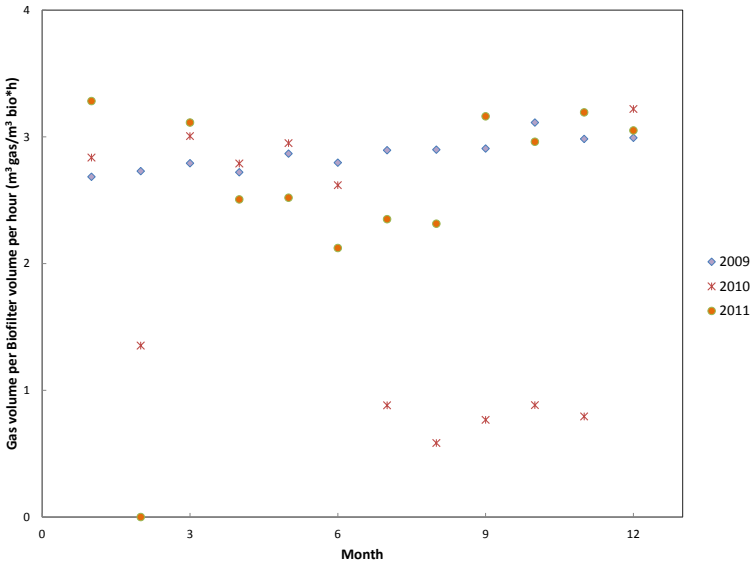


Figure 50: Pinerolo, First parameter, second biofilter

The methane flow per biofilter volume data presented in Fig. 51, showed that in the three years under consideration this parameter was varying from 6 to 23, from 3 to 19 and from 10 to 20, respectively.

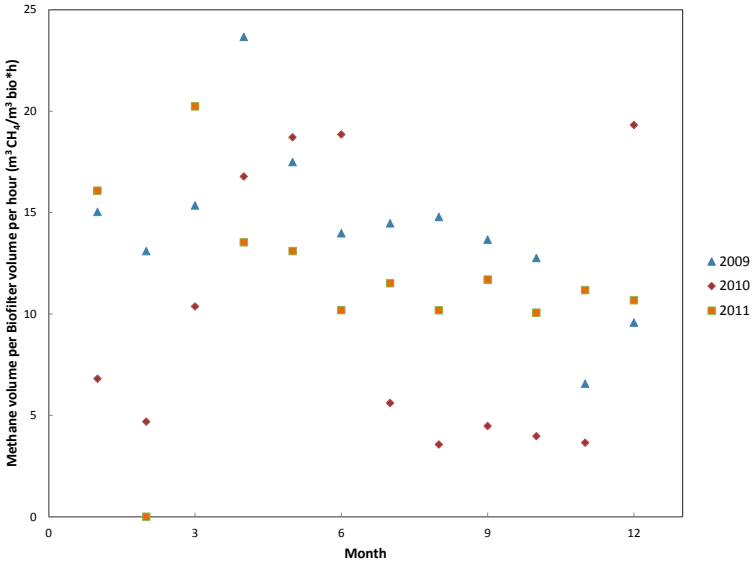


Figure 51: Pinerolo, Second parameter, second biofilter

Third biofilter

As in the previous case, due to the experimentation, the 2010 data seems out of range presenting values below the average results obtained in the other two years, which were varying around $3 \text{ m}^3_{gas}/\text{m}^3_{bio} * h$, as shown in Fig.52.

