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Degree course in Environmental and Land Engineering

Master degree in Climate Change

Analysis of the bio-oxidative methods and Assessment of the feasibility study of an emissions treatment plant which takes place in Piedmont

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Academic Year 2021/2022

ACKNOWLEDGEMENTS

The following lines are aimed to thank all the people who contributed to write my thesis and thus to achieve a great goal. The first person I have a duty to thank is the Mr. Claudio Mattalia which gave me the opportunity to carry out the thesis at his company. Throughout his technical advises an experimental thesis was performed by making the whole work as a practical project.
A special thanks is addressed to my academic advisors Prof. Tiziana Tosco and Prof. Alessandro Casasso for hanging my requirement in the thesis accomplishment. Their precise suggestions were valuable in order to realize a worth thesis from both a formal and content point of view.
Moreover, I would like to thank Mr. Enrico Magnano (Emendo Srl) and Dr. Isabella Pecorini (University of Pisa) for having helped me, respectively, in examining the correlation between biogas release and meteorological parameters and in deepening the biofiltration technologies and the features of the respective plants.
Finally, a heartfelt thanks is dedicated to my family and my university friends who accompanied me on this tough university journey. I will always be glad to them for supporting me and for spending joyful times when I was in trouble.

ABSTRACT

The thesis concerns the study of the biogas emissions from a landfill site located in Piedmont.
The origin of the waste mass is mainly attributable to paper and cardboard which degradation leads to the biogas production. Landfills are among the main sources of greenhouse gases release into the atmosphere. The biogas is mainly composed of methane and carbon dioxide, both climate-altering gases. This thesis focuses on the analysis of the best technologies aimed to the treatment of the landfill gas emissions with respect to the site under investigation. The biogas emissions referred to the Piedmont site own low values in terms of methane flow as the maximum value sets at $0.038\ \mathrm{Nl\,CH_4/m^2h}$. In this scenario, one of the suitable methods to be implemented for such a kind of operation appears to be the bio-oxidation *in situ*. This technique consists in conveying the biogas flow through a filter media which is usually made up of compost and bark. From a bibliographic search, four different bio-oxidation methodologies can be identified which refer to biotarp, biocovers, biowindows and biofilters. In this regard, by comparing these technologies, biofilter and biowindows are the only suitable techniques that can be implemented to the site under investigation. Furthermore, by searching both case studies and field applications, two different biowindows pattern were identified, developed in Italy and Denmark. Thus, three different treatment plants are outlined in order to evaluate the best biofiltration technique after performing a practical feasibility study. The greatest difference between biofilter and biowindows consists in the project design. On one hand, biofilter is signified by an active biofiltration system where the biogas flow needs to be conveyed towards the filter media. On the other hand, as the biowindows are placed over the soil surface, they naturally exploit the upwards gas movement coming from the waste mass. The feasibility study leads to examine the different plant design in terms of realization procedure, performances, and costs. In this regard, because of the lower implementation costs and the highest performance in the methane reduction (efficiency up to 88 %), the Italian biowindow results to be the best bio-oxidative technology to be realized for the site under investigation.

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1. INTRODUCTION

The work of this thesis focuses on the study of landfill gas emissions produced by the anaerobic degradation of the organic matter, and the identification of possible treatment and mitigation technologies in order to reduce the release of GHGs into the atmosphere. The area under investigation is a site in Piedmont (North-West of Italy) which was subject to several reclamation activities at the beginning of 2000s. The area is currently labelled as "permanent safety site" where most of buried waste is represented by paper and cardboard. This work focused first on the study of biogas emissions from the waste mass and thus the analysis of the concentrations of CO_2, CH_4 and O_2. In this regard, the historical data belonging to these quantities were provided by the company Enviars S.r.l where the thesis work was carried out. Moreover, three investigation campaigns were carried out (two in October 2021 and one in December 2021), aimed at measuring biogas fluxes and the associated concentrations of the gaseous substances under investigation from existing wells.
A bibliographic search concerning the main drivers affecting the biogas production and emission was also carried out. As a result of the scientific search, it appeared how the biogas emissions can be affected, on one hand, by the landfill features and on the other hand, by the meteorological events. Therefore, the data were analysed to find eventual correlations among the biogas concentrations and key meteorological parameters. As a next step, possible technologies for the treatment of gas emissions were studied, in the framework of the prescriptions of legislative Decree n.121/20, Annex 1 on landfill gas control. Based both on the regulatory rules and on the biogas fluxes produced by the waste mass, *in situ* bio-oxidation resulted to be the most suitable technology in order to face out the gas emissions. The last part of this work focused on the design of a biofiltration system, based on the site characteristics (site morphology, power line supply and effective gas emissions) and the costs for the full-scale plant realization. Three different biofiltration systems were compared in a feasibility study, aimed at identifying the best treatment plant in terms of both environmental benefits and lower implementation costs.

2. BIOGAS PRODUCTION AND RELEASE

Biogas represents the fundamental product of the biodegradation process of the organic fraction of the waste. It is usually made up of 50-70 % of methane (CH_4), 30–40% of carbon dioxide (CO_2) and small amounts of hydrogen sulfide (H_2S), ammonia (NH_3), hydrogen (H_2) and carbon monoxide (CO). The generation of the biogas can take place spontaneously due to the natural activities of anaerobic bacteria, or the process can be induced artificially (An introduction to biogas and biomethane – Outlook for biogas and biomethane: Prospects for organic growth – Analysis, 2020). The three main sources of controlled biogas production include:

- Biodigesters: they consist in airtight systems (such as containers or tanks) in which organic matter is decomposed by naturally occurring micro-organisms.
- Landfill gas recovery systems: the breakdown of municipal solid waste under anaerobic conditions at landfill sites produces biogas. This can be conveyed through pipes and extraction wells along with compressors to induce flow to a central collection point.
- Wastewater treatment plants: these systems can be entrusted with recovering organic matter, solids, and nutrients such as nitrogen and phosphorus from sewage sludge.

Since the thesis focuses on the analysis of biogas production and diffusion from landfill sites, the natural biogas formation from municipal solid waste will be addressed in more detail.
Municipal landfills receive partly biodegradable waste which generate landfill gas during waste decomposition.
The waste decomposition can take place throughout three mainly different mechanisms: physical, chemical and biological processes. However, the biogas production is only attributable to the biological process which will be deeply examined in the following pages.

2.1 LANDFILL BIOGAS PRODUCTION

The biological processes that characterize the waste degradation can be subdivided in two main stages which lead to the biogas formation:

- Aerobic phase
- Anaerobic phase

In this regard, Figure 2.1 illustrates all the steps involved in the biogas formation where the generation rates as well the landfill gas vary through the landfill's life ('EPA-_Management_Of_Low_Levels_Of_Landfill_Gas', 2011).

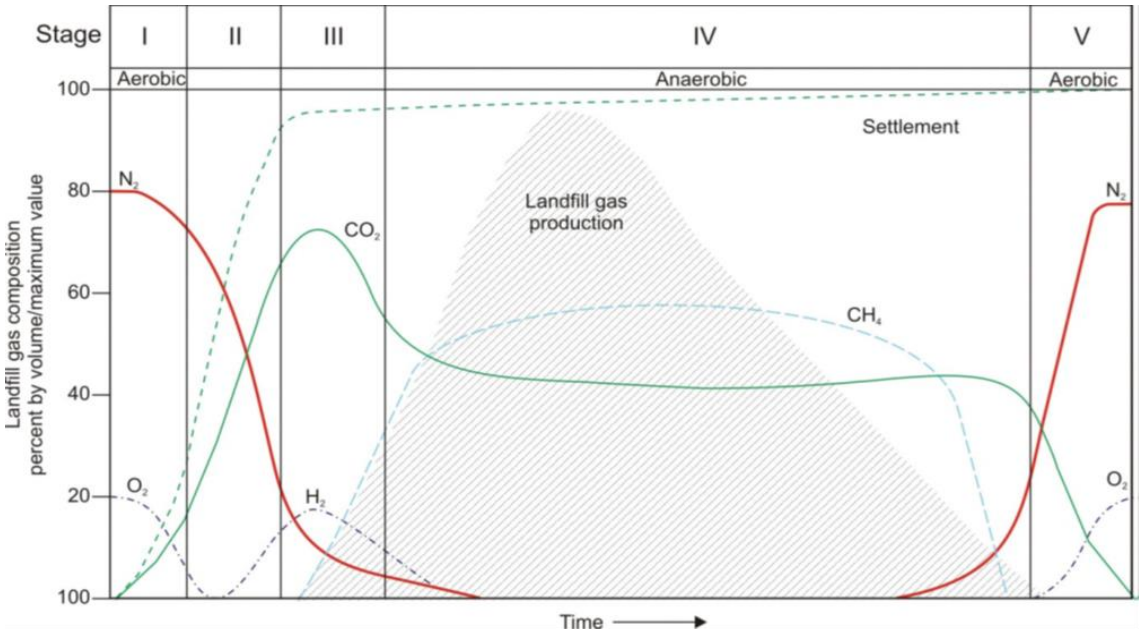


Figure 2.1, Changes in the production and composition of landfill gas over time. ('EPA-_Management_Of_Low_Levels_Of_Landfill_Gas', 2011)

As the image suggests, the biogas formation can be outlined in five main stages which are here described:

- <u>Aerobic stage (I)</u>

Originally the gas phase in a landfill cell is composed of atmospheric gases. The oxygen presence allows aerobic, , highly exothermic microbial processes to start. The aerobic decomposition takes place rapidly, and it is faster than the following anaerobic decomposition. The general reaction of this transformation is given as follows:

Degradable waste + O_2 → CO_2 + H_20 + Heat + Materials partially degraded

The previous relation explains how, during exothermic processes, carbohydrates are converted into water and carbon dioxide. Aerobic micro-organisms produce CO_2 in very high concentrations, up to 90% by considering temperatures setting at 70°C.

- Anaerobic stage

Once oxygen is consumed, the anaerobic phase of the decomposition process begins. It is favoured by the internal conditions of the landfill cells which are characterized by acidic pH, absence of oxygen and high temperatures. The main stages of the anaerobic degradation are:

a) hydrolysis and acidogenesis;
b) acetogenesis;
c) methanogenesis.

a) hydrolysis and acidogenesis (II): during this phase, each compound characterized by high molecular weight undergoes hydrolysis processes performed by enzymes. In particular, they lead to the formation of compounds with a lower molecular weight. This phase, usually lasts for a few days or few weeks. Subsequently, the acidogenesis takes place which is called also "unstable acid phase". Because of the action of the acidogenic bacteria, the products which were obtained during the first phase are transformed into compounds characterized by an even lower molecular weight. In this stage, a prelaminar H_2 production occurs that is carried out by the optional anaerobic bacteria placed in the waste mass. In this regard, H_2 percentages can reach also 20% by volume. At the same time, it is possible to notice N_2 percentages ranging from 30-50%.

b) acetogenesis (III): it represents the stable acid phase where fermentative bacteria produce volatile fatty acids in addition to ethanol, lactic acid, carbon dioxide and hydrogen. Furthermore, these products undergo other reactions by transforming them into acetic acid and hydrogen, the reference transformations are carried out by acetogenic bacteria present in this phase. The overall time needed for this kind of process lasts for few months to two-three years.

c) methanogenesis (IV): this is the phase where the methane production occurs for the first time. At the same moment, methane and carbon dioxide are produced because of the acetate cleavage or by the chemical reaction between hydrogen and carbon dioxide:

$CH_3\ COOH \rightarrow CH_4 + CO_2$

$H_2 + CO_2 \rightarrow CH_4 + 2\ H_20$

Furthermore, during the stable methanogen phase, the hydrogen is consumed to low concentrations (5% by volume). On the other hand, it is possible to observe an increase in CH_4 and CO_2 concentrations, they can reach high values ranging from 45-60% and 40-60%, respectively.

d) maturing phase (V): it is the last stage of the production process. Once the available organic matter is completely degraded, the production of carbon dioxide and methane begins to become negligible, until it stops. Air comes back to spread over the landfill and N_2 and O_2 are measured again.

The last two stages involve a large time window. Methane production needs many years to completely occur, sometimes up to 30 years. Thus, considering young landfills, it can happen that the bio stabilization process has not entirely developed yet and the stable phase could not be reached. In this scenario, the biogas composition includes H_2 presence and CH_4 concentrations lower than 45%. On the other hand, CO_2 and N_2 percentages are slightly higher than the methanogen stable phase.

2.2 ASSESSMENT OF LANDFILL GAS EMISSIONS

The need to avoid possible gas uncontrolled releases at landfill surface requires a successful maintenance of the site. In this regard, UK and Wales Landfill Directive established guidelines for controlling gas leaks (Bristol, 2010). This Landfill Directive deals with following gas control measures :

- suitable measures to monitor the accumulation and migration of landfill gas;
- landfill gas must be picked up from all landfills receiving biodegradable waste and the gas must be treated and (whether it is viable) re-used;
- the collection, treatment and use of landfill gas should be aimed to minimise damage or deterioration with respect to the environment and to the human health;
- flare landfill gas that cannot be used to produce energy.

Landfill gas is continuously produced by micro-organisms present in the waste body. Thus, the installation of an active landfill gas collection system decreases the risk of uncontrolled releases.

Before realizing an active collection system in the body of a landfill, the guidance points out as a first step the detection of eventual gas leaks throughout faults in the impermeable landfill cap.

The main methods which can be used for this purpose refer to walkover surveys and flux box surveys. In the first stage, walkover survey is carried out to identify where methane emissions are high by using a hand-held gas monitoring equipment. Subsequently, in the second stage flux boxes are employed to quantify the rate of emissions throughout capped zones and from recognizable features within the cap. With regard to this Landfill Directive, the term “zone” refers to an “extensive area of the landfill site surface that is generally uniform and homogeneous in those factors that affect surface emissions” such as, for example, type of capping, slope and surface integrity. On the other hand, “feature” is intended as a “smaller, discrete area or an installation from which methane emissions are different from the adjoining or surrounding zone”.

It means that, zones are larger areas where the methane emissions are likely uniform to the surrounding area, while features represent anomalies surface where it is possible to find gas fluxes which values do not reflect values from closer areas.

On one hand, “flux box surveys are compliance checks and they do not point out short-terms fluctuations in performance”. On the other hand, walkover surveys are used to identify areas of high methane percentages and they can instantly highlight possible changes in methane concentrations. Furthermore, when facing out such a kind of topics, it needs to consider also the frequency of monitoring. At the beginning of monitoring activity, a walkover survey is performed in order to detect eventual gas leaks because of capping faults. After evaluating the presence of methane emissions, flux box survey will be taken for one year period. Whether the on-site tests show that the emissions values do not comply with the threshold limits, a further remedial work must be realized and checked by a suitable survey. On the other hand, if the emissions values respect the standard emissions and no appreciable physical changes in the gas management were detected during the year, a detailed annual walkover survey is carried out to signify that the surface emissions are compliant. In this case, a new flux box survey is not necessary.

Surface standard emissions differ depending on the type of zone. In this regard, by considering zones with permanent cap the reference value sets at 0.001 $\frac{\mathrm{mg}}{\mathrm{m^2 s}}$, while for zones characterized by a temporary cap the reference value is fixed at 0.1 $\frac{\mathrm{mg}}{\mathrm{m^2 s}}$.

Finally, the rules just mentioned refer to a general case study and the frequency of monitoring could not be always the same as the time interval is site-specific.

2.1.1 Walkover surveys

Walkover survey represents one of the possible solutions described in the UK Landfill Directive in order to detect gas emissions. As it was previously mentioned, the walkover survey is usually performed by a hand-held gas detector which can be ,for example, a flame ionisation detector (FID). The walkover survey of the zone is carried out along regular lines or transects. Referring to a permanent cap, transects are typically placed 50 metres apart, while, regarding a temporary cap they are usually placed 25 metres apart. Whenever odours coming from the ground surface represent a critical issue, the transects should be closer than 25 meters. The surveyor which is responsible for carrying out the work, he starts by walking on predetermined lines, in this way the gas concentration is continuously monitored. Once high methane concentrations are detected, the survey should address towards the likely emission source. At this point, it is possible to identify several emission points and the surveyor is able to create a 2D map to represent the areas where the methane emissions are higher. The difficult operations related to the initial walkover survey depends on the nature and on the quality of the cap, large faults can be also determined by visual feedback. Furthermore, surface scanning techniques can be implemented to map changes in methane concentrations over the source of emissions. In order to carry on a successful walkover survey two parameters should be considered:

- current meteorological conditions (barometric pressure, recent precipitation, wind speed and direction);
- kind of infrastructures close to the survey area (for example activities that may release gas or lead to gas migration)

In this regard, the last two guidance need to be taken into account when analysing the methane emissions because they can affect the results of the surveys. Finally, the definite result will consist in creating a map of the site showing the areas with the higher methane concentrations which correspond to the larger faults of the capping surface. Whether methane surface emissions set at low values, no remediation plans are needed. In this case, the following actions consist in designing and planning the flux box survey. On the other hand, if the gas emissions overcome the standard emissions it is necessary to implement an action plan which is followed by the remediation activity.

2.2.2 Flux box surveys

A flux box is an efficient technology used to measure surface emissions through the landfill cap. Usually, it is not recommended to implement other direct methods for quantifying methane surface emissions (such as depth/concentration profiling) because of the amount of assumptions and parameters needed to perform the on-site activities. A flux box consists in an enclosed chamber where it is possible to detect the changes in methane concentration over a specific, limited area (Figure 2.2). The reference area covered by the flux chamber, usually, sets at around 1 m^2. The flux box gives individual values in terms of methane concentration at that location. Therefore, whether several flux boxes are placed over the entire area, it is possible to calculate the overall flux coming from the landfill site. In this regard, the methodology to be used is simple, quantitative and repeatable for each location, so many individual locations can be measured in one day. Furthermore, the measurements do not require information about the on-site variables such as soil physical parameters and prevailing meteorological conditions.

For a successful monitoring activity, the design of the flux box survey should guarantee the following criteria:

- areas identified by similar characteristics are monitored together;
- zones and features must be uniquely identified and measured;
- all zones and features should cover the total capped part of the landfill site;
- monitoring locations are representative of the zone or feature.

Flux boxes should be placed in flat zones which number is calculated as (USEPA, 1986):

$$n = 6 + 0.15\sqrt{z}$$

where "z" represents the surface of the zone under investigation expressed in m^2. The equation can be only applied in sites larger than 5,000 m^2.

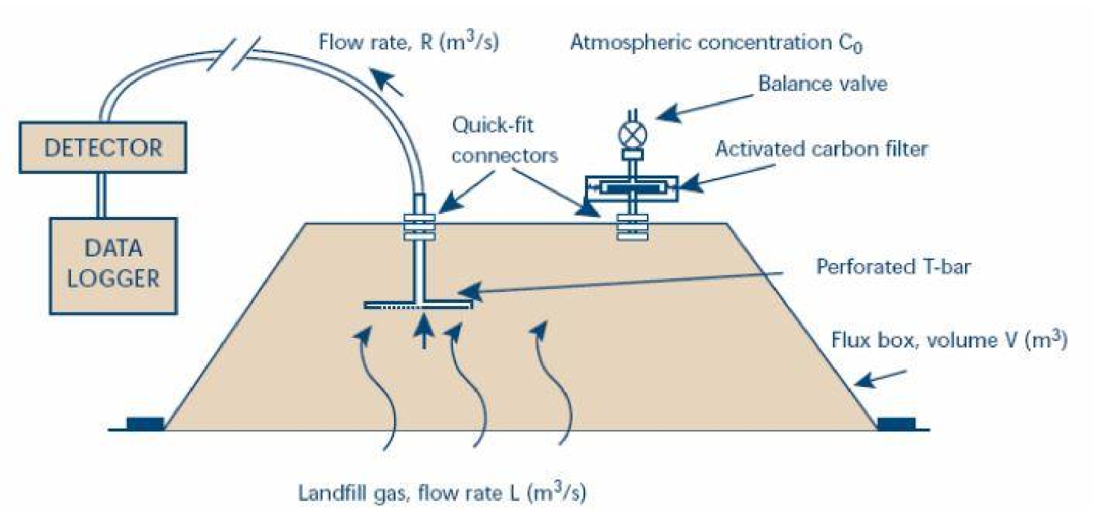


Figure 2.2, Schematic of a passive flux box. (Bristol, 2010)

Figure 2.2 represents a passive flux box (Bristol, 2010). It consists in a chamber of known volume, with two ports in the top part. The inlet port is used for pressure equilibration, while, the outlet port concerns the samples removing. This kind of arrangement simplifies the sampling of gases without interfering the pressure within the box. Subsequently, the methane concentration is analysed outside the box by using a portable gas detector which can be a flame ionisation detector (FID) or another tool characterized by a similar sensitivity and response time. The main parameters used for the flux box working are here listed:

- a simple container with a level, open base that can cover a surface of approximately 1 m^2.
- two controlled openings placed on the top face of the box;
- a sampling line,
- a gas detector with an optional data logger.

Usually, the flux box has a footprint lower than 1 m^2, therefore it is a reasonable compromise between footprint area and viability on site. To conclude with this topic, it is worth to remember that the functioning of a flux box leads to identify locations where the gas flux overcomes threshold limit and thus, it needs to begin a further remedial work.

3. GENERAL OVERVIEW OF THE PIEDMONT SITE

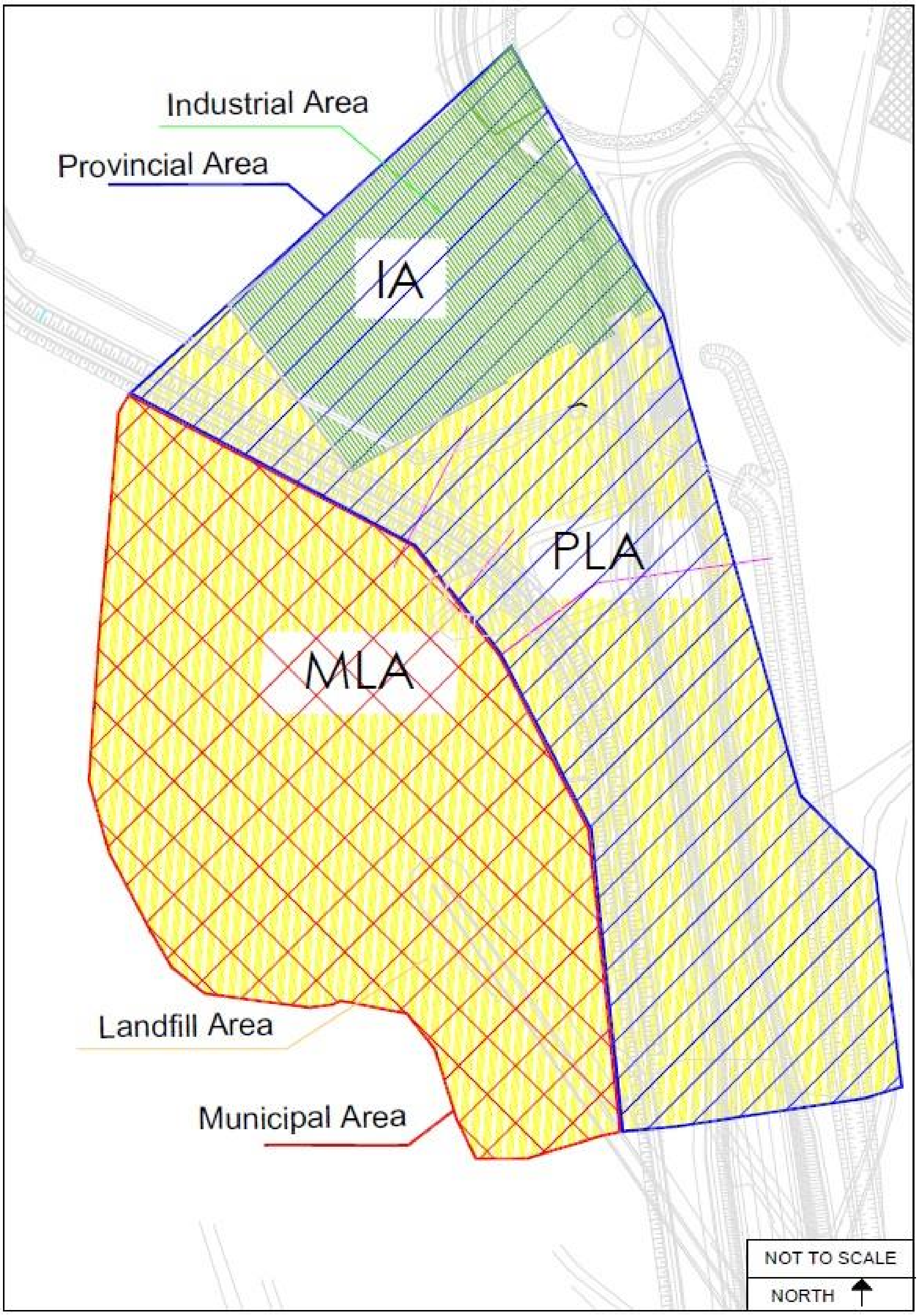
3.1 SITE CHARACTERIZATION

The site under investigation is a small landfill in Piedmont, in the North-West of Italy. From an administrative point of view, the area is labelled as “permanent safety site” according to the Ministerial Decree 471/99, as it was subject to several remediation activities. The definite area will be named as “Site”. The altitude of this area ranges between 255 and 265 m above the sea level where the land holds an average slope of 0.7 %.

In 2005, the area included some vegetable gardens and an obsolete inert treatment plant with settling tanks and heaps of various materials, mostly paper and polyethylene scraps which were partly colonized by dense spontaneous weed vegetation.

In this regard, a preliminary project was realized in order to achieve the reclamation of the site. During the characterization studies, the area was divided into two sections: industrial area (IA) and landfill area (LA). Subsequently, during the planning phase related to the permanent safety actions, the landfill area was further subdivided into provincial (PLA) and municipal area (MLA), the whole planimetry of the site is represented in Drawing 3.1. In particular the three areas mentioned above have the following features:

- Landfill Area administered by a provincial authority: it is the eastern sub-area of the site occupied by paper material and polyethylene scraps with settling tank. This area is aimed for the infrastructures building.
- Landfill Area administered by a municipal authority: it is the western sub-area of the site occupied by paper material and polyethylene scraps. This area is intended for agricultural-productive use.
- Industrial Area: it is located in the NE sub-area of the site occupied by industrial buildings, plants and areas of expertise.



Drawing 3.1, Planimetry of the authority areas.

The Provincial Landfill Area extends over a surface equal to 45,000 m^2. Because of the topographical survey, the presence of nine heaps of waste was detected. They are characterized by an average height of about 3 m occupying a total area equal to 10,000 m^2. So, the reference volume is estimated at around 30,000 m^3.

The characterization was carried out in July 2005 and it showed the presence of mixed material paper, plastic, aluminum, similar to the surface heaps, even in the subsoil. The total extension of the area characterized by the presence of buried paper and plastic waste has been estimated at approximately 35,000 m^2, for a conservatively estimated total volume close to 140,000 m^3. Field activities also

highlighted a diffuse contamination by heavy hydrocarbons which are spread over most of the landfill area. Contamination induced by metals was also detected Municipal Landfill Area where numerous exceedances were recorded belonging to the following parameters: cadmium, total chromium, lead, antimony, cobalt, mercury, copper, zinc and tin.
On the other hand, the Industrial Area which takes place in the north zone of the site presents a surface equal to 8,300 m^2. In this case, most of the uncovered portion is occupied by heaps of waste, which are mainly made up of plastic and metal waste. With regard to these waste, they derive from the demolition of household appliances and plastic and paper residues of various kinds. The average height of the mounds is equal to about 2.5 m. Field surveys carried out in November 2005 highlighted the absence of waste stored below the ground level and a limited presence of pollution for this area.

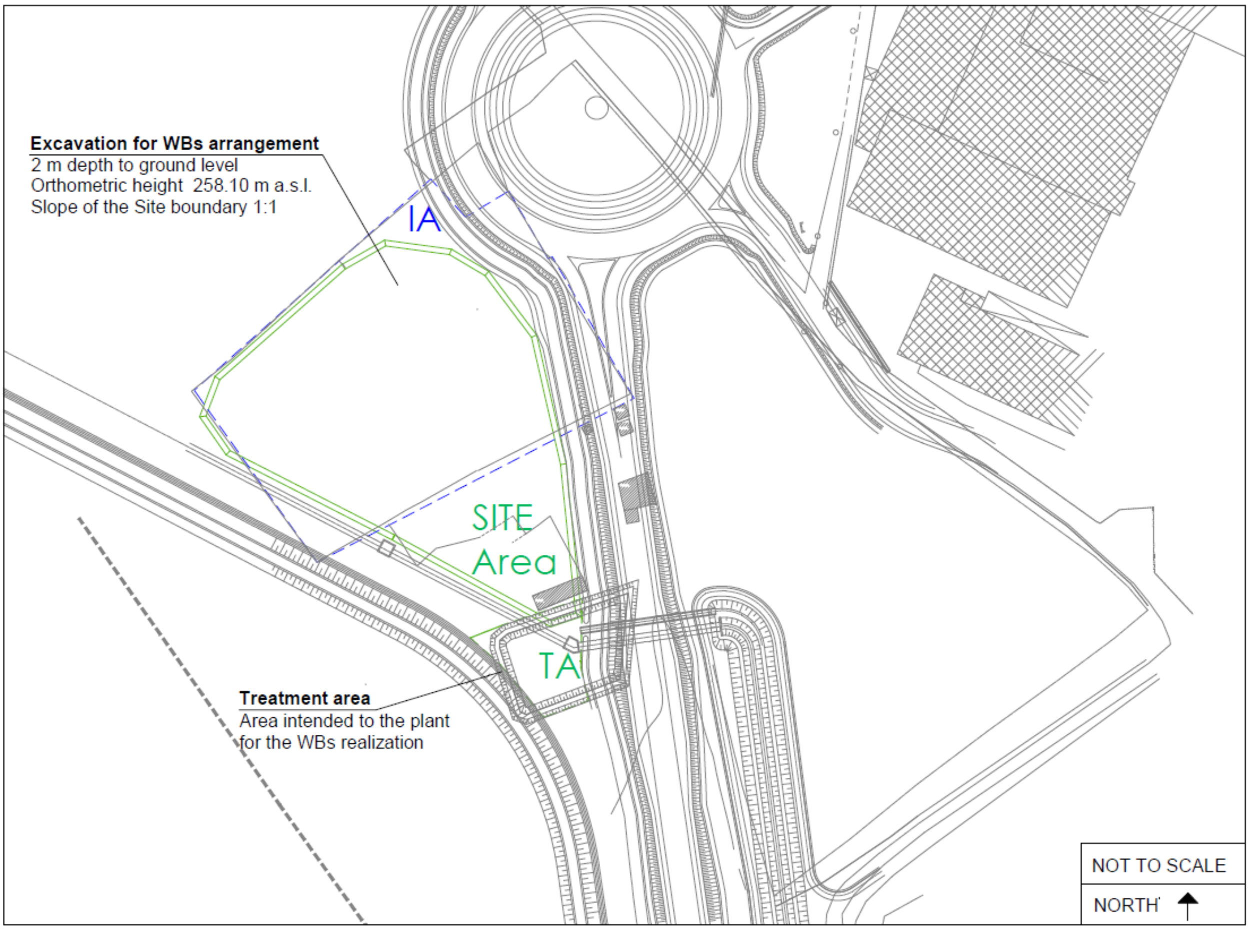
3.2 SITE RECLAMATION

The remediation activities were planned and implemented in the framework of the Ministerial Decree 471/99. The possible alternative included:

- Complete remediation of the site through the removal and delivery of waste and contaminated soil which are aimed to suitable authorized facilities for the disposal or treatment of waste.
- Remediation with safety measures (pursuant to art. 5 of Ministerial Decree n. 471/99) characterized by the removal of waste and contaminated soils that exceed the specific limit concentration values for the site defined according to a specific risk analysis. Soil contaminants which are signified by lower concentration values than the previous limits can be left on site with suitable safety measures.
- Permanent safety measures (pursuant to art. 6 of Ministerial Decree n. 471/99) divided into interventions that make it possible to isolate waste and avoid risks for the population and the aquifer and in interventions for the removal of contaminated soils that exceed the specific limit concentration values for the site defined according to a specific risk analysis. Soil contaminants which are signified by lower concentration values than the previous limits can be left on site with suitable safety measures.

Based on a cost-analysis, the complete removal of waste and the off-site treatment of the contaminated soil was discarded because it was economically unfeasible, and the implementation of a permanent safety area (named Site in the map) was adopted.

The waste treatment consisted in the removal by excavation, the volume reduction by mechanical compaction, and their packaging in cylinders wrapped in an impermeable film. The result of the treatment is an ecologically safe waste bale (WB) which was easy to transport and to place on site in the area designed for the storage, that is called "Dune". The planimetry of the site for the Waste bales arrangement is illustrated in Drawing 3.2.



Drawing 3.2, Planimetry of the Excavation area for the Waste Bales placement

3.2.1 Pilot test

A pilot test was performed to verify the effectiveness of the mechanical treatment for volumetric reduction of the waste, by evaluating the compressibility and insulation of the treated waste within the plastic film. The pilot test was divided into two phases:

- Phase 1: an external plant to evaluate of the compression coefficient of waste and then to verify the volumes of Wasta Bales and final arrangement within the Site area.
- Phase 2: another storage facility where the compacted product was sent and stored for three months to verify the physical-chemical evolution of packaged waste.

Here, the work was focused on the analysis of several parameters, namely pH, temperature, humidity, and the possible production of odours and gases.

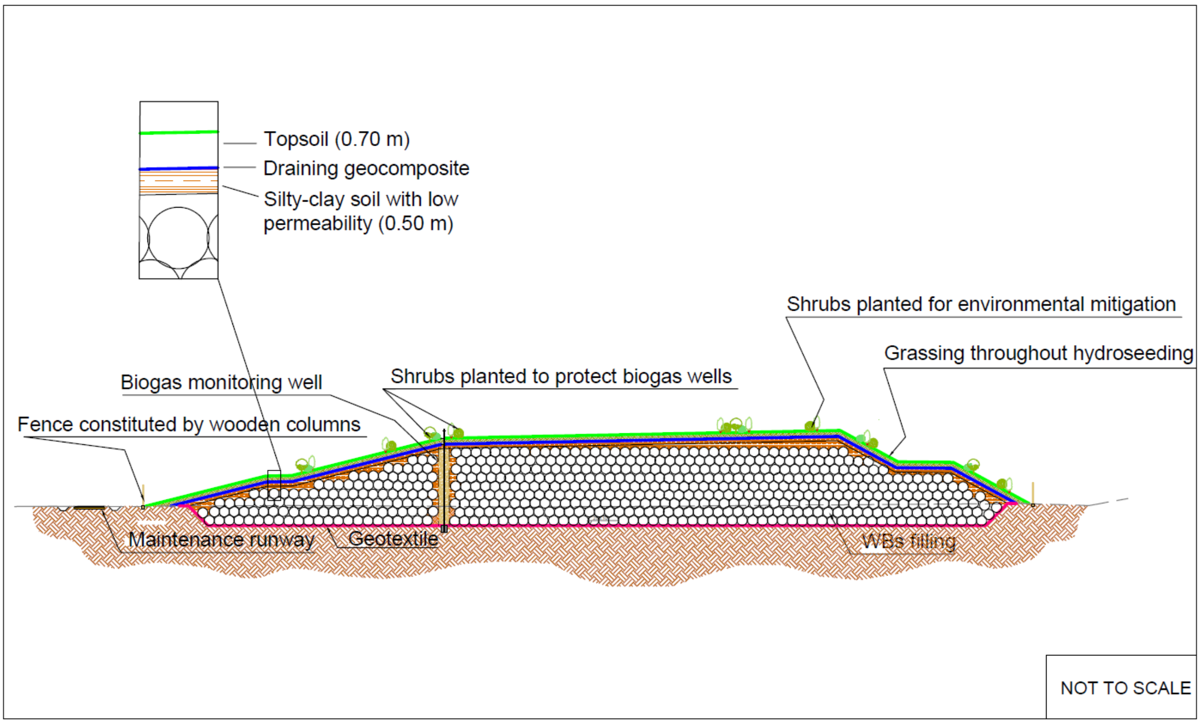
The pilot test took place in June 2006 and involved a volume of 10 m^3 of waste (4,700 kg, in-situ bulk density 0.4 t/m^3). Following compaction and packaging of the waste a compaction index equal to 65% was obtained.

3.2.2 Description of the full-scale remediation works

After the pilot test, the waste was excavated and deposited in the Provincial Area. A treatment plant was built close to this area, designed to convert about 66.600 m^3 of waste into the final material, with an expected final waste volume of approximately 43,290 m^3. The design characteristics of the Dune (area where the Waste Bales was placed after treatment) are summarized in Table 3.1, while the Dune section is illustrated in Drawing 3.3.

Table 3.1, Dimensioning of the Dune.

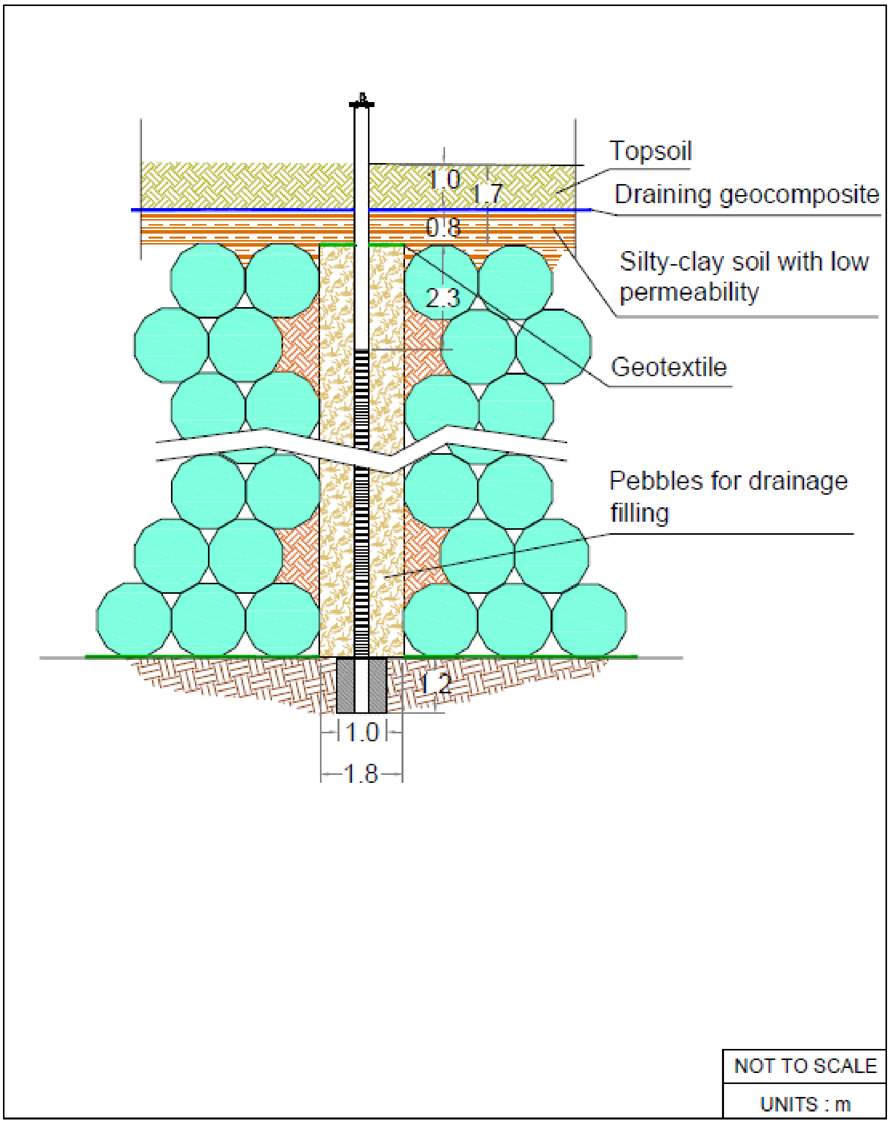
Description	U.M.	Value
Available surface: Site area	m^2	7,200
Orthometric height of the excavation floor	m a.s.l.	258.1
Waste volume excavated	m^3	66,600
Volume of the packaged material in WBs	m^3	43,200
N° layers Waste Bales (max)	-	9
Height of the waste deposition	m	10,8
Height of the waste deposition (max) -after settling	m	10.1
Capping layers	m	1.2
Height of the ultimate Dune (max)	m	11.3
Orthometric height of the Dune	m a.s.l.	269.43



Drawing 3.3, Dune cross section.

At the bottom of the Dune section, the plinths that form the foundation of the biogas well were built. A scheme related to the well construction is represented in Drawing 3.4.

At the same time as the Waste Bales are dismantled, the biogas monitoring wells were raised by inserting through threaded HDPE pipes, for a maximum height of 12.5 m from the foundation. Finally, the whole area holds seven biogas monitoring wells.



Drawing 3.4, Scheme of the biogas well.

3.2.3 Biogas monitoring in the waste body

Once the working plan was completed, a periodical monitoring campaign was started, including monthly surveys of the quality of the interstitial air with special portable instrumentation. This monitoring dealt with periodic measurements of the parameters listed below at the appropriate inspection points:

- Concentration (% v/v) of methane (CH_4), oxygen (O_2) and carbon dioxide (CO_2), in addition to the lower explosive rate;
- Differential pressure (mbar);
- Temperature (° C);
- Atmospheric pressure (mbar) and temperature (°C).

The frequency of the monitoring took place every fifteen days for the first six months from the Dune realization and subsequently with a monthly frequency.

3.2.4 In-process variations

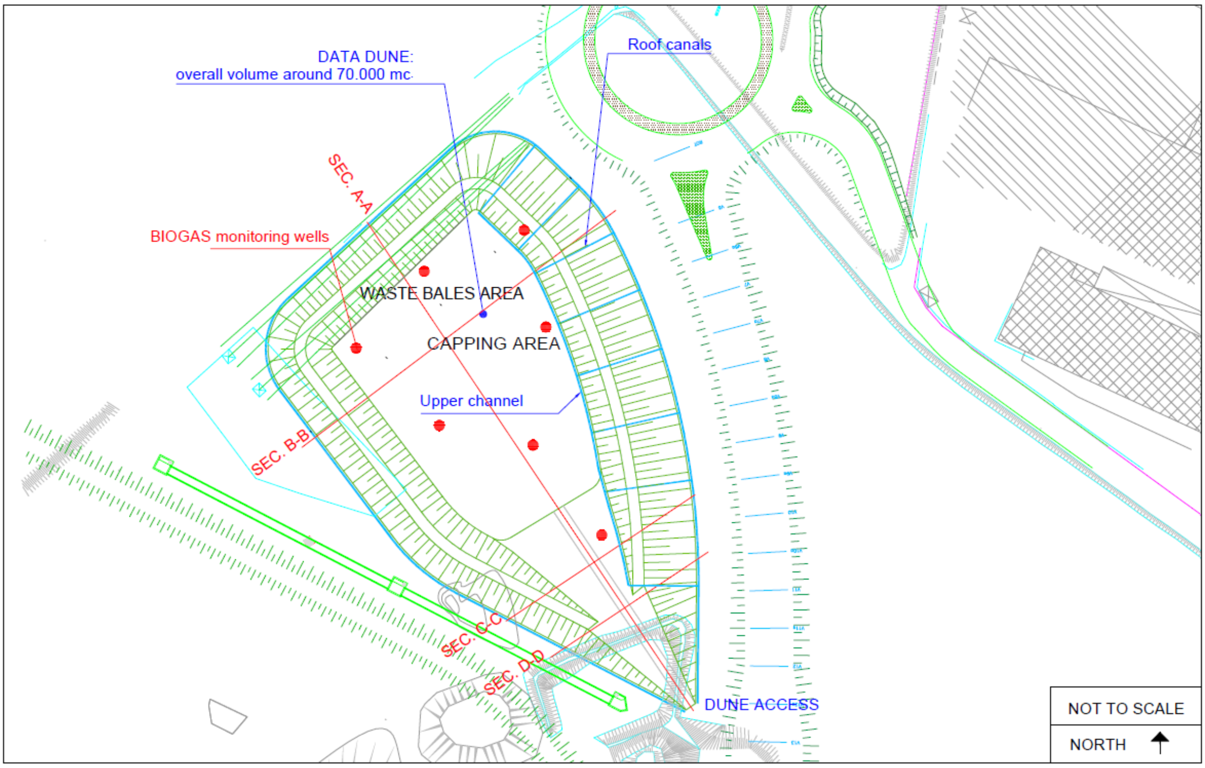
The original working plan, which was signed in July 2006 provided for the following actions:

- Demolition of all buildings
- Installation of the mechanical plant for the waste treatment and arrangement of the WBs within the Site area.
- Dune coverage and realization of the ancillary works.

However, after performing the first activities it was noted that two in-process variations needed to be carried out. In particular they referred to:

- 1st variation: it was aimed to a new Dune configuration with the enlargement of the permanent security area. This condition refers to a greater available area due to some variations related to road works. In this regard, the new area extended towards the South-West direction with respect to the original planimetry.

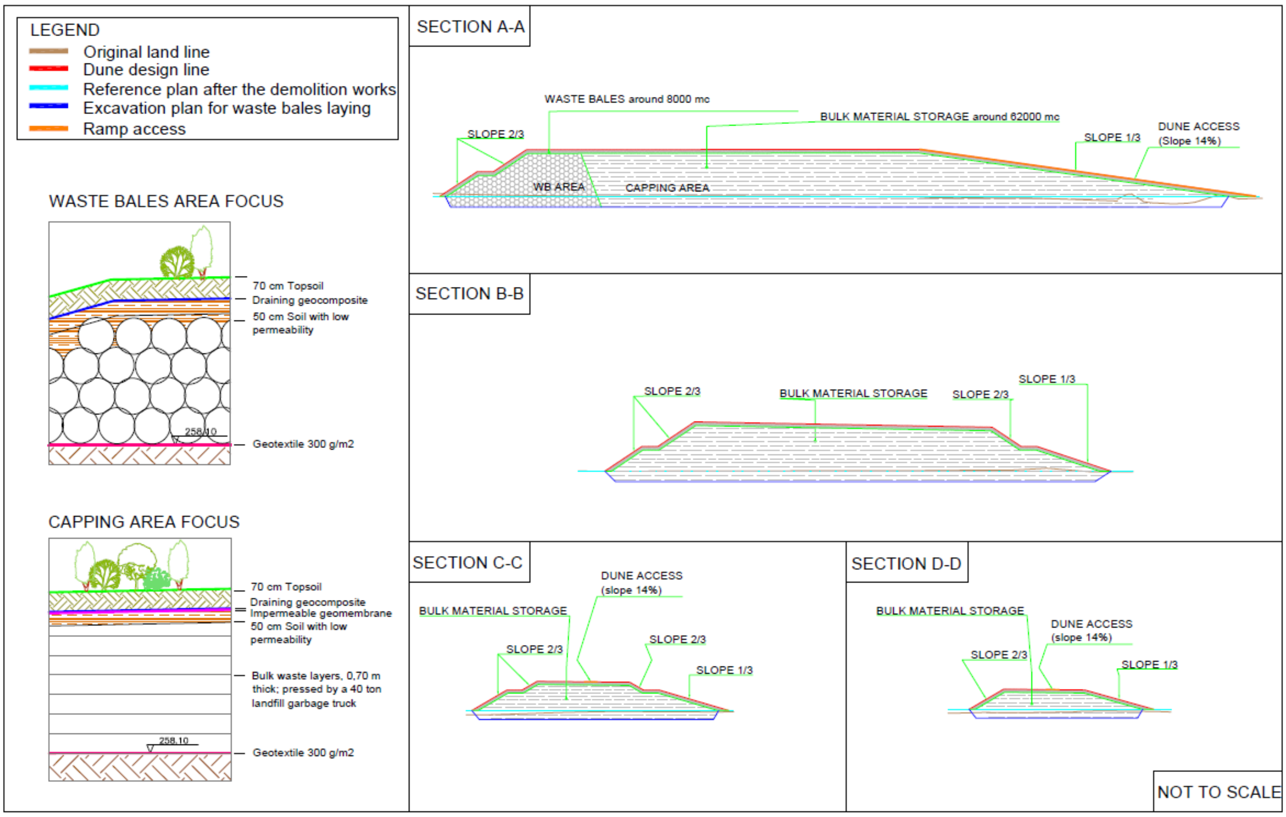
The new Site configuration is shown in Drawing 3.5.