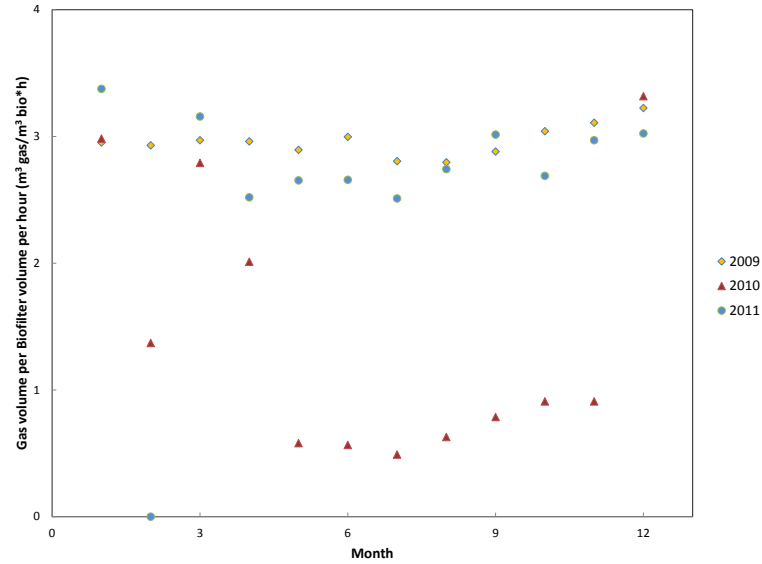


Figure 52: Pinerolo, First parameter, third biofilter

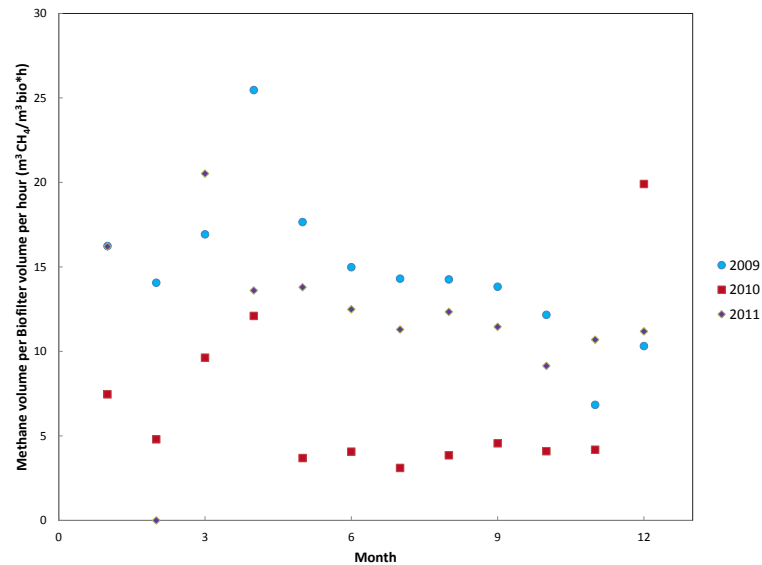


Figure 53: Pinerolo, Second parameter, third biofilter

Presenting a similar behavior with the previous biofilter, Fig. 53 shows that the

results of the second parameter were fluctuating between 6 and 25, 3 and 20, 9 and 21 $m^3CH_4/m_{bio}^3 * h$, respectively.

Fourth biofilter

The results obtained on this biofilter were similar to those reported on the previous two cases, due to the fact that were exposed to the same conditions, which is possible to observed in Fig. 54, where the gas volume per biofilter volume per hour was varying around 3 in 2009 and 2011, and the 2010 data presented the lowest values from 0.5 to 3 $m_{gas}^3/m_{bio}^3 * h$.

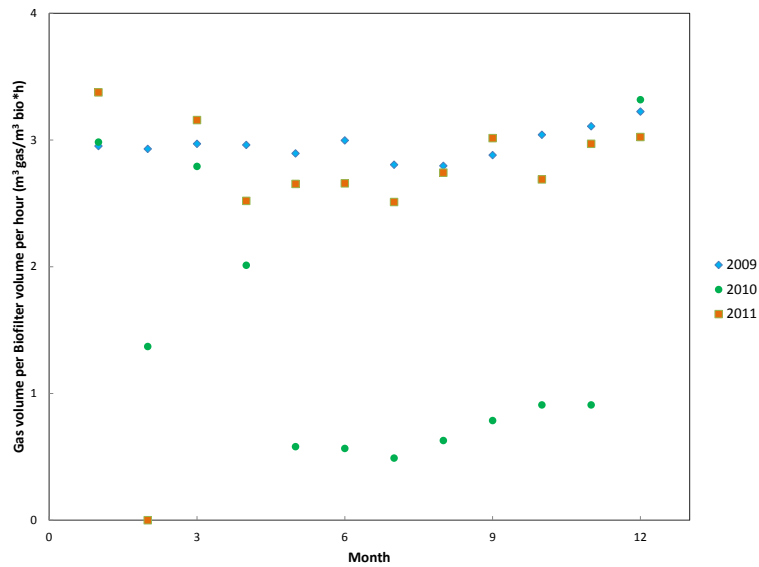


Figure 54: Pinerolo, First parameter, fourth biofilter

The second parameter calculated also presented a behavior similar to the second and third biofilter, fluctuating from 7 to 30 $m^3CH_4/m_{bio}^3 * h$ in 2009, from 1.8 to 21 $m^3CH_4/m_{bio}^3 * h$ in 2010 and from 9 to 21 $m^3CH_4/m_{bio}^3 * h$ in 2011, as shown in Fig.55.

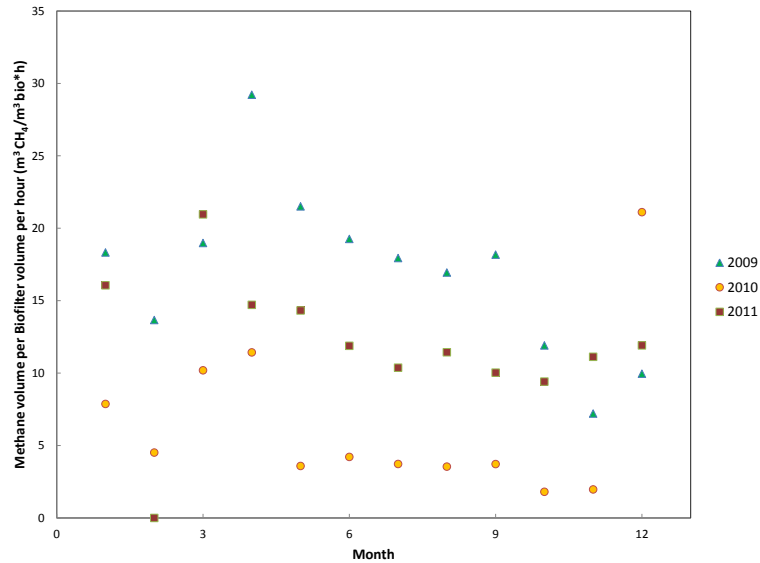


Figure 55: Pinerolo, Second parameter, fourth biofilter

After determinate the parameters for this landfill, the following aspects were noticed:

- The first parameter was stable around the $3 \text{ m}_{gas}^3/\text{m}_{bio}^3 * h$ on the four biofilters, in the 2009 and 2011, whilst the 2010 data followed the same behavior of the flow experimentation which was based in higher values on the first biofilter and lower on the rest.
- Regarding the second parameter, the values obtained were fluctuating approximately between 6 and 23 $\text{m}^3\text{CH}_4/\text{m}_{bio}^3 * h$ in the 2009, 3 and 20 $\text{m}^3\text{CH}_4/\text{m}_{bio}^3 * h$ in the 2010 and 10 and 20 $\text{m}^3\text{CH}_4/\text{m}_{bio}^3 * h$ in the 2011. It was also observed that the 2009 and 2011 data presented peaks corresponding to the maximums reported in the input.
- Comparing the 2009 and 2011 data, it was possible to establish that the quality of the gas decrease over the years.

Grosso

The values of the first parameter were not as stable as those obtained in the previous landfill, as shown in Fig. 56, where is possible to observed that the 2010 data was varying from 3 to $5.4 \text{ m}_{gas}^3/\text{m}_{bio}^3 * h$, whilst the 2011 from 1.1 to $3.1 \text{ m}_{gas}^3/\text{m}_{bio}^3 * h$.

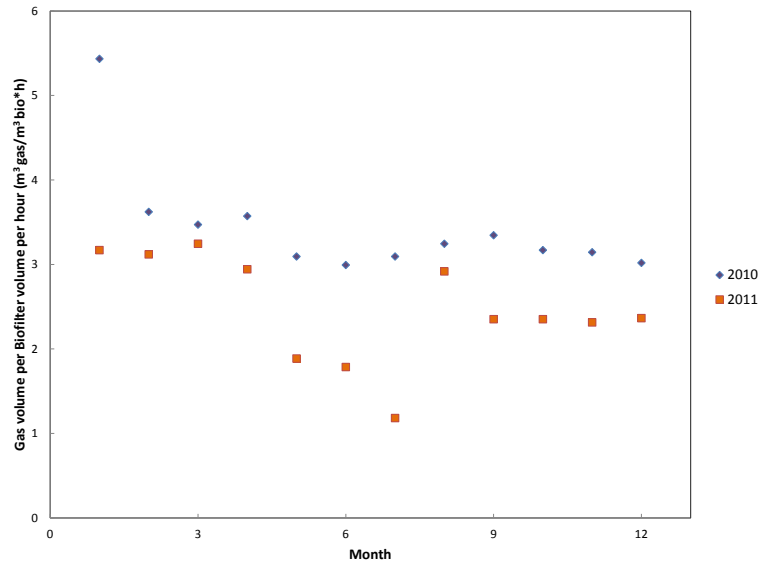


Figure 56: Grosso, First parameter

The parameter referring the methane flow per biofilter volume of this landfill, shows in Fig. 57 a 2010 data fluctuating between 10 and 36 $m^3CH_4/m^3_{bio} * h$; while the 2011, presented a downward trend from 31 to 8 $m^3CH_4/m^3_{bio} * h$, with a peak of 45 $m^3CH_4/m^3_{bio} * h$ on August. It is important to notice that as in the previous landfill, the maximums observed in this parameter corresponds with those of the input percentage of methane.