Drawing 3.5, Planimetry of the definite Site area.

- 2nd variation: it dealt with a partial modification of the system adopted for the waste disposal. It comes from some technical issues encountered during the first months of the waste treatment. In fact, because of the great presence of earthy material, the specific weight of the treated material resulted higher making the Waste Bales realization harder. At this point, the waste arrangement area appeared to be subdivided into two sections:
  a) Waste Bales disposal area as it was originally planned, in this case waste are mainly made up of the lighter material fraction.
  b) Direct disposal waste in a new storage area (waste as it stands) where the waste shows high percentages of earthy fraction.

On one hand, in the northern area of the Site the waste bales storage takes place, their coverage was performed throughout a 50 cm silty-clay material layer, followed by laying of a draining geo-composite and a 70 cm final covering layer of topsoil. In the southern area, on the other hand, the waste material as it stands (WAIS) takes place. Moreover, such a kind of waste was isolated on the roof by a continuous waterproof geomembrane for the entire stored body. A draining geotextile and a final covering made up of about 70 cm of topsoil were placed on the waterproof sheet.
In this regard, Drawing 3.6 illustrates the cross sections related to both the waste bales and the waste as it stands.



Drawing 3.6, Definite Dune cross sections.

3.3 POST-COMPLETION ACTIVITIES: BIOGAS MONITORING

After concluding all the working activities ended up in December,2012, the operation plan required also monitoring actions in order to detect potential biogas emissions within the Site. The monitoring was performed on a fortnightly basis for the first six months from the date of works completion and then with a monthly frequency. In particular the limit value for CH_4 concentrations was settled at 1% and the overall monitoring campaign will last for 5 years.

Therefore, the periodic monitoring allows to detect the eventual formation of methane starting from the evolution of the concentrations of carbon dioxide and oxygen. This would make it possible to plan operations such as:

- a possible biogas extraction and treatment plant
- the positioning of any monitoring wells in the soil surrounding the Dune, which are aimed for the detection of possible leaks from the portion of the Waste Bales buried.

Since the first monitoring campaign started in January 2013, methane concentrations were significant and they resulted higher than the threshold value which was previously mentioned. The following tables (Table 3.2 and Table 3.3) shows the reference values for CH_4 concentrations belonging to the first two years monitoring.

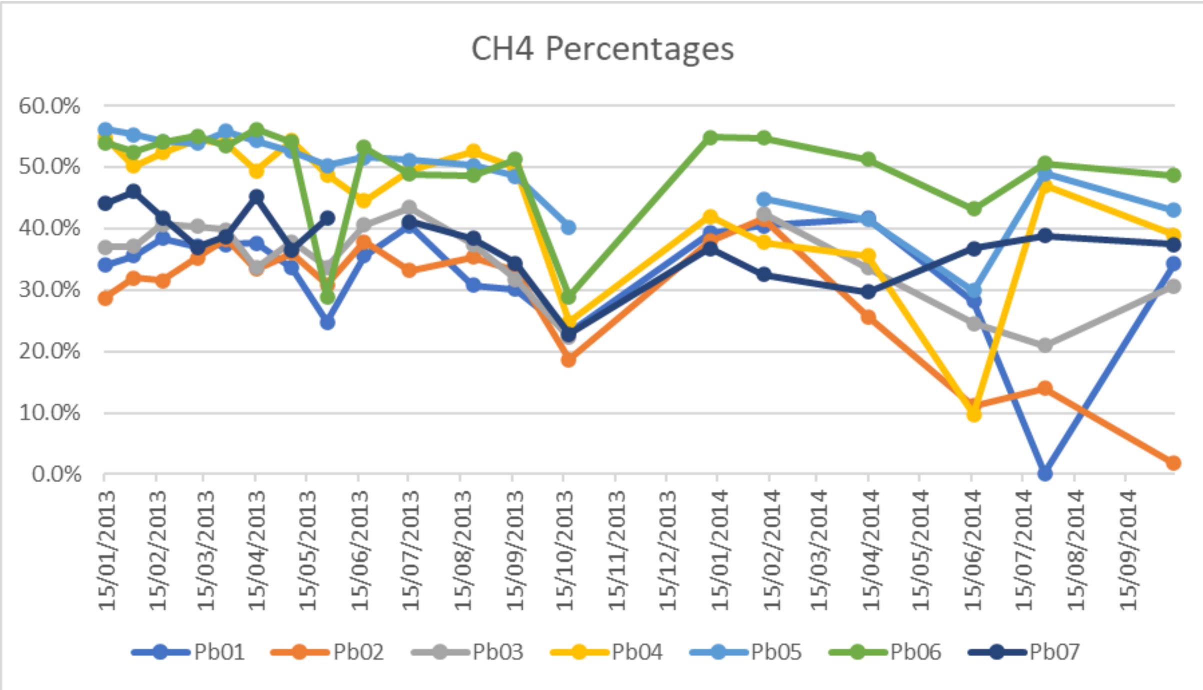
Table 3.2, Methane percentages - inner wells.

Well	Pb01	Pb02	Pb03	Pb04	Pb05	Pb06	Pb07
15/01/2013	34,0%	28,7%	37,0%	54,8%	56,1%	54,0%	44,1%
01/02/2013	35,6%	32,0%	37,1%	50,2%	55,3%	52,4%	46,0%
18/02/2013	38,4%	31,5%	40,7%	52,3%	54,2%	54,1%	41,8%
11/03/2013	37,1%	35,2%	40,3%	54,5%	53,8%	55,1%	37,0%
28/03/2013	37,4%	38,3%	39,8%	53,8%	55,8%	53,4%	38,7%
15/04/2013	37,6%	33,4%	33,6%	49,4%	54,3%	56,1%	45,1%
06/05/2013	33,6%	36,0%	37,8%	54,3%	52,5%	54,1%	36,5%
27/05/2013	24,8%	30,9%	33,7%	48,7%	50,3%	28,9%	41,6%
18/06/2013	35,5%	37,8%	40,6%	44,5%	51,6%	53,2%	
15/07/2013	40,5%	33,1%	43,4%	49,5%	51,1%	48,8%	41,1%
22/08/2013	30,8%	35,3%	37,4%	52,5%	50,3%	48,6%	38,4%
16/09/2013	30,1%	33,1%	31,7%	49,8%	48,5%	51,2%	34,3%
18/10/2013	23,1%	18,7%	22,3%	24,8%	40,2%	28,9%	22,8%
10/01/2014	39,2%	37,9%		42,0%		54,8%	36,8%
11/02/2014	40,4%	41,5%	42,4%	37,7%	44,8%	54,7%	32,5%
14/04/2014	41,6%	25,6%	33,6%	35,6%	41,4%	51,2%	29,7%
16/06/2014	28,1%	11,1%	24,6%	9,7%	29,9%	43,2%	36,7%
28/07/2014	0,2%	14,0%	20,9%	47,0%	48,9%	50,6%	38,8%
13/10/2014	34,2%	1,8%	30,7%	38,9%	43,0%	48,6%	37,4%

Table 3.3, Methane percentages - outer wells.

Well	Pn1	Pn2	Pn3	Pn4	Pn5
28/07/2014	15,5%	27,3%	0,2%	0,2%	1,4%
13/10/2014	0,2%	24,7%	0,1%	0,1%	0,2%
05/12/2014	5,8%	28,1%	0,2%	0,1%	5,1%
19/02/2015	0,2%	1,7%	0,1%	0,1%	0,1%
09/03/2015	0,1%	0,2%	0,2%	0,0%	-

Subsequently, Graph 3.1 was realized to better show the CH_4 concentrations trend during the first two-year monitoring.



Graph 3.1, Methane concentrations monitoring (2013-2014).

By looking at the Graph 3.1 it is possible to observe the CH_4 concentrations trend related to the inner wells of the Site. From January,2013 to October,2013 it is easy to distinguish the difference in methane percentages between the North and the South wells. Greater values belong to the second category where the waste as it stands takes place. This list includes Pb04, Pb05 and Pb 06 where the methane values overcome the 50%. On the other hand, the North wells, namely Pb01, Pb02, and Pb03 show lower methane concentrations which set between the 30% and 40%. Finally, Pb07 well holds intermediate values among the two categories above mentioned. The Autumn,2013 highlights a common characteristic among every well which is identified by a clear decline in the methane concentrations. Referring to the second part of the Graph 3.1, instead, Pb06 is the only well that seems to show a regular trend.

Its values, in fact, reflect similar CH_4 percentages with respect to the initial monitoring period. On the other hand, all the other wells highlight a slight decrease in terms of methane percentages.

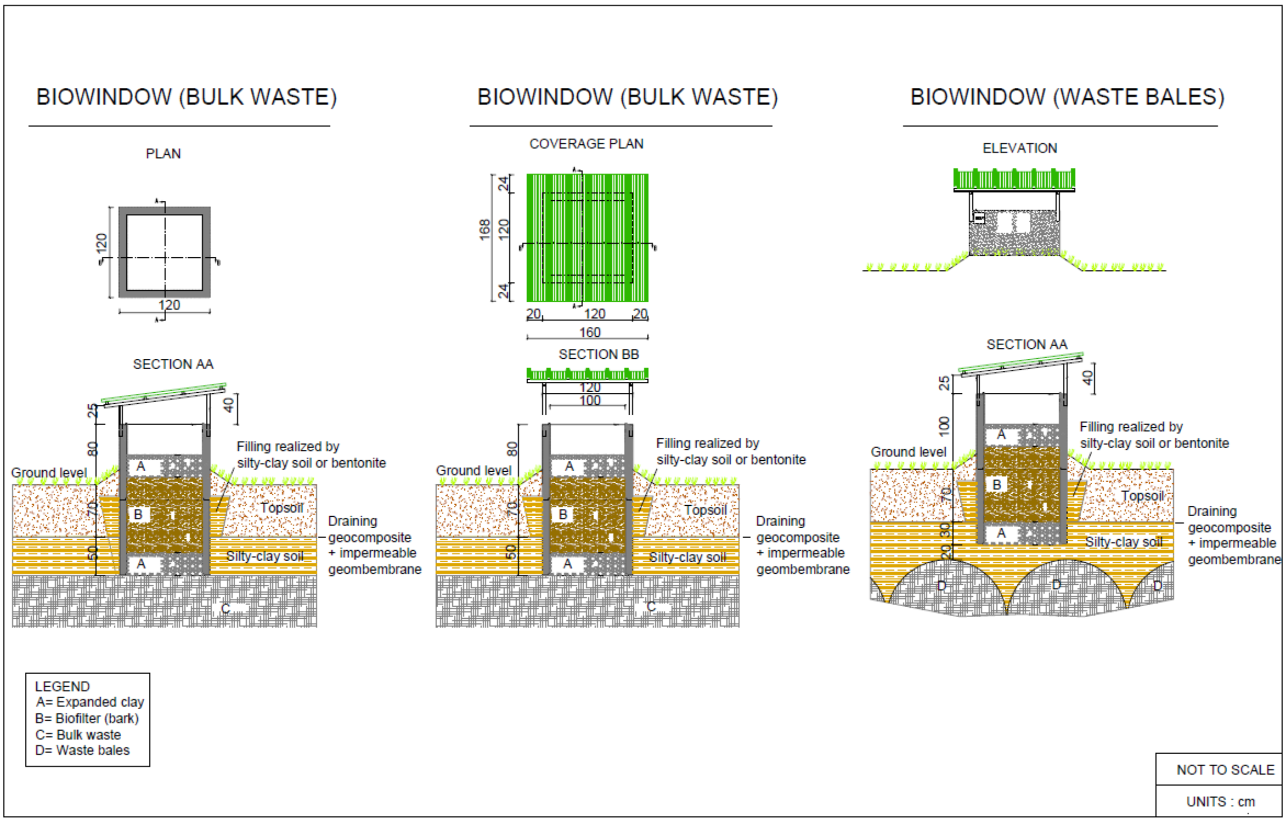
Finally in Summer 2014 it is possible to notice an opposite behaviour between the two wells categories. On one hand, an evident drop in methane values occurs by regarding the North wells, on other hand, the CH_4 concentrations related to South wells are characterized by a peak where the maximum value sets at 50%.

3.3.1 Implementation of the emergency plan: biowindows realization

Because of the high values detected in the methane percentages, it needed to build a treatment plant for the biogas emissions as it was suggested in the working plan. Originally, it was thought to realize an intake and treatment system. However, such a kind of system may present issues in terms of both implementation and management. In this regard, the detected CH_4 quantities do not allow to supply a system of static torches because of the limited volumes about the waste stored. Furthermore, the realization of the torches system would require the supply of electricity and a new requalification of the area followed by restoration works. In this scenario, the best solution to treat the biogas emissions resulted to be a passive biofiltration system that was obtained by the realization of eight biowindows. In more detail, biowindows refer to openings built on the Dune surface that can permit the natural release of biogas throughout the implementation of natural compost. They allow the CH_4 oxidation for the reduction of emissions into the atmosphere. The proposed project involved the construction of eight openings of 1 m^2, they are distributed appropriately on the surface of the Dune due to the different disposal of material. Biowindows sections are illustrated in Drawing 3.7 and their main components are listed below:

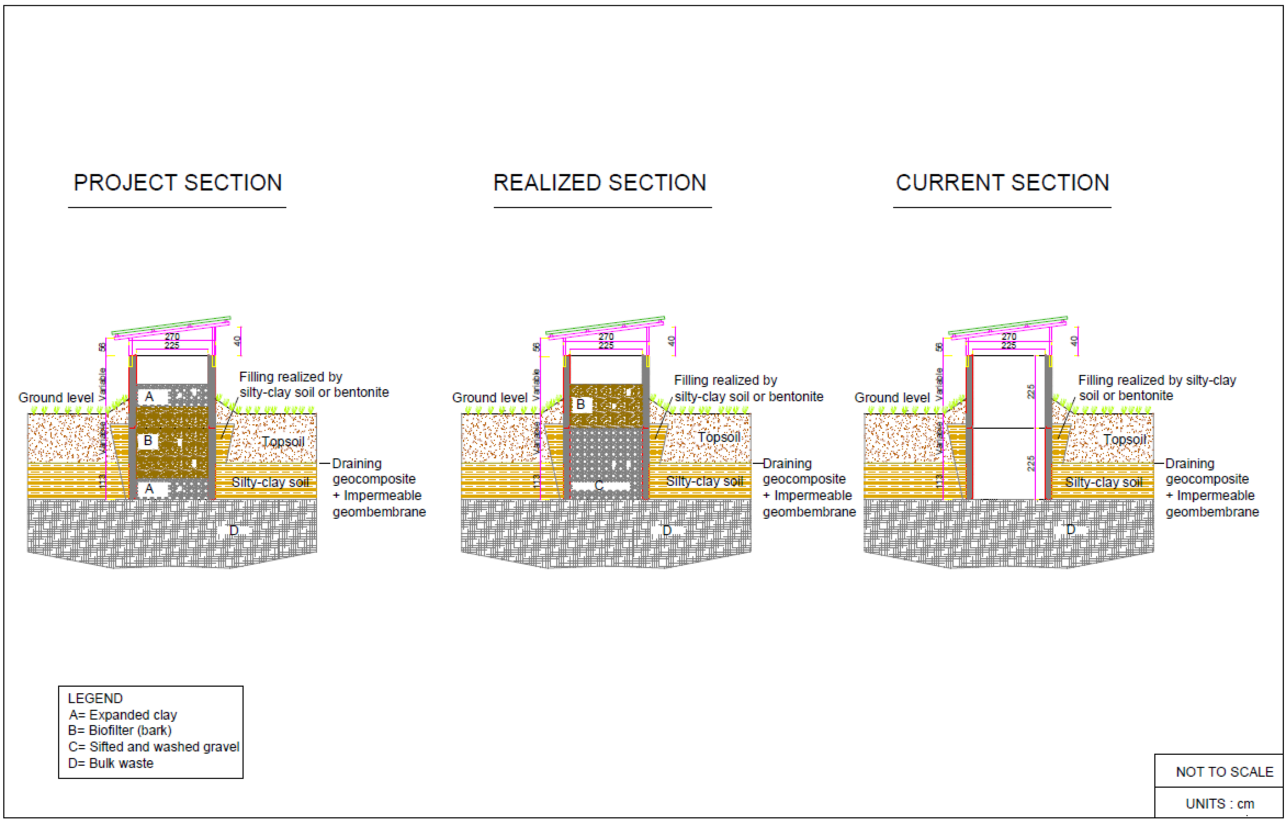
- about 30 cm of expanded clay, with a density of 300 kg/m^3 in order to create a filtering zone constituted by high permeability;
- a layer of approximately 1 m of natural compost (bark) forming the bio filter;
- approximately 30 cm of expanded clay with a density of 300 kg/m^3 to cover the bio filter, which is necessary to ensure adequate protection and maintenance of the moisture of the biofilter.

The last component of the biowindow refers to the roof which aim is to guarantee the regimentation of surface water and to cover the structure itself. The construction works of the biowindows took place between the 9th and the 13th of March 2015.



Drawing 3.7, Biowindows original cross sections.

Actually, with respect to the original design plan, a small change occurred. With respect to the first layer, it was originally made up of expanded clay, then it was substituted by sifted and washed gravel. Such a kind of variation is represented in Drawing 3.8. After the realization of biowindows, the campaign of methane gas monitoring was carried out evaluating both the seven wells inside the Dune and the five wells just outside the Dune perimeter.



Drawing 3.8, Biowindows realized cross sections.

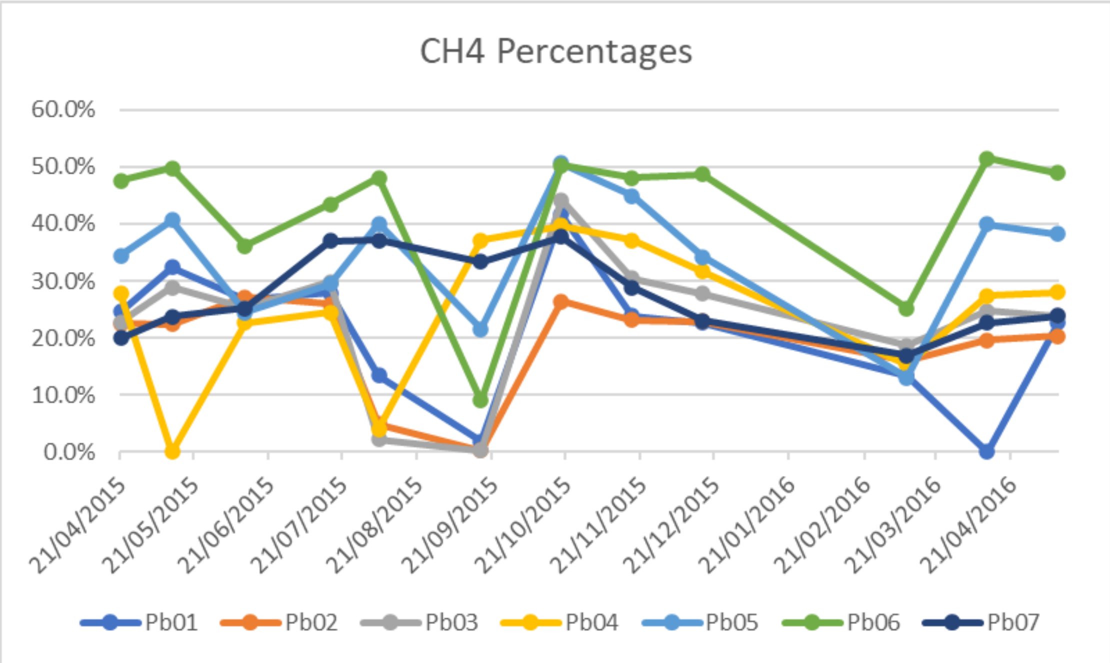
In this regard, the results coming from the monitoring activity are summarized in Table 3.4. In this table methane values only belonging to inner wells are given because they represent the site area where biowindows are built.

Table 3.4, Methane percentages after the biowindows realization.

Well	Pb01	Pb02	Pb03	Pb04	Pb05	Pb06	Pb07
21/04/2015	24.6%	22.5%	22.8%	27.8%	34.4%	47.6%	20.0%
12/05/2015	32.4%	22.4%	28.8%	32,1%	40.6%	49.7%	23.7%
11/06/2015	26.8%	27.2%	25.2%	22.7%	24.5%	36.1%	25.2%
16/07/2015	27.9%	25.9%	29.8%	24.5%	29.5%	43.4%	37.0%
05/08/2015	13.4%	4.9%	2.3%	4.1%	40.0%	48.1%	37.1%
16/09/2015	1.9%	0.3%	0.3%	37.1%	21.5%	9.1%	33.3%
19/10/2015	41.6%	26.4%	44.1%	39.6%	50.6%	50.2%	37.7%
17/11/2015	23.9%	23.1%	30.4%	37.1%	44.9%	48.1%	28.9%
16/12/2015	22.6%	22.9%	27.8%	31.6%	34.2%	48.6%	23.0%
09/03/2016	13.4%	16.0%	18.7%	15.4%	13.0%	25.2%	16.9%
11/04/2016	21,2%	19.6%	24.7%	27.4%	39.9%	51.5%	22.7%
10/05/2016	22.7%	20.3%	23.9%	28.0%	38.2%	48.9%	23.9%

The last measurements indicated a slight decrease in the methane percentages with respect to the previous monitoring campaign, thus it was decided to evaluate the effective gas production by applying an impermeable barrier on top of the biowindow.

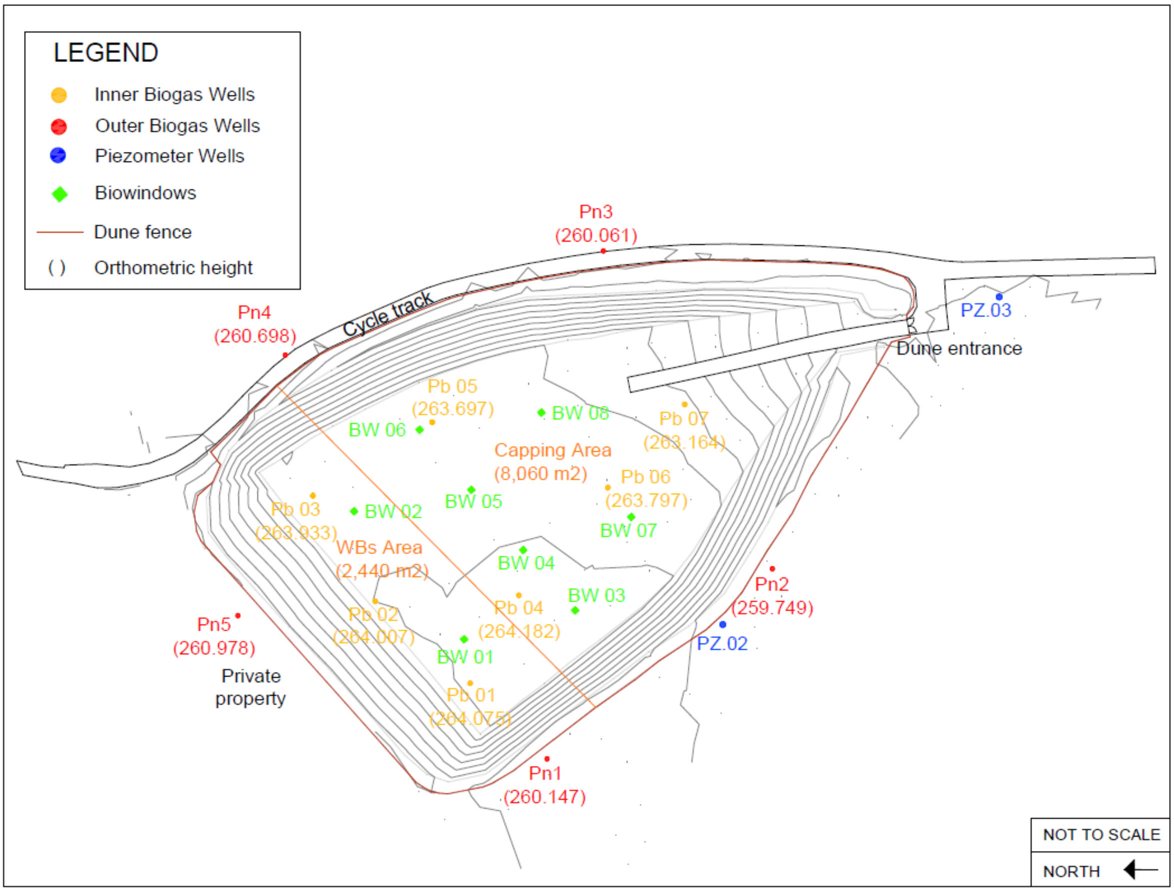
Moreover, in order to better understand the CH_4 concentrations trend, a further graph was created (Graph 3.2). In the following graph it is possible to observe the values related to methane percentages belonging to the wells located inside the Site perimeter.



Graph 3.2, Methane concentrations monitoring (2015-2016).

By looking at the Graph 3.2, it appears hard to detect clear trend in the methane concentration related to the inner wells. The greatest values often belong to the wells located in the South area of the site (mainly Pb05 and Pb06) where the waste material as it stands takes place. An anomalous behaviour is represented by Pb04 well which values seem to be similar to the wells located in the North area of the Site. A quick drop in the methane concentrations can be observed in September,2015 where CH_4 percentages approach to zero with respect to Pb01, Pb02 and Pb03. It means that, in this month, the area characterized by the waste bales presence cannot produce methane concentrations. Furthermore, between September and October 2015, the methane values quickly get higher, every well holds its maximum CH_4 value at this date. Subsequently, a common characteristic among all the wells of the Site occurs from October,2015 to March,2016. Over this period, the methane concentrations are characterised by a steady decline. It means that, during the late winter and the early spring months the CH_4 production decreases. The last stage of monitoring activity (after April,2016) is signified by an increase in the methane values where the greatest increment belongs to Pb05 and Pb06.

Moreover, the result of the tests shown that natural gas production was not observed throughout the biowindow filter medium. One of hypotheses suggested about lack of methane production was attributed to the presence of the filtering layers constituting the natural compost (bark). In particular, they can have created a cap for the biowindow, also considering the absence of internal overpressure. Therefore, in May 2016, the complete emptying of the biowindows was carried out, removing both the filtering layer (bark) and draining layer (sifted gravel). Nowadays, no material takes place between the waste and the atmospheric air. At this point, after mentioning all the intervention activities described in the previous chapters it can be useful to observe the final Site configuration which is illustrated in Drawing 3.9. According to the last in-process variations the site results to be subdivided into two areas: the northern area (about 2,440 m^2) where the Waste Bales take place and the southern area (about 8,060 m^2) characterized by the presence of the waste as it stands (WAIS). The overall area counts for around 10,500 m^2, while the whole waste stored sets around at 70,000 m^3. The last stage of the site description represents the starting point for the data processing concerning the evaluation of the biogas emissions and the subsequent methane flow treatment.



Drawing 3.9, Current planimetry of the Site.

3.3.2 On-site testing: biogas extraction

On 26th and 27th June and 7th July 2019, a number of on-site tests were carried out in order to extract the biogas located in the subsoil from the seven inner wells. The tests were performed by applying a well-head vacuum using an aspirator in ATEX configuration which was equipped with a flow control system. In addition to the atmospheric pressure and air temperature it can measure the depression, the flow rate, the percentages of methane, carbon dioxide, oxygen, carbon monoxide and hydrogen sulphide. The aspirator used for the biogas extraction can pull out a maximum flow rate equal to 220 m^3/h with a relative depression greater than 200 mbar. The on-site teste were divided into two categories: short term tests and long-term tests. The first category refers to the first two days. In this case, tests shown an overall duration equal to 120 min characterized by four flow steps (approximately 10, 20, 40, 80 m^3/h). So each case lasts for about 30 min., with the following measuring times: 1', 2', 3', 5', 7', 10', 15', 20', 25' and 30'. On the other hand, long-term trial was performed on 7th July focusing only on Pb05 well because it results as the most interesting one in terms of volume of extracted methane and the central location in the site.

The test lasted 469 minutes which measurements were characterized by eight flow steps (about 14, 25, 37, 49, 66, 72, 84, 91 m^3/h), for 60' each one (except for the last one).

The relative measuring times are represented by the following time slots: 1', 2', 4',8', 15', 30', 45' and 60'. The results related to the methane concentrations are given in the Table 3.5 and Table 3.6.

Table 3.5, Short-term tests.

	Short-term tests		
Well	Flow rate	CH_4	
	m^3/h	%	m^3/h
Pb01	20	5.5%	1.10
Pb02	20	6.0%	1.20
Pb03	20	8.0%	1.60
Pb04	5	15.0%	0.75
Pb05	40	7.0%	2.80
Pb06	20	5.0%	1.00
Pb07	20	8.5%	1.70
Total	145	7.0%	10.15

Table 3.6, Long-term tests.

	Long-term test		
Well	Flow rate	CH_4	
	m^3/h	%	m^3/h
Pb05	50	6.5%	3.25

Outcomes coming from the on-site tests highlighted as the methane concentrations settled on values below 10%. Most of the wells (Pb1, Pb2, Pb4 and Pb6) shown concentrations close to 5%.

During the on-site tests, the ratio CH_4/CO_2 was evaluated too. It clearly highlighted the two areas in which the site results to be identified in terms of different deposition of materials. In this regard, the northern wells (Pb1, Pb2 and Pb3) show an average ratio CH_4/CO_2 between 35% and 42% which is significantly lower than the characteristic ratio of cellulose degradation (100%). This condition could be attributed to both the atmospheric air infiltration and the reduced degradative activity due to polyethylene packaging of paper materials. On the other hand, the central and southern wells (Pb04, Pb05, Pb06 and Pb07) show a 100 % ratio which is characteristic of the cellulose degradation. The last sentence signifies a greater methane concentration in the biogas flow which appears even more evident when the data processing will be performed.

4. MAIN PARAMETERS AFFECTING THE BIOGAS PRODUCTION

4.1 LITERATURE BACKGROUND

The aim of this chapter is to find all the possible phenomena leading to the production of biogas from landfill sites. The work can be basically subdivided into two sections. In the initial step, a bibliographic search was carried out in order to investigate the topic from a literature point of view. Then, data processing about the Site parameters was performed in order to understand what the main correlations between the meteorological parameters and the biogas production were.

From a preliminary analysis, the main elements affecting the landfill biogas production were identified (Table 4.1):

Table 4.1, Factors affecting the biogas production.

Waste features	Landfill conditions	Environmental conditions
Merceological composition	Soil moisture	Air temperature
Size	Soil temperature	Barometric pressure
Density	Nutrients	Rainfall
Waste moisture	Oxigen	Windiness
Pre-treatment activities	pH	Solar radiation

4.1.1 Waste features

Evaluating the biogas production, the first thing to consider is signified by the waste features. Waste is a heterogeneous matter, so the prevailing material typology can affect the biodegradation of the same matter, a higher presence of organic substance leads to a higher production of biogas.

Particle sizes can also contribute to enhance or decrease the methanogenic process. On one hand, particle size reduction can increase the reactive surface and subsequently the hydrolysis process: this phenomenon could take advantage of the biogas production rate. However, if the hydrolysis process takes place over a wide surface, it can lead to the birth of volatile fatty acids.

In particular, they represent a serious threat for the methanogenic bacteria because of the reduction of pH (Enrico Magnano, 2010). Density is another parameter which can affect the biodegradation process, because an increase in density could lead to a field capacity reduction (weight % of the dry matter of waste).

In this way, compounds present in the aqueous phase can spread over the waste mass, decreasing the overall reactive surface belonging to the solid fraction and so the hydrolysis kinetics. Finally, pre-treatment activities can carry out a significant role concerning the fermentation process, for example in order to properly manage the waste matter, a good compaction of the substance can be decisive. In fact, if successfully performed, it can reduce the waste field capacity which leads to the decrease of air presence located in the waste matter. In this way, the aerobic fermentation is reduced over time, saving a greater amount of carbon for the next anaerobic phase.

4.1.2 Landfill conditions

One of the key elements effecting waste biodegradation is the water within the landfill body, affecting nutrients transport and enzymatic activity. Water is directly related to the soil moisture, which increase can help in the biogas production (Carnevale and Tucci, 2010). The best environmental conditions for the biodegradation process can be achieved when the moisture rate is similar to the field capacity, a higher value in the moisture percentage does not take additional advantages. It is important to remember that to ensure fermentation takes place, moisture should be settled at around 40-50%. Another parameter to consider is the soil temperature. The optimum temperature aimed to the methane production ranges between 25-45°C, carried out by mesophilic bacteria. If warmer temperatures occur, they can produce the methane production break off, otherwise colder temperatures make the bacterial activity slower. The absence or the presence of nutrients and oxygen contribute to the waste fermentation. In particular, if the amount of nutrients (nitrogen and phosphorus) is high enough they can favor the cell growth, while the oxygen absence represents the primary condition for the development of methanogenic bacteria. The last parameter which affects the methane production is the pH number, which value should be around 7-7.2 to get a satisfactory result (Carnevale and Tucci, 2010).

4.1.3 Environmental conditions

The environmental characteristics affect the phenomenon of biogas production depending on the landfill morphology and on the site location. The first element suggests that if a given landfill holds great sizes and volumes in terms of waste placement, it will be less affected by the outer environmental factors. On the other hand, landfills characterized by smaller volumes (less than 10 m thick), they will be more affected by boundary conditions (Enrico Magnano, 2010). Another factor that should be considered for this kind of study, is the type of soil used for the roof. Because the air temperature can lead to different effects. Whether the soil cover adopted has a great permeability to air, the temperature acts on both the shallow layer of the ground and the deeper one. However, if the landfill cover is detected by a low permeability material, the inner body of the landfill remains isolated. This would result in the air temperature having no effect on the storage of waste. A relevant dependance on temperature occurs in the shallow layer of soils, where a more significant aeration takes place. In countries where the temperature drops below 10°C, the biological activity performed by bacteria is drastically reduced to the extent that oxidation is considered absent in this layer. The highest values of oxidation occur for temperatures between 26 and 36°C. Barometric pressure can also act on the shallow layers by dragging air into them or by discharging gas outside the layers, this is an actual phenomenon when the waste is not consolidated to the typical density of the soil. The wind, instead, may only affect the gas diffusion into the deeper layers by reducing the gas concentration at the soil surface (Carnevale and Tucci, 2010). Now, analyzing the rainfall influence needs to consider a double effect on the biogas production. On one hand, precipitation helps increasing the humidity degree in the subsoil, taking advantage to the biodegradation process and its kinetics ; on the other hand, a heavy rainfall negatively affects gas generation processes by supplying water to the reaction and bringing dissolved oxygen into the bulk of the mass. Finally, the biogas production is slightly dependent on the solar radiation which can contribute to enhance the soil cover temperature which influences the CH_4 oxidation.

4.2 LITERATURE CASE STUDIES

In this paragraph three case studies will be shown in order to better understand the main influences of meteorological parameters as compared to both the biogas production and emission. The common characteristic found in these documents is signified by an existing correlation between the barometric pressure and the methane emission (Sonia Gervasoni, 2000). In the Gervasoni paper, the author explains how the biogas is forced to move from high pressure areas (located near its power source) to lower pressure areas outside the landfill. Biogas movement varies according to the obstacles and the preferential routes it encounters on its path. This kind of movement is neither steady in flow rate nor in direction, but it is strictly related to the fluctuations in barometric pressure. Thus, when the atmospheric pressure decreases, the gas is forced out of the landfill and to expand into the surrounding land, while when the atmospheric pressure increases, the gas tends to remain trapped in the landfill until a new pressure change (Figure 4.1).

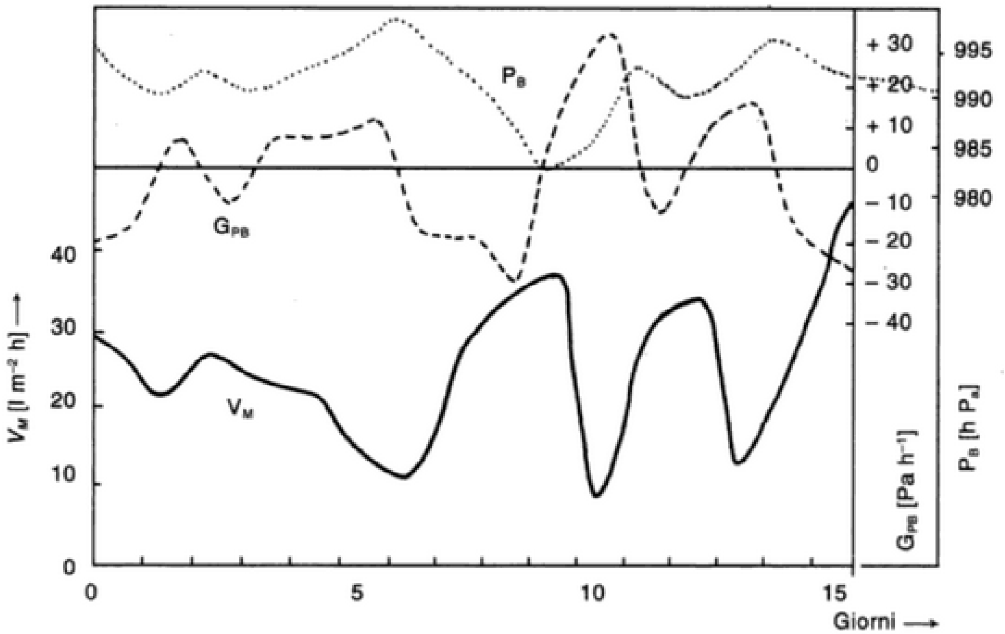


Figure 4.1, Comparison between the values of the methane migration rate Vm ($\frac{l}{m^2 h}$), the barometric pressure Pb (hPa) and barometric pressure gradient G_{pb} ($\frac{dP_b}{dt}$). (Staka F.,1997). (Sonia Gervasoni, 2000)

The methane production affected by the pressure variation is also a key element when facing out explosive events triggered by the presence of biogas as a fast drop in atmospheric pressure can cause a rapid rise in methane levels in the area surrounding the landfill. Now, it is possible to summarize this kind of movement and its consequences:

- When the atmospheric pressure occurs in stable conditions, the rate of biogas emitted is constant regardless of pressure value.
- When the atmospheric pressure increases, the rate of biogas emitted decreases proportionally to the pressure increase.
- When the atmospheric pressure decreases, the rate of biogas emitted increases proportionally to the decrease in pressure.

In addition to this kind of study, it is here reported the relation between the barometric pressure gradient and the biogas flow rate estimated by Young in 1990. In this regard, he was able to compare these two parameters in a landfill area during a 200 hour overall period:

Gas flux = $\alpha + \beta \left(\frac{dPatm}{dt}\right)$

where α = overall gas rate within the landfill and β = constant value dependent on the physical parameters of the landfill. In the next pages three field activities will illustrate the possible correlations between biogas emissions and meteorological parameters.

4.2.1 Lateral gas transport in soil adjacent an old landfill: factors governing gas migration (Skellingsted-DENMARK,2002)

Field experiments were conducted to investigate the lateral gas transport in soils adjacent to an old landfill in Denmark during a one-year period. These experiments started in 1997 and they took place in the Skellingsted landfill, which is in the south of Holbæk, Western Sealand, Denmark. In Figure 4.2 the landfill's map is shown. The landfill's area was subdivided into 10 sections and the measurements were taken from two measuring transect (Transect House and Transect Field).

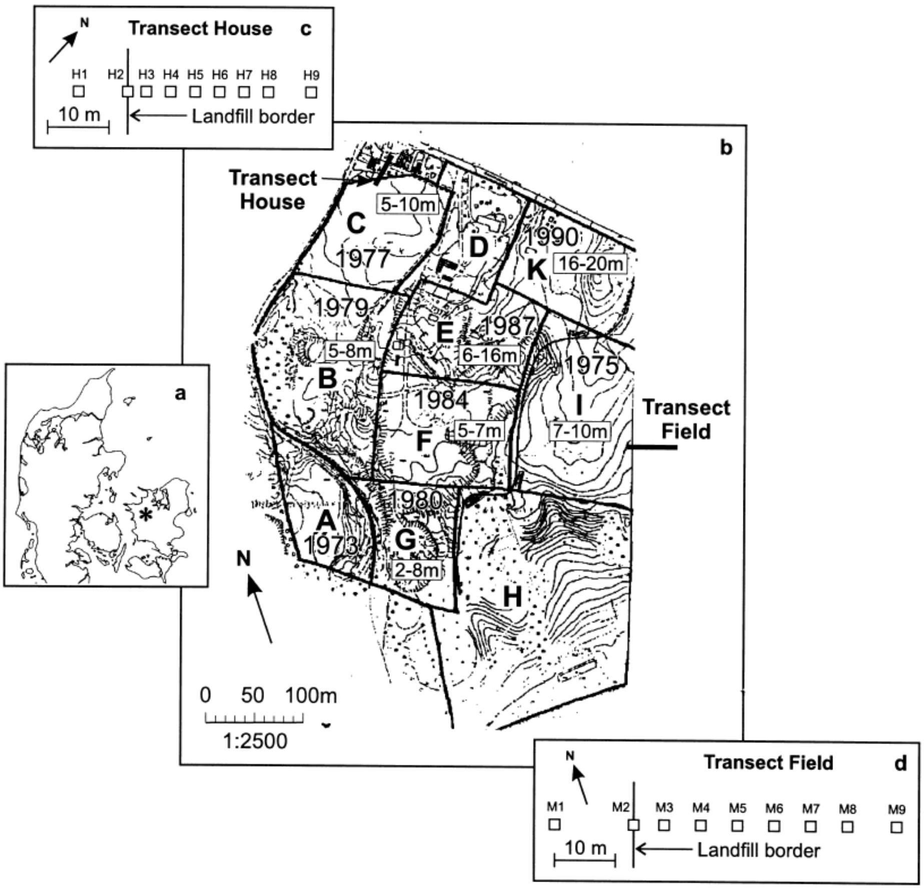


Figure 4.2, (a) The geographical location of Skellingsted landfill in Denmark. (b) Map showing the sections of the landfill. (c) Detailed map of the measuring stations in transect House. (d) Detailed map of the measuring stations in transect field. (Christophersen and Kjeldsen, 2002)

The first parameter to be investigated was the barometric pressure. The data have shown a good correlation between the methane concentration and pressure above barometric (Figure 4.3). The measurements took place from October 29th at 12 a.m. to October 31st at 6 p.m. at 100 cm below surface at stations H4, H5, H6 and H7 at 7, 11, 15 and 19 m respectively from the landfill.

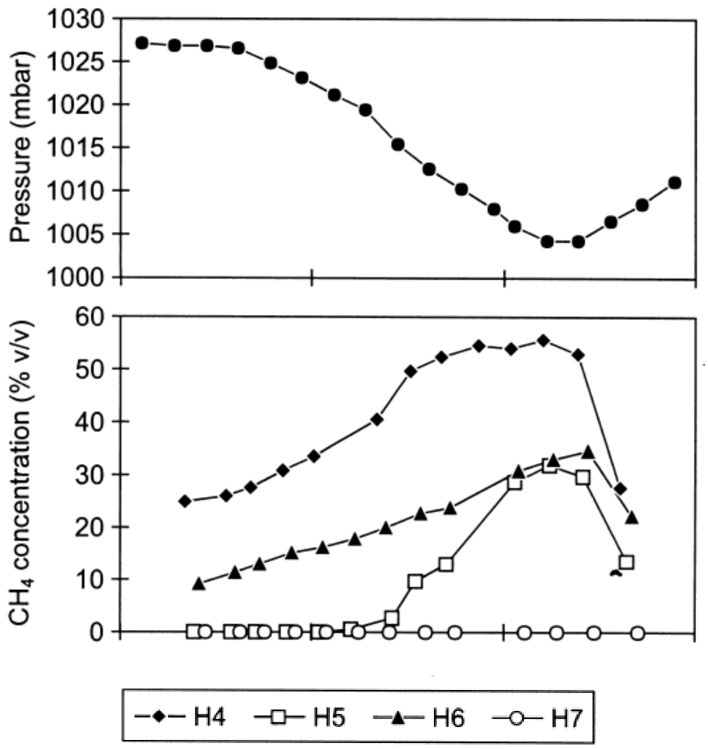


Figure 4.3, Barometric pressure and methane concentrations as a function of time. (Christophersen and Kjeldsen, 2002)

In this investigation, the lateral gas migration enhancement is due to an increasing pressure gradient between the landfill and the atmosphere caused by the drop in barometric pressure, and it can be concluded that advective flow is an important process controlling the lateral LFG migration.
Results from the investigations found out that close to the landfill, the effect of pressure changes was insignificant due to steady advective flow driven by the higher pressure in the landfill, but further away from the landfill changes in barometric pressure had great impact on the pore gas composition. An explanation could be that the advective gas flow in the area they investigated was higher and therefore, changes in barometric pressure had little influence close to the landfill.
The second element to be studied concerns the soil moisture content. In this regard, it was observed a seasonal variation with higher moisture content in winter.

Tendencies of increasing methane concentrations at high soil moisture content were observed (Figure 4.4). The correlation between the methane concentration and the soil moisture gave $R^2 = 0.63$. Measurements were collected at station M6 at different soil depths (20, 60 and 100 cm).

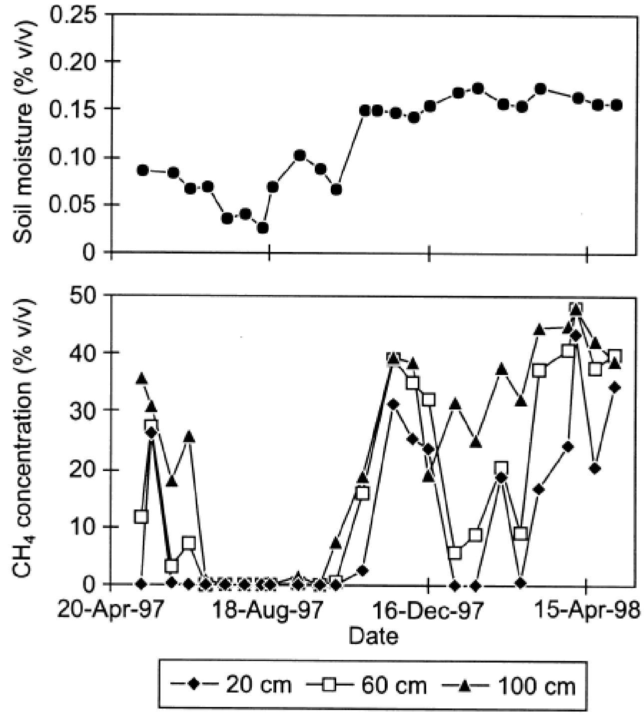


Figure 4.4, Methane concentrations and soil moisture as a function of time. (Christophersen and Kjeldsen, 2002)

Subsequently the air and soil temperatures were measured (Figure 4.5). The result seemed to highlight an inverse relationship between temperature and methane concentrations, which was attributed to methane oxidation. The R^2 was 0.40 and 0.49 respectively for air and soil temperatures when compared to methane concentrations.

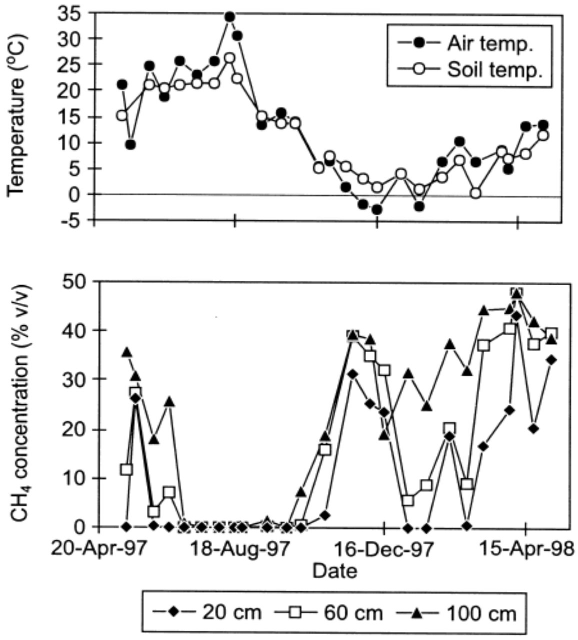


Figure 4.5, Comparison between air and soil temperature and methane concentrations. (Christophersen and Kjeldsen, 2002)

Precipitation is the last element to be compared with the methane concentrations. Correlation between rainfall and methane concentration was evaluated after periods of heavy rain. This meteorological condition resulted in wet topsoil and therefore the vertical gas migration was reduced, consequently the gas migrated further away from the landfill.

Conclusions from these field activities highlighted as the carbon dioxide was significantly higher in the summer (May to October) compared to the winter (November to April). The seasonal variation was caused by oxidation of methane to carbon dioxide, which is a temperature-based process. Methane oxidation was occurring throughout the year, but most of methane resulted to be oxidised in summer. The concentration of both methane and carbon dioxide were significantly lower in the summer further away from the landfill border. During the winter, the soil moisture content was higher especially in the topsoil and that reduced the vertical gas permeability and increased the lateral migration distance. As it was previously mentioned, there was a good correlation between pressure above the barometric pressure and the methane concentration in the soil, indicating that advective flow was an important process at the Skellingsted landfill. The advective flow increased during the barometric depression leading to a substantially higher landfill gas migration.

4.2.2. The influence of atmospheric pressure on landfill methane emissions (Nashua-USA, 2003)

The measurements were conducted in 1996 and 1997 at the Nashua municipal landfill located in the state of New Hampshire in the north-eastern United States. The primary goal of this activity was to collect CH_4 emissions aimed to produce electricity using conventional internal combustion generators. The gas recovery system installed in 1995 consisted of 60 vertical and horizontal wells installed in a gridded patter. The second objective of this work was to understand if gas emissions were affected by boundary conditions and if there are some correlations with the barometric pressure variation. Because of the final goal of this thesis chapter, the topic which is going to be discussed concerns only the second activity related to the Site. An atmospheric tracer method was used to calculate the total landfill CH_4 emission rate from measurements conducted in August 1996, February, March, and April 1997. In this regard, it was estimated that measured whole landfill emissions from the Nashua landfill ranged from 7.3 to 26.5 m^3 CH_4 min^{-1}.

Since the main objective of my study was to detect the possible correlations between CH_4 emissions and barometric pressure, the figure below (Figure 4.6) presents measured CH4 emissions as a function of atmospheric pressure measured during the field surveys.

A significant inverse relationship was observed between these two parameters. These data were modelled by linear regression and the resulting correlation coefficient, R^2, of the linear regression was 0.93.

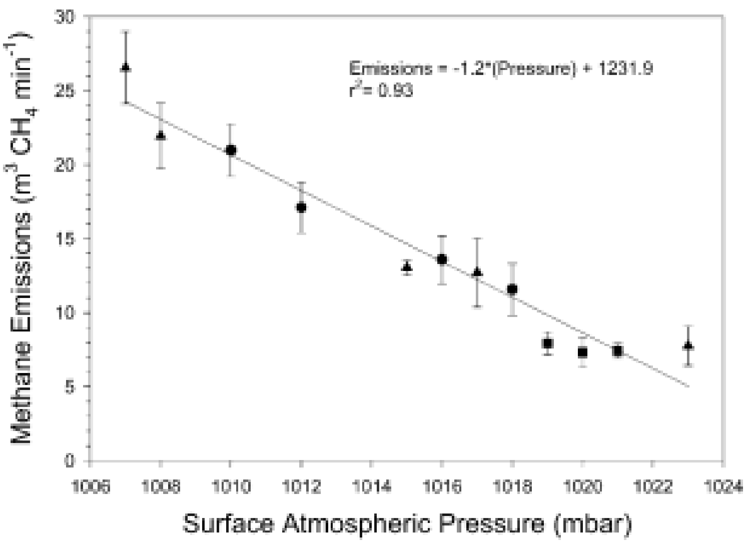


Figure 4.6, CH_4 emissions trend compared with the atmospheric pressure. (Czepiel *et al.*, 2003)

This kind of result highlighted the clear proportionality between these two physical quantities, so it represented an important element that was considered in order to extract the gas from the landfill site. Subsequently, it was decided to find out if a direct relation exists between the CH_4 oxidation rates and the soil temperature. In this regard, Figure 4.7 illustrates this precise condition.

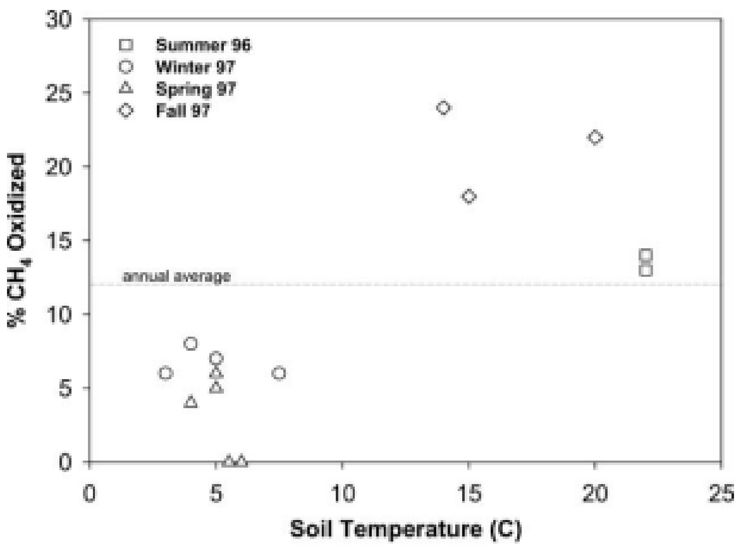


Figure 4.7, Fraction of whole landfill CH_4 emissions oxidized as a function of cover soil temperature at 5 cm. (Christophersen and Kjeldsen, 2002)

Looking at the graph it is possible to observe how the reported oxidation rates ranged from 0% in April 1997 to 24% in October 1997.The highest oxidation rates belong to the summer/autumn period when soil temperature usually rises. Furthermore, from previous analyses it was noted that the correlation between landfill cover soil temperature and oxidation was good among the total data set (R^2 =0.53) but poor among the highest oxidation rates measured in summer 1996 and fall 1997, in fact the picture shows how the data points are scattered. In any case, it needs to take into account the distribution of samples was not uniform; nine cold weather samples and five warm weather samples. Calculated oxidation rates ranged from 0 to 9% during the cold weather period and 13–24% during the warm weather. Therefore, it was calculated with two sample averages, 5% for cold weather and 18% for warm weather, and assumed them to be seasonally representative. By accepting these values as CH4 oxidation extremes, then the average of 12% can be assumed to be reasonably representative of the annual oxidation rate (it is characterized by the dashed line in Figure 4.7).

At this point, the possible correlations with the soil moisture were studied, however no data was measured during the emission and oxidation measurements in 1996 and 1997 even if rainfall parameter can help in performing such kind of work.
In this regard, only 0.3 cm of rain fell during August 1996, so the probable low soil moisture content could account for the relatively low oxidation rates observed in August 1996. Trying to summarise all the work performed, the boundary conditions can certainly affect the gas emissions from this landfill in a non-homogeneous way. Hence, the most important factor governing such kind of process resulted to be the barometric pressure.

4.2.3 Impact of the meteorological parameters on extracted landfill gas composition and flow (Odense-DENMARK, 2018)

The objective of this study was to investigate the impact of four pre-selected meteorological parameters (barometric pressure, wind speed, ambient temperature and solar radiation) on recovered landfill gas (LFG) flow, methane (CH_4) content of the LFG and the recovered CH_4 flow by performing statistical correlation tests and a visual check on correlations in scatterplot. The interested site referred to the Odense and Stige Ø landfills, in Denmark, where the measurements activities have spread over four periods: 11.08.2015– 06.09.2015, 15.08.2016–25.08.2016, 05.09.2016–11.09.2016 and 05.12.2016–08.12.2016. In Odense landfill, LFG is collected from the cells with mixed waste and shredder waste, and it is sent to a local power plant where a gas engine and a boiler produce electricity and heat. The four periods were chosen because no manual adjustments were performed on the gas extraction system during these periods. In Figure 4.8 the map of the landfill site is shown.

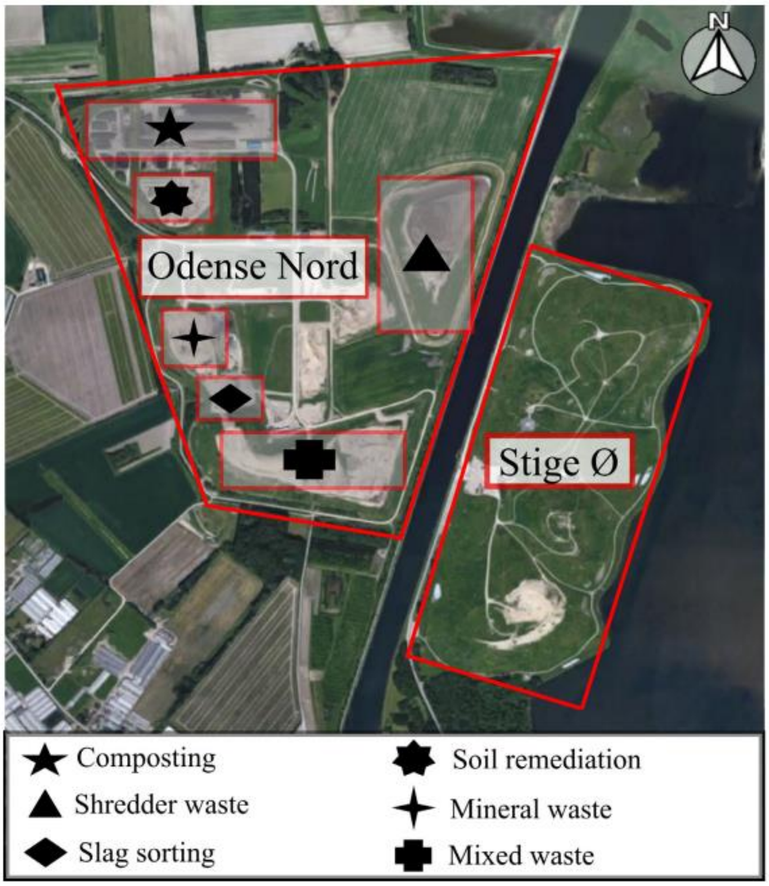


Figure 4.8, Map of Odense Nord (left) and Stige Ø (right) landfills.(Fathi Aghdam, Scheutz and Kjeldsen, 2018)

As the final aim consisted in finding out if a correlation between meteorological parameters (barometric pressure, ambient temperature, wind speed and solar radiation) and LFG data took place, correlation coefficients and p-values were calculated.

The Spearman method was used in this study which gives a correlation coefficient between -1 and +1 showing how strongly the two variables are correlated. Correlation coefficients of -1 and +1 show a perfect linear relationship between the two variables, number "0" shows that there is no correlation. Negative correlation coefficients, instead, show an inverse relationship. Moreover, p-values were calculated in this study, to show whether the correlation coefficients were significantly different from zero: $p < 0.001$ shows very high significance, $0.001 < p < 0.01$ shows high significance, $0.01 < p < 0.05$ shows significance, $0.05 < p < 0.10$ shows weak significance and $p > 0.10$ shows no significance.

Now, by starting to analyse the barometric pressure it can be said that it showed the highest correlation coefficients with LFG CH_4 concentration, LFG flow and CH_4 flow.

Barometric pressure showed quite strong negative correlation with LFG CH_4 concentration ($r = -0.73$ and -0.56 in 2015 and 2016, respectively) and a positive correlation with LFG flow ($r = 0.51$ and 0.64 in 2015 and 2016, respectively), and both correlations were found to be significant ($p < 0.001$).

This means that higher barometric pressure resulted in lower LFG CH_4 concentrations. The reason for this could be that at higher barometric pressures, more air entered into the landfill, which resulted in a higher recovered LFG flow rate, while the recovered LFG was more diluted and thus had a lower CH_4 concentration. In order to better visualize the possible influences among them it can be useful to look at the graphs which date from 2015 (Figure 4.9).

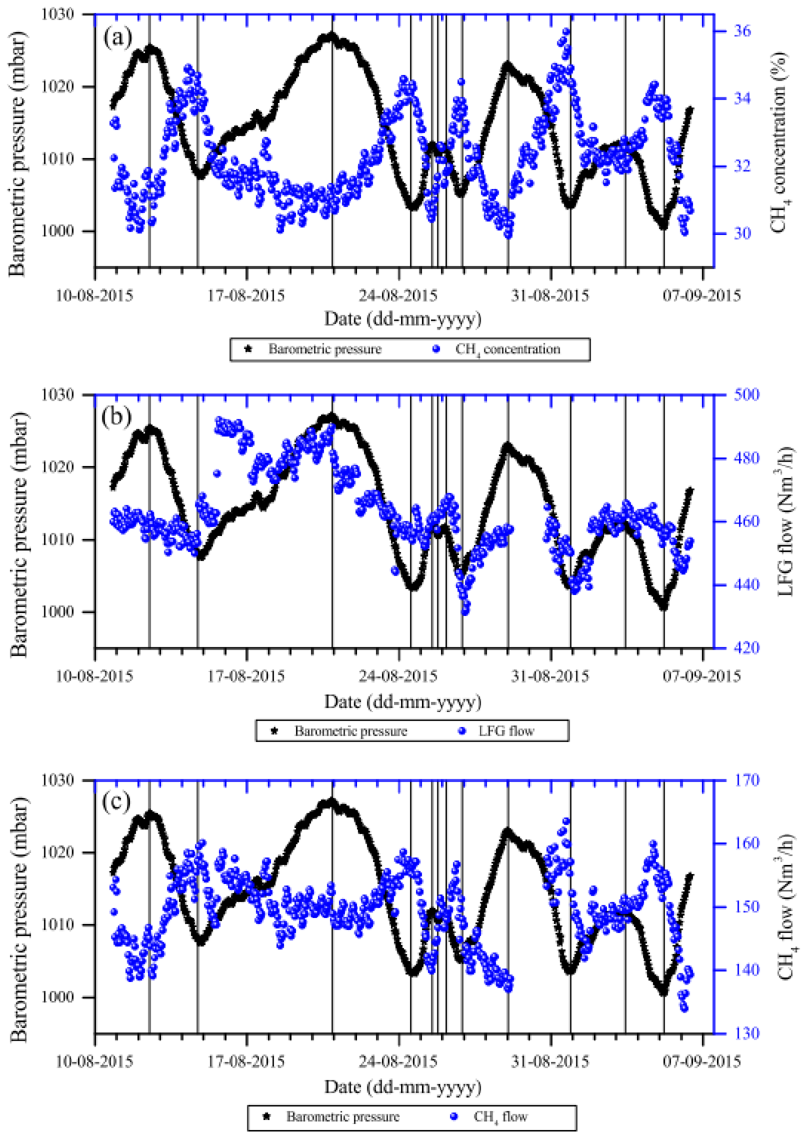


Figure 4.9, Barometric pressure (mbar) against LFG CH_4 concentration (%), LFG flow (Nm^3 /h) and CH_4 flow (Nm^3 /h) during 11.08.2015–06.09.2015. (Fathi Aghdam, Scheutz and Kjeldsen, 2018) (Fathi Aghdam, Scheutz and Kjeldsen, 2018)

From the previous figure, it is evident that higher barometric pressure corresponded with lower LFG CH_4 concentrations, higher LFG flow and lower CH_4 flow. Studies were carried out also in 2016 even if no strong or significant correlation was observed between barometric pressure and CH_4 flow over this year ($r = 0.01$, $p > 0.10$). The results obtained from these measurements are shown in Figure 4.10. The average CH_4 collection rate in the studied period of 2015 was 149 Nm^3/h, while it was 170 Nm^3/h in 2016. The higher concentration of CH_4 collection rate in 2016 was due to the commencement of gas extraction from the section of the shredder waste cell in May 2016. According to the landfill operators, the gas engine had reached its maximum capacity in 2016, and thus it could not burn more CH_4. This resulted in automatically regulating the gas engine to reduce suction pressure, when CH_4 concentrations increased, in order to maintain a constant CH_4 flow to the engine.

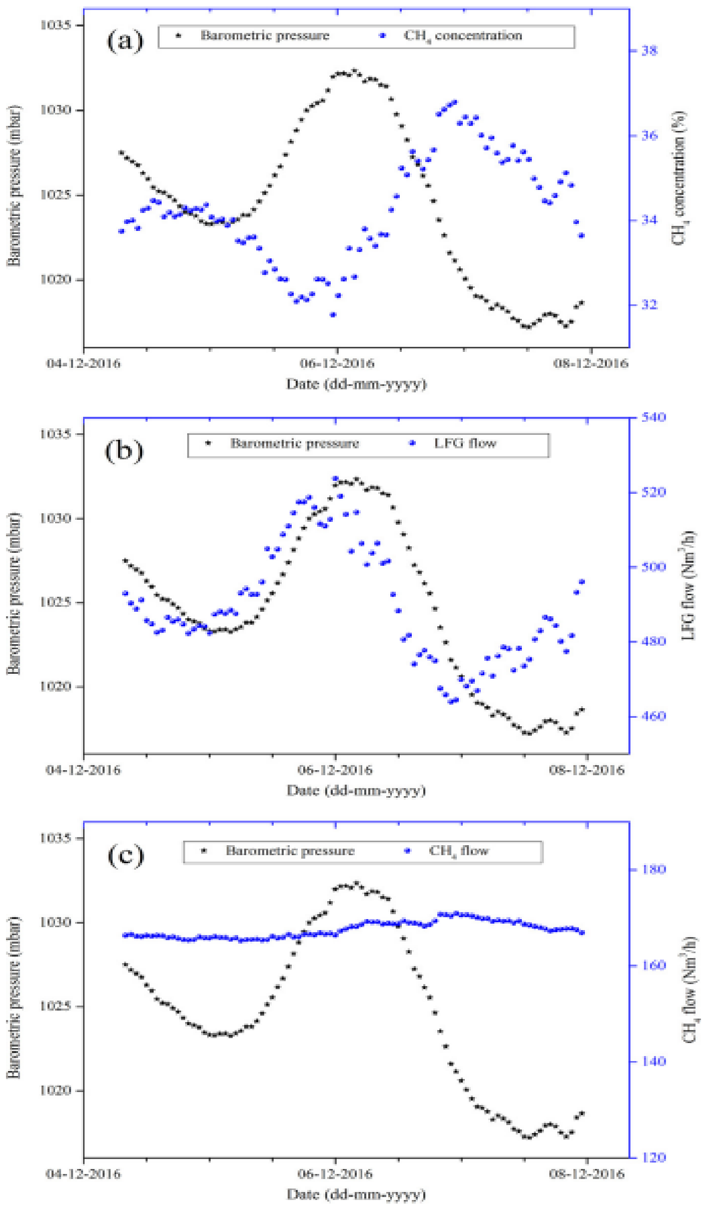


Figure 4.10, Barometric pressure (mbar) against LFG CH4 concentration (%), LFG flow (Nm^3 /h) and CH4 flow (Nm^3 /h) during 05.12.2016–08.12.2016. (Fathi Aghdam, Scheutz and Kjeldsen, 2018)

The second parameter to be investigated refers to the ambient temperature. In this case, weak correlation coefficients were observed between ambient temperature and landfill gas data, moreover weak correlation coefficients (absolute value of r between 0.04 and 0.41) were identified between ambient temperature and landfill gas data during the three periods in 2016, when the periods were studied individually. However, the study reported the ambient temperature trend in 2015 as it was compared to LFG CH_4 concentration, LFG flow and CH_4 flow (Figure 4.11).

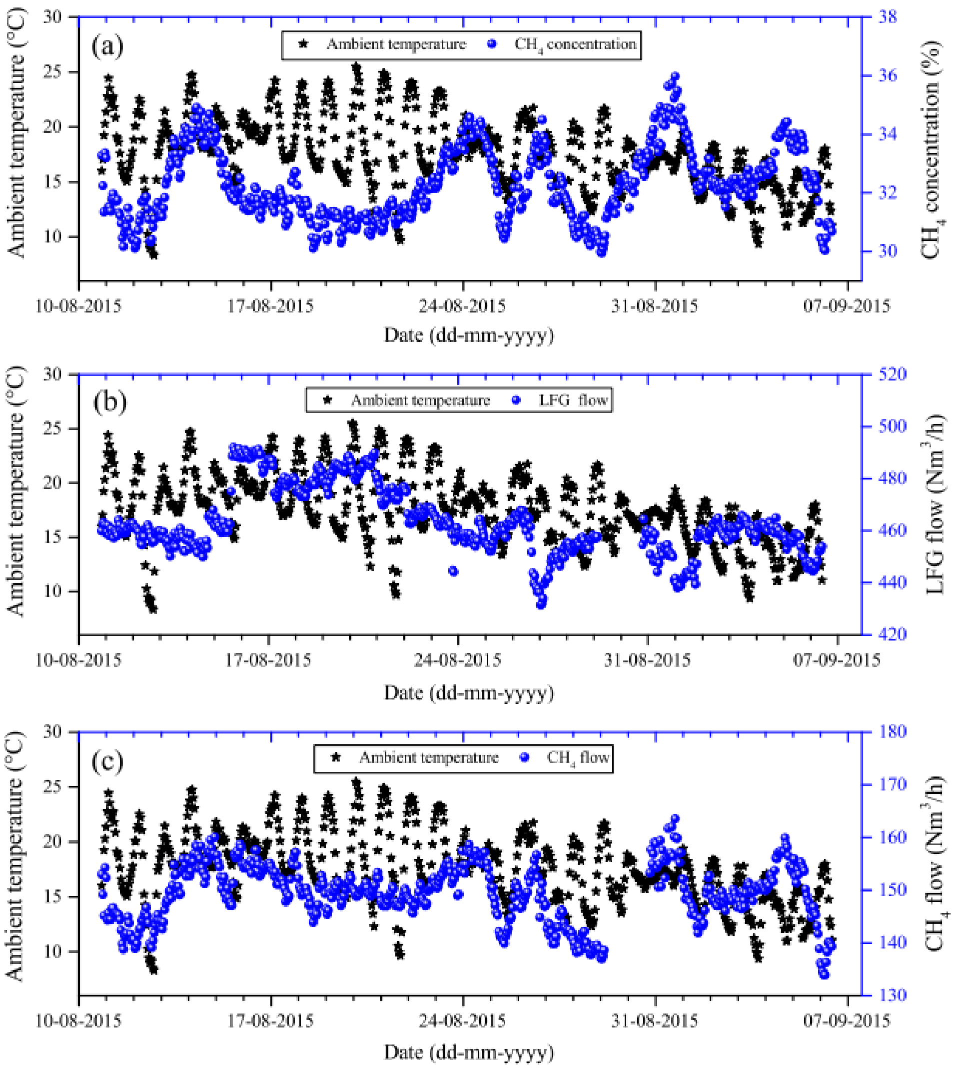


Figure 4.11, Ambient temperature (°C) against LFG CH_4 concentration (%), LFG flow (Nm^3 /h) and CH_4 flow (Nm^3 /h) during 11.08.2015–06.09.2015. (Fathi Aghdam, Scheutz and Kjeldsen, 2018)

Looking at the previous graphs, no visual correlation was observed between ambient temperature and LFG data, which shows that ambient temperature does not affect LFG collection rates or composition in these landfills.

Biological processes such as anaerobic digestion and microbial CH_4 oxidation are influenced by temperature, in that higher temperatures lead to higher microbial activities and result in higher CH_4 generation rates or CH_4 oxidation rates. However, it should be considered that temperature inside the waste body will be elevated and is not affected by the ambient temperature. This condition takes place because the waste fermentation acts as an exothermic process and leads to a heat production in the subsoil. Thus, it is the temperature inside the waste body that affects CH_4 generation rather than ambient temperature. Subsequently, the third parameter to be studied was the wind speed.

In general, very low correlation coefficients were observed between wind speed and LFG CH_4 concentration, LFG flow and CH_4 flow. However, it needed to distinguish the different periods when measurements were performed, because air temperature and humidity can affect the wind speed. In particular, very weak correlations were observed between wind speed and landfill gas data during the summer periods (15.08.2016–25.08.2016 and 05.09.2016–11.09.2016), while a strong and statistically significant correlation was noticed in winter (05.12.2016–08.12.2016). The higher correlation between wind speed and gas emissions which was encountered in winter can be explained by the higher moisture content in the soil cover in this period when the winds are also stronger. For this reason, Figure 11 illustrates the wind speed trend measured in winter 2016. The correlation seen during winter was positive with LFG CH_4 concentrations and negative with LFG flow, meaning that higher wind speeds resulted in higher LFG CH_4 concentrations and lower LFG flows. On the other hand, there was no correlation between wind speed and CH_4 flow during winter 2016, most likely because of the constant CH_4 flow in 2016, due to the regulatory measure of the gas engine as previously discussed. To conclude with the wind speed analysis, it is worth to remember that the advection motion is one of the main driving forces when facing out the gas transportation. In particular, such a kind of process can be due to the pressure difference induced by wind blowing. This could mean that wind speed (when strong enough) creates a pressure difference between landfill body and the landfill surface, which then affect gas extraction and emissions from landfill. Figure 4.12 illustrates the relation between landfill gas parameters and the wind speed.

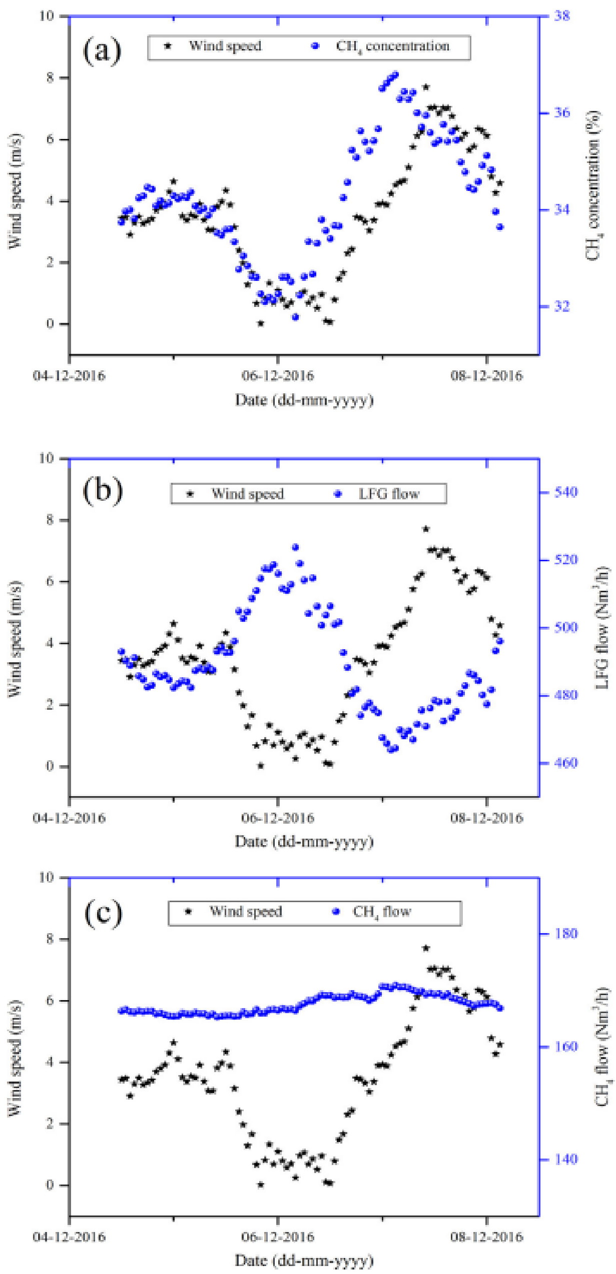


Figure 4.12, Wind speed (m/s) against LFG CH_4 concentration (%), LFG flow (Nm^3/h) and CH_4 flow (Nm^3/h) during 05.12.2016–08.12.2016. (Fathi Aghdam, Scheutz and Kjeldsen, 2018) (Fathi Aghdam, Scheutz and Kjeldsen, 2018)

As the last parameter to be analysed, this study focused on the solar radiation. In this regard, a very weak correlation (absolute value of r between 0.03 and 0.21) was observed between solar radiation and landfill gas data. This result showed that solar radiation does not appear to be an important factor affecting landfill gas collection rates and composition. Unfortunately, no graphs are available for this parameter, however, it should be noted that solar radiation can affect the CH_4 emissions because of

vegetation-covered areas. Whether solar radiation increasing results in internal pressurization of plants, it can lead to an advective CH_4 emissions from the plants.
In this study a strong influence between solar radiation and landfill gas data was not found and this could be due to the lack of vegetation cover over the landfill. To conclude with this analysis, solar radiation can certainly affect the temperature referred to soil cover, which influences CH_4 oxidation and emissions at landfill. Finally, the bio-degradation process is mainly affected by the subsoil temperature which is already kept at high values because of micro-organisms action which are responsible for the waste fermentation.

4.3 REMARKS ABOUT BIBLIOGRAPHIC RESEARCH

As the thesis focuses on the study of the landfill gas emissions, the relation between meteorological parameters and biogas production/emission will be thoroughly investigated. A landfill body which was not completely isolated from the surrounding environment can be affected by the meteorological conditions which can increase or decrease the amount of biogas leaving out the landfill. In this regard, it seems that the gas emissions appear to be mainly governed by the barometric pressure. All the authors who were mentioned in the previous paragraphs agree with the following thesis: a barometric pressure drop takes advantage to the biogas emission coming from the topsoil because of the advection process which is one of the main drivers for the gas movement. Once advection takes place, biogas flow is forced to move towards lower pressure areas. In particular, one of the authors was able to show in her document a graph comparing the gas flux trend with the pressure gradient and barometric pressure trend. From the graph, it was possible to notice a close relation between them, which was also analytically studied by Young in 1990 where a linear correlation was identified between the physical quantities. This kind of inverse relation between gas flux and barometric pressure was also present in each of the field activities carried out in Denmark and USA, which were previously summarized. Because of the common results existing among all the documents it is worth to say that this parameter certainly plays a crucial role in the biogas spreading into the atmosphere. The same concept was confirmed by E. Magnano during a phone call. Moreover, he highlighted how the barometric pressure drop is not considered enough to observe a biogas leak. In fact, once the biogas formed, it stores in the landfill subsoil and it can only move on because of relative pressure induced by the gas itself.

The relative pressure can be both found negative and positive. In this regard, if it is negative, it needs an external work to allow the biogas to be picked up outside the landfill surface, while if it is positive, an overpressure phenomenon is created. Focusing on the second possibility, the gas can move on spreading over the whole subsoil.

Similar correlations between biogas leaks and the other meteorological parameters are not univocally identified in the literature. Referring to the ambient temperature, for example, it was not found a precise correlation with the landfill gas flow: results coming from the Odense landfill study shown a weak correlation between ambient temperature and biogas flow. On the other hand, a kind of link raised up about methane oxidation and ambient temperature. Starting from the Skellingsted landfill, an inverse relation occurred between temperature and methane concentration because of the methane oxidation, which is mostly encouraged when the temperature gets higher.

Then, focusing on the Nashua landfill, it seems to confirm the results already obtained at the Skellingsted landfill. In this case, greater oxidation rates occur when soil temperatures rise, and it usually happens during the summertime.

In this regard, in order to ensure a successful CH_4 oxidation, temperature should be high enough (at least 30°C), in this scenario a greater temperature value can help such a kind of process. Summarizing the phenomenon related to this parameter, it can be said that methane oxidation can be affected by temperature gradient which occurs in the subsoil, while it is not strictly dependent to the ambient temperature. However, it needs to consider that ambient temperature can affect the upper soil layers when the waste body is not completely isolated to the surrounding environment, leading to some temperature variations in this layer of the subsoil (E.Magnano-phone call).

After evaluating the barometric pressure and ambient temperature the atmospheric humidity needs to be taken into account. Unfortunately, from the bibliographic research it was not simple to extract information about this parameter, every document from the bibliographic search did not focus on the possible relation between air humidity and methane concentration. Regardless, looking at the case study performed at the Skellingsted landfill, the relation between soil moisture content and CH_4 concentration was evaluated. Researchers have found a proportional correlation between them, in fact, the soil moisture increasing matched with the methane spreading, pointing out a kind of correlarion. In this scenario, it seems that moisture presents in the subsoil can enhance the methane production, by allowing microorganisms to better carry out the waste fermentation. The soil moisture certainly affects the methane production. Landfill waste is usually placed underground holding a humidity degree ranges from 20% to 30%, by considering these percentages waste fermentation cannot occur (E.Magnano-phone call).

In this regard, to make the methane production happen, it is necessary that humidity reaches higher values, setting between 40-50%. Soil moisture can be affected by rainfall occurring in a given site, which can cause an increase in the humidity degree. Nevertheless, an intense rainfall event can lead to the decrease in terms of the vertical gas migration.

In fact, if the topsoil results to be completely wet, a greater saturation degree is reached. Thus, it leads to reduce the gas permeability. This kind of scenario was explained during the field activities occurred at the Skellingsted landfill, where because of heavy rain, the gas migrated further away from the landfill. The correlation between precipitation and soil moisture was also mentioned by I. Pecorini (Carnevale and Tucci, 2010) which confirmed the inverse relation between wet topsoil and gas emissions. In particular, if the soil surface has got a high moisture value the biogas flow is not allowed to leave out the landfill because of the great pores' saturation.

By reading her document, it can be implied that air temperature and air humidity variation can affect the biogas emissions because they can lead to condensation and evaporation processes, which prevent or allow the biogas spreading into the atmosphere.

Another parameter which was investigated during the field activity at Odense landfill refers to the wind speed. Looking at the graphs previously posted, very low correlation coefficients were observed between wind speed and LFG CH_4 concentration, LFG flow and CH_4 flow. However, wind speed can affect the gas flow because of a pressure gradient, which was created by the wind motion itself. In this way, whether the pressure difference between landfill surface and atmospheric air is found positive a biogas emission can be observed. The same concept can be also found in Pecorini document where it is said that a drop in barometric pressure can suddenly change the value of the biogas stream emitted in a small-time window.

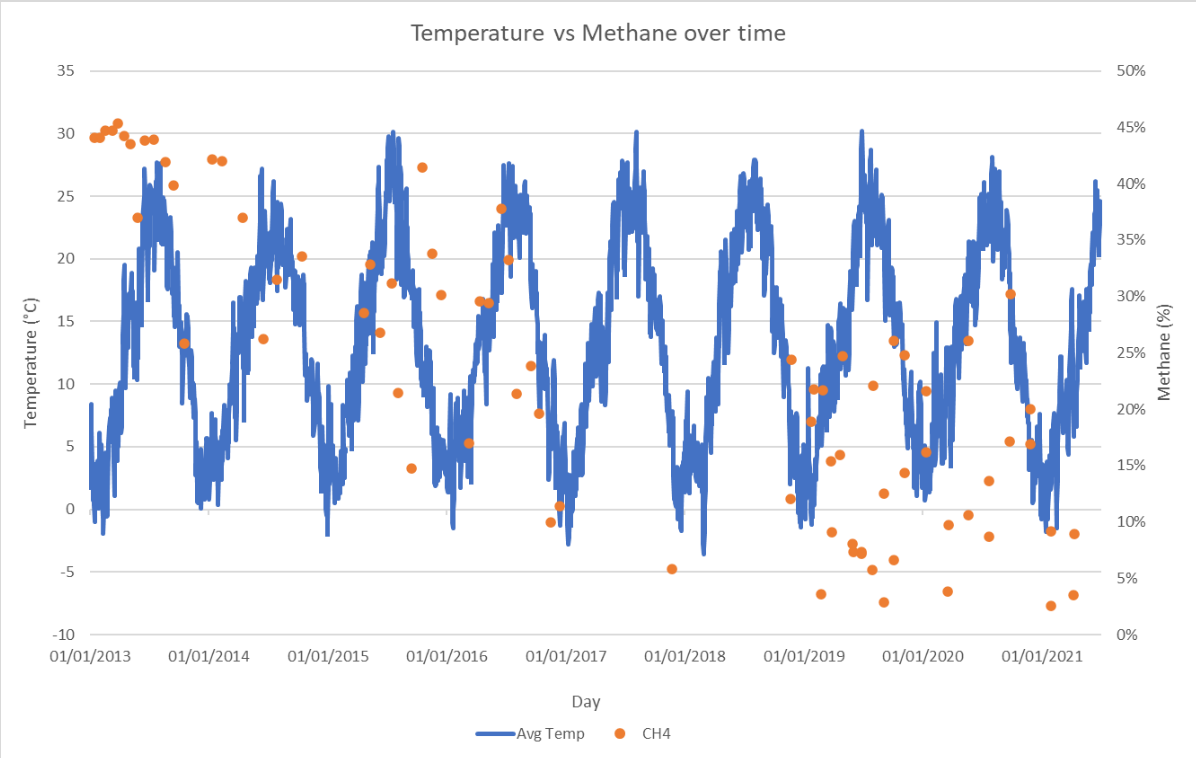
5. DATA PROCESSING RELATED TO THE PIEDMONT SITE

In this chapter an analysis of the possible correlations between biogas production and emission, methane concentration and meteorological parameters is presented for the study site. Detailed data on soil moisture and the soil temperature were not available and thus they were not considered in this study. The meteorological data for the nearest monitoring station (Caselle Torinese) were downloaded from the Arpa Piemonte database, and they included:

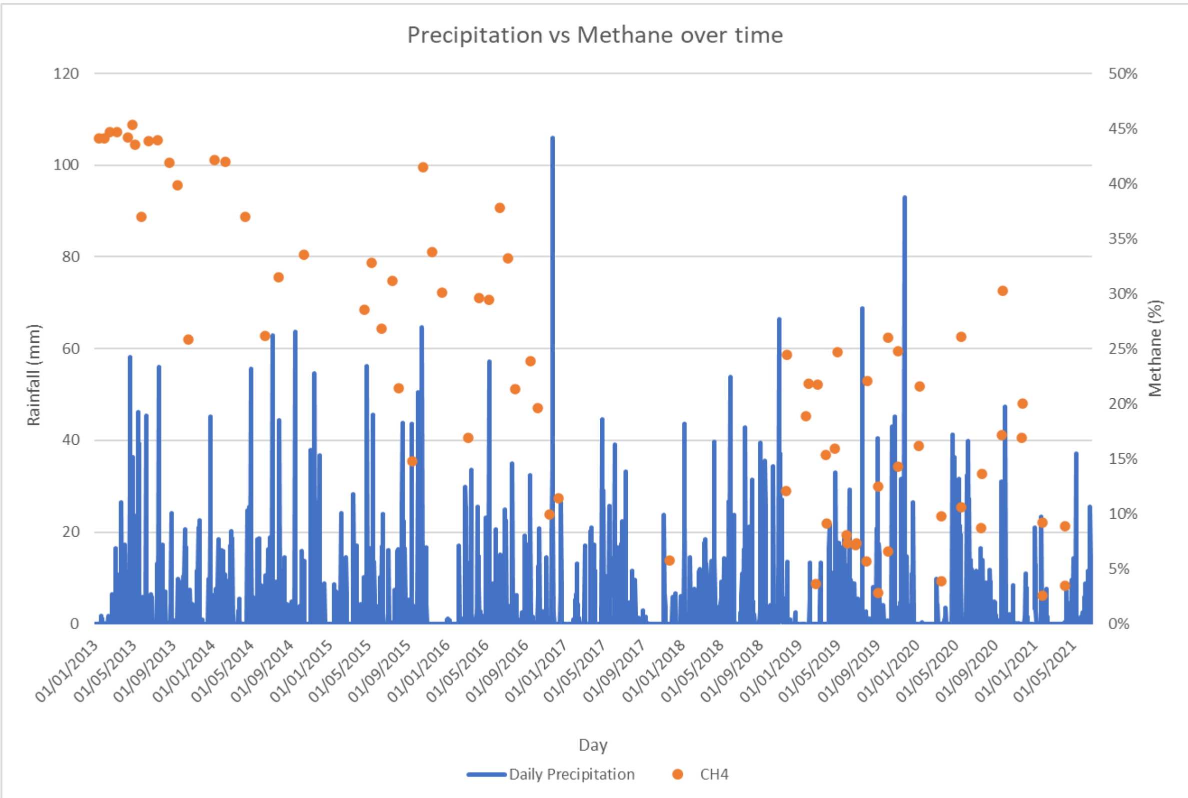
- Air Temperature (°C): average daily temperature
- Precipitation (mm): average daily rainfall
- Air Humidity (%): average daily humidity
- Wind speed velocity (m/s): average daily wind speed
- Atmospheric pressure (hPa): hourly pressure

The refence data belongs to following period: January 2013 to June 2021 concerning the air temperature, precipitation, air humidity and wind speed according to the database availability. However, it was possible to download pressure values until October 2021 because they were extracted following a different source path. On the other hand, the biogas data were supplied by the companies which were commissioned to work at this site, including Enviars company. The biogas data which were analysed mainly refer to CO_2 and CH_4. In this regard, because of a limited amount in CO_2 values during the investigated period, the whole analysis focused on the CH_4 concentration (%) and emission (Nl CH_4/m^2h) with respect to the previous meteorological parameters.

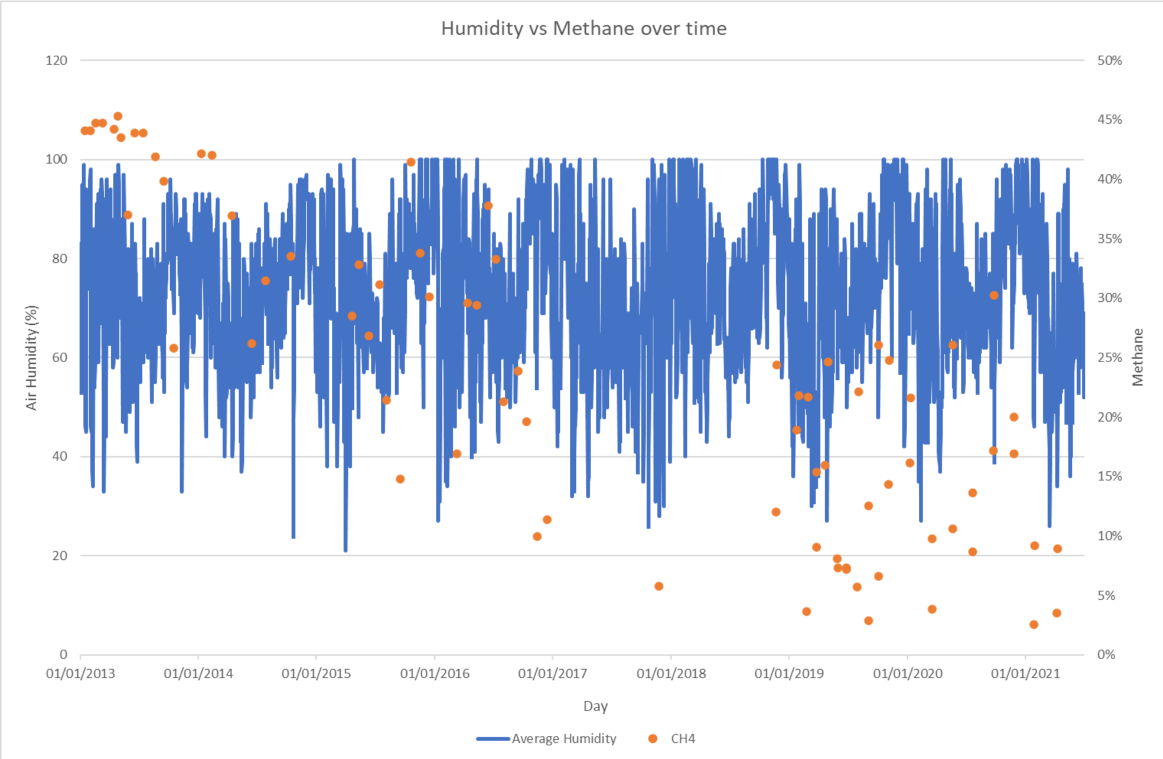
The first graphs to be represented highlight the methane concentrations trend over the whole monitoring period. In this regard, the first graph refers to air temperature (Graph T1), the second deals with precipitation (Graph R1), the third one with the air humidity (Graph H1), the fourth one with the wind speed (Graph W1) and the last one with the atmospheric pressure (Graph P1).