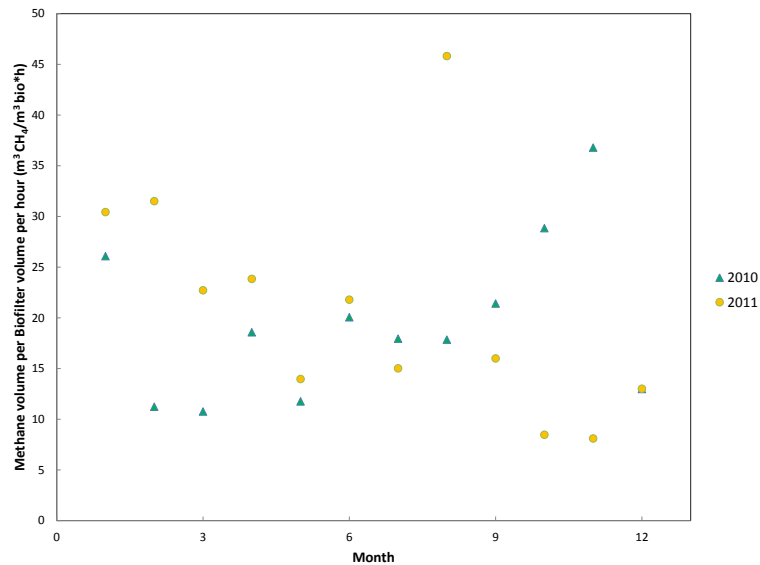


Figure 57: Grosso, Second parameter

Collegno

Due to the fact that the flow rate of this landfill was constant during the years under consideration, the first parameter was equal to $4 \text{ m}^3_{gas}/\text{m}^3_{bio} * h$. On the other hand, as shown in Fig. 58, the second parameter, was varying from 6 to 16, from 2 to 22 and from 3 to 13 $\text{m}^3\text{CH}_4/\text{m}^3_{bio} * h$ in 2009, 2010 and 2011, respectively.

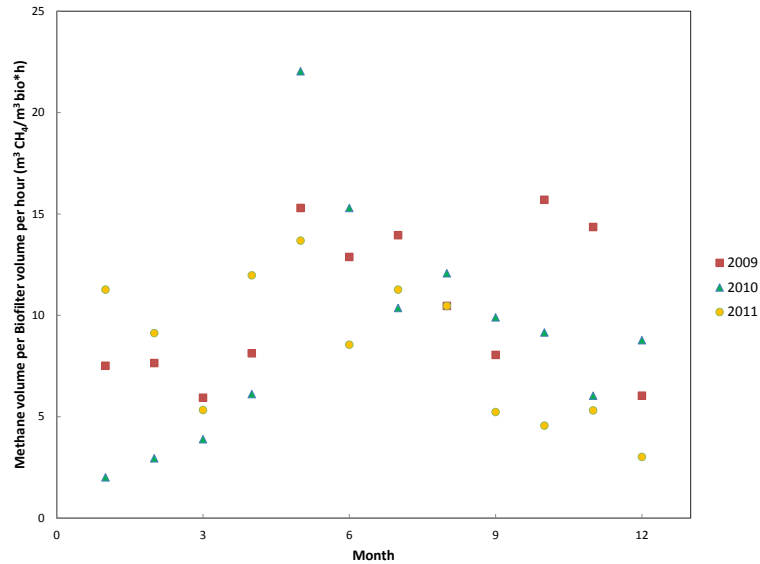


Figure 58: Collegno, Second parameter

Bairo

In this case the flow was not fixed, but the values observed were stable around $250 \text{ m}^3/h$, for that reason, as in the previous landfill, the first parameter was calculated and not graphed. The flow of gas per biofilter volume obtained was around 6.3; while the parameter referred to the methane volume was varying between 6 and 35 $\text{m}^3\text{CH}_4/\text{m}^3_{bio} * h$ in 2009, 19 and 36 $\text{m}^3\text{CH}_4/\text{m}^3_{bio} * h$ in 2010 and 18 and 36 $\text{m}^3\text{CH}_4/\text{m}^3_{bio} * h$ in 2011, as shown in Fig. 59.

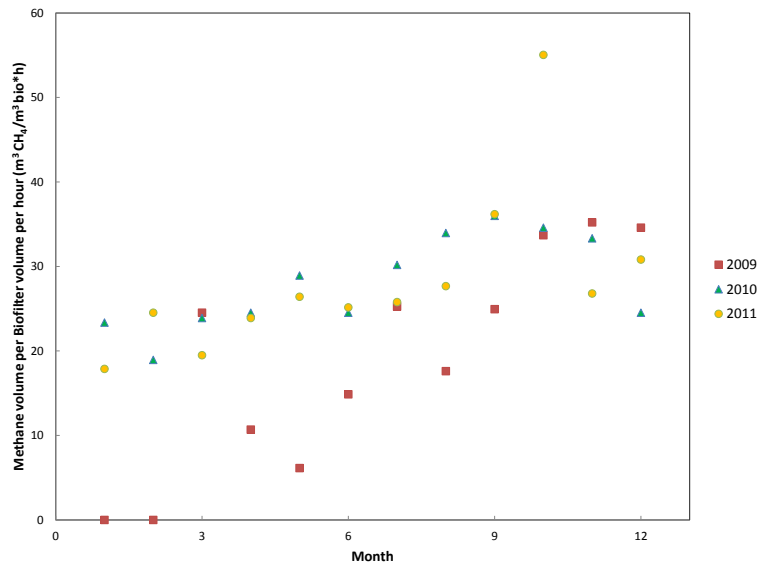


Figure 59: Bairo, Second parameter

Colleretto Giacosa

This landfill presented a gas volume per biofilter volume per hour relatively stable in the three years under consideration, varying from 1.7 to 3.1, 1.3 to 3 and 2.5 to 4, respectively; as it is shown in Fig.60.