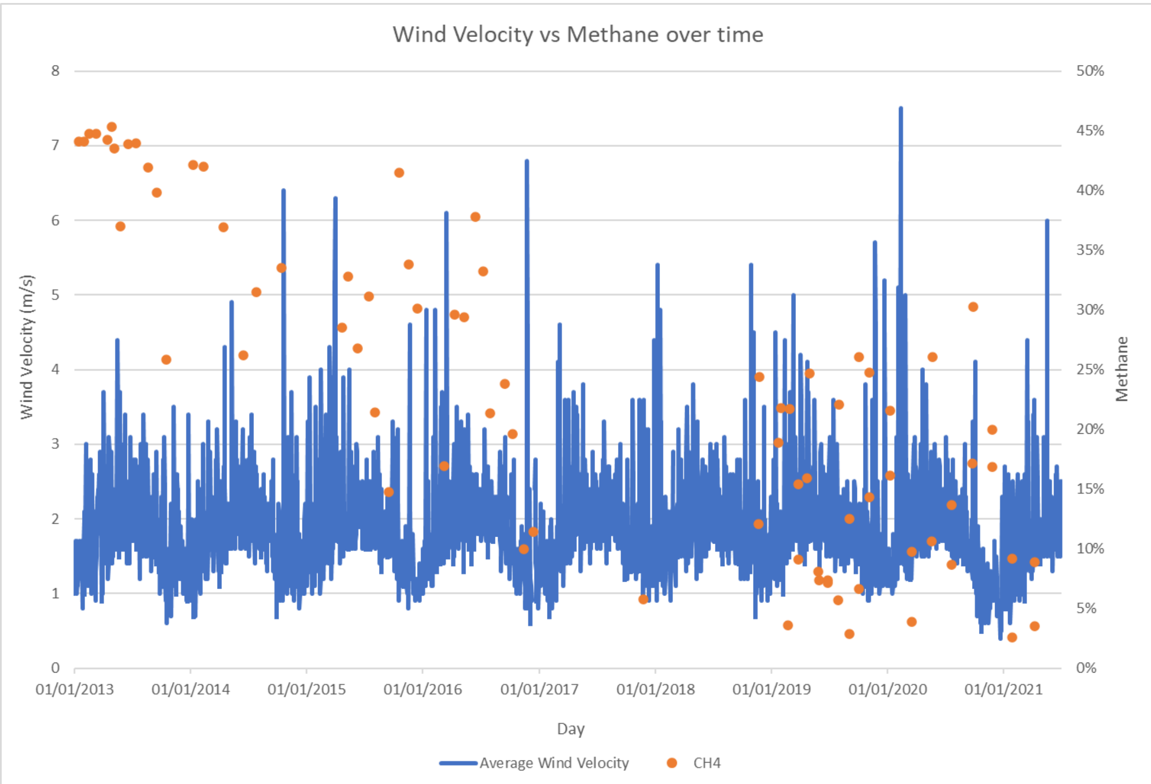
Graph T1, Temperature vs methane concentration: 2013-2021.



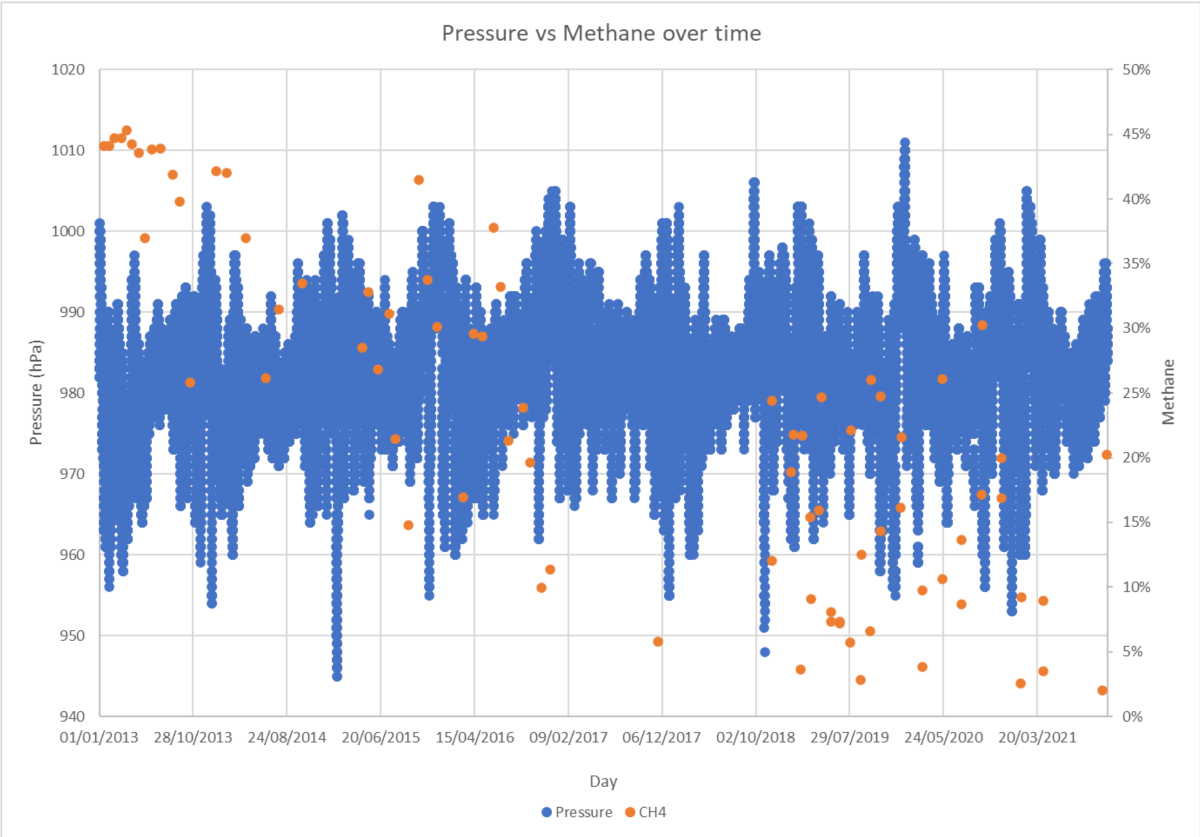
Graph R1, Precipitation vs methane concentration: 2013-2021.



Graph H1, Humidity vs methane concentration: 2013-2021.



Graph W1, Wind velocity vs methane concentration: 2013-2021.



Graph P1, Pressure vs methane concentration: 2013-2021.

From the previous graphs it is possible to notice that a homogeneity lack appeared in the data processed as they refer to time periods characterized by an irregular frequency in the surveys and they were performed by different firms. For example, from January 2013 to February 2014 measurements were carried out by using closed wells, while from April 2014 to November 2017 they were performed by using opened wells. The last period, on the other hand, was characterized by measurements carried out by the same company, namely Enviars on a regular basis.

In this regard, from November 2018 the monitoring activity was performed twice per month, the first time by considering opened wells, while the second time by considering closed wells.

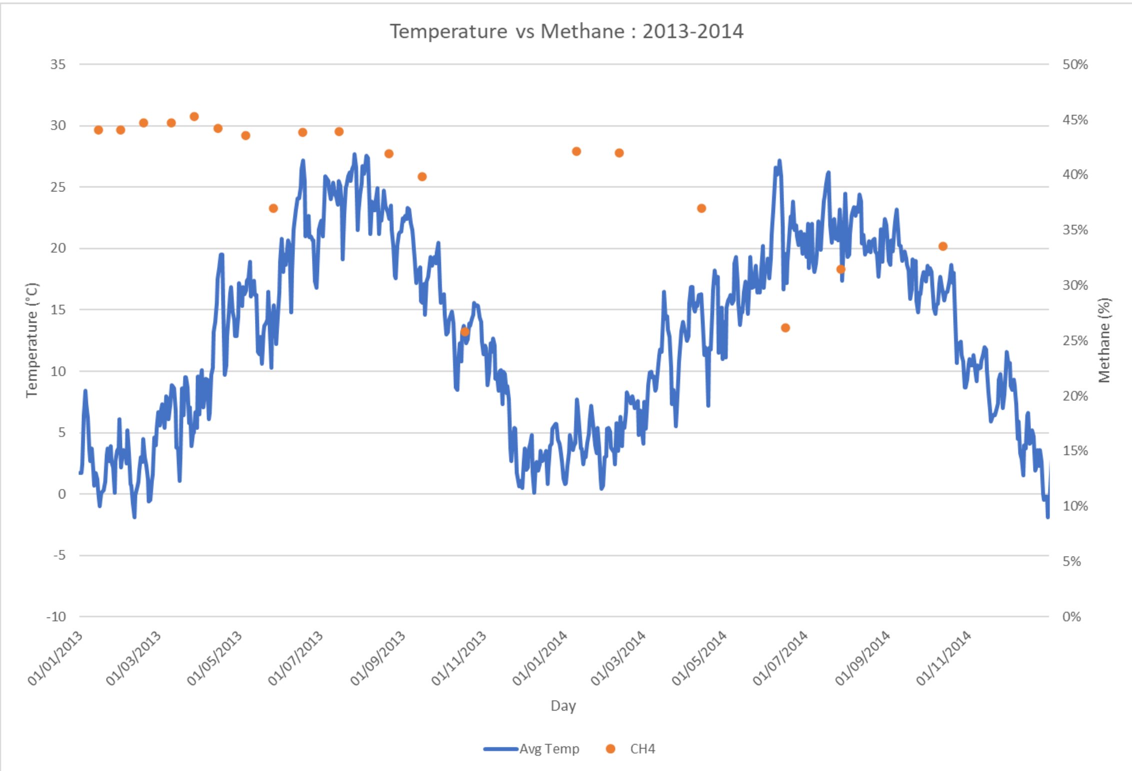
In this scenario, a scatter plot based on three different time windows was realized to better highlight the CH_4 values distribution by considering a smaller monitoring period.

Thus the five meteorological parameters will be further analysed by looking at the following time slots: 2013-2014, 2015-2016 and 2019-2021. Another inhomogeneity in the methane measurements refers to the high difference in values between the first data monitoring (2013) and the last data monitoring (2021). Higher percentages belonging to the first period are compared to lower values related to the last period, this situation could be caused by the waste fermentation which was going to decrease over time.

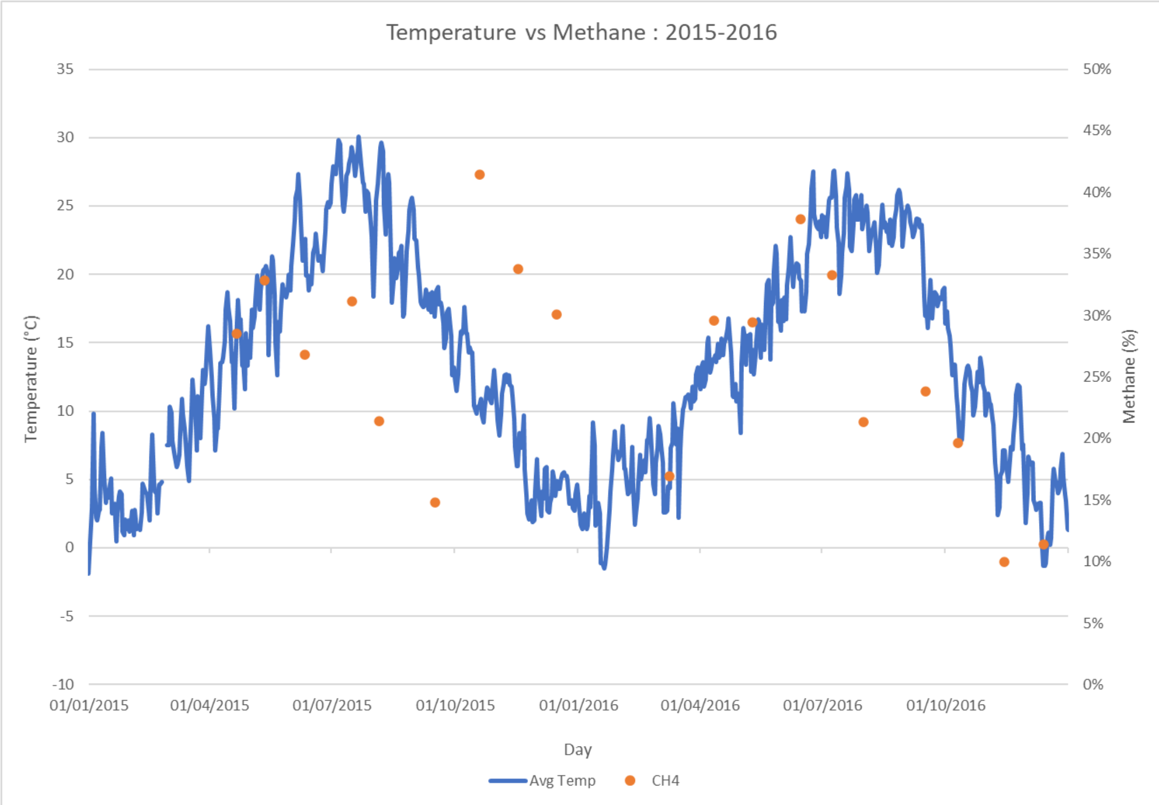
Before starting to evaluate all the possible correlations between the physical quantities previously mentioned, it is worth to remember how the landfill site was subdivided and how the waste body coverage was carried out. In the northern area, although the waste bales are covered by a geomembrane, there is not an impermeable coverage. Therefore, this area can be mainly affected by meteorological influences, mostly when precipitation occurs. On the other hand, the southern part presents a waterproof geomembrane which does not allow meteorological parameters to affect the waste body. Nevertheless, the two landfill sections are not completely isolated from each other because no divider sheet takes place between them, thus they can interact each other. For example, whether precipitation occurs, rainwater can infiltrate from the northern part and then it can flow to the next side where the bulk material was arranged. Accordingly, because of wells presence there could be a physical interaction between the landfill waste and the outer environment with possible consequences concerning the biogas production and emission.

5.1 AIR TEMPERATURE

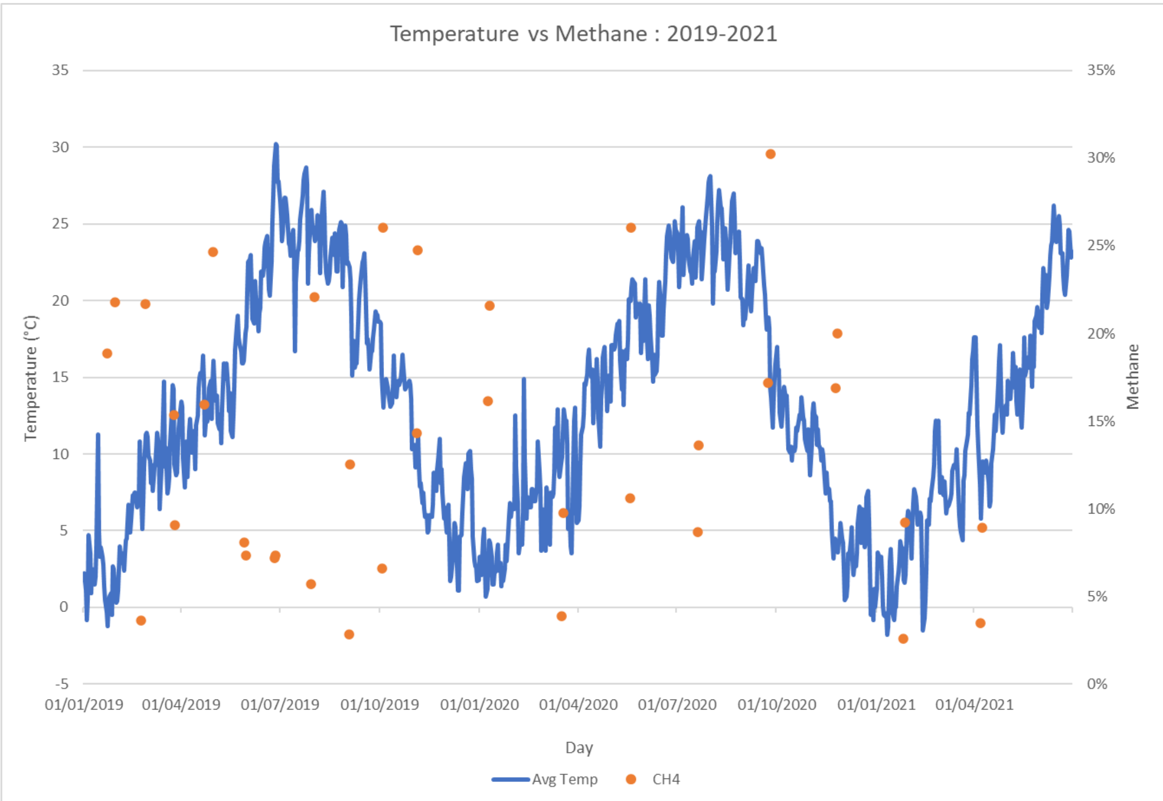
The first parameter to be analysed refers to ambient temperature. As it was previously mentioned a further characterization was realized in order to distinguish different time windows. In this regard, Graph T2, Graph T3 and Graph T4 deals with the correlation between air temperature and methane in 2013-2014, 2015-2016 and 2019-2021, respectively.



Graph T2, Temperature vs methane concentration: 2013-2014.

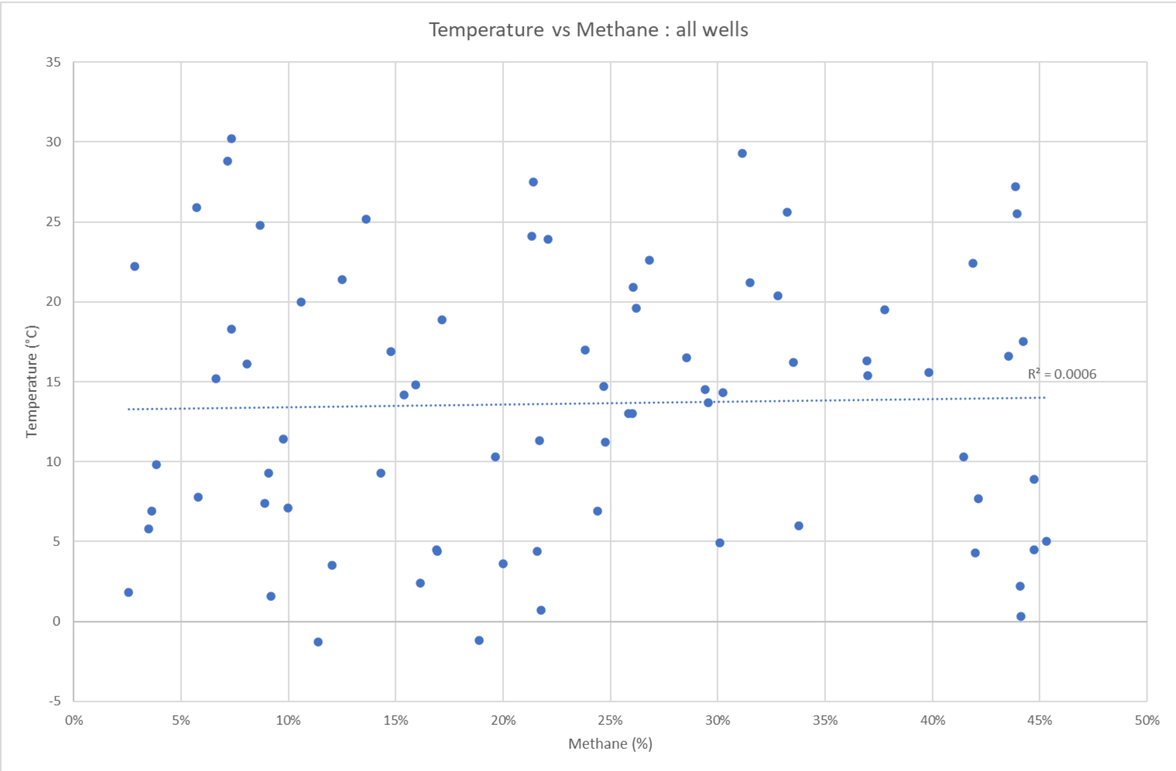


Graph T3, Temperature vs methane concentration: 2015-2016.



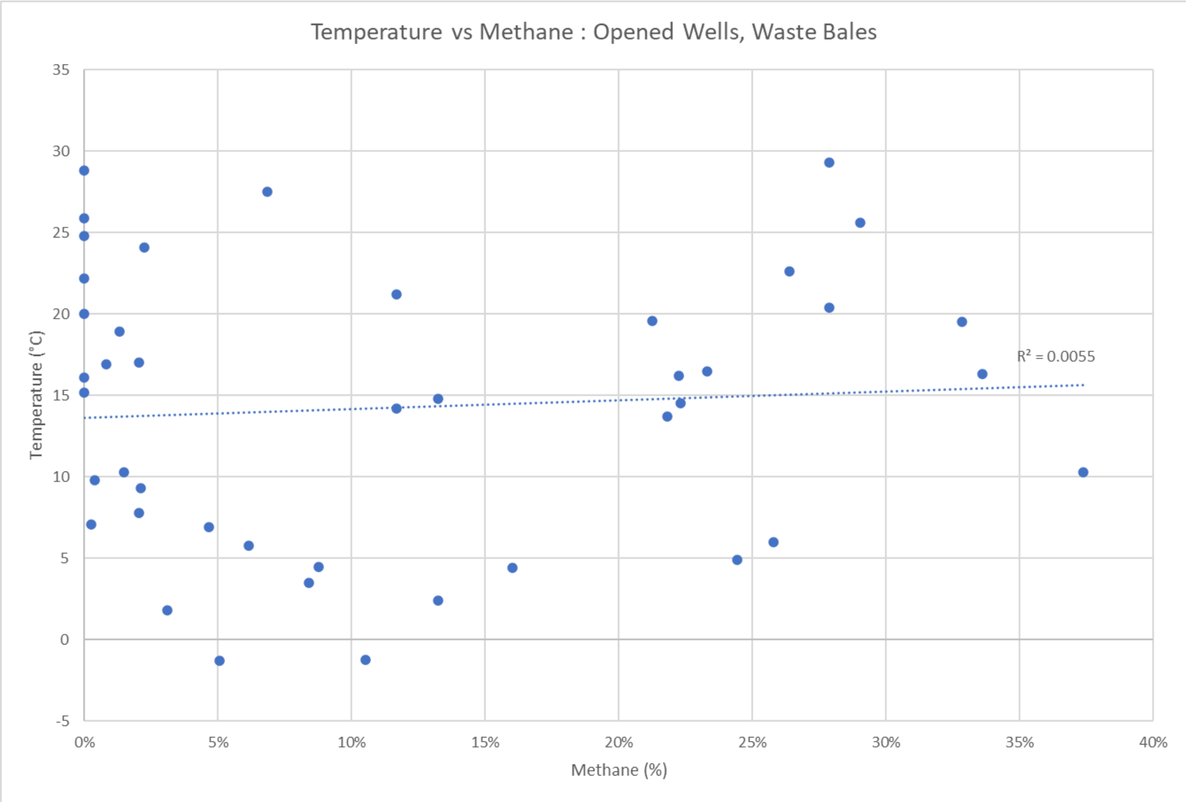
Graph T4, Temperature vs methane concentration: 2019-2021.

From the preliminary analysis related to the initial four graphs it can be inferred that the temperature trend follows a seasonal variation, as it was expected to be. In this case, by adding the methane concentrations it seems that its values follow a specific path which can be superimposed on temperature values by considering a time shifting equal to three or four months. Such a kind of phenomenon can be determined by the methane oxidation which is usually performed in summertime when temperature gets higher. In this regard, graphs seem to show an inverse relation between methane concentrations and air temperature, higher temperatures correspond to lower values in methane percentages. On the other hand, greater values in methane percentage can be observed in winter or during the colder months. A similar behavior was also found during the field activities concerning the Skellingsted landfill, where the CH_4 concentration shown an opposite trend with respect to the ambient temperature. At this point, by keeping on with the data processing it was interesting to evaluate the methane concentration compared to the temperature increase [Graph T5].

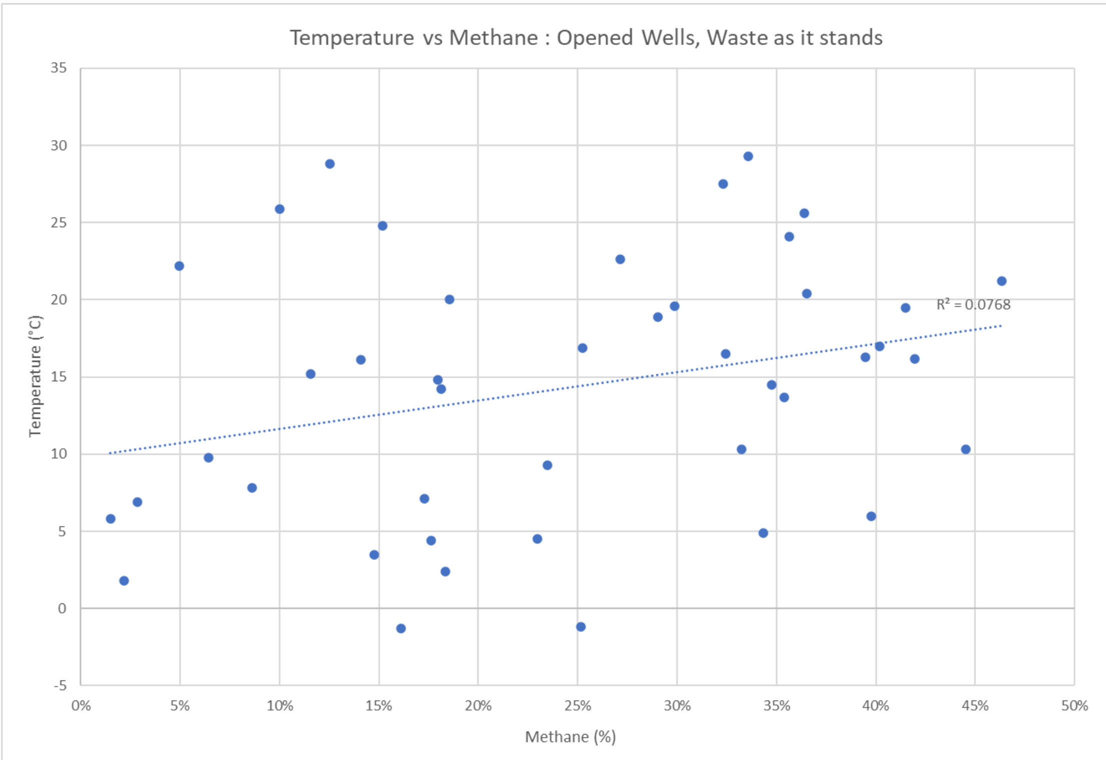


Graph T5, Temperature vs methane concentration: all wells in the Site.

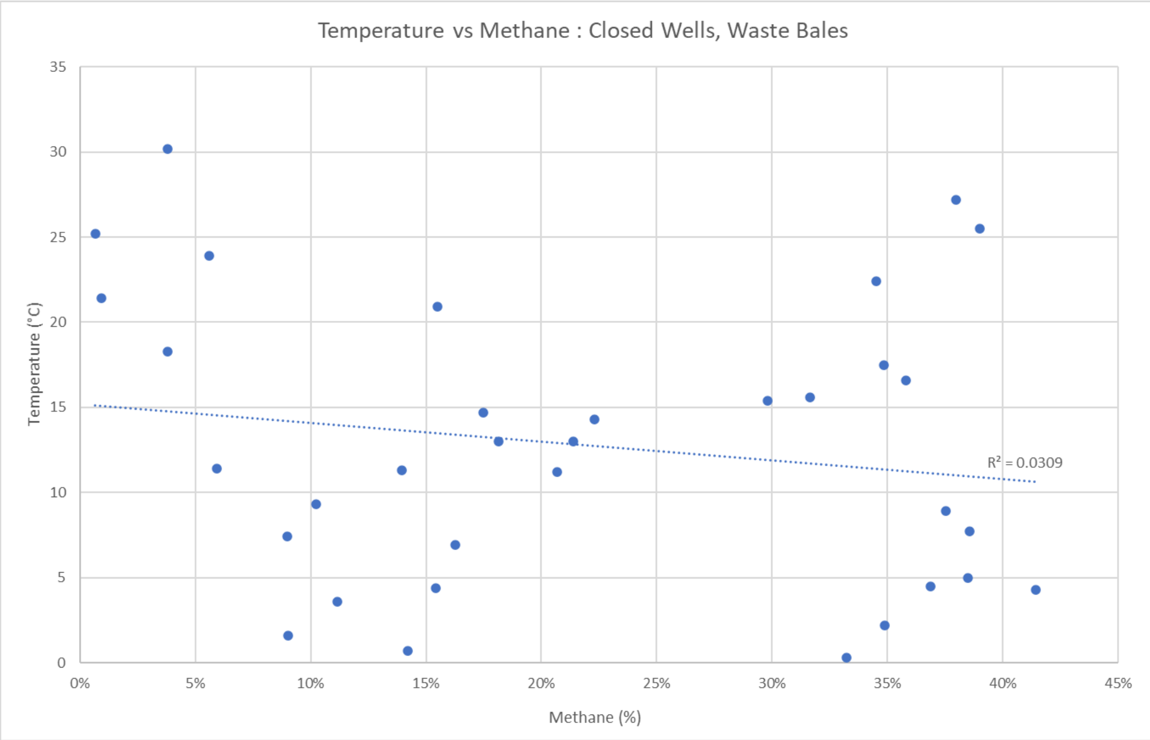
With respect to Graph T5, a very low correlation coefficient results by signifying a scarce correlation between the two quantities. This situation can be due to the great inhomogeneity in the collected data which was previously discussed. The following step consisted in plotting the methane percentages with respect to the four conditions related to the waste material and wells typology [Graph T6], [Graph T7], [Graph T8] and [Graph T9].



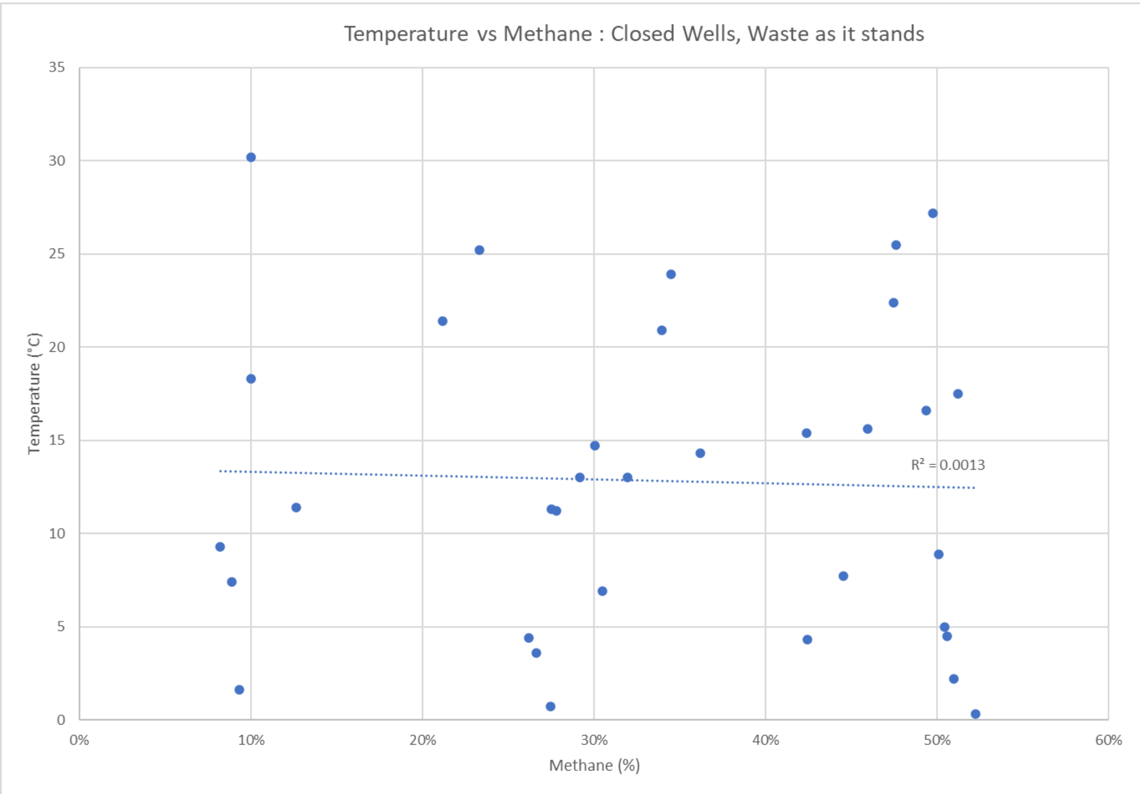
Graph T6, Temperature vs methane concentration: Opened wells, Waste bales.



Graph T7, Temperature vs methane concentration: Opened wells, Waste as it stands.



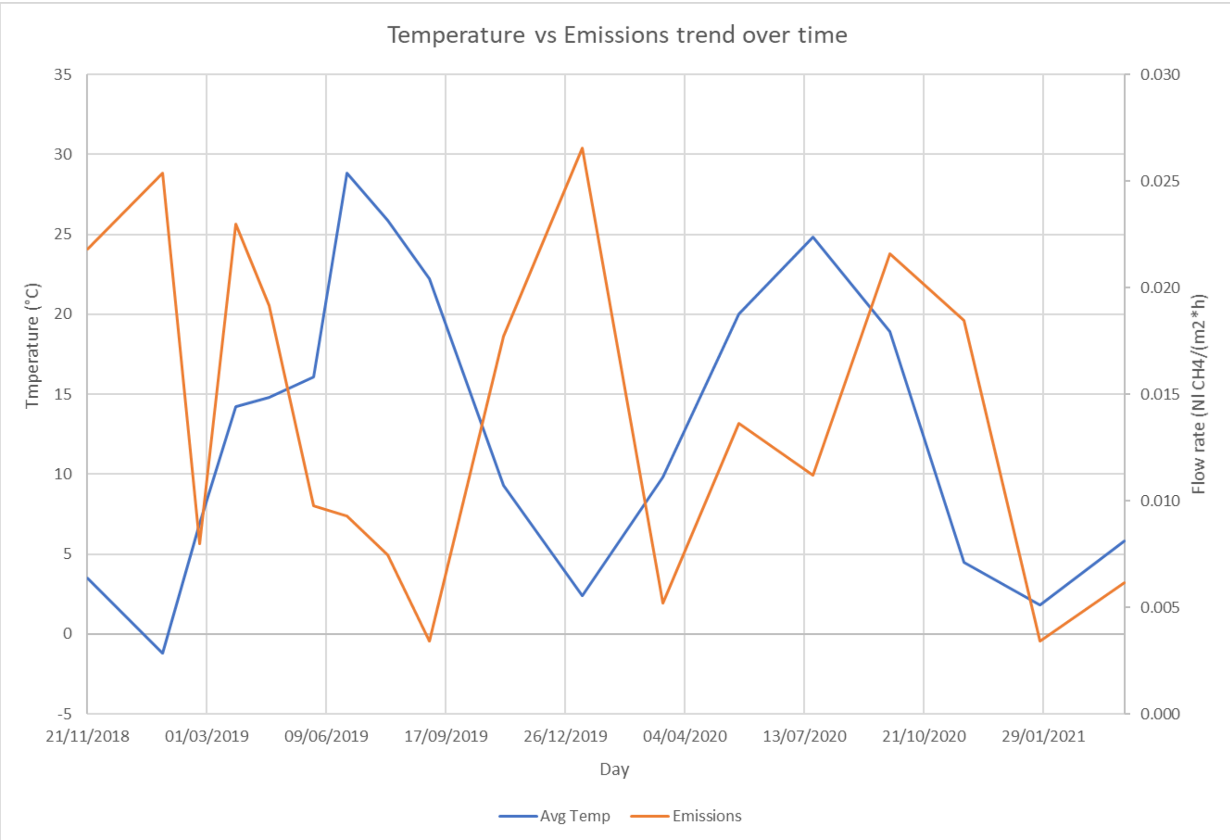
Graph T8, Temperature vs methane concentration: Opened wells, Waste bales.



Graph T9, Temperature vs methane concentration: Closed wells, Waste as it stands.

Unfortunately, by performing a further investigation by examining both the opened and the closed wells, a correlation between these quantities was not found. Subsequently, after evaluating the correlation between the methane percentages and the air temperature, the gas flow rate was analyzed as $\mathrm{Nl\,CH_4/m^2h}$, emissions refer to whole site by adding the gas flux coming from each well. The emissions trend is represented in the last two graphs according two different methods. The first picture [Graph T10] contrasts the methane flow rate with the air temperature over time.

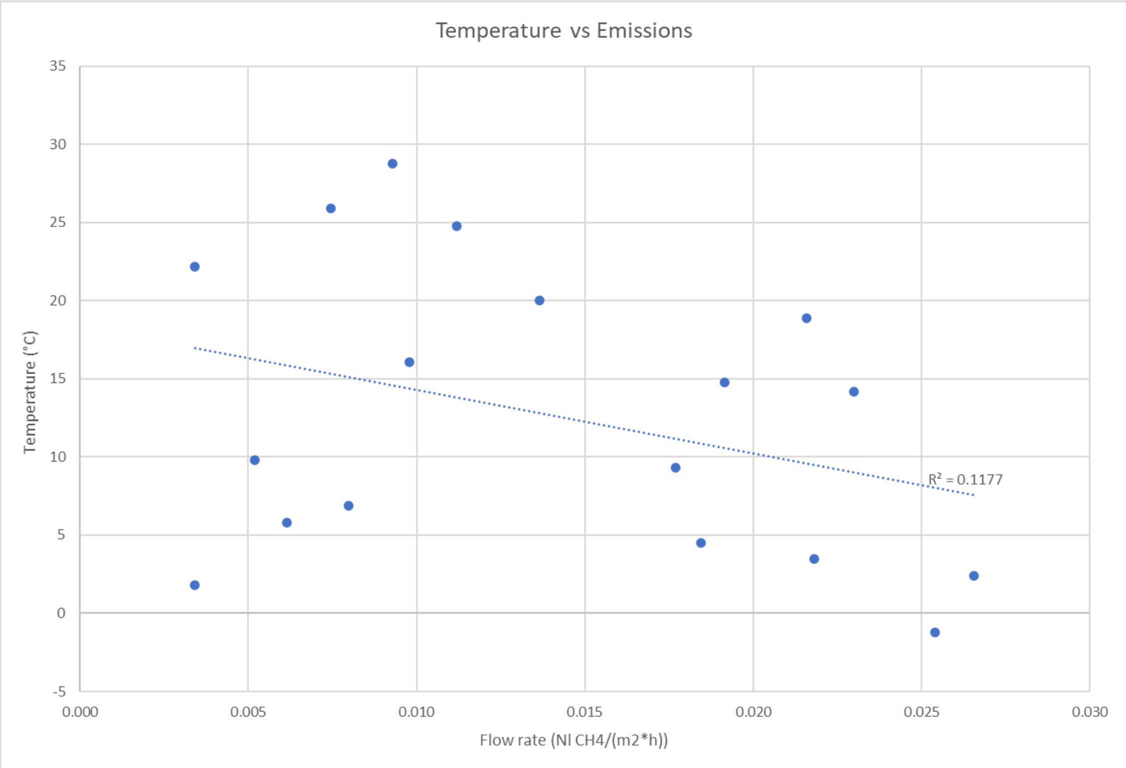
In this case, it does not appear to be there a clear relation between them, anyway, the same reasoning which was previously mentioned concerning the four initial graphs can be told again. The graph shows how the maximum emission values are identified in the winter periods, while the lowest emission values approach to the warmer months.



Graph T10, Temperature vs Emissions trend over time.

Trying to find out an eventual statistical correlation, a further graph was created [Graph T11] by comparing the temperature variation with the gas emission increase. However, the correlation coefficient shown a low result (0.11). To finish with the temperature analysis, very weak correlations were found with both the methane percentages and the gas emissions.

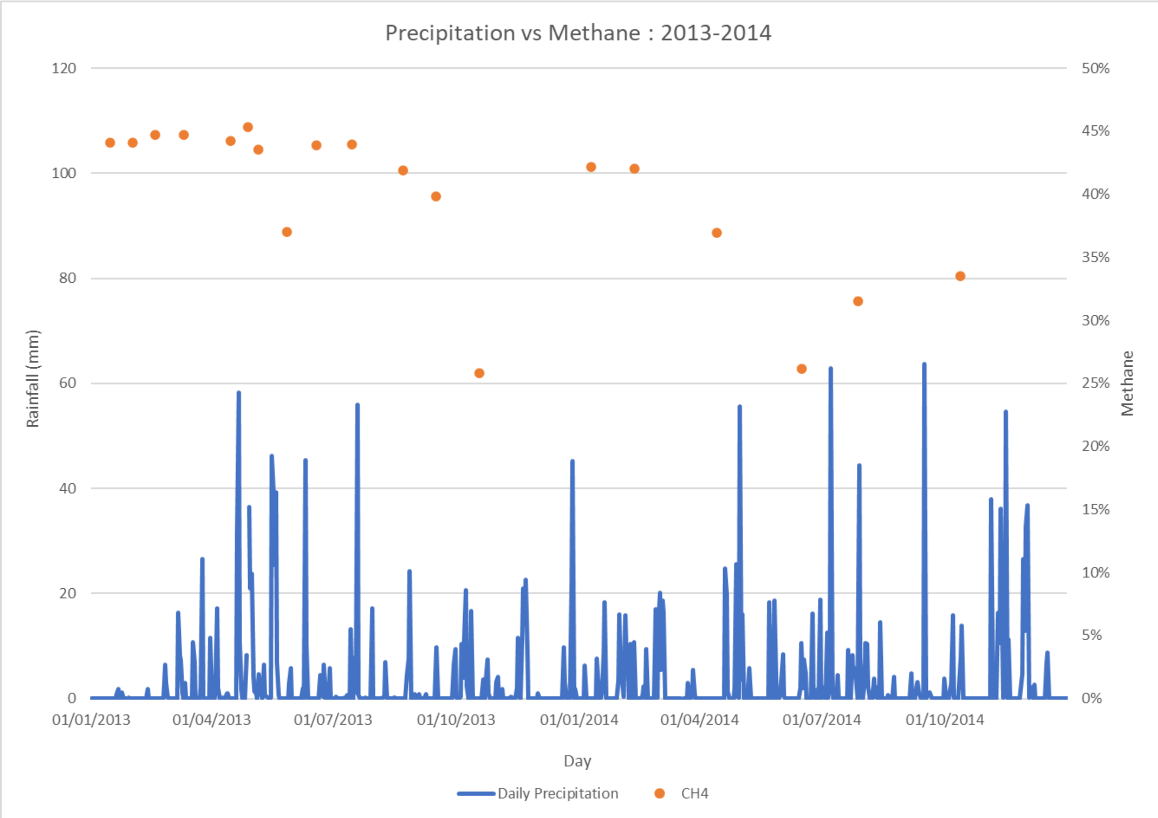
In this way, the same result related to the Odense landfill was obtained, thus it seems that the air temperature does not affect the methane concentrations at the Site.



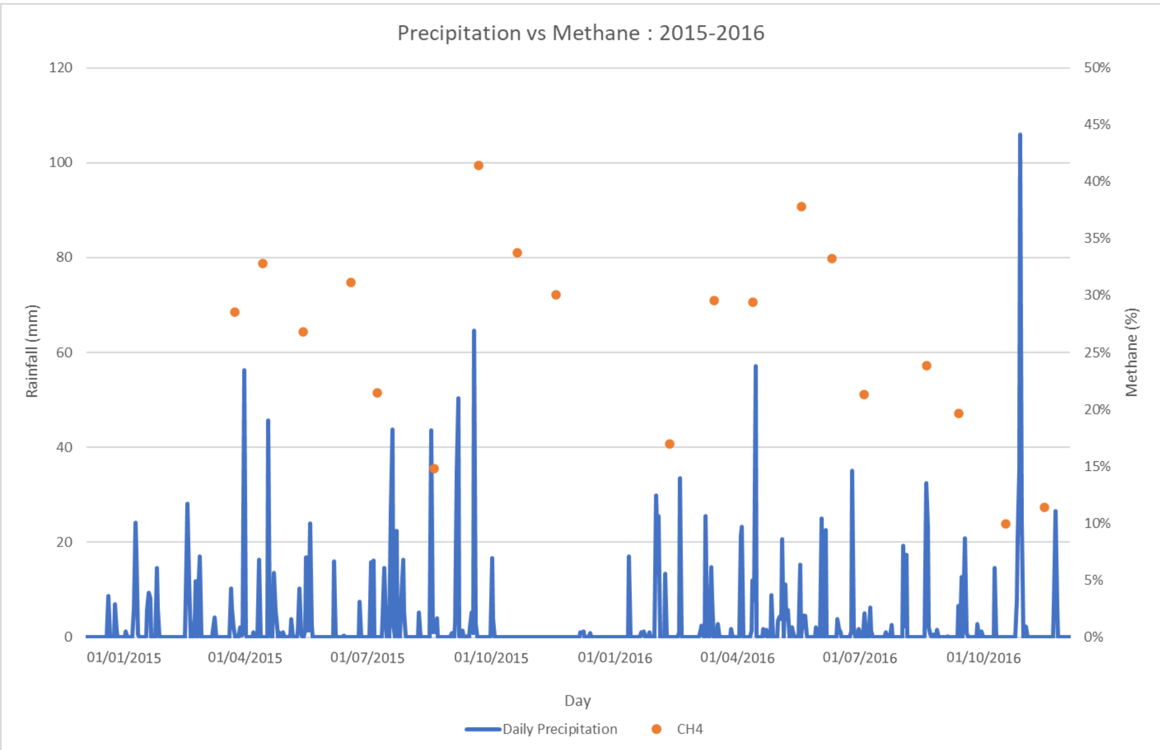
Graph T11, Temperature vs methane emissions.

5.2 RAINFALL

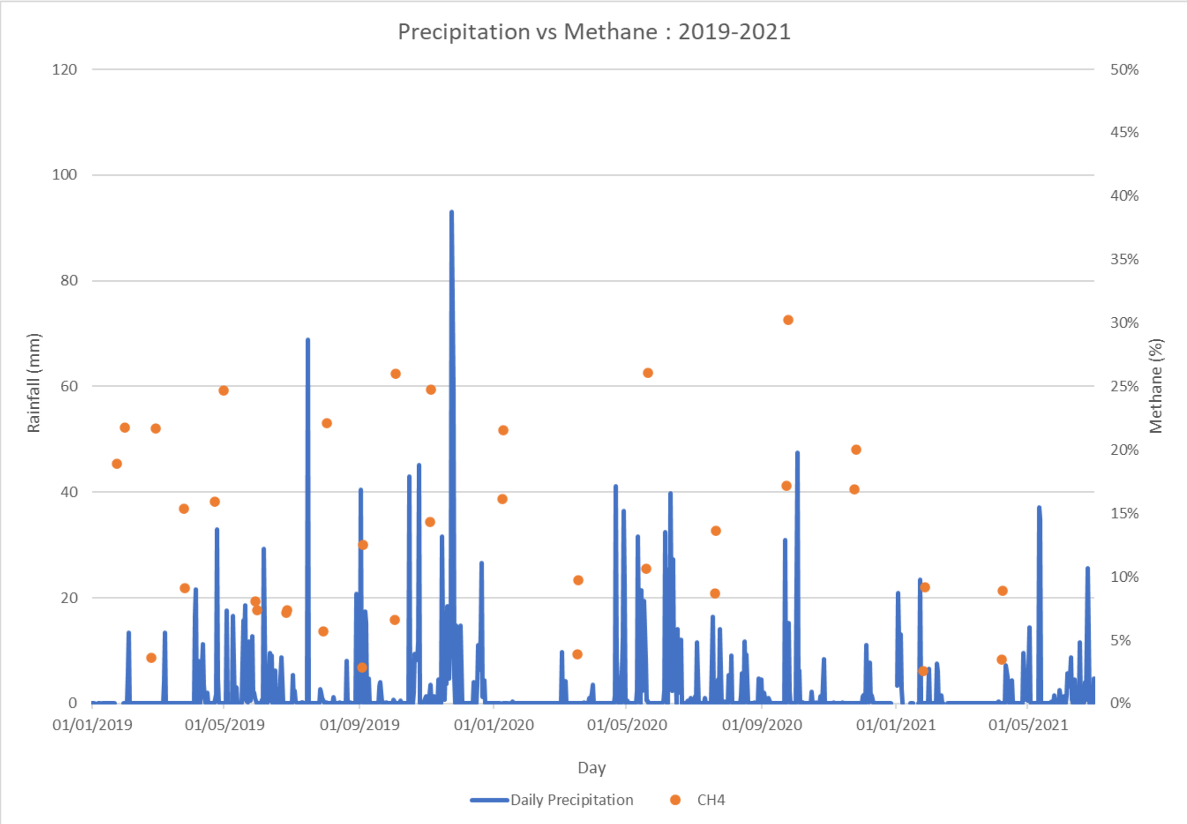
The second parameter to be examined deals with the precipitation. The first four graphs (Graph R2, Graph R3 and Graph R4) representing the different time windows are represented below:



Graph R2, Precipitation vs methane concentration: 2013-2014.



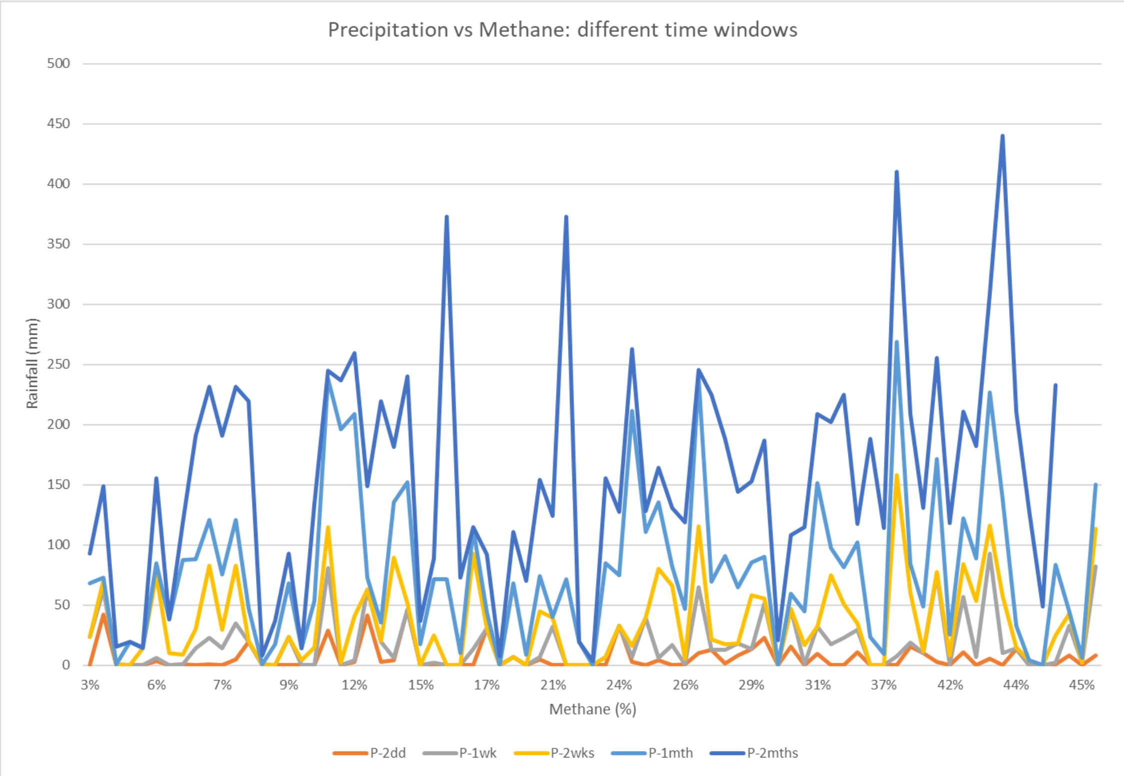
Graph R3, Precipitation vs methane concentration: 2015-2016.



Graph R4, Precipitation vs methane concentration: 2019-2021.

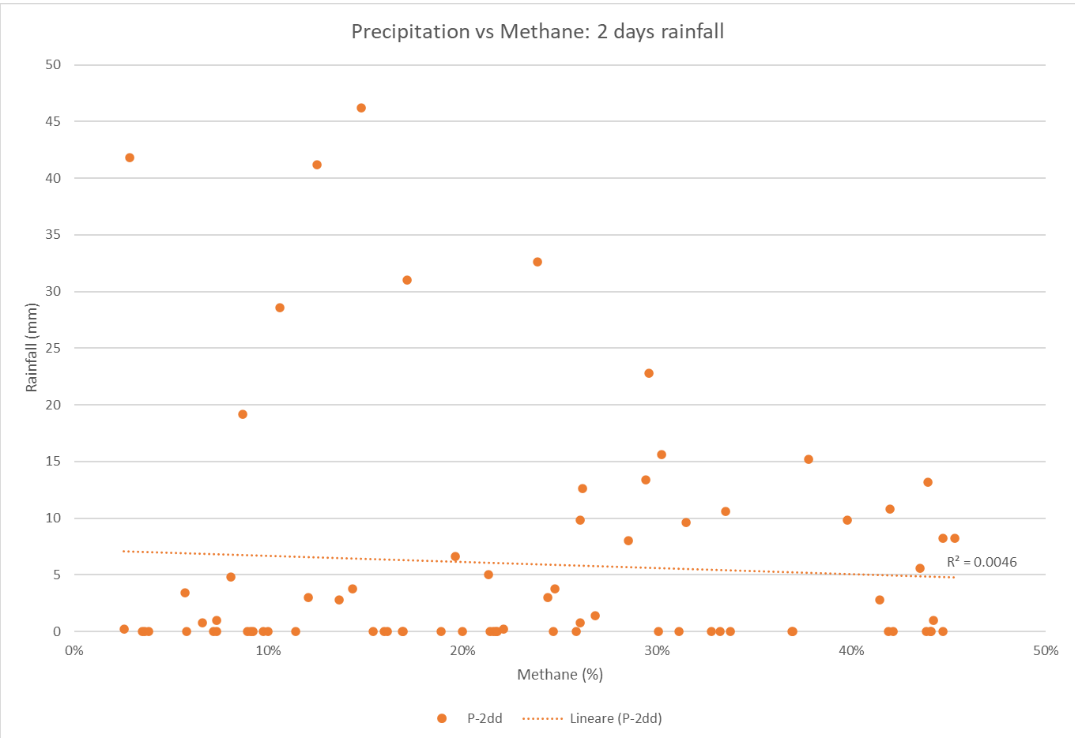
From a first look about the four initial graphs, it can be shown that there is not a clear seasonal correlation between the daily rainfall and the methane concentration recorded over the years. Therefore, it is necessary to carry out an in-depth study by selecting limited time windows to better understand if significant correlations take place between these two quantities.

As a first analysis, it was decided to highlight the amount of rain that fell over a limited time period with the consequent increase in the methane percentage. The following time windows were chosen as reference samples: two days, one week, two weeks, one month and two months. Thus a first graph was then created which compares the different rainwater events about this characterization [Graph R5].

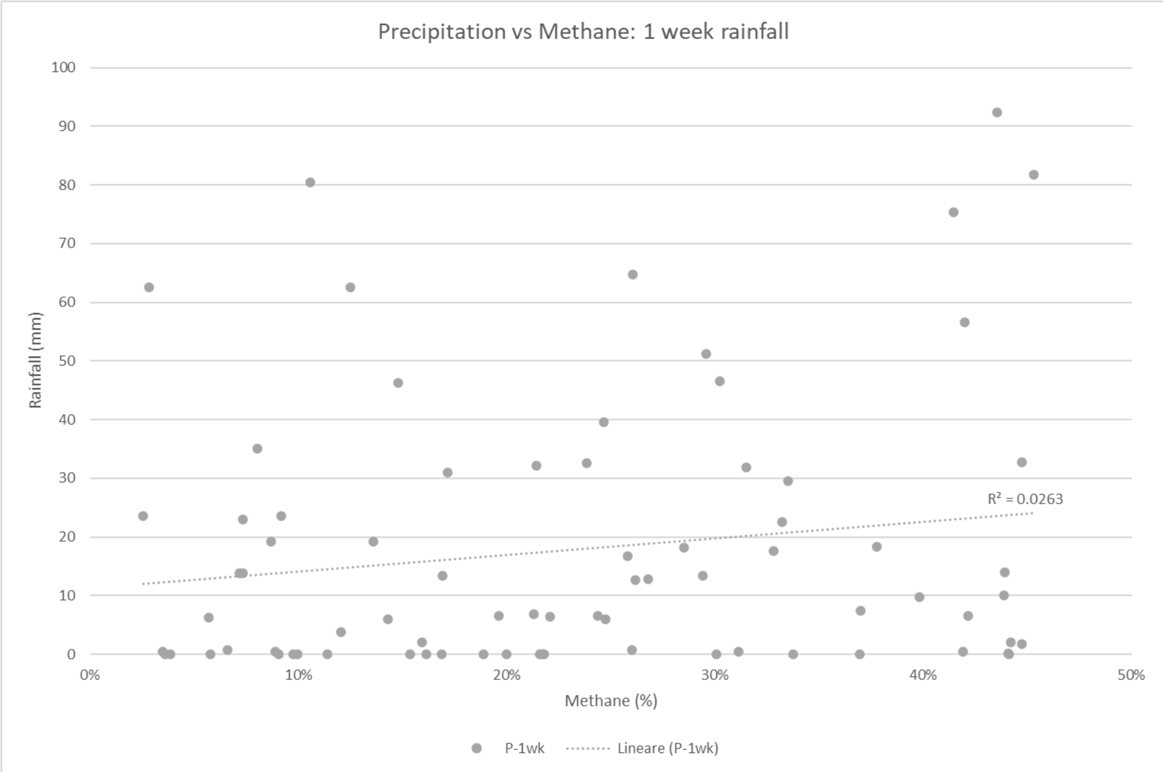


Graph R5, Precipitation vs methane concentration: different time windows.

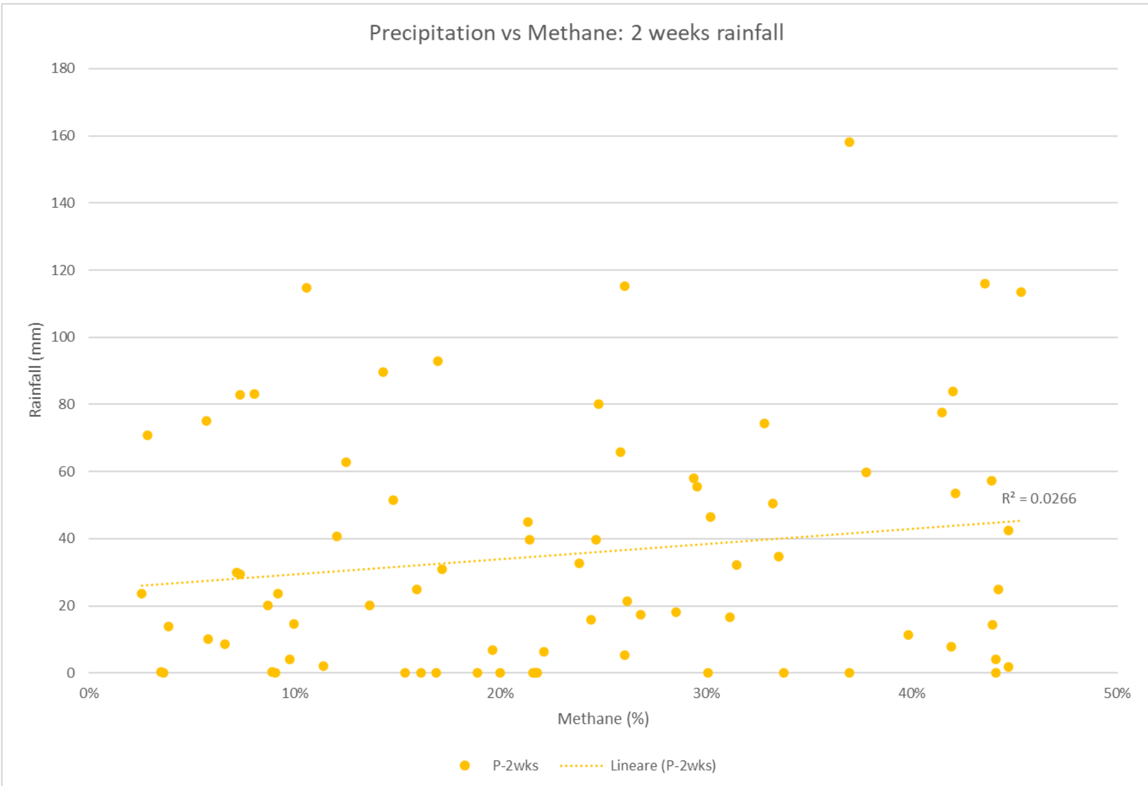
On the other hand, in the following graphs (from Graph R6 to Graph R10) the different time windows are displayed in a scatter plot evaluating the possible correlations between the reference quantities.



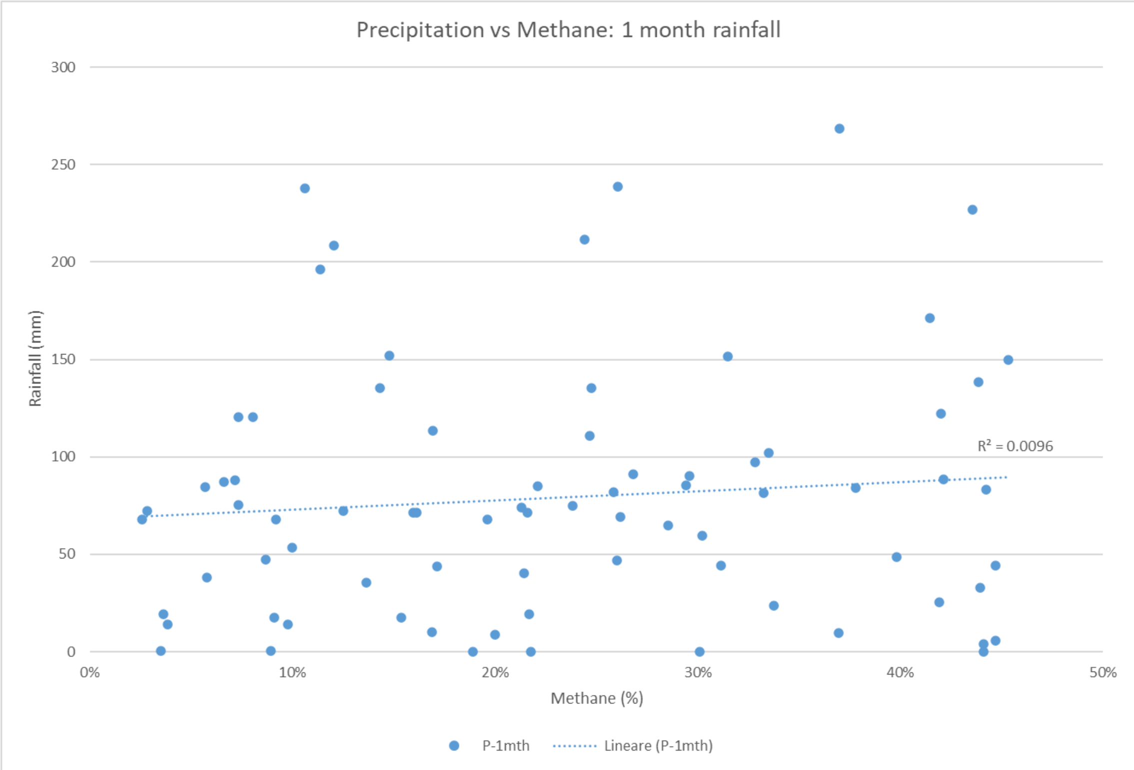
Graph R6, Precipitation vs methane concentration: 2 days rainfall.



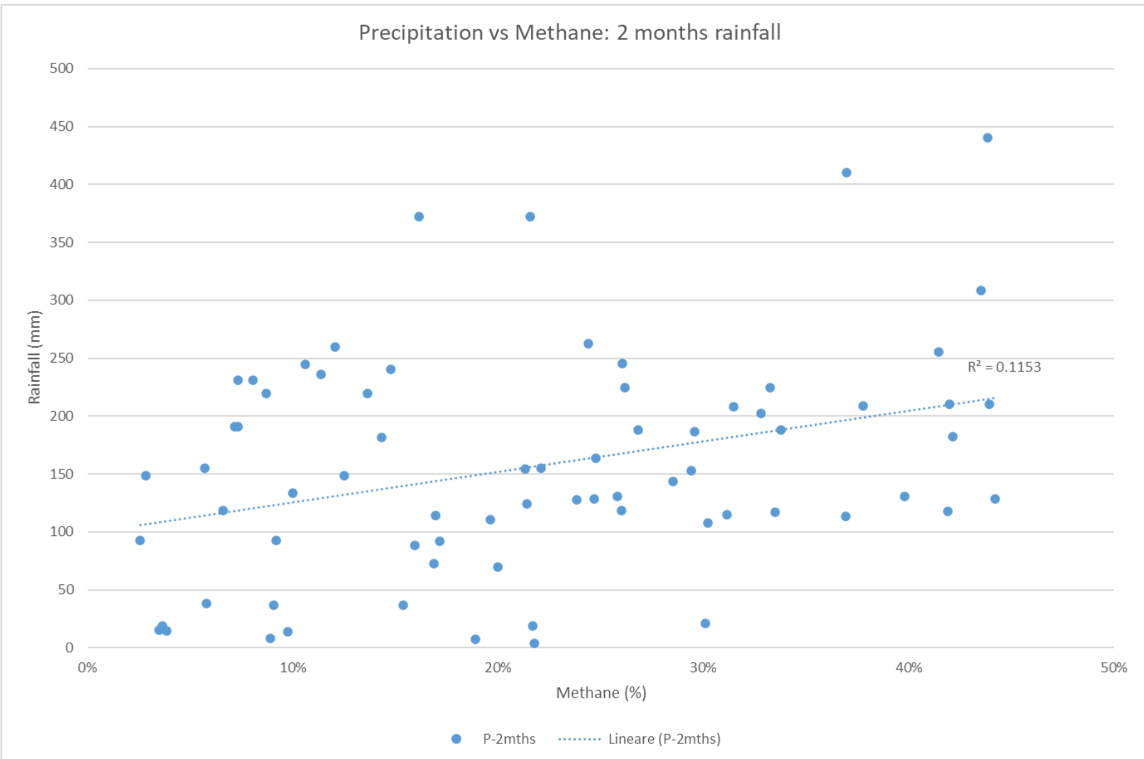
Graph R7, Precipitation vs methane concentration: 1 week rainfall.



Graph R8, Precipitation vs methane concentration: 2 weeks rainfall.



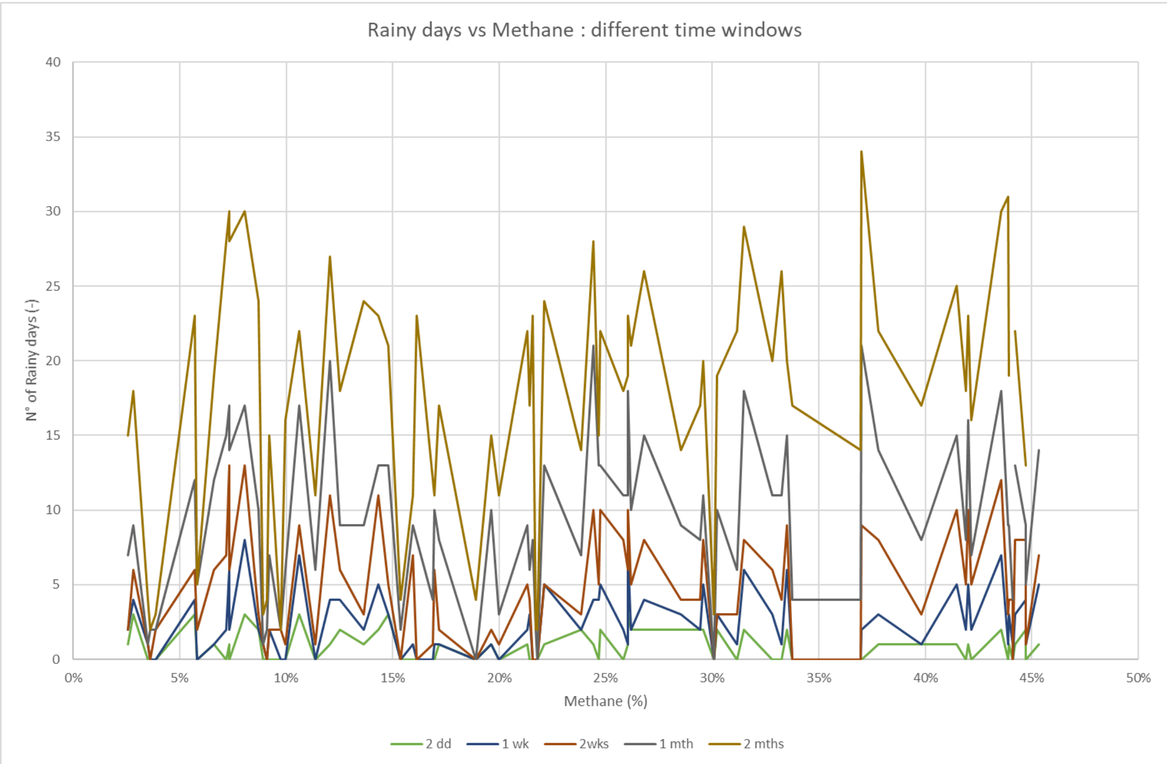
Graph R9, Precipitation vs methane concentration: 1 month rainfall.



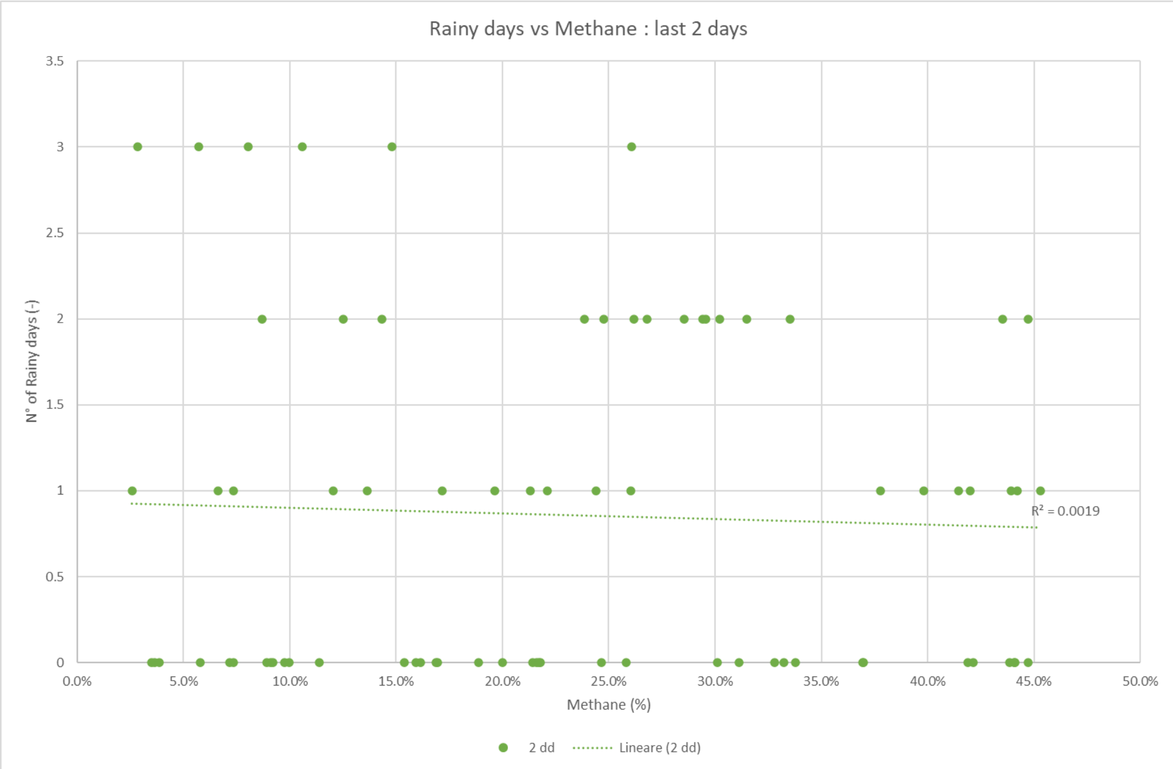
Graph R10, Precipitation vs methane concentration: 2 months rainfall.

The results from the previous graphs show weak correlation coefficients comparing the amount of rain which has fallen and the increase in the methane percentage. In the last graph where the two months rainfall is represented [Graph R10] a correlation index R^2 equal to 0.11 takes place. It represents the highest correlation coefficient but it is still relatively low.

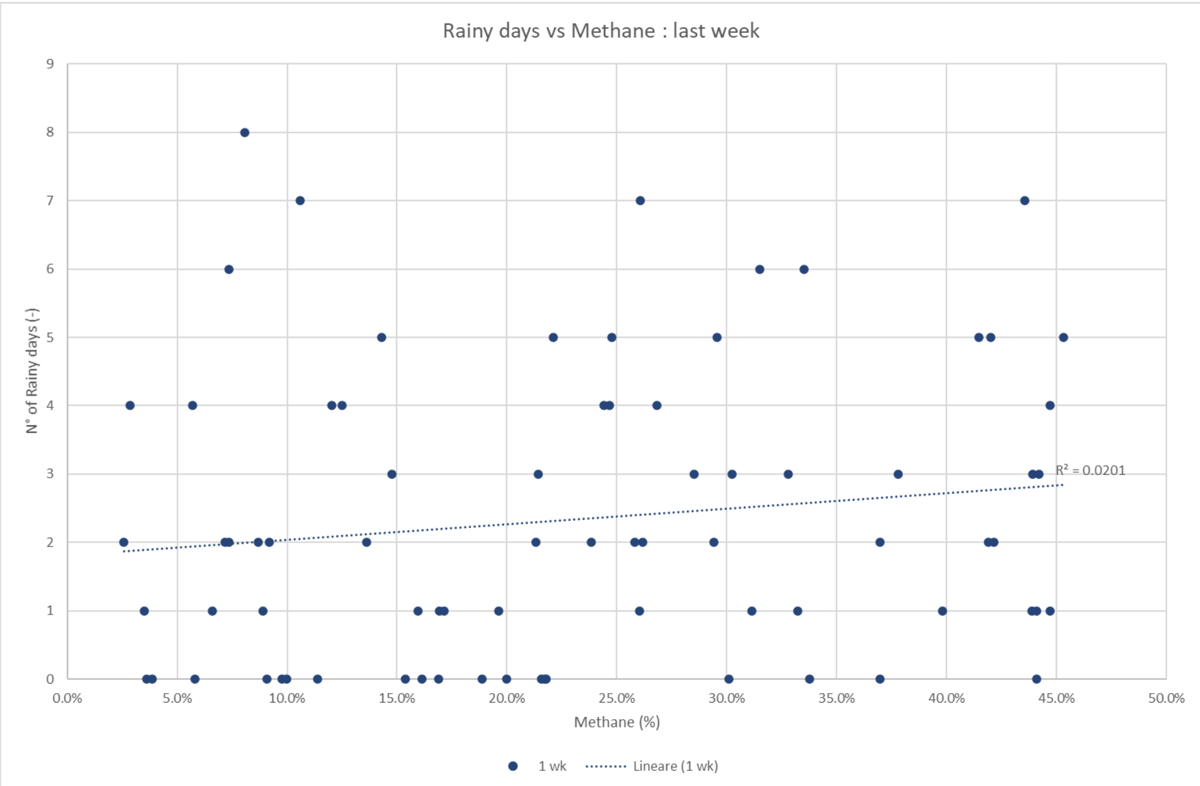
As this kind of approach did not highlight successful results, another type of work was carried out trying to better match the reference data. In this regard, it was decided to extend the analysis including also the number of rainy days prior to a certain methane detection. As in the previous case, an illustrative graph was created representing all the whole-time windows considered [Graph R11] and then a specific scatter plot was made for each time interval (Graph R12 to Graph R16).



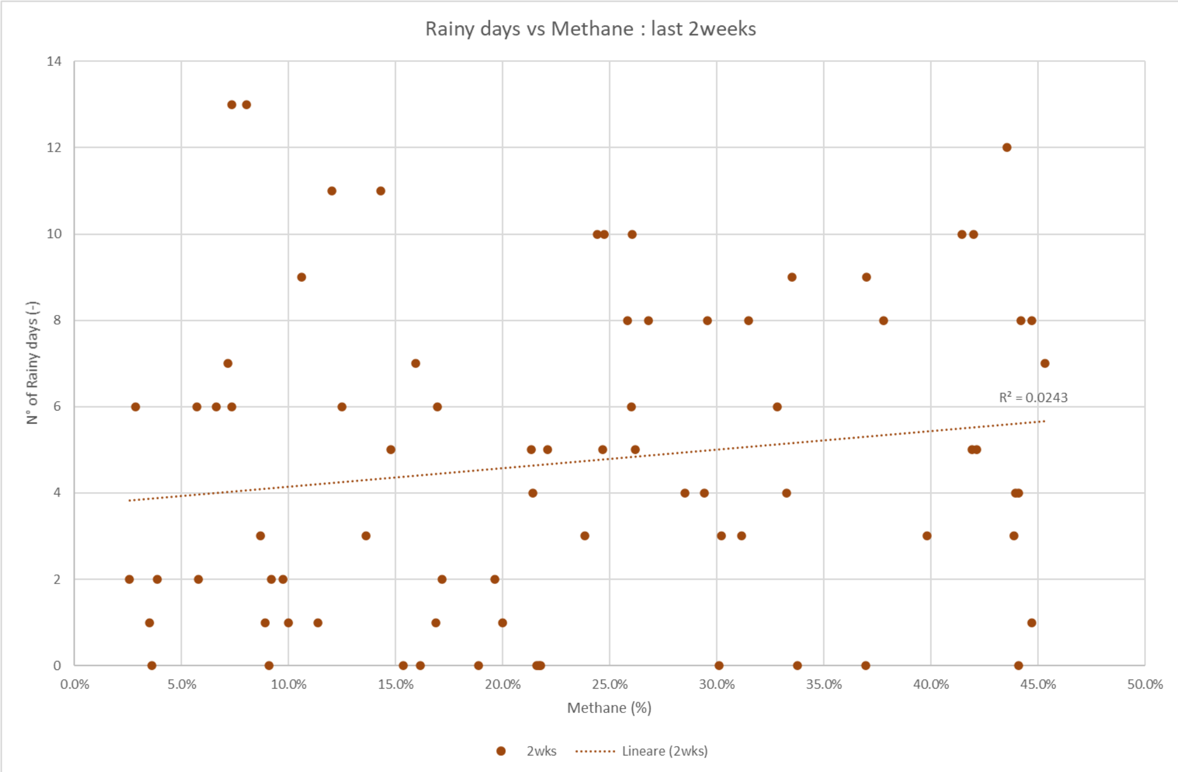
Graph R11, Rainy days vs methane concentration: different time windows.



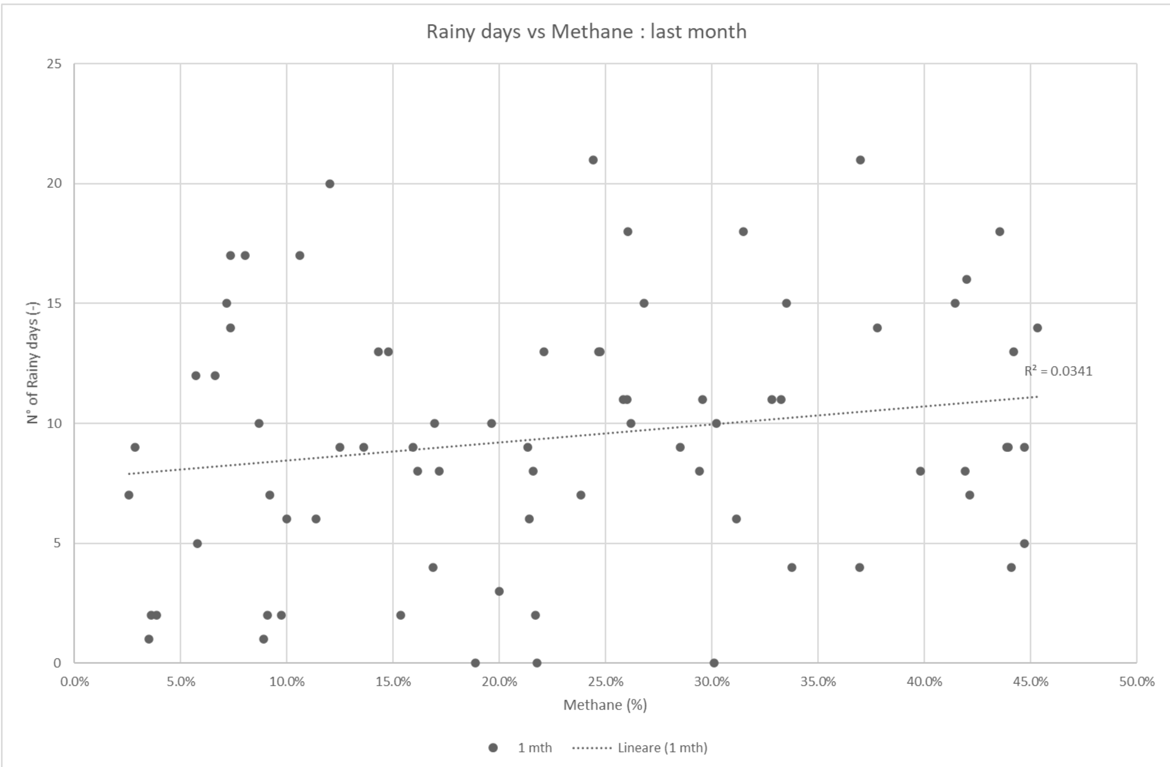
Graph R12, Rainy days vs methane concentration: last 2 days.



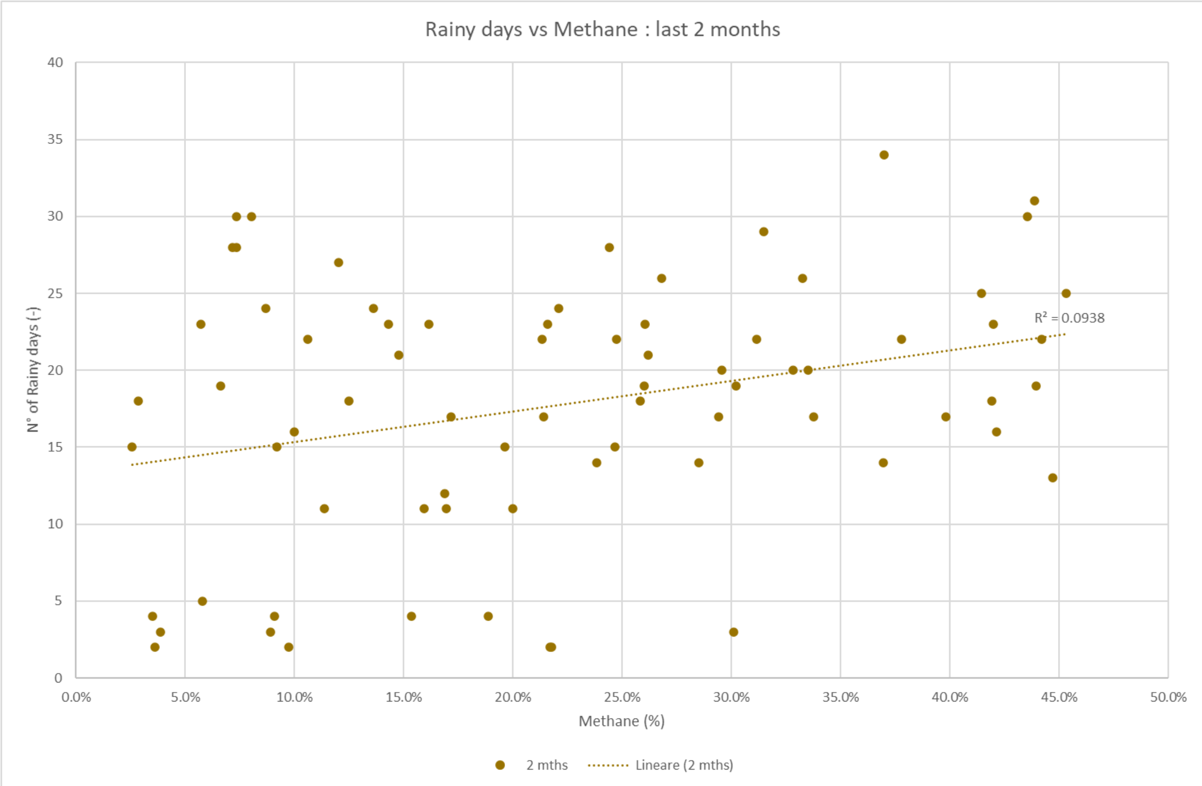
Graph R13, Rainy days vs methane concentration: last week.



Graph R14, Rainy days vs methane concentration: last 2 weeks.



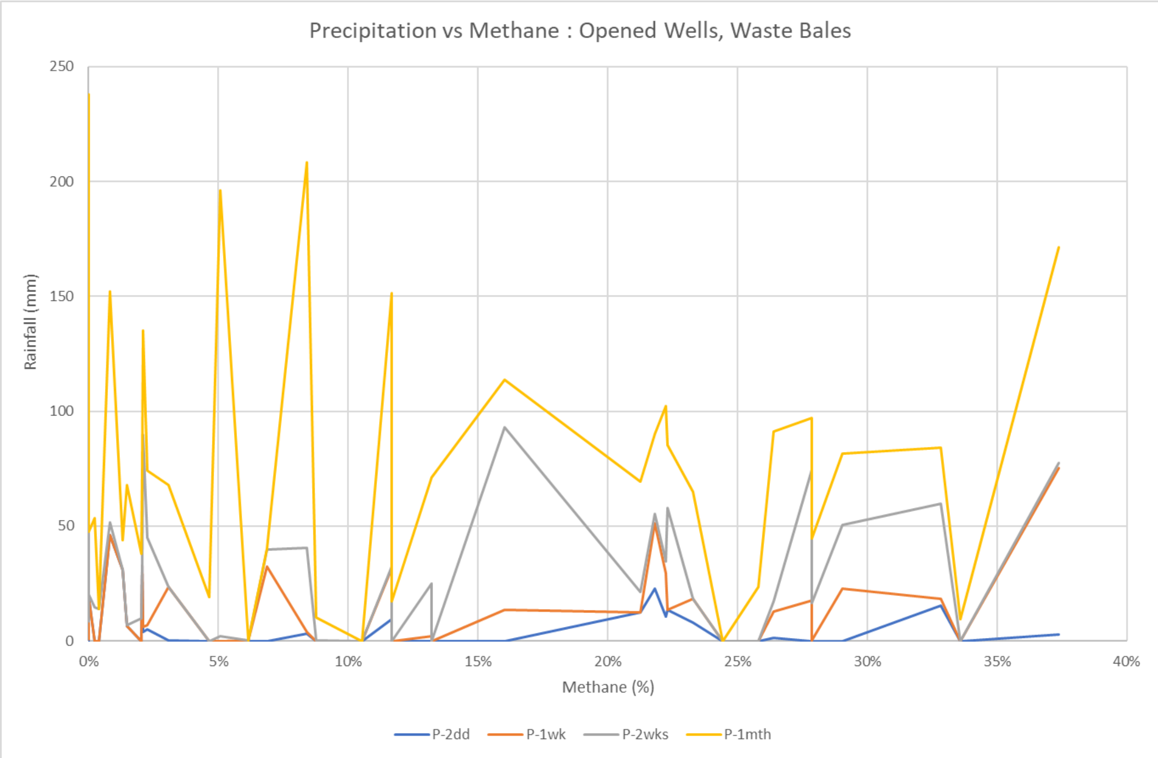
Graph R15, Rainy days vs methane concentration: last month.



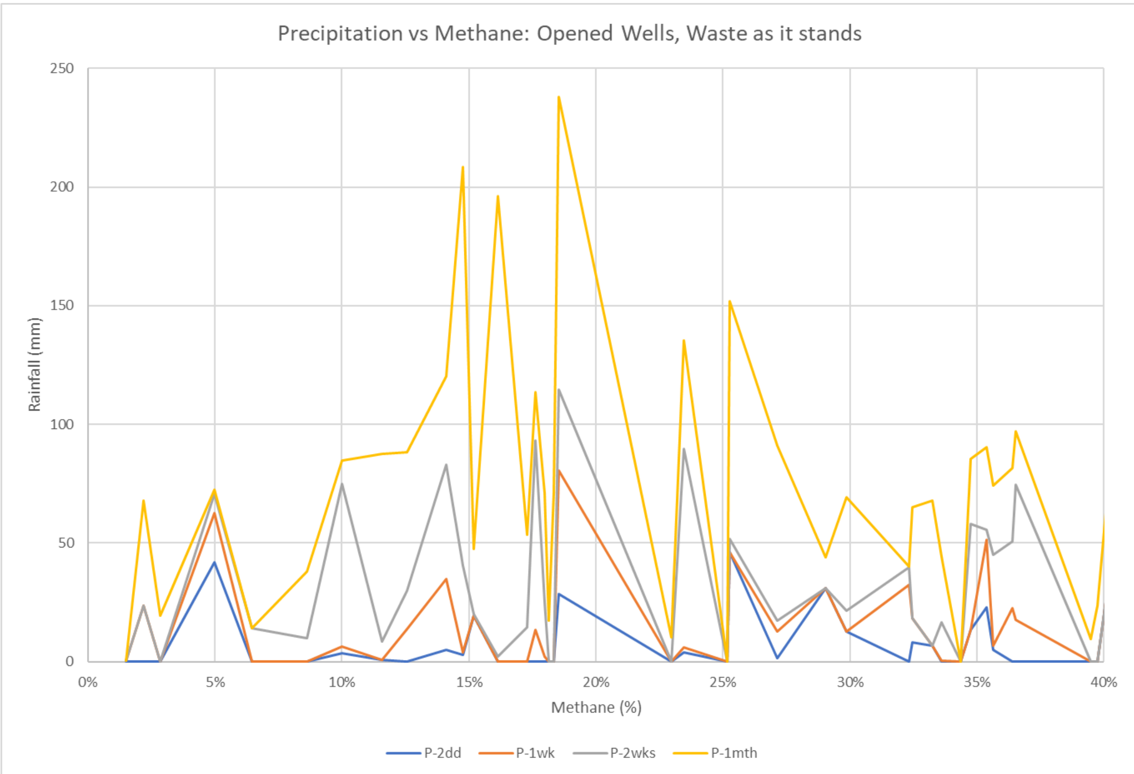
Graph R16, Rainy days vs methane concentration: last 2 months.

Unfortunately, the results coming from this second analysis were similar to the first approach. In fact, low correlation coefficients occurred by highlighting the weak relation between the rainfall event and the methane concentrations. A further investigation was performed concerning the CH_4 percentage study considering each one of the wells present in the Site.

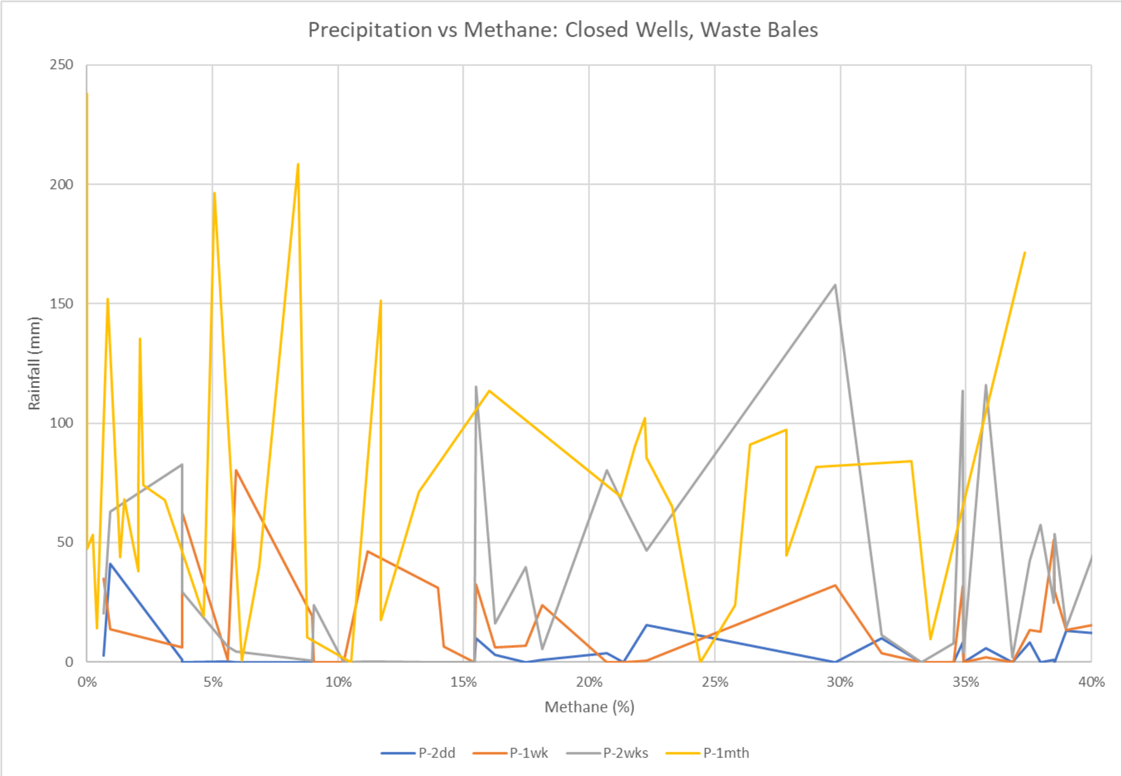
Therefore, in order to distinguish the different material typology an additional study was carried out by evaluating the possible existing correlations between opened wells and closed wells referring to both waste bales and bulk material. This set of pictures include graphs from Graph R17 to Graph R20. In particular, they represent the amount of rain which fell down in two days, one week, two weeks and one month. Nevertheless, the resulting trend coming from the graphs did not show shown any significant correlations between the quantities under investigation.