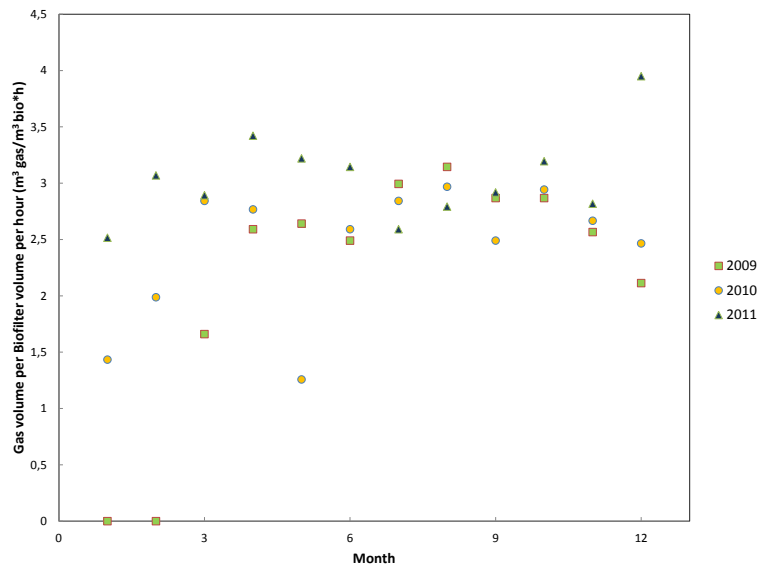


Figure 60: Colleretto, First parameter

The second comparative parameter calculated, reported in Fig. 61, presented a peak

of $22 \text{ m}^3\text{CH}_4/\text{m}^3_{\text{bio}} * h$ in July 2009, which corresponds with the maximum value of internal input observed above. Meanwhile, the rest of 2009 data, as well as the other two years considered were relatively stable fluctuating between 3.4 and 9.7, 1.6 and 9, 3.5 and $8 \text{ m}^3\text{CH}_4/\text{m}^3_{\text{bio}} * h$ in 2009, 2010 and 2011, respectively.

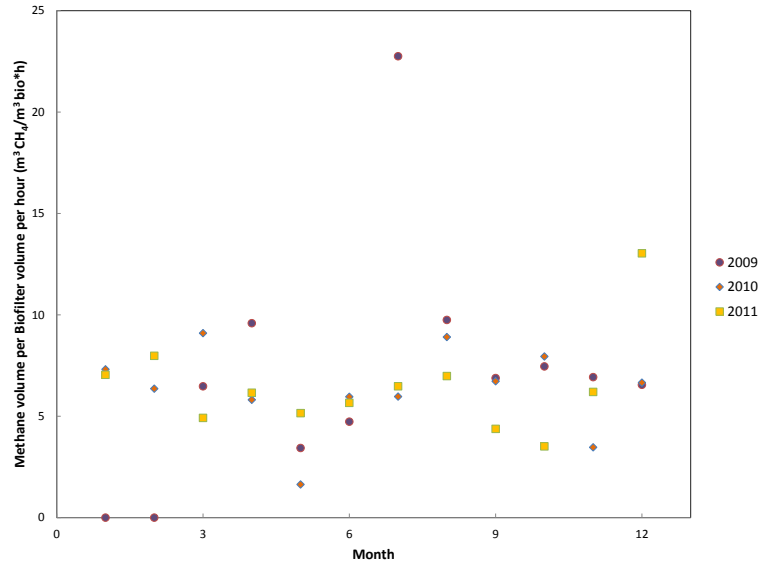


Figure 61: Colletterto, Second parameter

It is important to consider that only in the landfill of Pinerolo was observed a particular behavior regarding the quality of the gas over the years.

As it was established in the beginning of this section, the new parameters allow to determinate that when the gas flow per biofilter volume was high, the residence time was lower; while on the second factor, the amount of methane and the quality reported a direct relationship. Being Colletterto Giacosa the site with worst quality, and lower residence time.

Once analyzed the performance of the biofilters in the three years studied, the common aspects and differences were established; however, in order to determinate the conditions on the current year, new data were measured directly from the sites.