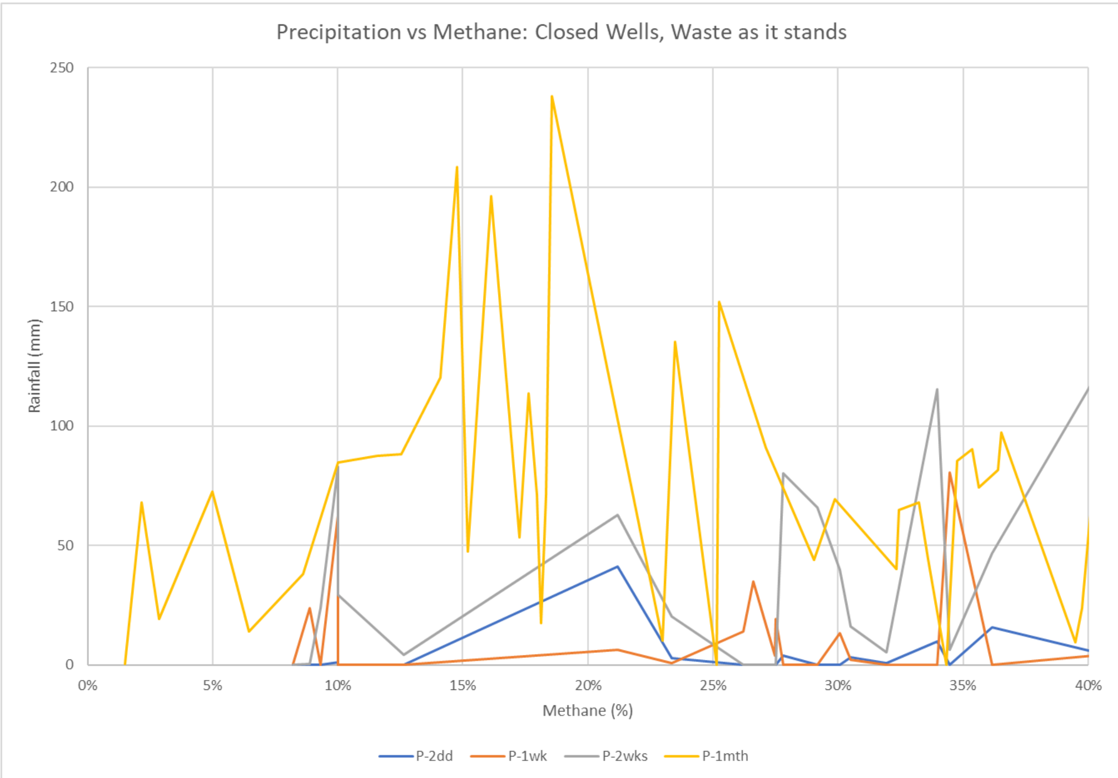
Graph R17, Rainy days vs methane concentration: opened wells, Waste bales.



Graph R18, Rainy days vs methane concentration: opened wells, Waste as it stands.

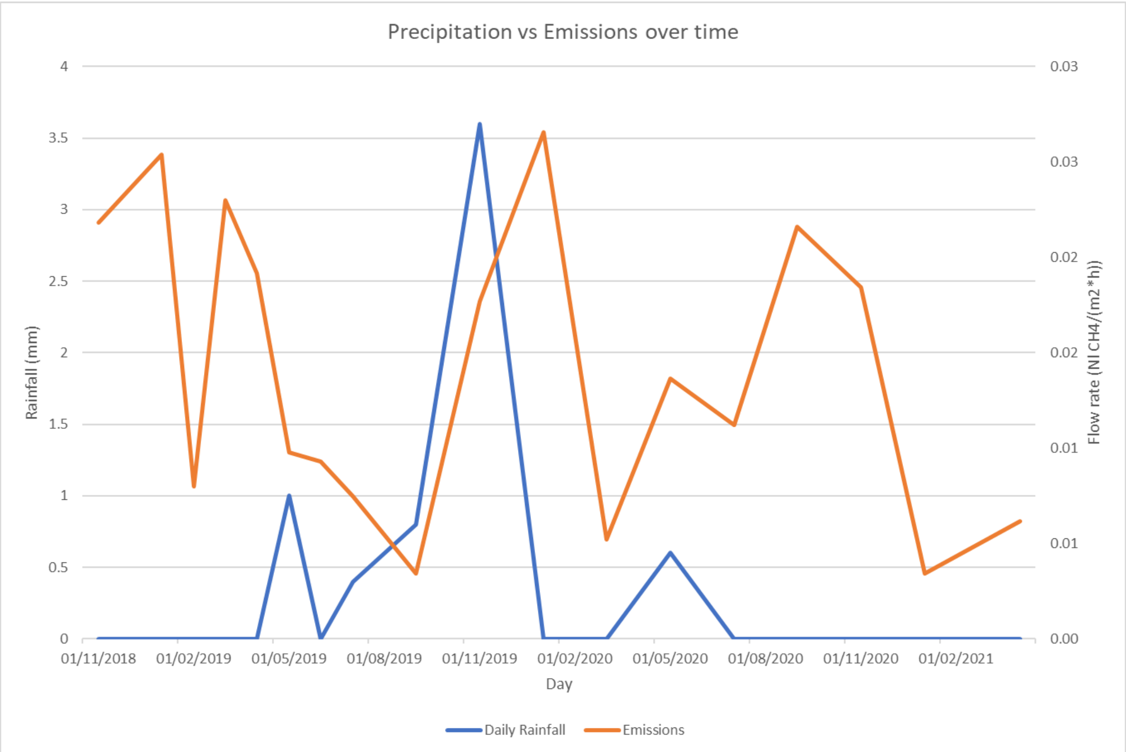


Graph R19, Precipitation vs methane concentration: closed wells, Waste bales.

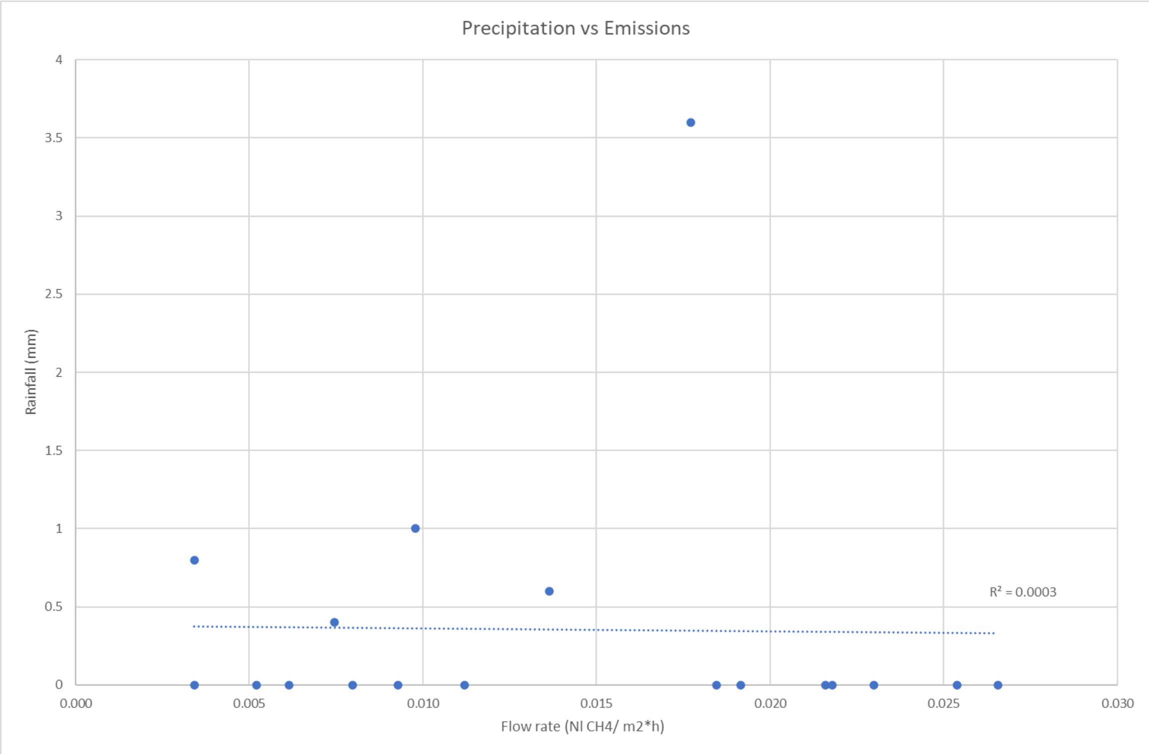


Graph R20, Precipitation vs methane concentration: closed wells, Waste as it stands.

To finish with the rainfall analysis, the last two graphs [Graph R21] and [Graph R22] illustrate the relation between methane emissions and rainfall data. In particular, from the last graph a null correlation seems to link the two quantities, pointing out that the whole landfill site is not affected at all by the precipitation event. It is known from literature that precipitation or rainwater infiltration can affect the methane production by increasing the humidity percentage. In terms of gas emissions, on the other hand, a wet topsoil cannot allow gas flow to leave out the landfill. In this regard, an increase in the amount of rainwater corresponds (theoretically) to a gas flow reduction.
Finally, such a kind of conditions were not really reached by examining this site, maybe because of an effective impermeable coverage related to the waste body. The whole amount of rainwater which could infiltrate did not affect the methane concentrations.



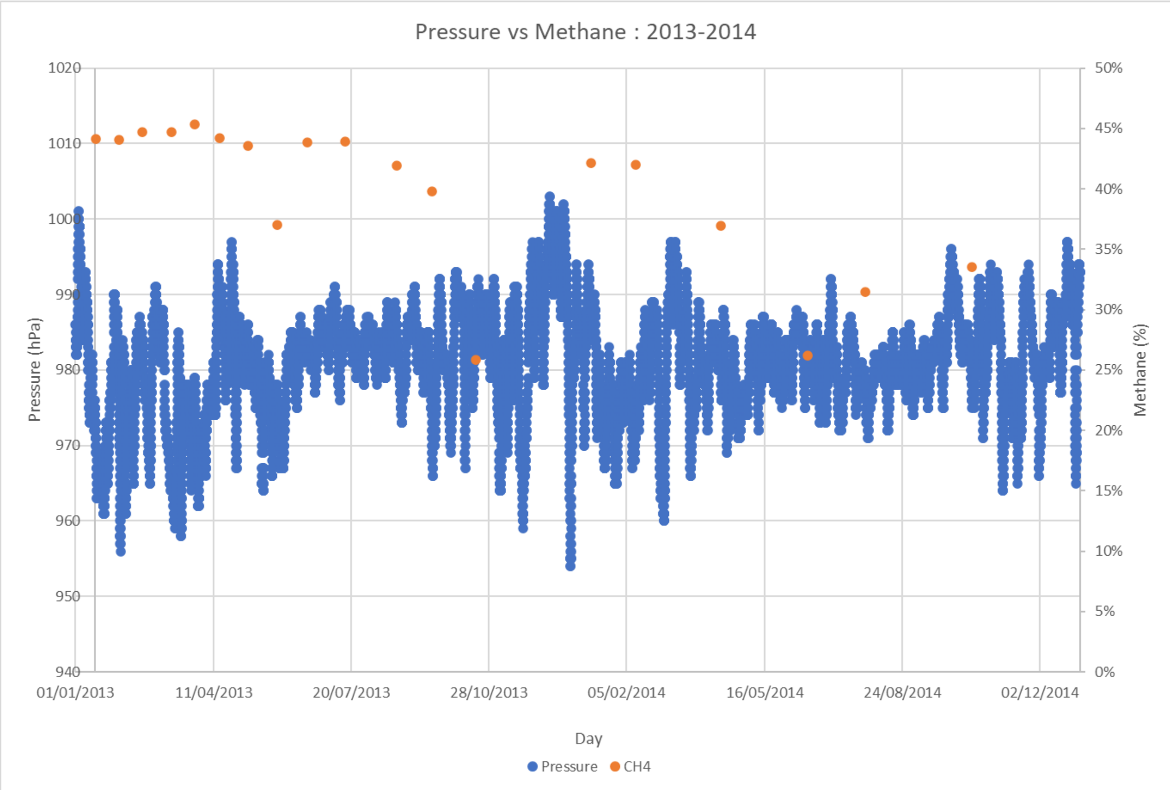
Graph R21, Precipitation vs Emissions over time.



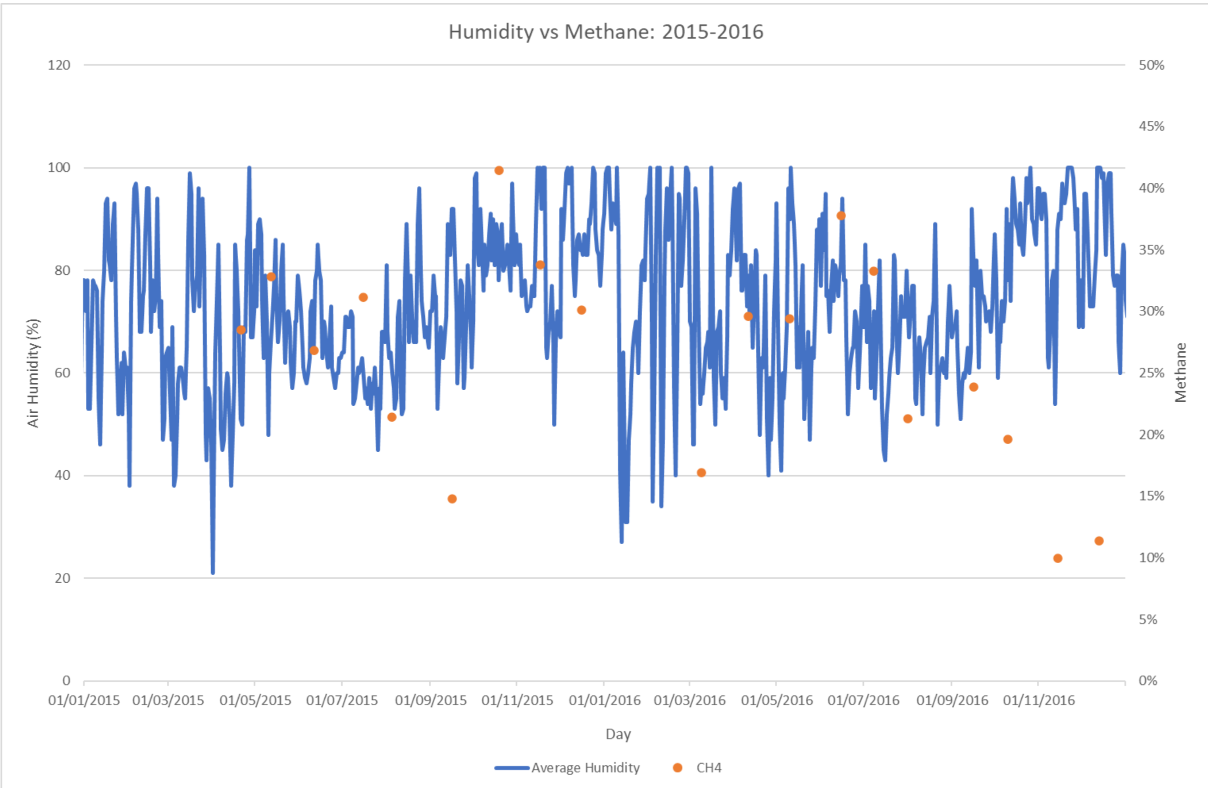
Graph R22, Precipitation vs methane emissions.

5.3 AIR HUMIDITY

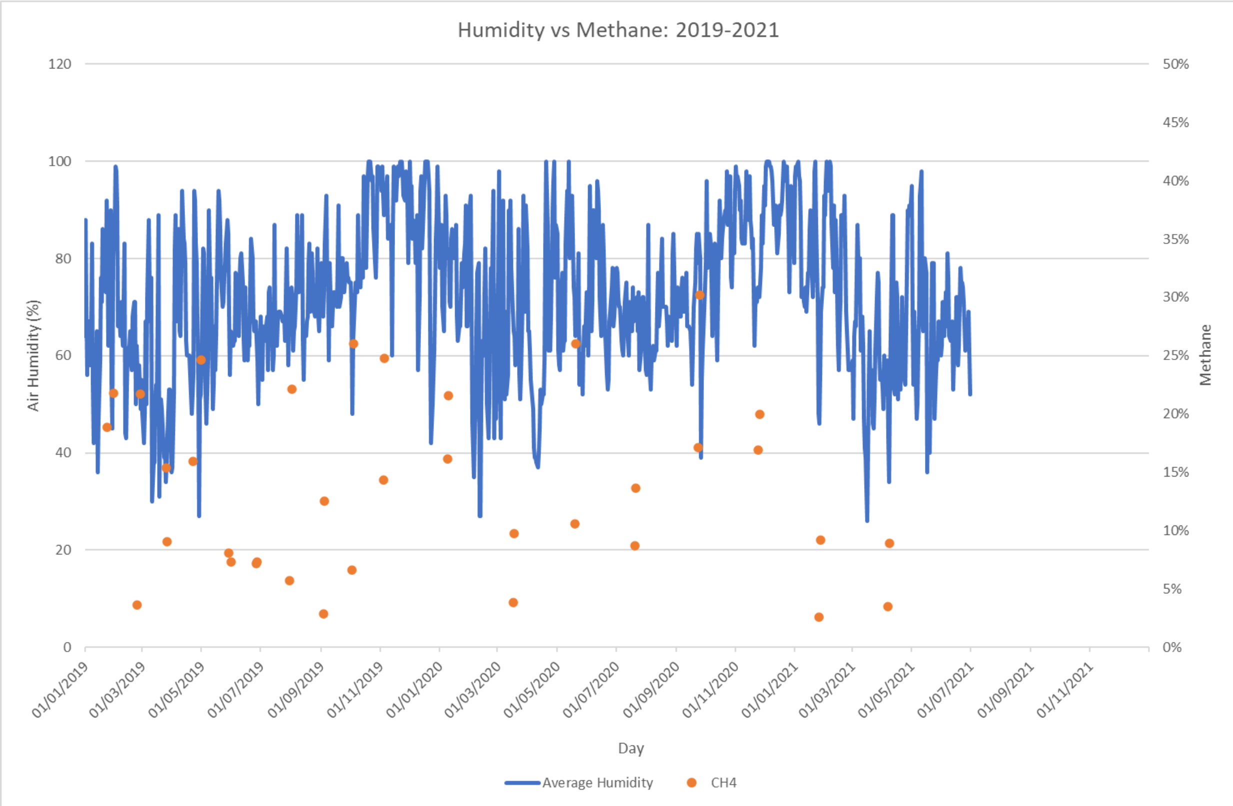
The initial graphs refer once again to the comparison between the CH4 concentrations and the air humidity trend dover time. Thus, the graphs result to be subdivide according to the three time slots previously mentioned: Graph H2 (2013-2014) , Graph H3 (2015-2016) and Graph H4 (2019-2021).



Graph H2, Humidity vs methane concentration: 2013-2014.

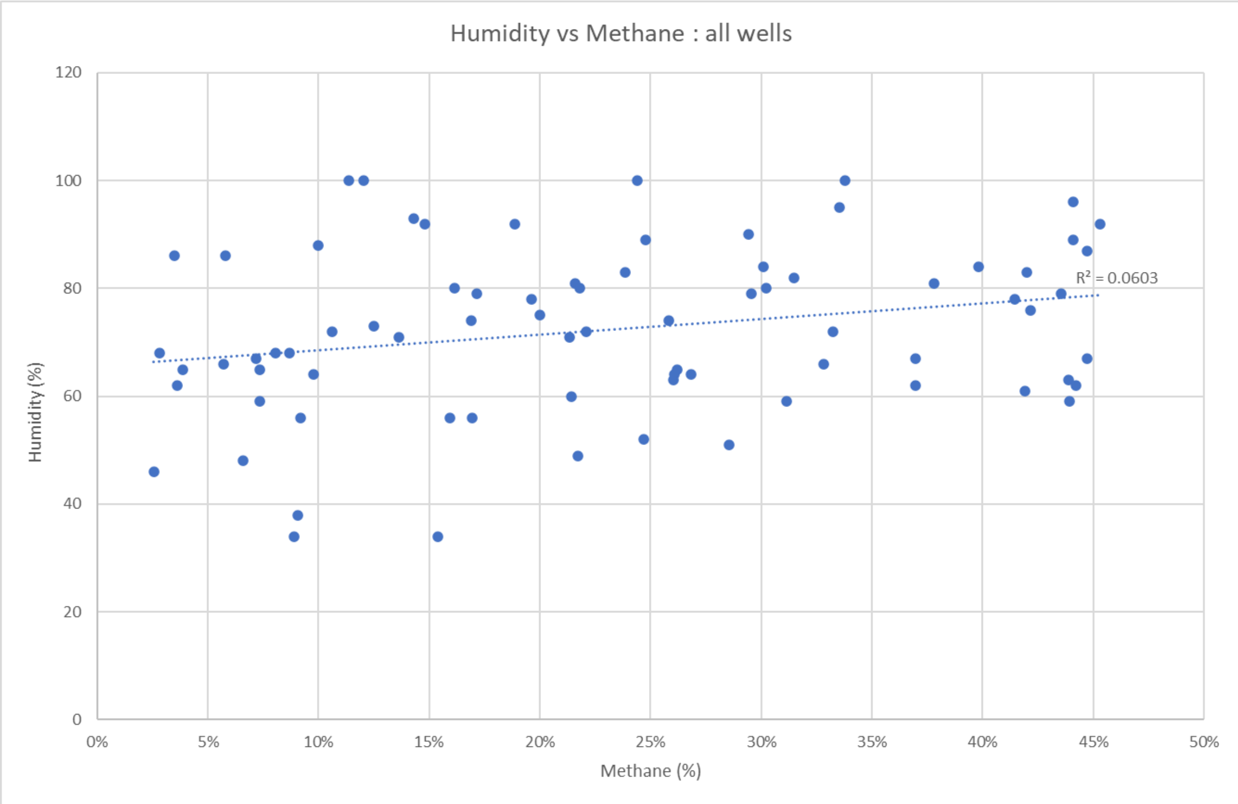


Graph H3, Humidity vs methane concentration: 2015-2016.



Graph H4, Humidity vs methane concentration: 2019-2021.

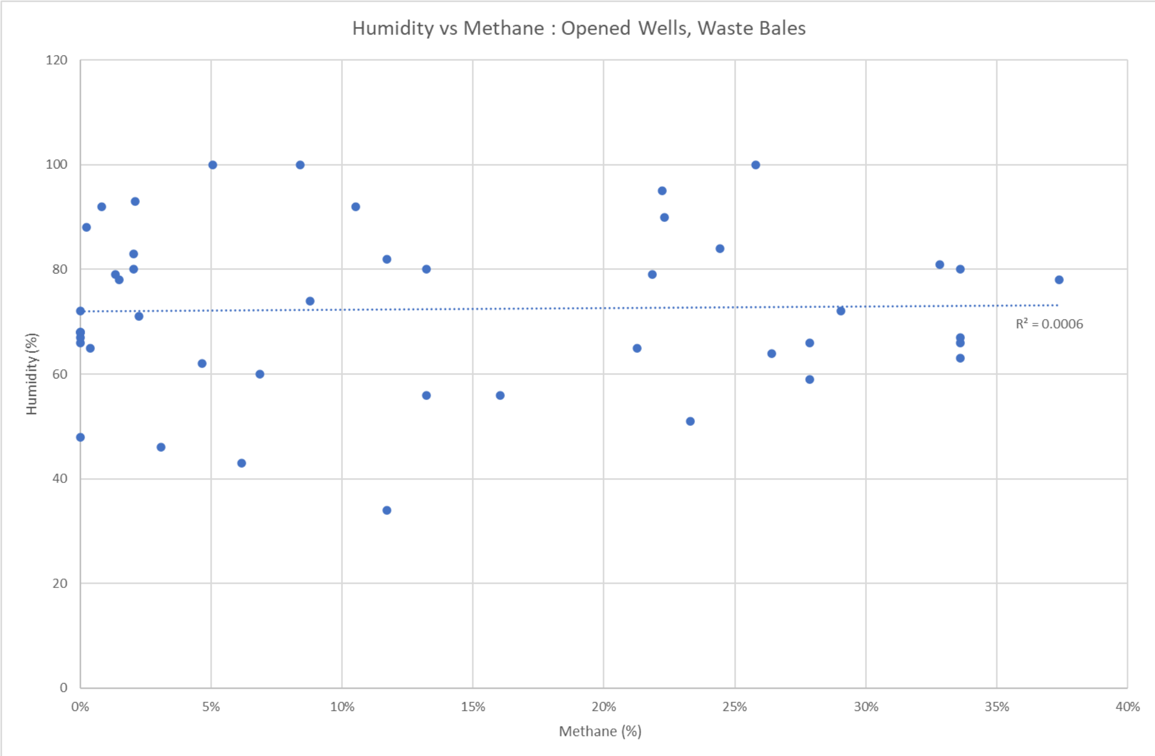
Looking at the initial three graphs, it was not easy to extract a possible trend between methane percentage and atmospheric humidity. As for the previous meteorological parameters, the first step concerned the study of the whole methane percentage related to each well compared with the air humidity [Graph H5]. In this regard, evaluating an increase in the methane concentration a slight increase in air humidity can be observed, even if a very weak correlation coefficient takes place.



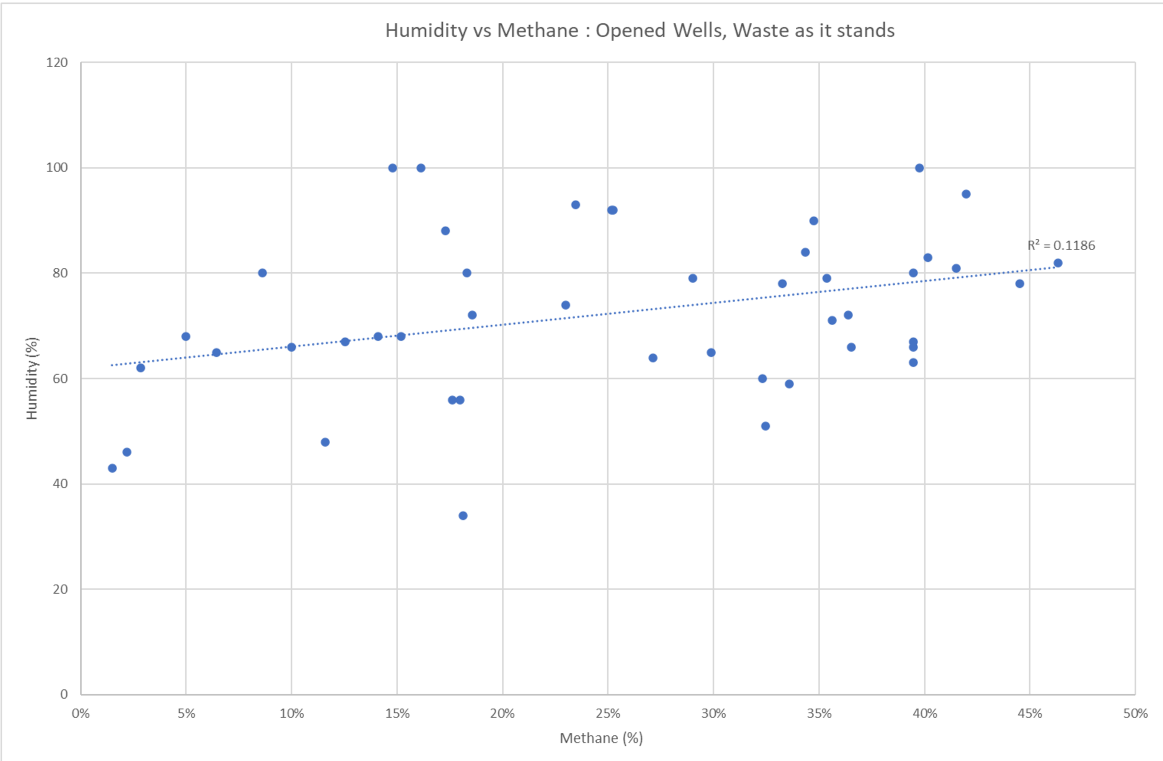
Graph H5, Humidity vs methane concentration: all wells in the Site.

Subsequently, four graphs were created according to the different four cases which were already mentioned. The aim of this operation is to deeper investigate the site area by distinguishing again both the type of material and the wells typology. The first graph [Graph H6] shows a very low correlation coefficient which signifies how methane percentages belonging to waste bales in opened wells are not linked at all. On the other hand, looking at the following graphs a common feature can be found, an increase in the methane concentration corresponds to a slight increase in the air humidity. However, low correlation coefficients appear in each one of the graph which values set at around 0.1. On the other hand, slightly higher values belong to the last picture [Graph H9] where bulk material takes place referred to closed wells. Here, the correlation coefficient is marked by a 0.22 value which is the highest correlation belonging to this set of graphs. Therefore, a slight correlation comes from the site data with respect to the atmospheric humidity.

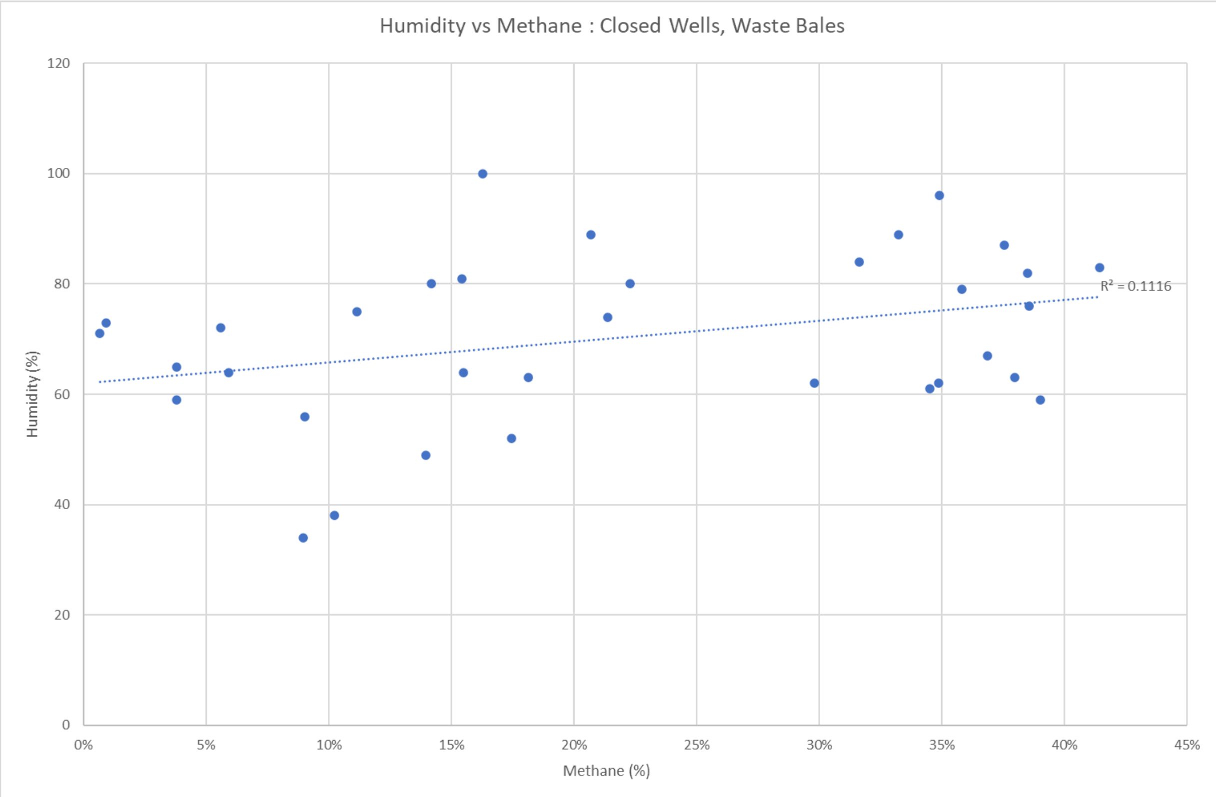
In this case, the bibliographic search highlighted as the soil moisture was the most predominant factor in terms of methane production. Focusing on this case, however, the air humidity does not seem to strongly affect the gas production.



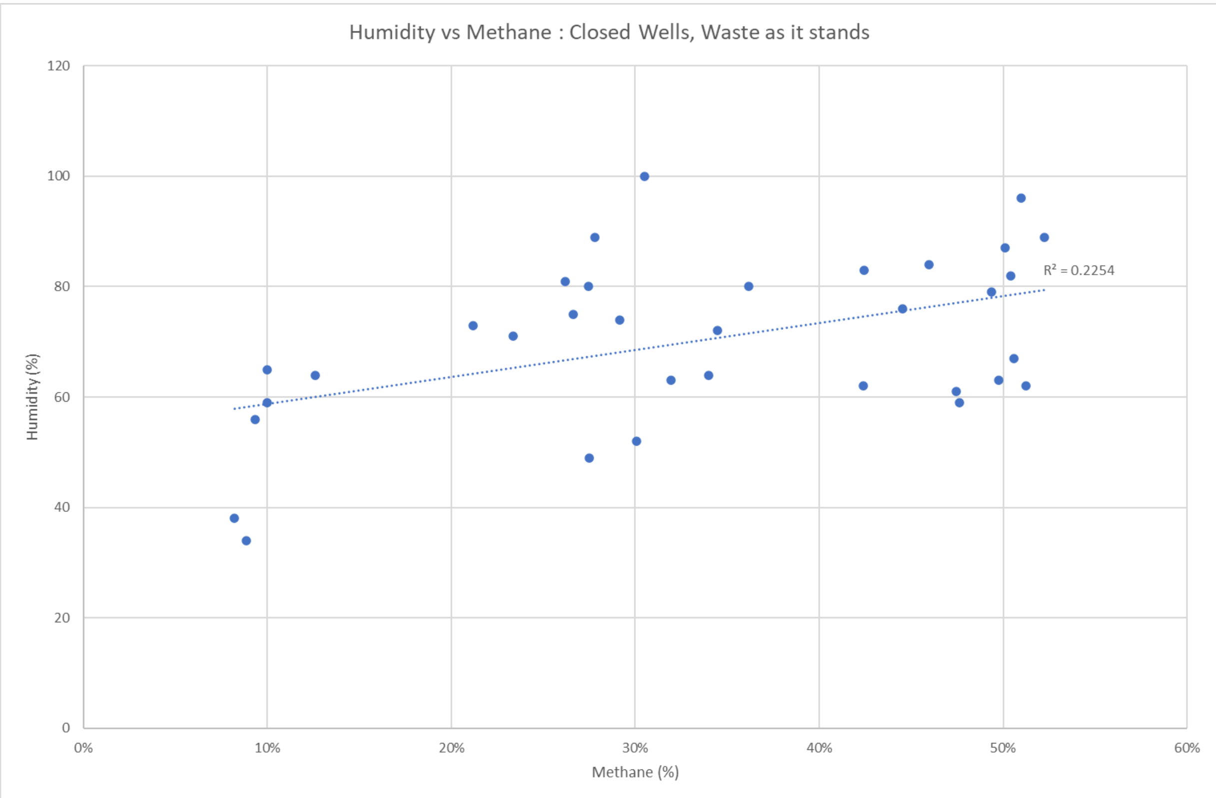
Graph H6, Humidity vs methane concentration: opened wells, Waste bales.



Graph H7, Humidity vs methane concentration: opened wells, Waste as it stands.

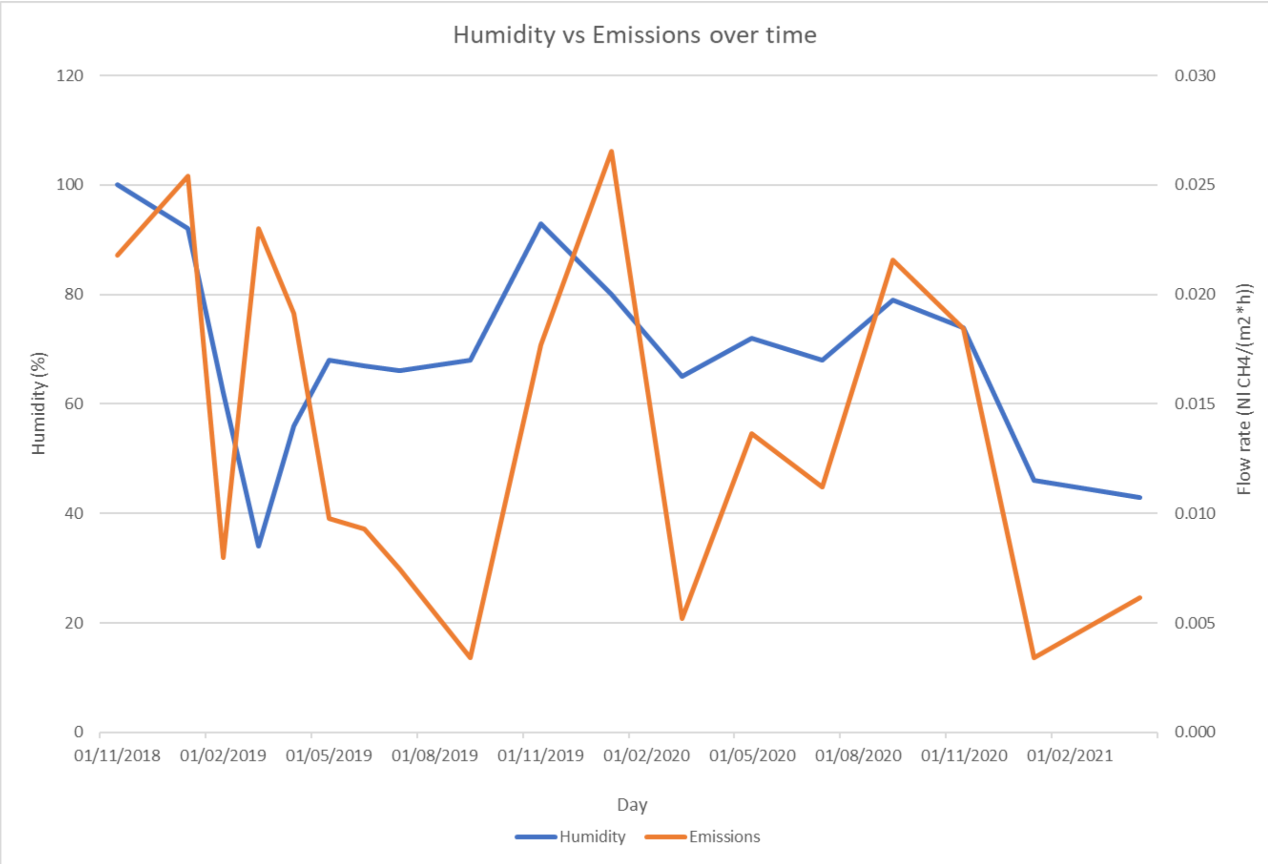


Graph H8, Humidity vs methane concentration: closed wells, Waste bales.

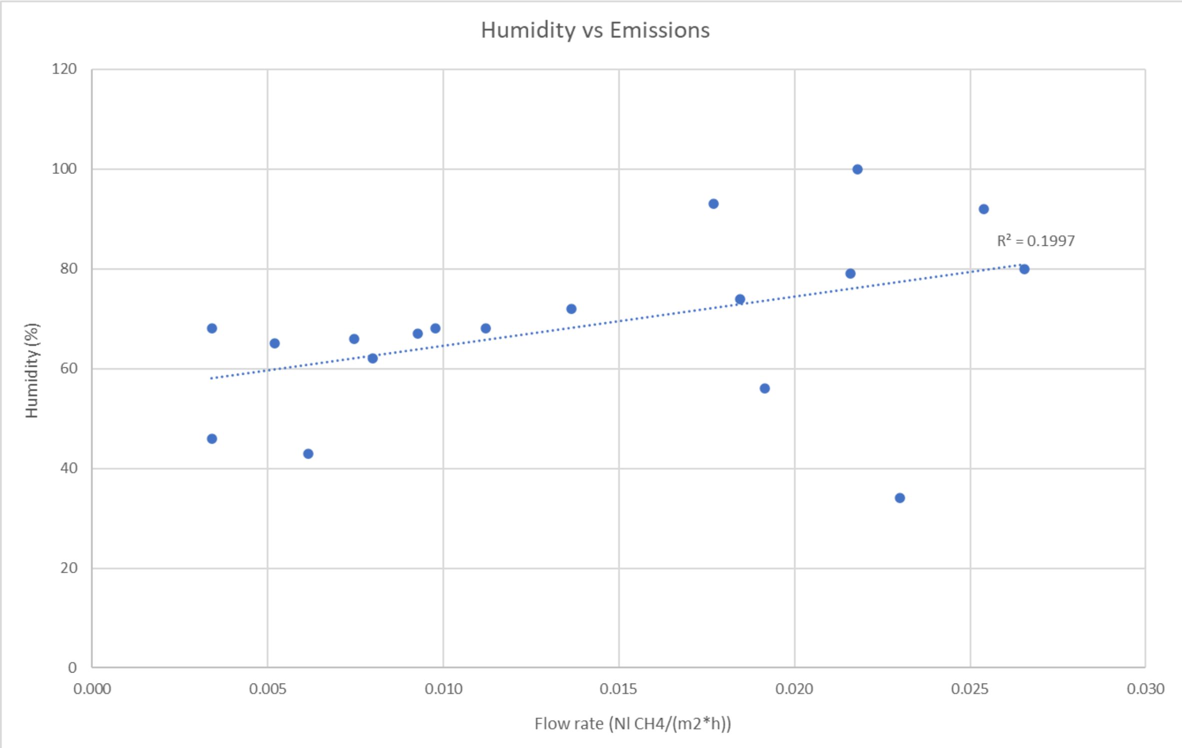


Graph H9, Humidity vs methane concentration: closed wells, Waste as it stands.

As for the previous parameters, the last graphs refer to the gas emissions. The first image [Graph H10] shows the different trend over time related to both gas flow rate and air humidity although it does not clarify whether a sort of relation takes place between them. In this regard, a second graph was created [Graph H11] which it relates the gas emission increase with the air humidity. Here, a direct correlation can be observed even if the R^2 coefficient reflects the values previously found. It sets at around 0.2 signifying that a weak correlation takes place between the considered data. To finish with the air humidity analysis, it can be said that the this parameter slightly affects the methane production in this Site.



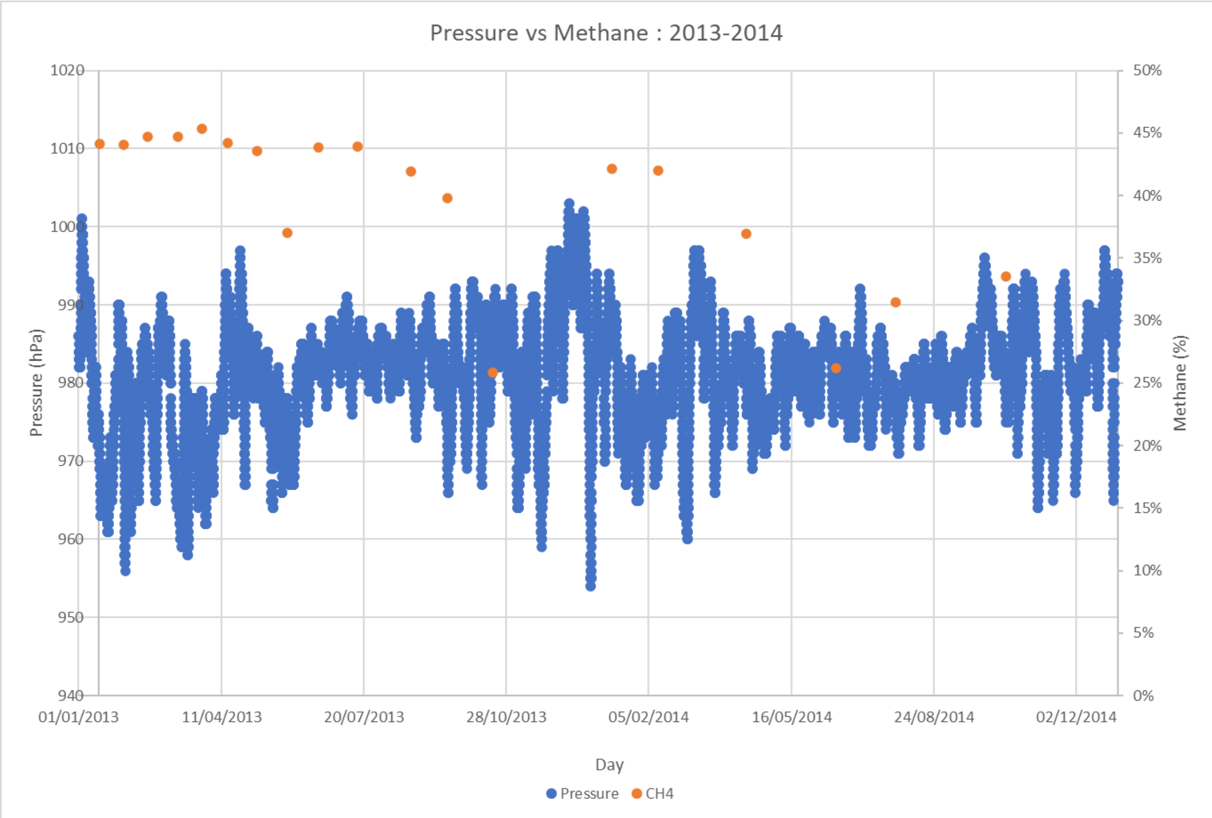
Graph H10, Humidity vs emissions trend over time.



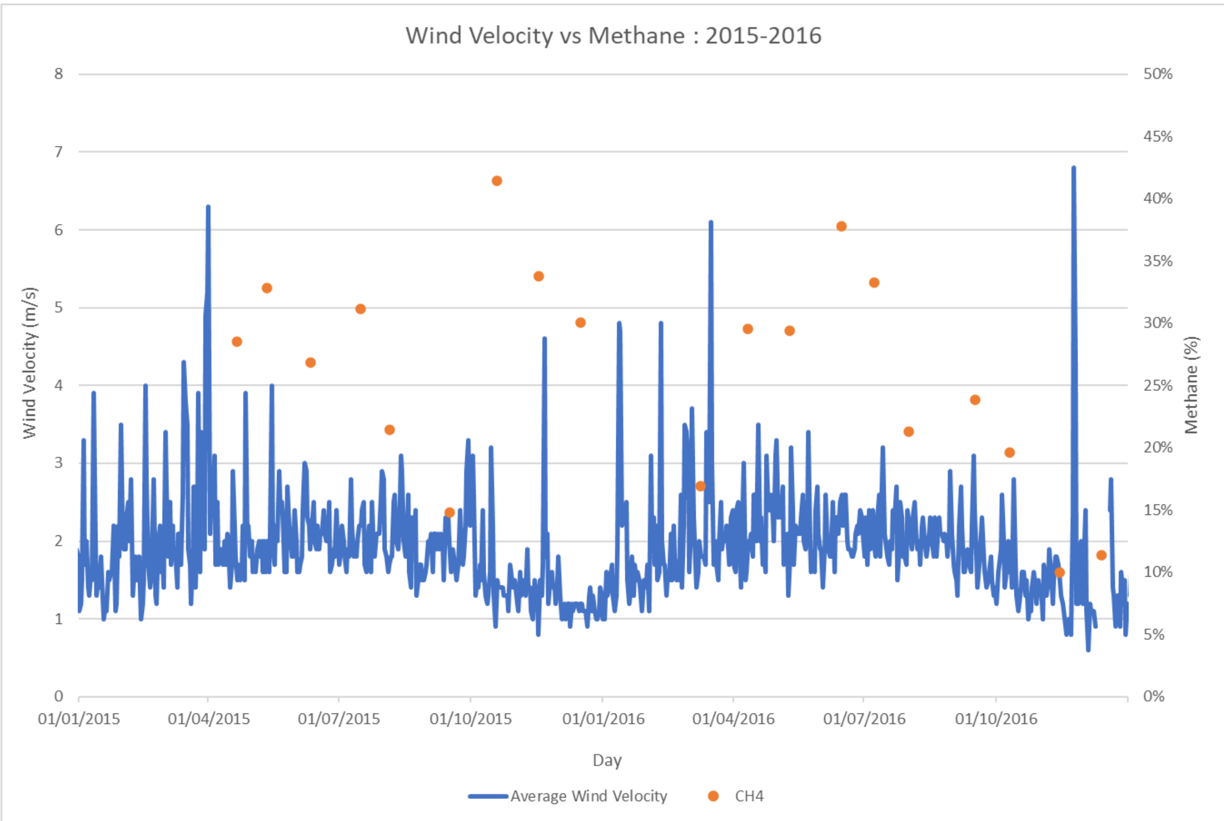
Graph H11, Humidity vs methane emissions.

5.4 WIND SPEED

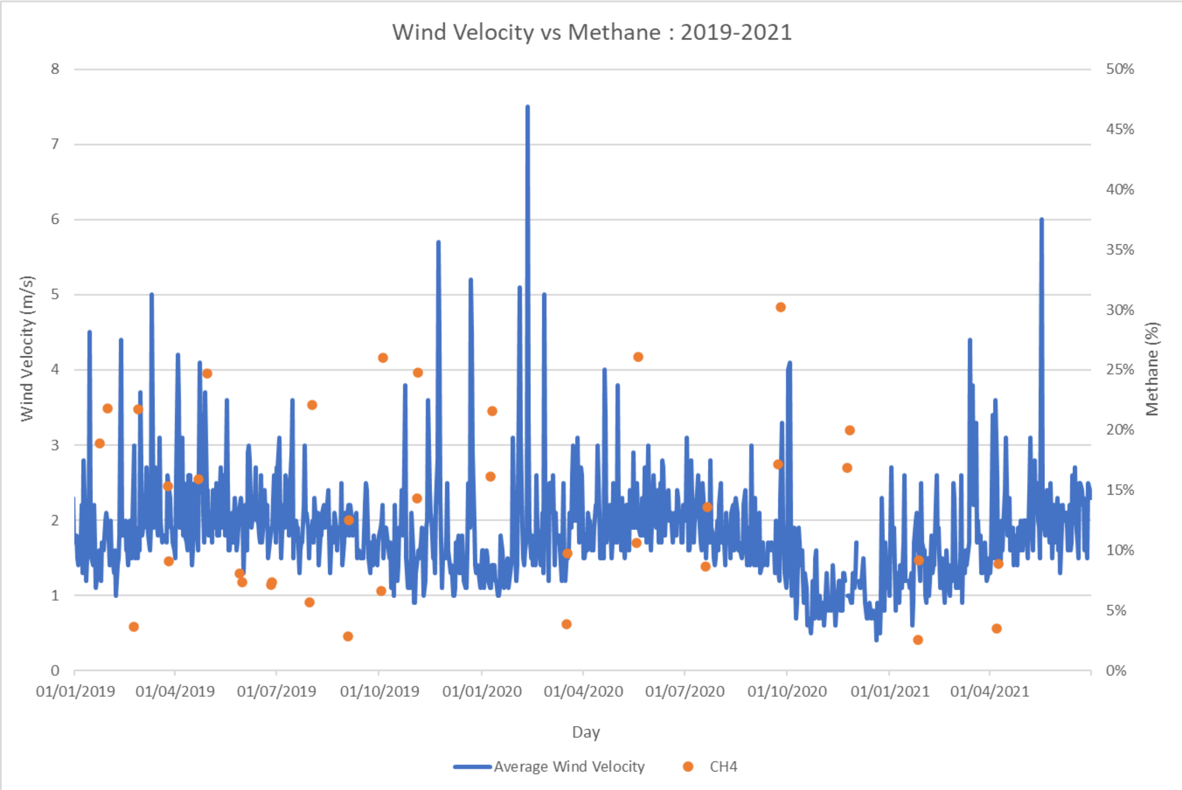
The fourth parameter to be investigated deals with the wind speed. After illustrating the methane concentration trend for the whole monitoring period, the same subdivision in three time windows occurred for the study of the wind speed too. Thus, Graph W2, Graph W3 and Graph W4 refer to the following time periods: 2013-2014, 2015-2016 and 2019-2021, respectively.



Graph W2, Wind velocity vs methane concentration: 2013-2014.

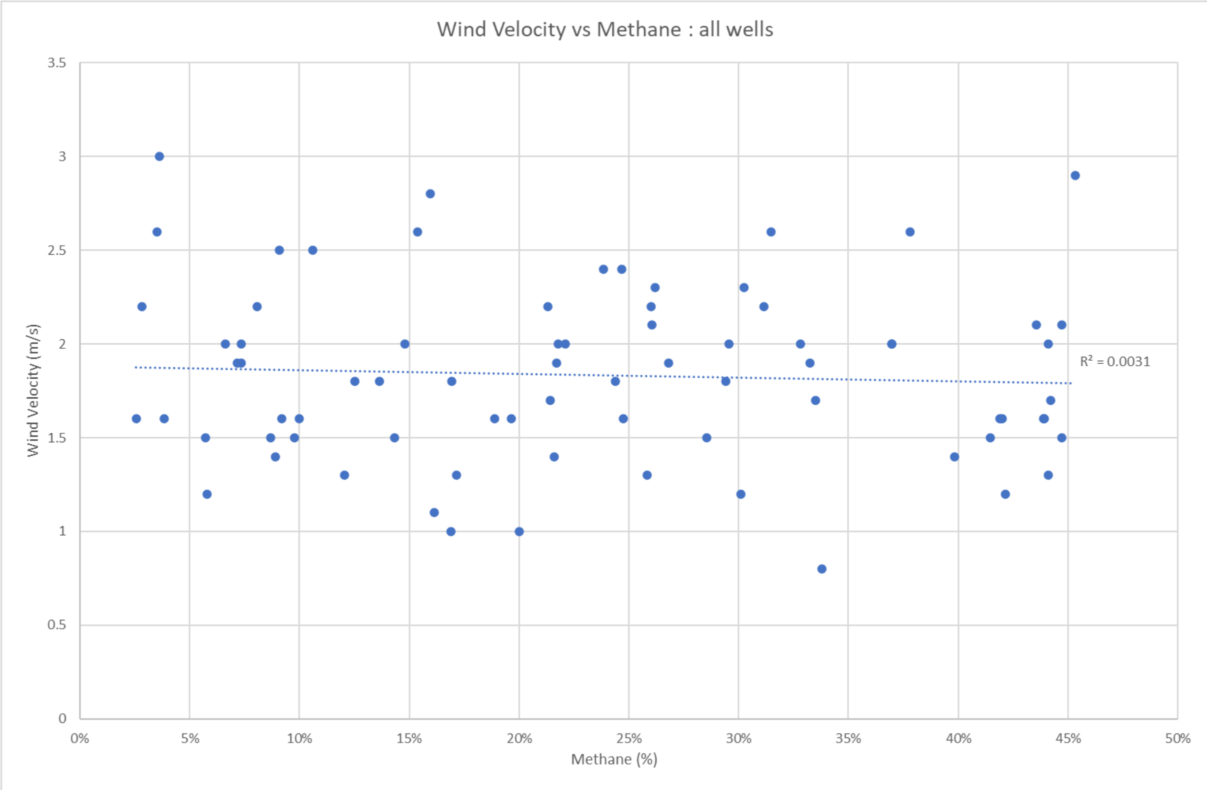


Graph W3, Wind velocity vs methane concentration: 2015-2016.



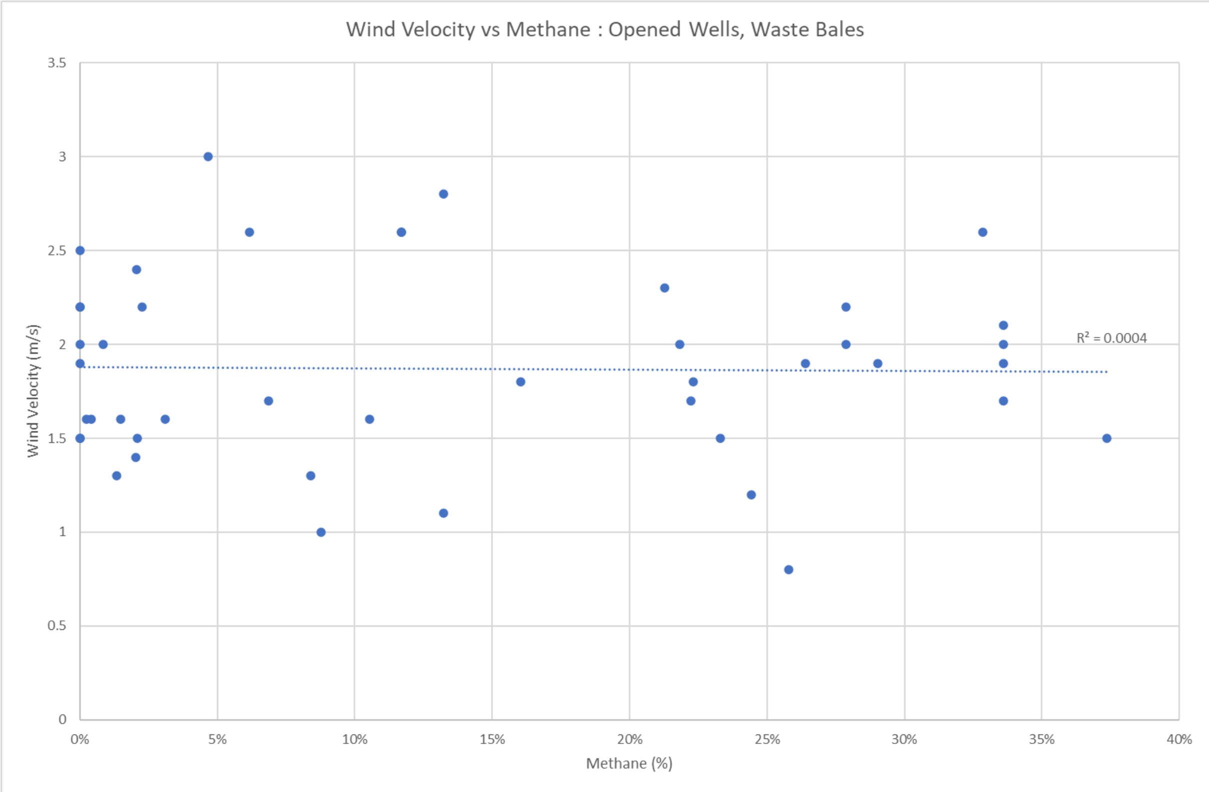
Graph W4, Wind velocity vs methane concentration: 2019-2021.

A preliminary overview about the wind speed trend did not signify a clear correlation when overlapping its data with the methane concentrations. In this scenario, the same work previously mentioned for the air humidity was carried out. Thus, in addition to the first four graphs, the wind speed trend was analysed related to the methane percentage increase. In the fifth graph [Graph W5] all the wells belonging to the site were represented. However the outcome resulted in a null matching between them because of the correlation coefficient which value was close to zero.

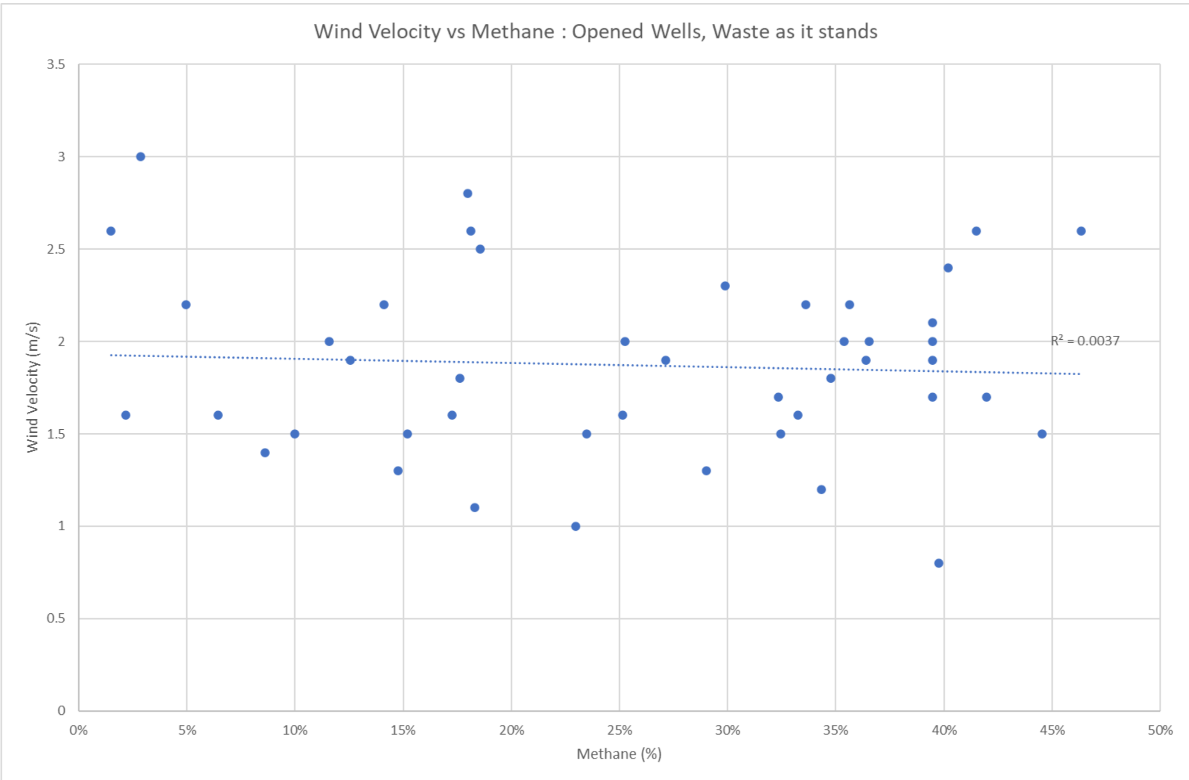


Graph W5, Wind speed vs methane concentration: all wells in the Site.

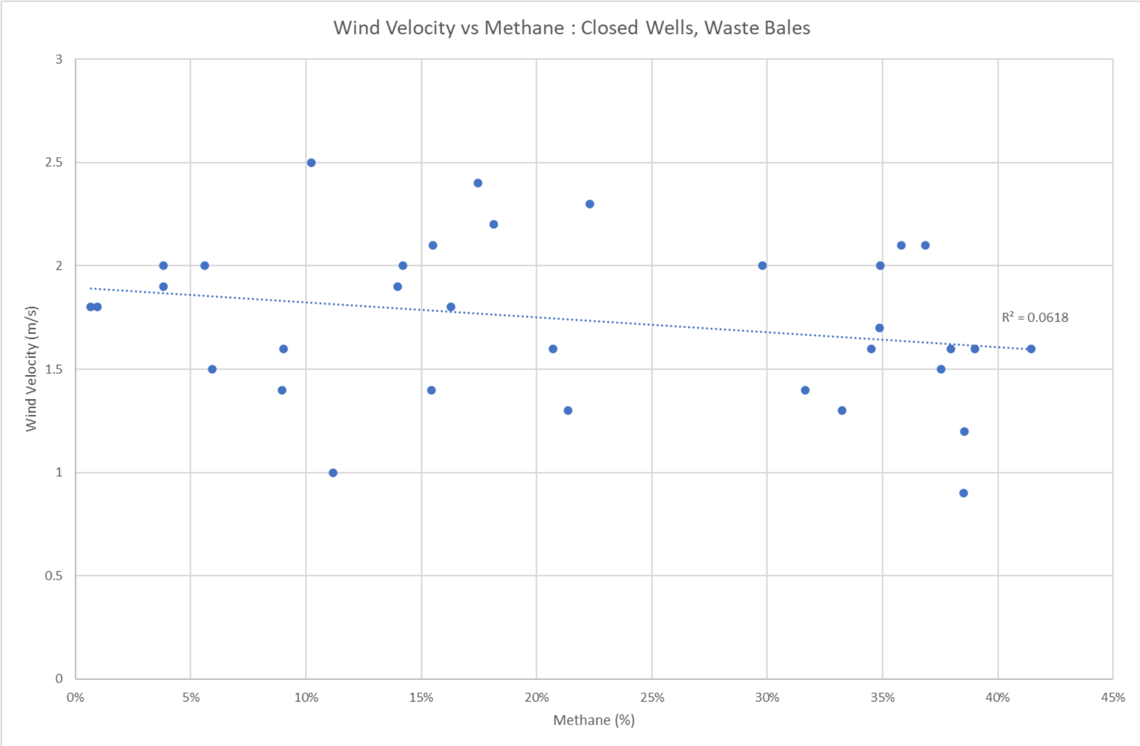
Subsequently, the four different scenarios were studied as it was performed for the other meteorological parameters. Once again, they refer to opened/closed wells and waste bales/waste as it stands and they are represented in Graph W6, Graph W7, Graph W8 and Graph W9. Although this kind of procedure was aimed to deeper investigate the correlation between wind speed and methane percentage, no correlation was found each other. From the analysis of these outcomes, it is worth to say that wind speed and methane concentration do not match very well as it was clearly shown by the graphs. In this regard, the wind motion does not seem to play a key role in the gas spreading.



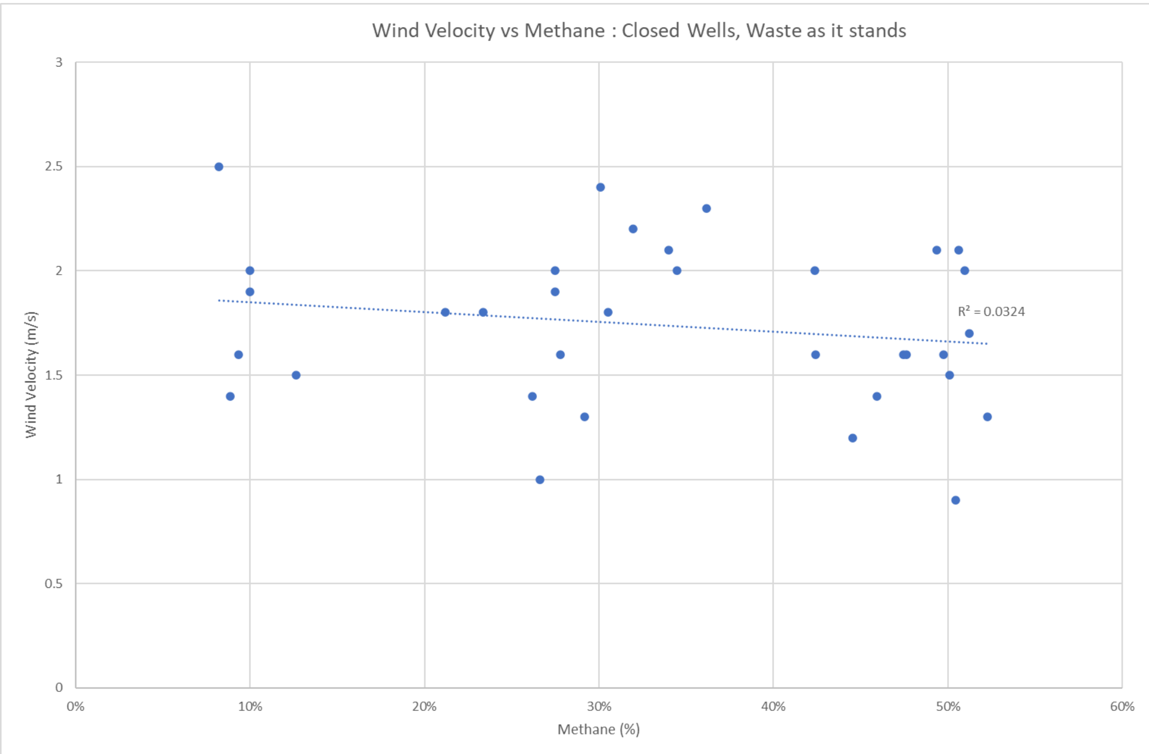
Graph W6, Wind speed vs methane concentration: opened well, Waste bales.



Graph W7, Wind speed vs methane concentration: opened well, Waste as it stands.

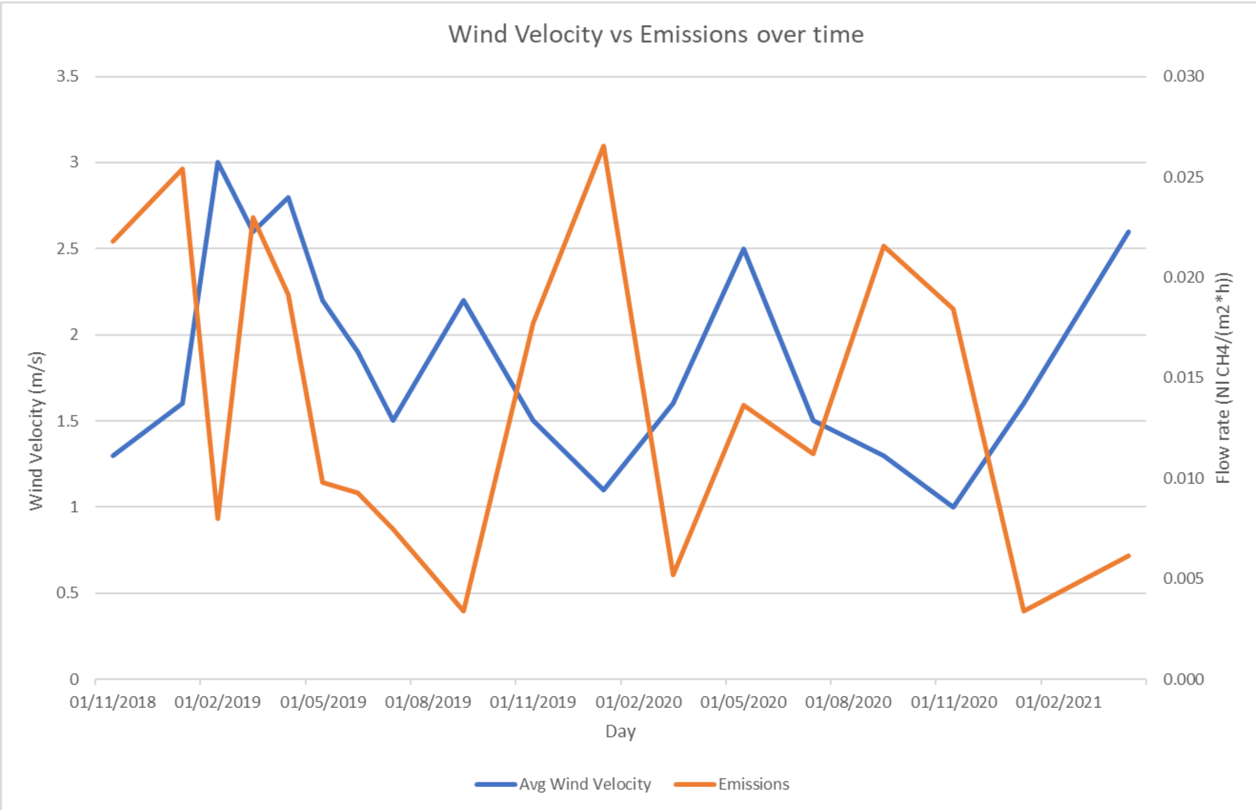


Graph W8, Wind speed vs methane concentration: closed well, Waste bales.

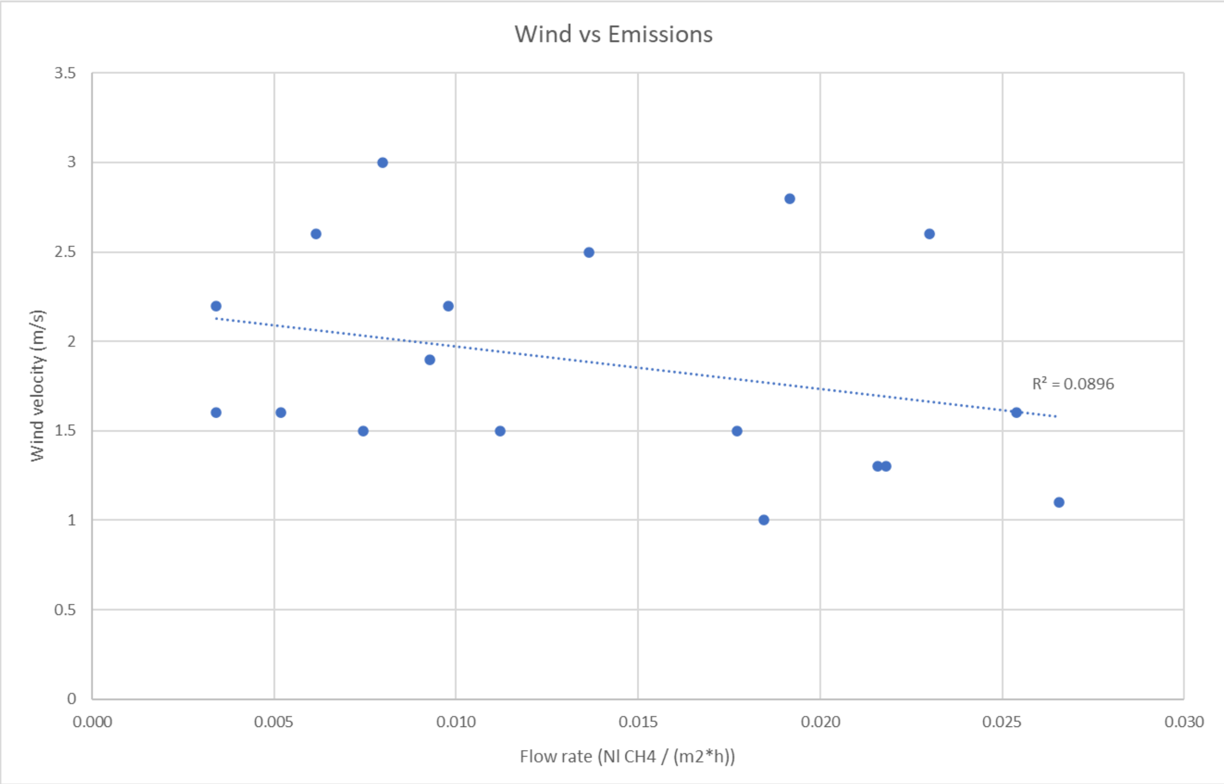


Graph W9, Wind speed vs methane concentration: closed well, Waste as it stands.

Finally, the last two graphs (Graph W10 and Graph W11) represent the emissions trend in the same ways observed for the previous parameters. The same outcome already achieved for the methane percentage seems to appear for the gas emissions. In the last graph [Graph W11] it is possible to notice a slight negative trend between them although the correlation index shows a very low value, testifying to the poor correspondence between the two quantities.



Graph W10, Wind velocity vs Emissions trend over time.

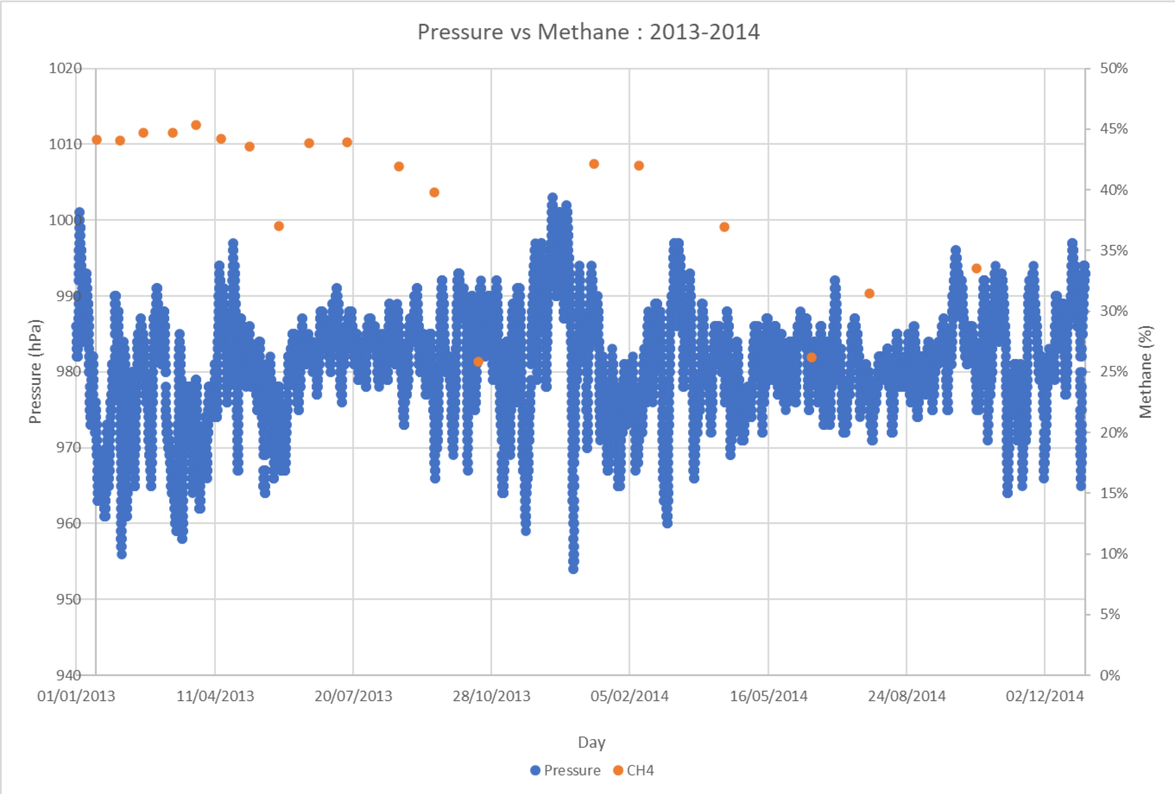


Graph W11, Wind velocity vs methane emissions.

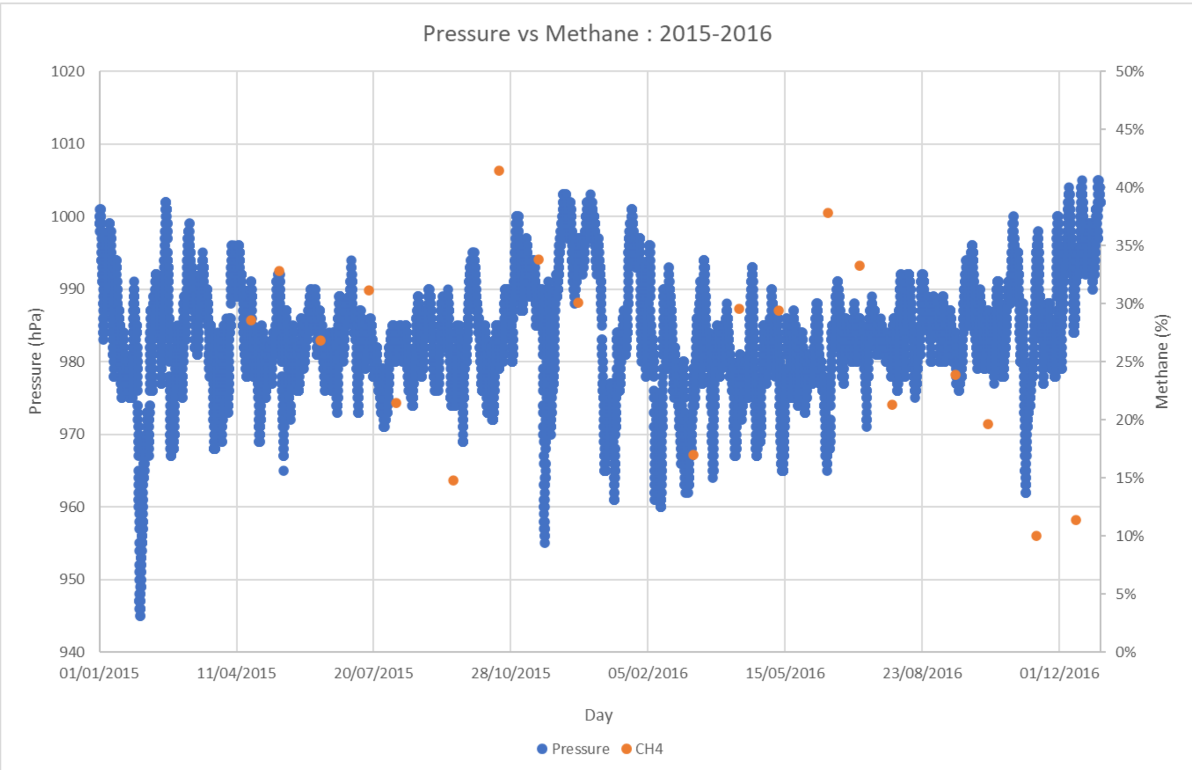
By studying the data coming from the site area, it seems that the wind speed does not affect the methane percentage detected as well as its diffusion into the atmosphere. In fact, very weak correlations were found, this is can be due to the low values related to the wind speed referred to the site under investigation. However, from the bibliographic search, wind can partially affect the gas flow rate coming from the landfill surface, in fact its motion is forced by a pressure gradient and this last parameter strongly interacts with the gas emissions. In particular, whether high wind speed values are detected, a greater pressure gradient can be found. This condition can allow atmospheric air to enter the soil surface leading to reduction in the CH_4 emission.

5.5 ATMOSPHERIC PRESSURE

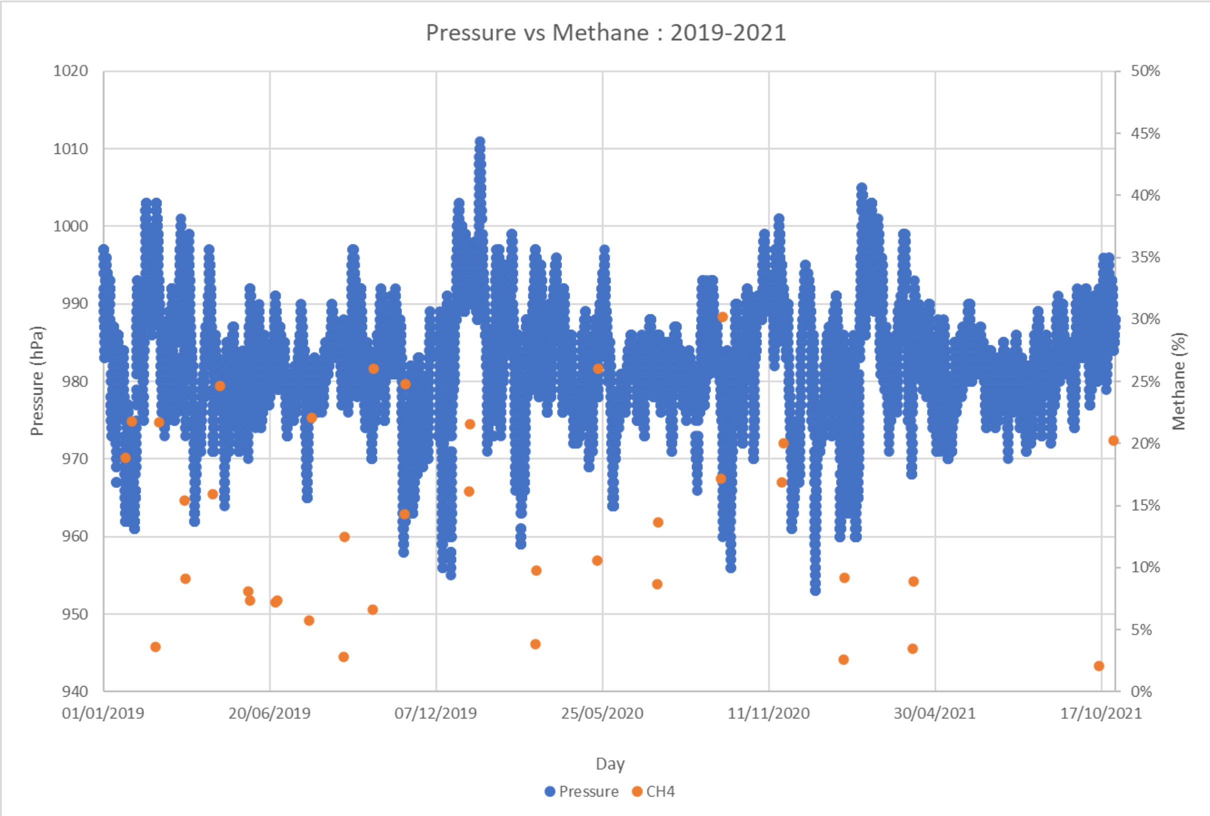
The last meteorological parameter to be examined deals with the atmospheric pressure. After observing the methane concentration trend all over the whole monitoring period, it was decided to perform a focus on the three different time periods (2013-2014, 2015-2016 and 2019-2021). Thus, the following graphs (Graph P2, Graph P3 and Graph P4) refer to the same time subdivision which was already occurred during the previous analyses.



Graph P2, Pressure vs methane concentration: 2013-2014.



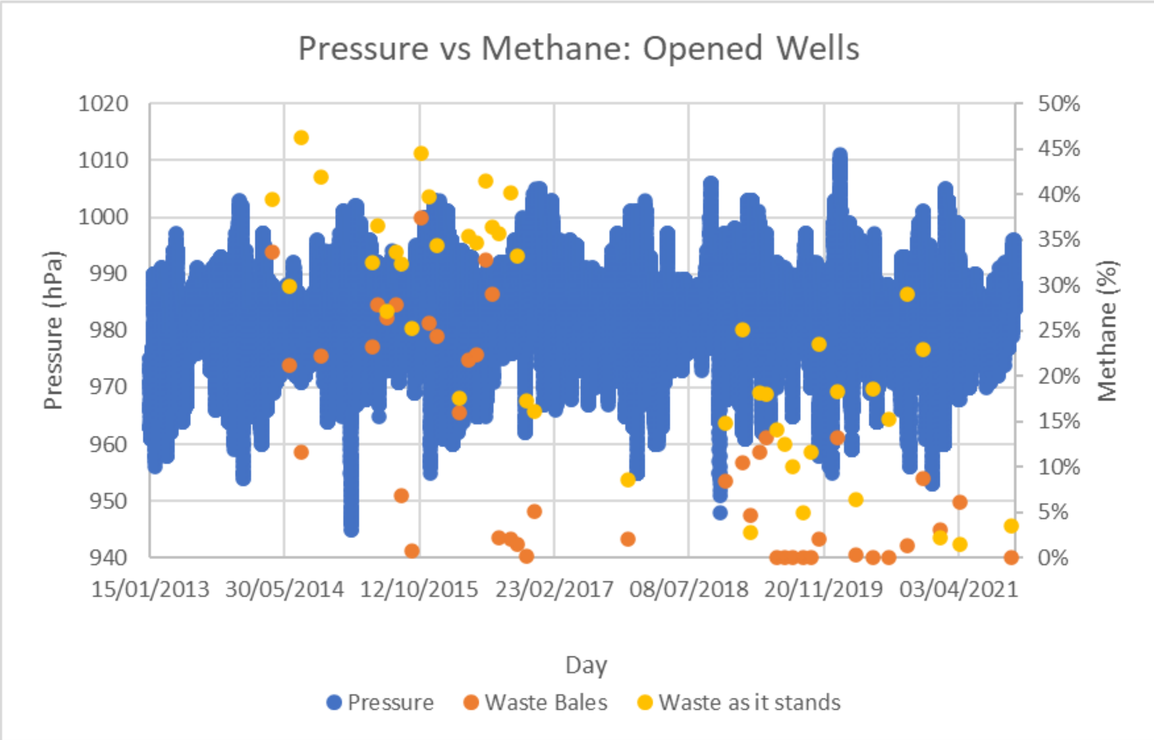
Graph P3, Pressure vs methane concentration: 2015-2016.



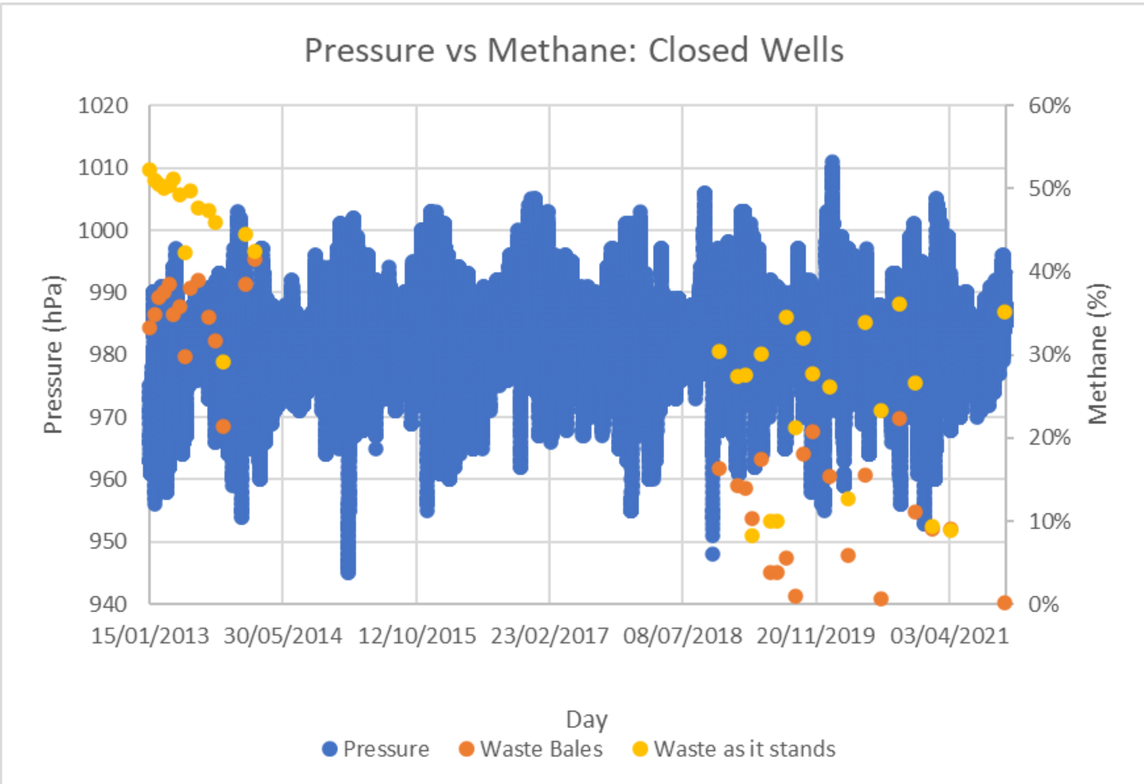
Graph P4, Pressure vs methane concentration: 2019-2021.

Looking at the three initial graphs related to the pressure values, it can be noticed that there is not a seasonal trend about the pressure variations. Furthermore, methane concentrations do not seem to be affected by pressure changes on a large temporary scale.

The same kind of relation can be also noticed in the following pictures [Graph P5] and [Graph P6] where methane concentrations were evaluated for both opened wells and closed wells.

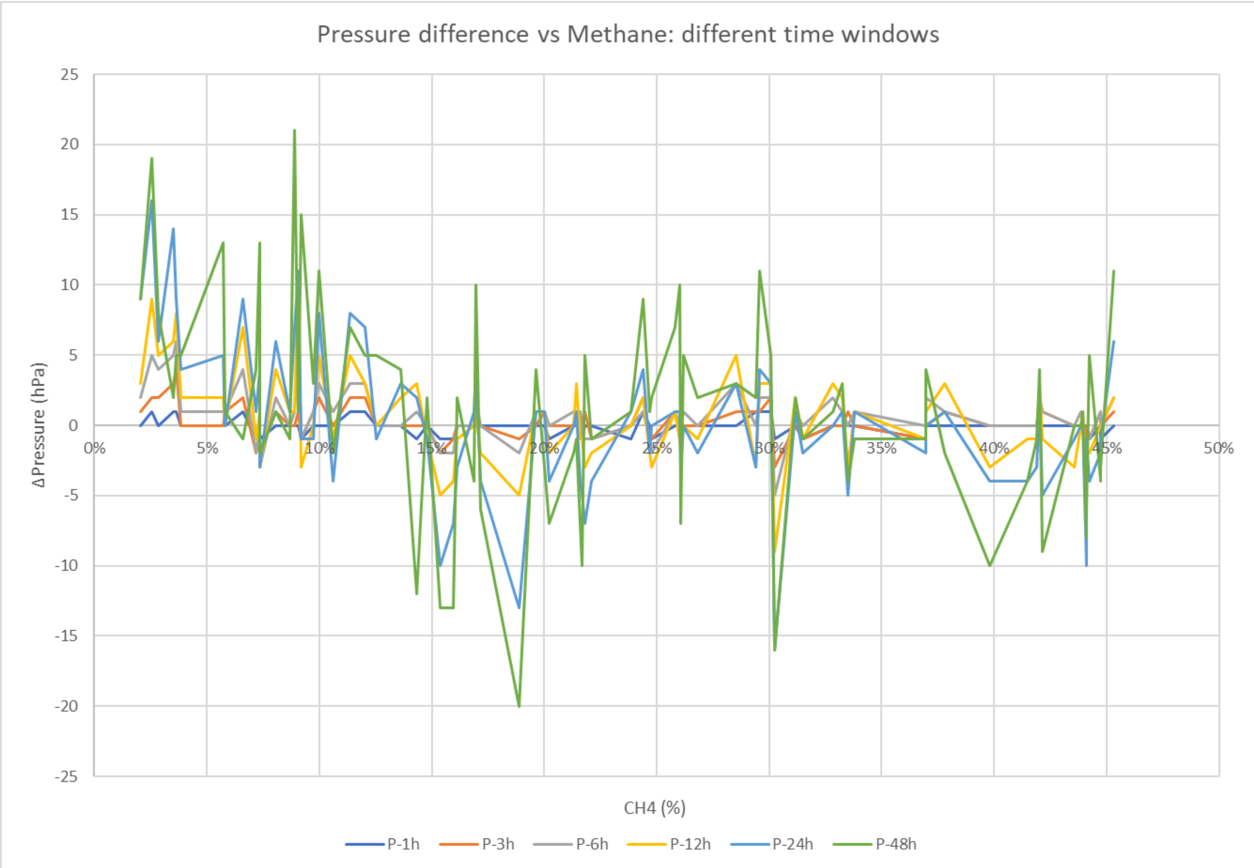


Graph P5, Pressure vs methane concentration: opened wells.



Graph P6, Pressure vs methane concentration: closed wells.