5.3 Inspections

As additional data to the three years under consideration in this study, measurements were taken (in the majority of the landfills) between late May and early June of

2012; these will be presented in tables referring to each biofilter, in which will be also reported the media of all the values obtained from 2009 to 2011.

It is known that a single measurement does not give information of an entire year, because in some cases a particular value may be out of the range, as observed in the previous sections; however, these will be analysed to make a prospective of the biofilters efficiency in the current year, and see if there was or not improvements in the system. For that reason, the following information was based on the values reported this year and its relationship with the data already analysed.

Pinerolo

This landfill was visited on May 31st 2012, where were measured the depression, as well as, the percentage of methane, carbon dioxide and oxygen in the input and output of the four biofilters; also, the velocity of the feed pipeline to the system and to the first biofilter (that will be assumed constant in all four, as an approximation due to the lack of information). However, only the common values with the ones analyzed on the previous section will be reported.

Another important aspect to remember is that due to the study developed on 2010, the flow data reported were considered out of the normal range; as well as the 2011 data of the methane percentage, these two events seem to indicate a malfunction in the system; therefore these will not be compared with 2012 measurements.

Considering the information presented above, the analysis of the four biofilters on this landfill was performed as follows:

First biofilter

As shown on the table 3, on May 2012 this biofilter presented input and output data close to those observed on the years 2009 and 2010, which was reflected as well in the efficiency obtained. The flow on the other hand, was slightly lower.

Table 3: Pinerolo, first biofilter

<i>Year</i>	<i>Input (%CH₄)</i>	<i>Output (%CH₄)</i>	<i>Efficiency (%)</i>	<i>Flow (m³/h)</i>
2009	5.0	1.1	77.6	112
2010	5.5	1.3	78.4	283
2011	4.3	2.3	43.7	108
2012	5.1	1.2	76.5	78

Second biofilter

The data obtained on this biofilter is reported on the table 4, where is observed that on the 2012 the input value was similar to those observed on the years 2009 and 2010; the output, was also close to the values of those years, but slightly higher, which was reflected in a decrease in the efficiency. The flow, on the other hand, as on the first biofilter, seems to be lower than usual.

Table 4: Pinerolo, second biofilter

<i>Year</i>	<i>Input (%CH₄)</i>	<i>Output (%CH₄)</i>	<i>Efficiency (%)</i>	<i>Flow (m³/h)</i>
2009	5.0	1.1	76.7	113
2010	5.2	1.3	74.9	75
2011	4.2	3.1	23.8	101
2012	5.0	1.6	68.0	78

Third biofilter

As on the first biofilter, table 5 reports that the 2012 input and output data were in the range of the values observed in 2009 and 2010, and that the flow was lower than the values of 2009 and 2011.

Table 5: Pinerolo, third biofilter

<i>Year</i>	<i>Input (%CH₄)</i>	<i>Output (%CH₄)</i>	<i>Efficiency (%)</i>	<i>Flow (m³/h)</i>
2009	5.0	1.1	77.7	118
2010	5.2	0.7	85.4	56
2011	4.2	2.0	47.8	103
2012	5.1	0.8	84.3	78

Fourth biofilter

In this particular case, the 2012 measurements, reported in table 6, showed that the input value was within the range of the 2009 and 2010 data; while the output was slightly lower, which was reflected on a higher efficiency. Finally, as in previous biofilters, the flow presented a value under the data reported on the 2009 and 2011.

Table 6: Pinerolo, fourth biofilter

<i>Year</i>	<i>Input (%CH₄)</i>	<i>Output (%CH₄)</i>	<i>Efficiency (%)</i>	<i>Flow (m³/h)</i>
2009	5.0	1.1	77.7	134
2010	5.2	1.0	80	55
2011	4.2	1.5	60.0	103
2012	5.1	0.8	84.3	78

The following characteristics were common in the four biofilters located on this landfill:

- As it was expected, the methane percentage in the input and output data on the year 2012, was similar to those reported on the first two years under consideration, because on February the media was changed, which solves the problem of malfunction reported on 2011.
- Although the first two biofilters presented output values of methane percentage higher than the 1% limit, in the four cases the abatement efficiency was above the 65%.
- The low flow reported on the year 2012, was always out of range, which seems to indicate that there was an error in the approximation made or in the measurement itself.

Grosso

On June 6th 2012, the following measurements were taken in this landfill: the depression and percentage of methane, carbon dioxide and oxygen in the input and output of the biofilter, as well as the flow of the input current. However, as on the previous

case, only the common values with the ones analyzed on the section above will be reported.

Table 7: Grosso

<i>Year</i>	<i>Input (%CH₄)</i>	<i>Output (%CH₄)</i>	<i>Efficiency (%)</i>	<i>Flow (m³/h)</i>
2010	5.8	3.7	36.4	137
2011	8.5	5.1	41.2	98
2012	4.1	1.4	65.9	96

As observed in table 7, the data of this landfill showed a considerable reduction in the values of input and output methane percentage; however the 2012 measurement, indicated that the limit of 1% was still not achieved in the output data, but the results were closer than those of the previous years; while the efficiency, on the other hand, reported a value in the range of abatement desired. Finally, it was noticed that the flow presented a decreasing trend.

Bairo

The data corresponding to the year 2012 of both SCS landfills, were taken the 28th of May, and reported: the input and output percentage of oxygen, carbon dioxide and methane, the depression applied in the input current and the flow.

It is important to remember the dilution of the flow that this landfill had in 2009, causing errors on the results, reason why this not will be compared with the 2012 measurements.

As seen on the table 8, this particular landfill showed an input value of methane percentage slightly higher than the previous years; however, it was also noticed that there

Table 8: Bairo

<i>Parameter</i>	2009	2010	2011	2012
<i>Input (%CH₄)</i>	3.3	4.5	4.4	4.9
<i>Internal Output (%CH₄)</i>	3.5	4.0	3.7	4.9
<i>External Output (%CH₄)</i>	0.6	0.7	1.9	1.5
<i>Internal Efficiency (%)</i>	0.0	10.4	15.8	0
<i>External Efficiency (%)</i>	82.2	85.2	57.8	69.4
<i>Flow (m³/h)</i>	209	250	254	198

was not any abatement caused in the path through the biofilter media, reason why the external output was not under the 1% limit, but at least reached the desired percentage of abatement. The flow, on the other hand, was lower than in previous years.

Colleretto Giacosa

This site, presented the same data and measurements reported on the previous landfill; however, it is important to establish that in this particular case, were observed two inputs arriving to the biofilter (internal and external), but the one under consideration was the current obtained after the mixture of these, reason why was named average input.

On the year 2012, this landfill showed input and outputs values within the range of those reported on previous years, which were satisfactory because the methane emissions were under the 1% and the abatement above the 65%, as seen on the table 9. Another aspect to consider was that the flow was higher than usual.

Table 9: Colleretto

<i>Parameter</i>	2009	2010	2011	2012
<i>Input Average (%CH₄)</i>	3.3	2.6	2.1	2.8
<i>Internal Output (%CH₄)</i>	2.7	2.2	1.6	1.0
<i>External Output (%CH₄)</i>	0.0	0.2	0.7	0.2
<i>Internal Efficiency (%)</i>	15.5	17.4	24.5	64.3
<i>External Efficiency (%)</i>	100	89.3	67.8	92.9
<i>Flow (m³/h)</i>	103	96	121	161

As it was previously established, the data observed on the 2012 was not significant of all the year, however, in the majority of the cases seems to indicate a improvement on the system which was a satisfactory result. In those cases where the result was not as expected, is recommended to pay attention to the operation conditions of the system.

Once evaluated the 2012 measurements, the performance data was completed; however, as part of the objectives of this project the cost will be also considered.

5.4 Costs Analysis

Until this point, the data analyzed were based on the parameters measured in the system or some calculated factors; however, especially in those cases where the system was not reaching the desired values, the initial and maintenance costs must be put into consideration to establish if the system worth the investment.

The first investment involved all the cost required to implementate the biofiltration system, such as:

Table 10: Initial items costs of the system

<i>Item</i>	<i>Value(€)</i>
<i>Biocontainer</i>	8500
<i>Cover</i>	1800
<i>Membrane</i>	8900
<i>Pump</i>	1000
<i>Pipeline</i>	2000
<i>Cabinet</i>	5000

An approximation of the singular costs required to obtain the equipment forming the system, were presented on detail in the Table 10; nevertheless, it was known that the total amount was around 35000 €. However, not only material things must be purchased; some technical assistance were required during the first steps, such as: a previous study to implement the pipeline, the installation and start up of it, which also involved an investment.

Table 11: Initial assistance costs of the system

<i>Assistance</i>	<i>Value(€)</i>
<i>Study of the implementation</i>	7000
<i>Installation and system start – up</i>	6000

Once the costs reported on the table 11 were considered, the total initial amount of the system was around **55000 €**. However, it is known that when the system was installed and running there is a necessity to maintain the optimum conditions of it,

which requires the replacement of the internal media and other particular expenses as substitute a equipment or a part of the system, such as: covers, pumps, and so on, that must be taken under consideration.

It is important to establish that the cost of the internal media was low, because it is based on natural materials; and that the values reported were an estimate calculated from the actual data of landfills in the region of Piedmont, but not precisely those under study.

Finally, it was observed that considering both analysis, the data seems to indicated that when a biofilter was obtaining satisfactory results the investment was worth it; however, when the regulations were not fulfilled or there was the necessity of having more than one system, more aspect must be put under consideration to establish if this is the best alternative to reduce the methane emissions in the atmosphere.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Seeking to fulfill the objectives of this thesis, this chapter will present the conclusions obtained by the previously analyzed data. On the other hand, recommendations were made in order to improve subsequent studies regarding the subject of this project.

Conclusions

- The characteristics of the input, regarding the quality and flow rate, determine the percentage of methane that will be obtained at the output, which is also affected by the conditions of the site where the landfill is located; for that reason, each biofilter under consideration presented different optimum values of the parameters affecting the process, as shown below:

It is important to remember that the values reported corresponds with the conditions that guarantees an output under the 1% limit and the efficiency of abatement above the 65%; reason why Grosso did not appear, because there were not any conditions reported under which satisfactory results were obtained.

- Even if the location of the landfills studied suffered variations of weather conditions due to the seasons, there was not relationship observed between period of the year and the characteristics of the input and output currents; however, in most cases, around August a methane percentage peak was observed in the input values, which may be caused by the increase in decomposition of the waste due to the higher external temperature.
- As a biological reaction, the degradation that took place in the biofilters, was

Table 12: Optimum values

<i>Landfill</i>	<i>Input of methane (%CH₄)</i>	<i>Flow (m³/h)</i>
<i>Pinerolo</i>	< 5	100 – 130
<i>Collegno</i>	< 6	160
<i>Bairo</i>	< 5	250
<i>Collereto</i>	< 5	100 – 120

Table 13: First comparison factor values

<i>Landfill</i>	2009	2010	2011
<i>Pinerolo</i>	3	3	3
<i>Grosso</i>	–	3 – 5,4	1,1 – 3,1
<i>Collegno</i>	4	4	4
<i>Bairo</i>	6,3	6.3	6,3
<i>Collereto</i>	1,7 – 3,1	1,3 – 3	2,5 – 4

considered a process that can not be controlled beyond the establishment of optimal values to ensure desired results, reason why some out of range values were observed without any particular cause.

- The external measurements regarding the output data were unreliable, due to the fact that in most cases the structure was not fixed, close or made by the same material of the cover, enabling the air to dilute the gas.
- In those landfills where both output methane percentage values (internal and external) were reported, the following common characteristics were observed:
 - On the passage through the biofiltration media, the abatement reported by the internal output was low; while the external values were always around the 100%; however, it was established the data reported in the outer measurement may suffer some alterations by the presence of air.
 - A direct relationship between the input and internal output percentage of methane was observed, corresponding with the theoretical information referring that the gas supply on the system affects the oxidation rate.
- The gas flow per biofilter volume results were:

Once observed the first comparison parameter calculated, it was possible to establish that:

- Bairo presented the highest values, corresponding with the lowest residence time of the treated gas on the system. The out of range result obtained in this landfill, was caused by the high flow rate previously reported.
- Without considering Bairo, the data allows to establish that the range of this particular factor was relatively stable between 1 and $4 \frac{m^3_{gas}}{m^3_{bio}} * h$ which indicated a time of residence fluctuating from 0.25 to $1 \frac{m^3_{bio}}{m^3_{gas}} * h$.

Table 14: Second comparison factor values

<i>Landfill</i>	2009	2010	2011
<i>Pinerolo</i>	6 – 23	3 – 20	10 – 20
<i>Grosso</i>	–	10 – 36	8 – 31
<i>Collegno</i>	6 – 16	2 – 22	3 – 13
<i>Bairo</i>	6 – 35	19 – 36	18 – 36
<i>Collereto</i>	3,4 – 9,7	1,6 – 9	3,5 – 8

Referring to the time of residence, it was considered that Pinerolo and Collereto presented most satisfactory results, because they reported the lowest flow, which ensured a good relationship between the contact media-gas (which was reflected in the abatement rate) and the time it took.

- The other comparison factor established was the methane volume per biofilter volume per hour, which presented the following results:

The following characteristics were observed in the data of the second comparison factor:

- In this case, the results obtained did not present a particular range or behavior over the years.
 - Collereto presented the worst quality of the gas, reporting the lowest values of this parameter.
 - Even if the landfill of Bairo is closed, it presented a high gas quality, which is caused by the values of flow and input percentage of methane reported.
- The 2012 data were not representative of the whole year, however, in the majority of the cases seem to indicate an improvement on the systems, which was considered very significant.
 - Regarding the investment needed for a biofiltration system, it is clear that it was worth it where the landfill was closed, and in the cases where only one biofilter was capable of reduce the methane emissions to reach desired results. Meanwhile, for active landfill other aspects must be taken into consideration.

Recommendations

To make the results more reliable, some aspects must be modified, such as: establish a generic structure over the cover, as the one showed on Fig.15(d), which was fixed, closed and made by the same material of the cover, ensuring a lesser dilution by air.

Finally, in those cases where the 2012 data presented a decrease in the efficiency of the system, it is recommended to follow the operation conditions to evaluate if a change of internal media must be done.

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