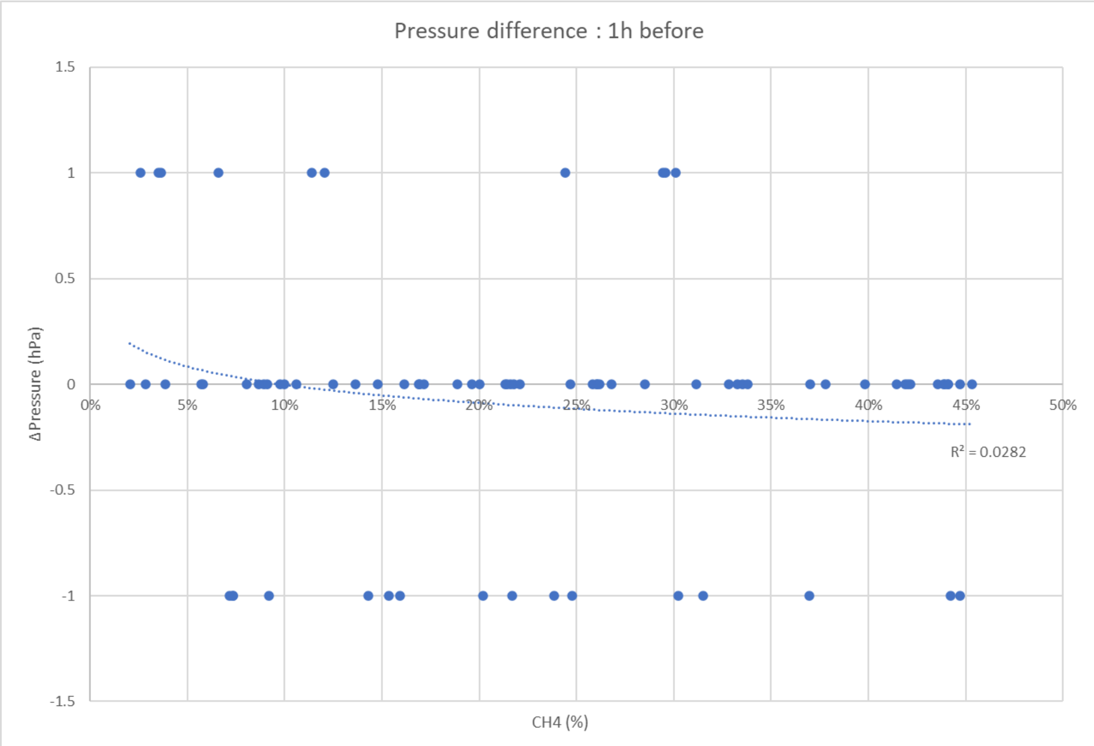
As it was difficult to detect a precise trend related to the methane concentration with respect to the atmospheric pressure, it was decided to analyze the pressure change over time on hourly basis. In this way, it was possible to appreciate the different variations in a more limited time window. In particular, the delta pressure was calculated as subtraction between the current pressure value (at the time of the CH_4 detection) and the pressure value related to some hours before. In this regard, the first graph [Graph P7] illustrates the trend of the different pressure variations depending on the different time frame by choosing the following time windows: 1h, 3h, 6h, 12h, 24h and 48h. In this case, all wells in the Site are considered by evaluating both the opened wells and closed wells.



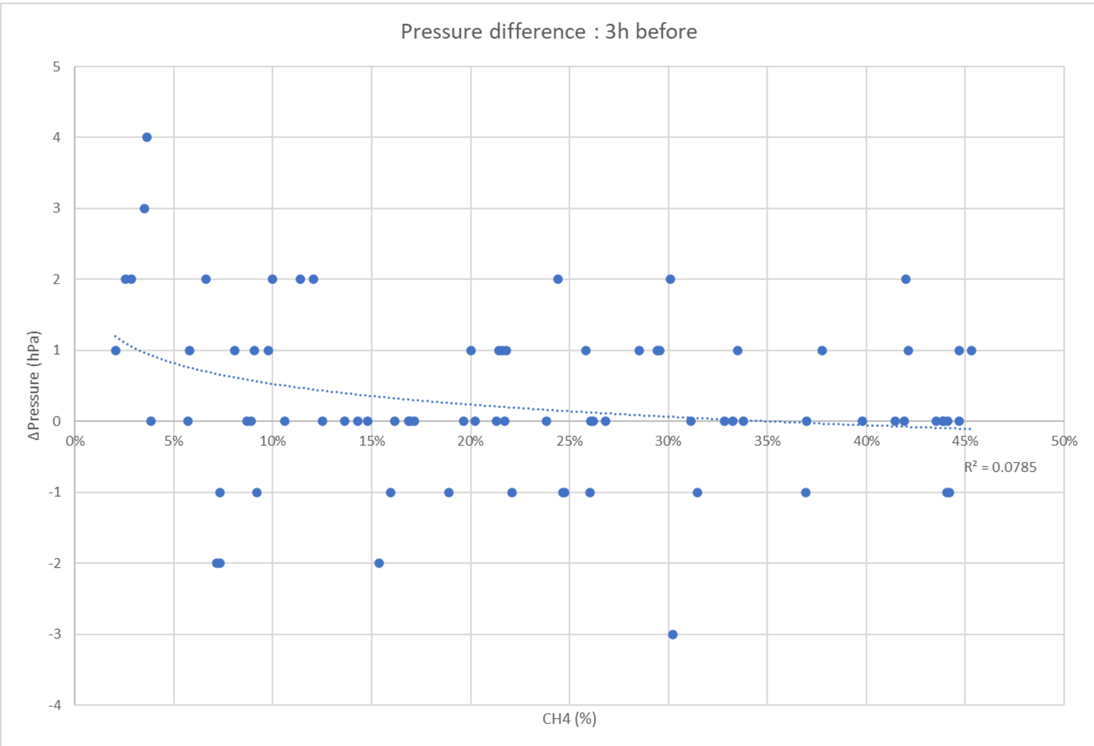
Graph P7, Pressure difference vs methane concentration: different time windows.

After observing all the pressure difference for each time slot , it was decided to realize (from Graph P8 to Graph P13) each time window in different graphs with respect to the methane percentage increase. Scatter plot was used to better visualize the different trends as the correlation was signified by using the R^2 coefficient.

With regard to Graph P8 and Graph P9, the correlation coefficient shows near-zero values. It means that the pressure variation evaluated a few hours before do not affect at all the methane production.

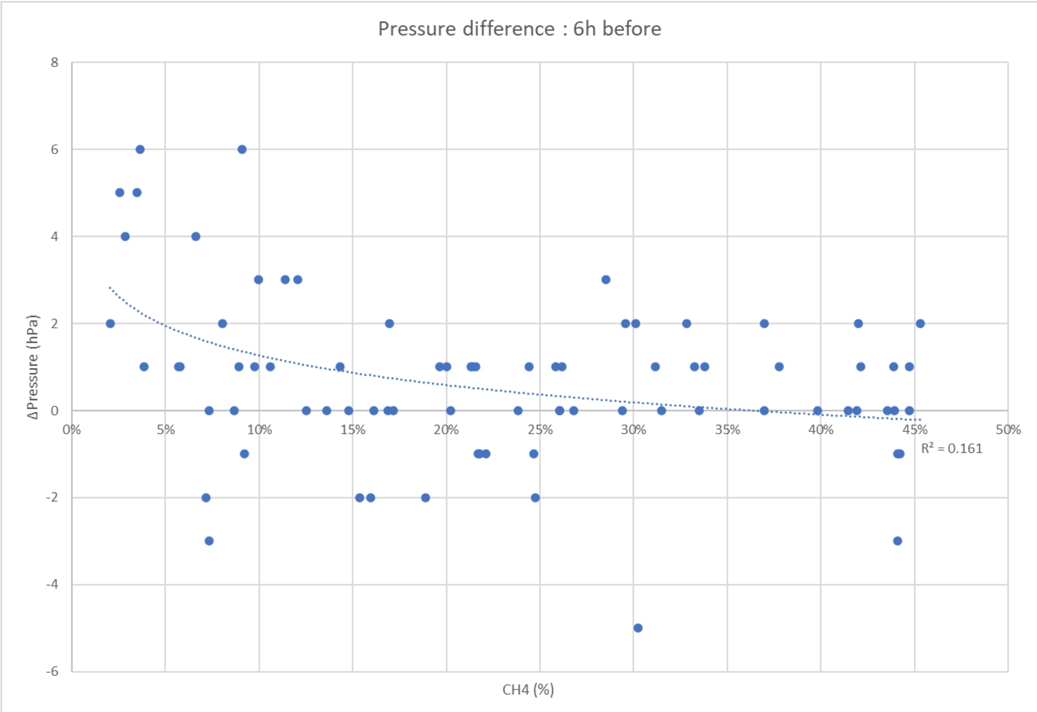


Graph P8, Pressure difference vs methane:1 h before.

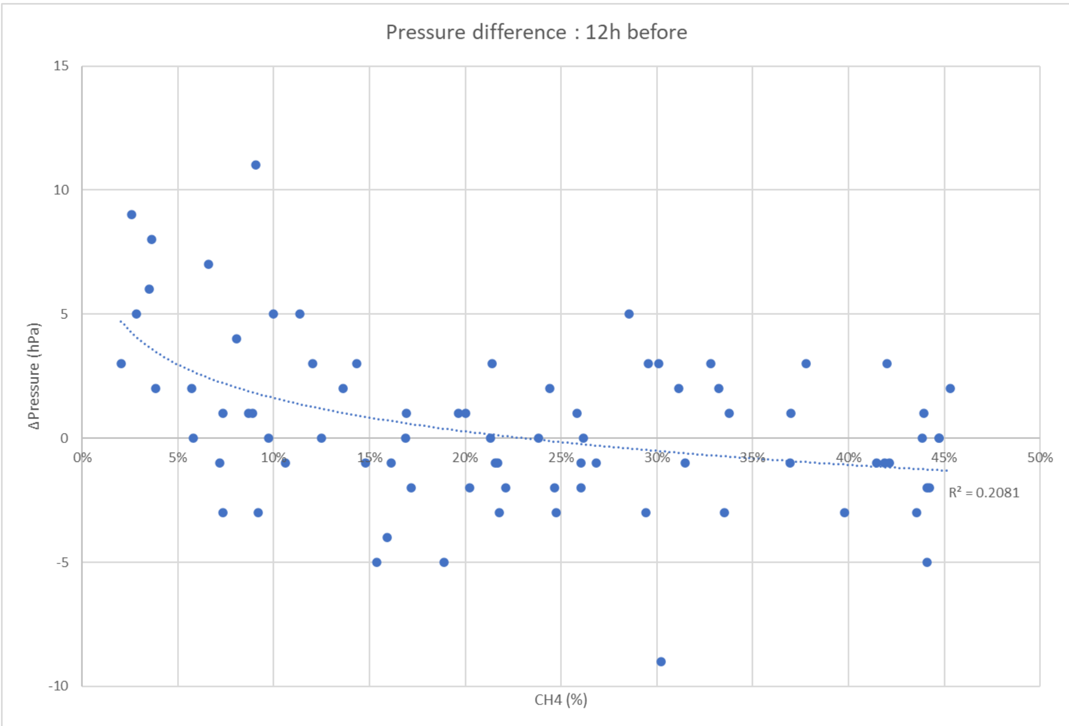


Graph P9, Pressure difference vs methane: 3 h before.

Subsequently, the analysis focused on the two different time slots which refer to the delta pressure calculated 6 hours (Graph P10) and 12 hours (Graph P11) prior to the methane percentage detection. Looking at the following graphs, it seems that a slight correlation takes place between the two quantities even if the R^2 index shows relatively low values.

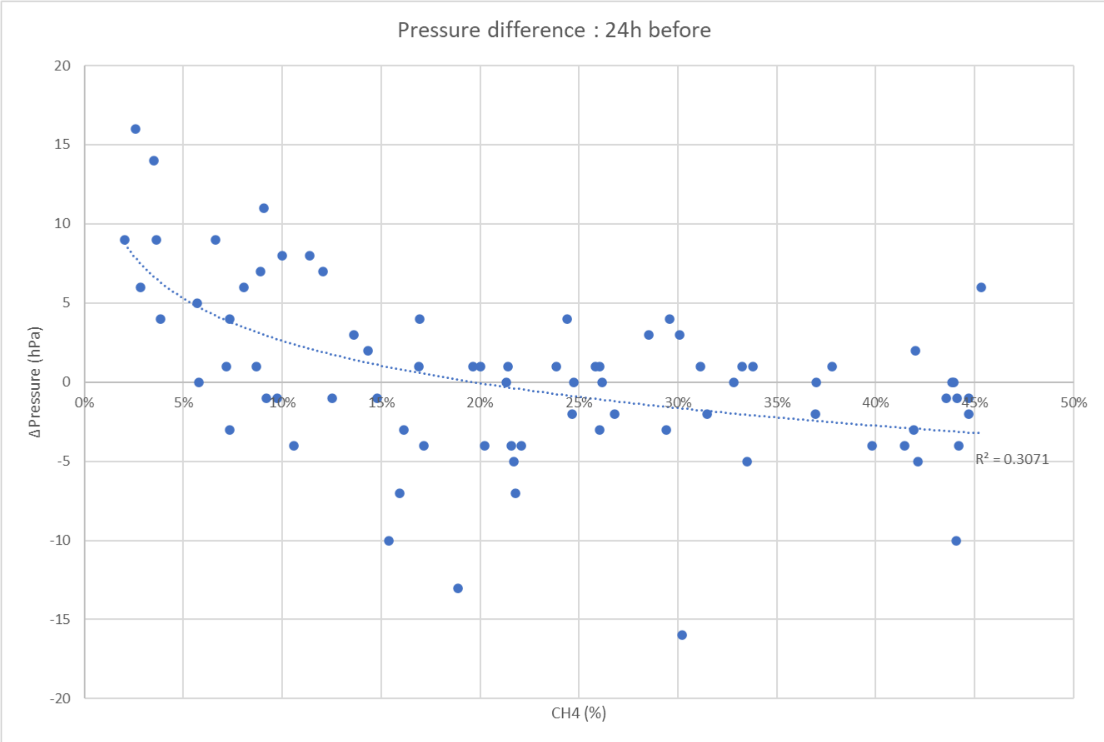


Graph P10, Pressure difference vs methane: 6 h before.

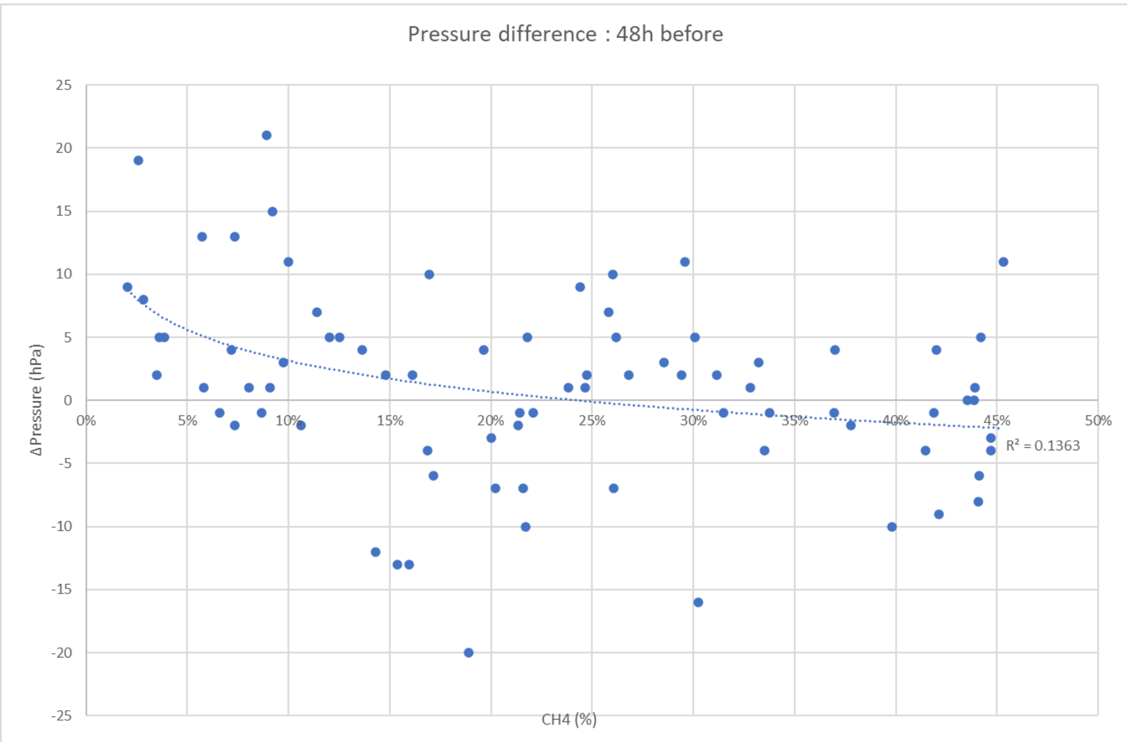


Graph P11, Pressure difference vs methane: 12 h before.

The last two graphs belonging to this set of images deal with the pressure difference evaluated one day (Graph P12) and two days (Graph P13) before the methane concentration monitoring.

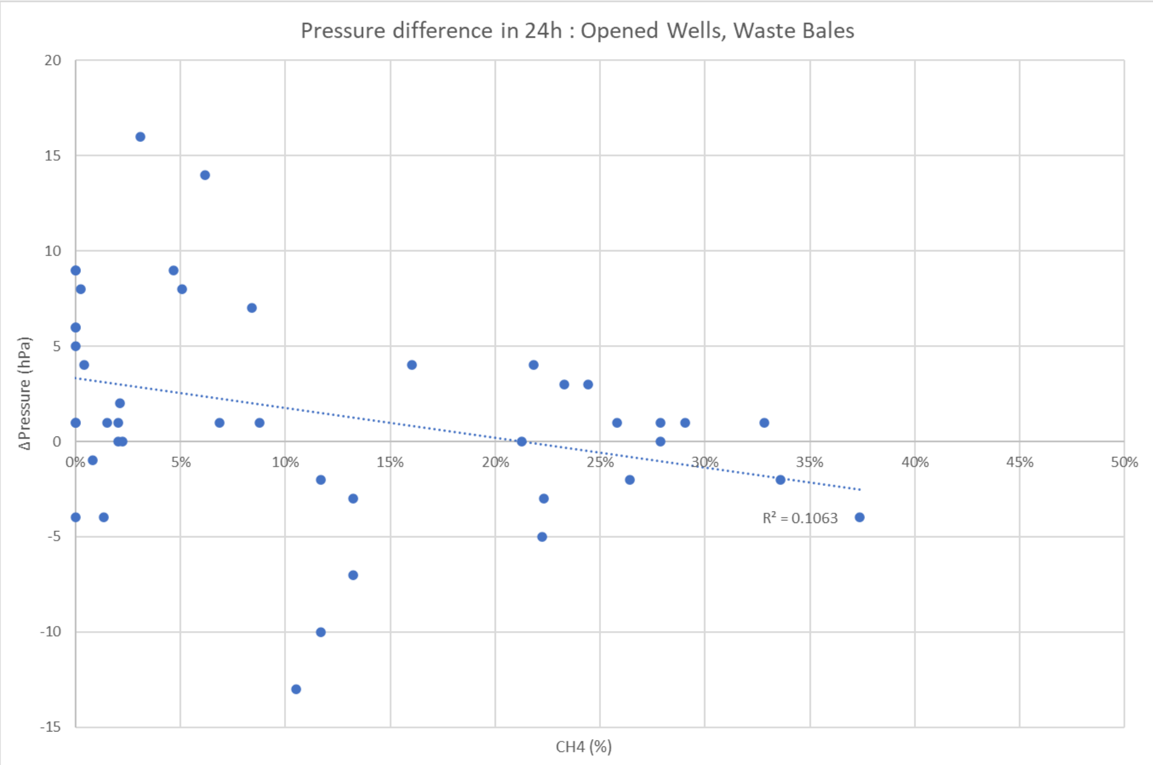


Graph P12, Pressure difference vs methane: 24 h before.

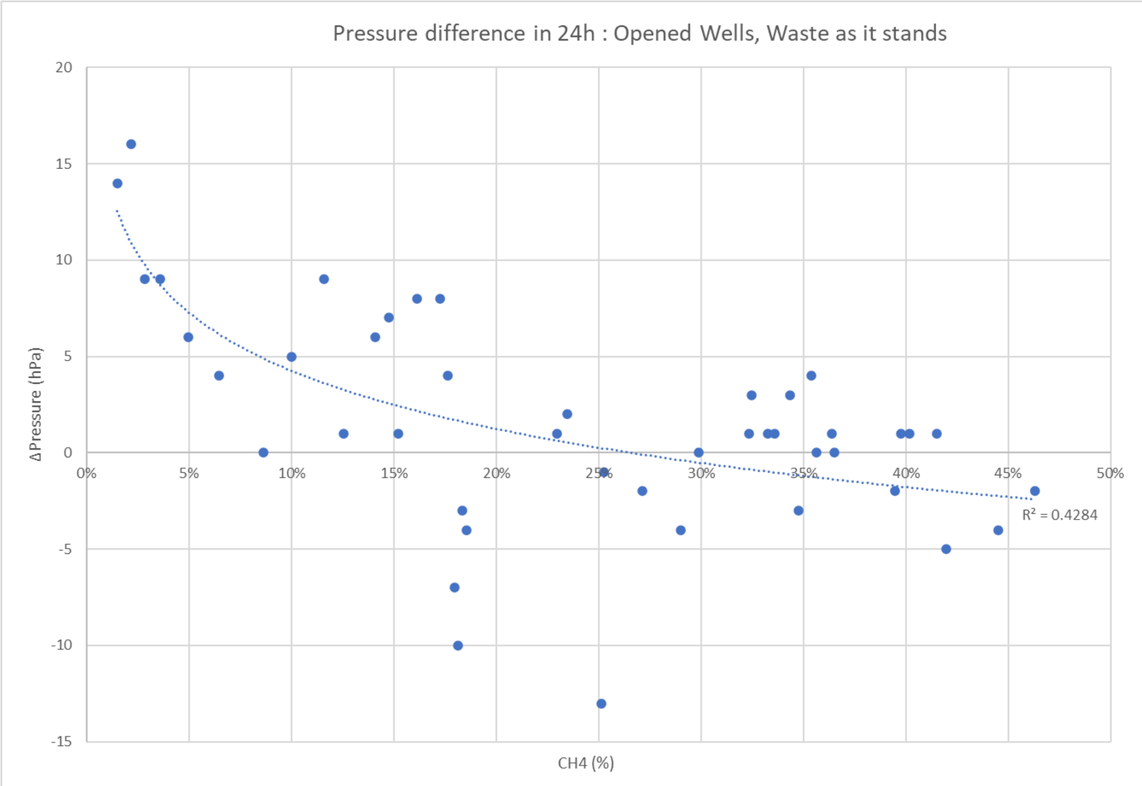


Graph P13, Pressure difference vs methane: 48 h before.

The most significant results belong to 12h and 24h graphs, where the higher correlation coefficients were found, respectively equal to 0.20 and 0.30. The main result coming from their analysis highlights as the methane increase is favored by the atmospheric pressure drop. Pressure gradients show a negative trend over time, corresponding to the methane concentration enhancing.
The result of these graphs seems to confirm what it was previously reported during the bibliographic search where an inverse relation was found between them. Given a higher correlation index belonging to the 24h scenario, it was decided to carry out an in-depth analysis of this case study according to the different wells typology. Thus, on one hand, opened wells and closed wells were considered, on the other hand, the material typology was evaluated by comparing both the waste bales and waste as it stands. In this regard, The first graphs to be represented (Graph P14 and Graph P15) concern the relation between pressure difference and methane percentage in opened wells.

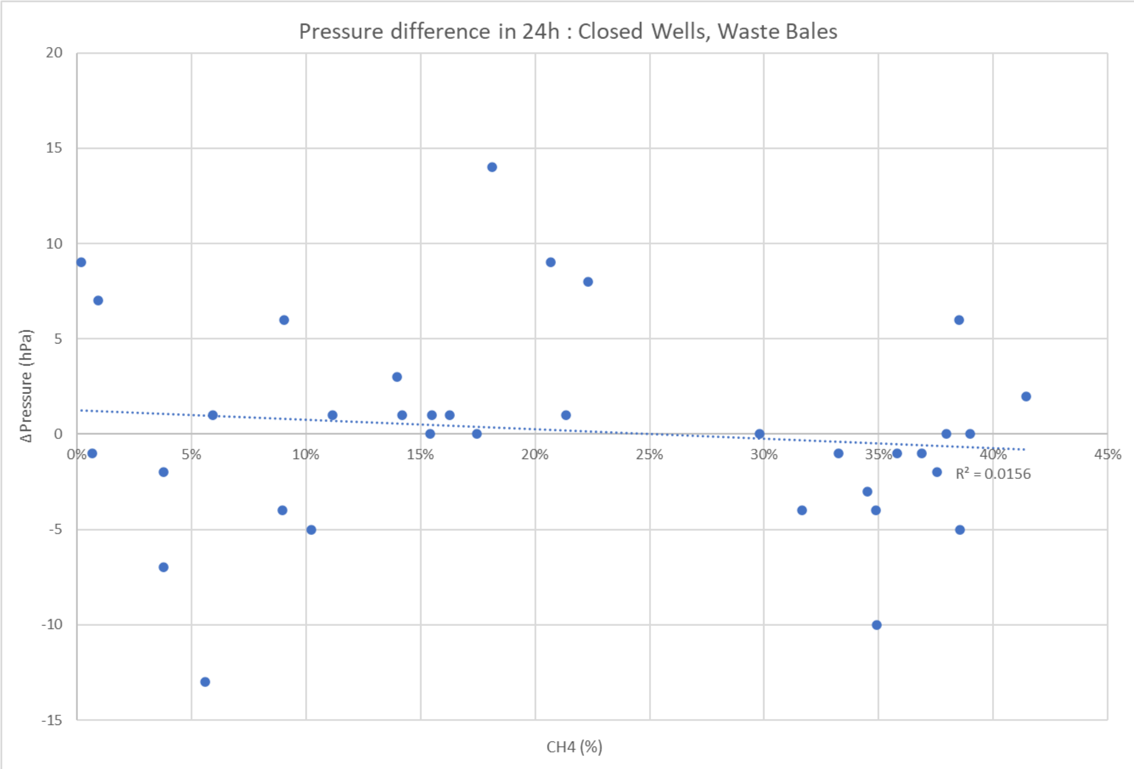


Graph P14, Pressure difference vs methane in 24 h: opened wells, Waste bales.

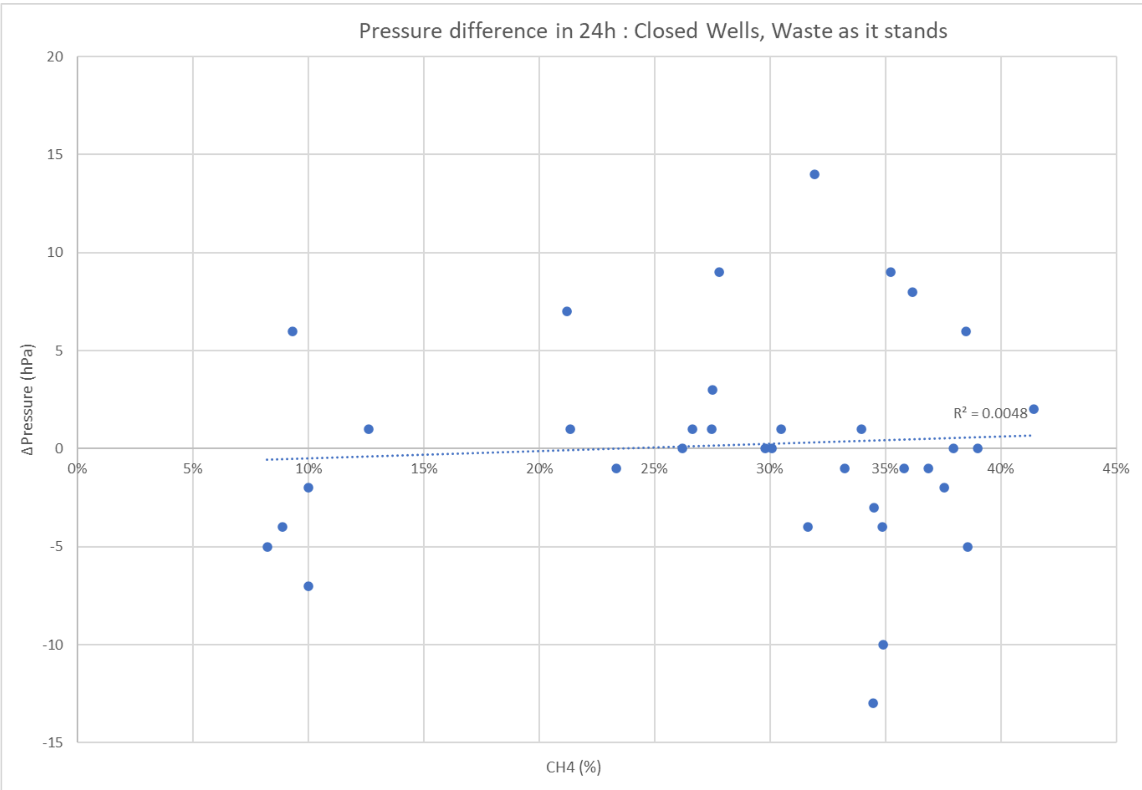


Graph P15, Pressure difference vs methane in 24 h: opened wells, Waste as it stands.

Subsequently, the study focused on the relation between pressure difference and methane percentage in closed wells by considering once again both the waste bales (Graph P16) and waste as it stands (Graph P17).

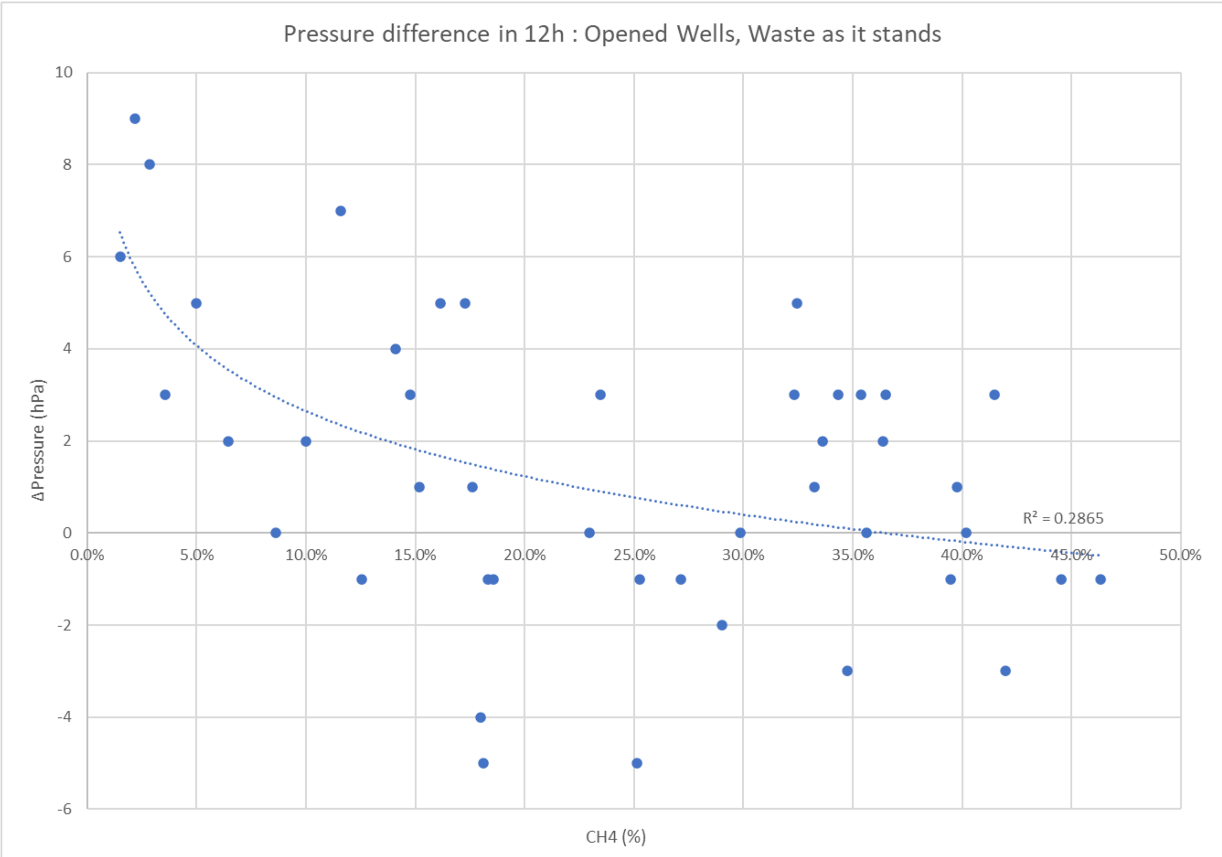


Graph P16, Pressure difference vs methane in 24 h: closed wells, Waste bales.



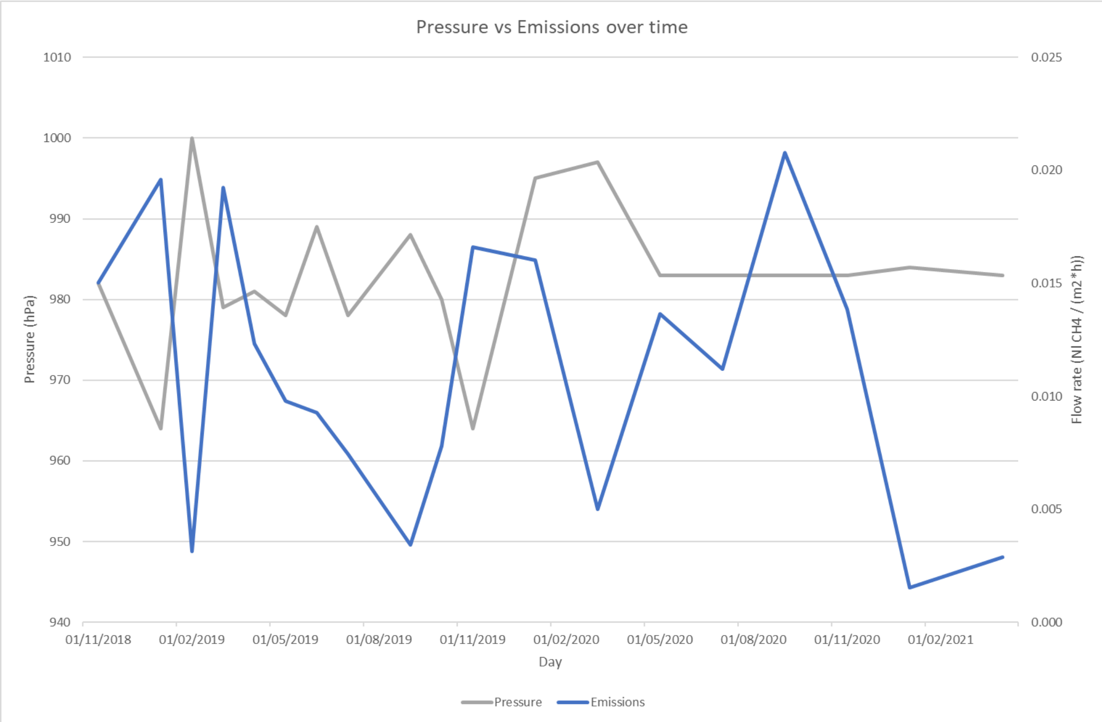
Graph P17, Pressure difference vs methane in 24 h: closed wells, Waste as it stands.

By looking at the previous graphs the most successful result refers to the open wells scenario related to the waste as it stands [Graph P15] where the R^2 index sets at 0.42. Furthermore, the 12h case was examined by only considering the bulk material in the opened wells [Graph P18], as this condition gave the most interesting result about the 24h analysis. In this case the correlation coefficient shown a lower value, equal to 0.28.

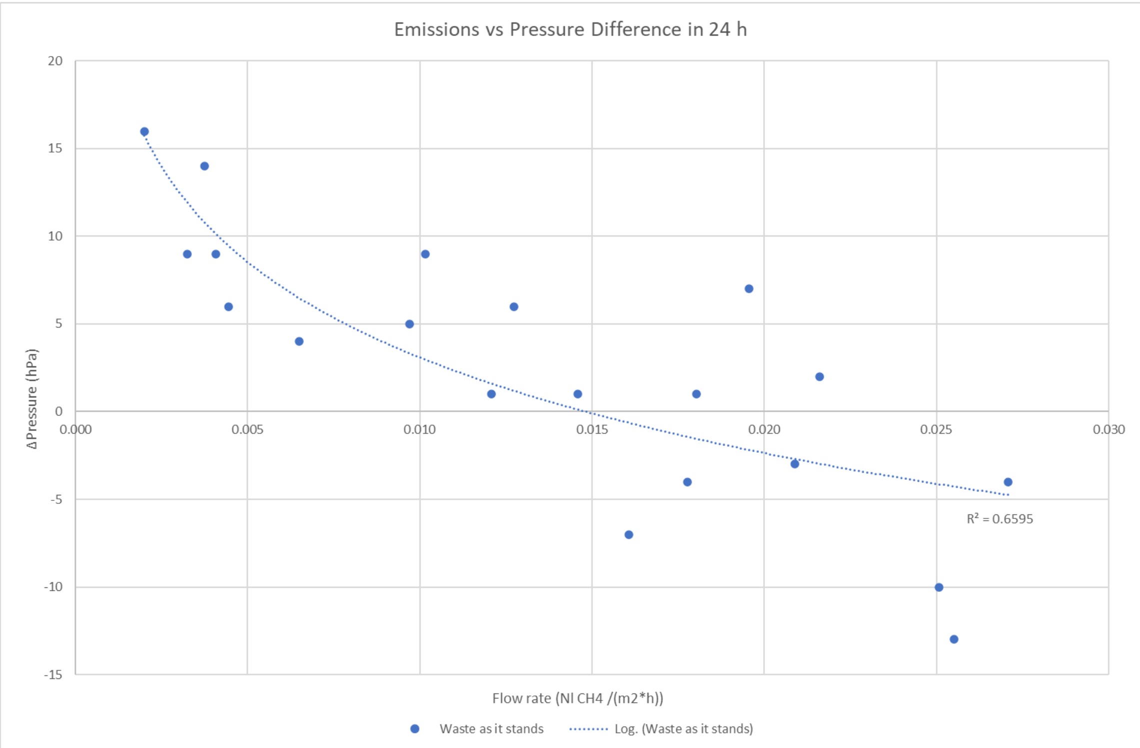


Graph P18, Pressure difference vs methane in 12 h: opened wells, Waste as it stands.

After evaluating the correlation between atmospheric pressure and methane concentration, the CH_4 emission flux was studied. In this regard, Graph P19 points out the pressure trend and the CH_4 flow rate over time. From this picture, it appeared hard to detect a straight relation between them, so it was decided to examine the pressure gradient during the last 24h with respect to the same emissions values [Graph P20]. In this case a significant R^2 number was obtained which is equal to 0.67. Because of the high correlation coefficient, the last graph highlights how the methane emission can be affected by the atmospheric pressure variation with regard to the 24 hours prior to methane detection.



Graph P19, Pressure vs methane emissions.



Graph P20, CH_4 emissions vs Pressure Difference in 24 h.

To conclude with the atmospheric pressure analysis, the greater correlations were found by comparing the pressure variation with the bulk material (waste as it stands) regarding the time window 24 h. Furthermore, higher methane concentrations belong to this category because the biogas can spread over the subsoil. In this case, in fact, the waste material was not treated with an enclosed geomembrane as for the waste bales. Since wells get opened a direct link was created between the waste material and the atmospheric air , this is the main reason why methane emissions were affected by the variation in the atmospheric pressure.

5.6 GAS FLUX EVALUATION FROM THE PIEDMONT SITE

The last part of the data processing focused on the calculation of the overall gas flux coming from the Site, starting from the pressure data extracted by the Arpa Piemonte database. The Young equation links the gas flux to the pressure gradient:

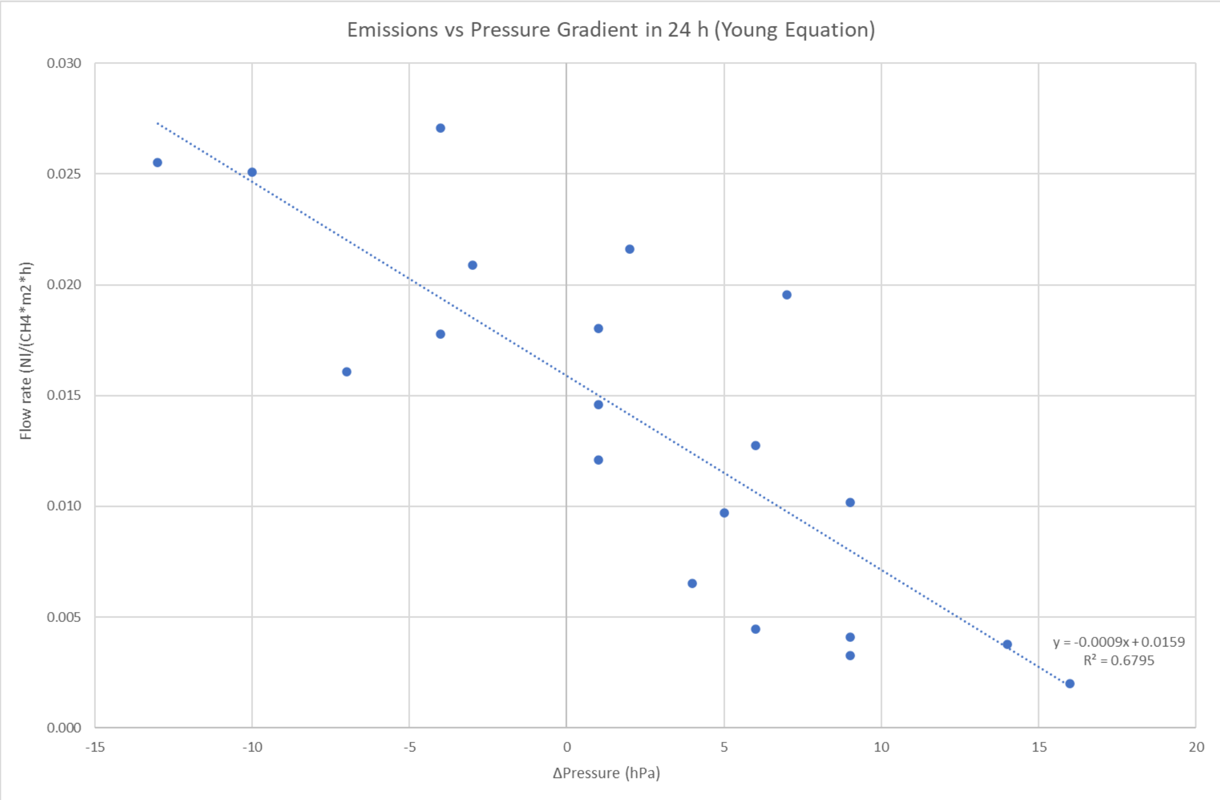
Gas flux = $\alpha + \beta \left(\frac{dPatm}{dt}\right)$ where:

α = gas rate produced within the site

β = constant related to the physical parameters of the landfill

$\frac{dPatm}{dt}$ = pressure gradient over time.

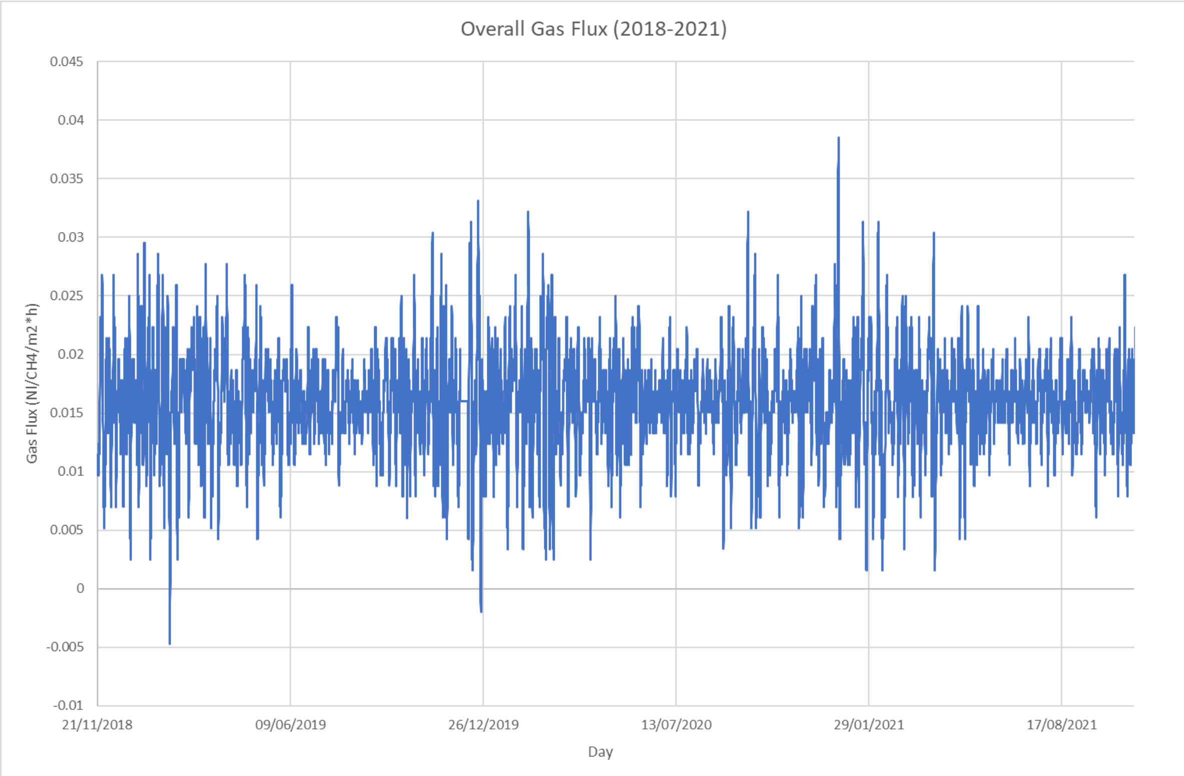
As the aim of this work was to obtain the whole gas flux the first step consists in obtaining the values from α and β in order to apply the previous formula with respect to the atmospheric pressure gradient. During this first phase, the gas flux in the Young equation was substituted by the CH_4 emissions from the Site monitored from November 2018 to October 2021. Consequently, the pressure variation was calculated during this reference time by considering the best scenario obtained so far , that is 24 hours prior to the CH_4 concentration detection regarding the southern part of the Site.
Graph P21 illustrates the Young Equation applied to the Piedmont site where the two parameters α and β are identified. The analysis refers only to the Southern area of the Site because the bulk waste shown a greater correlation with the pressure gradient. The CH_4 emissions trend seems to be similar with respect to Graph P20, thus confirming the goodness of the analysis. Furthermore , the great R^2 index relating the CH_4 emissions and pressure gradient testifies the high correlation between the two quantities.



Graph P21, CH_4 emissions vs Pressure Gradient in 24 h (Young Equation).

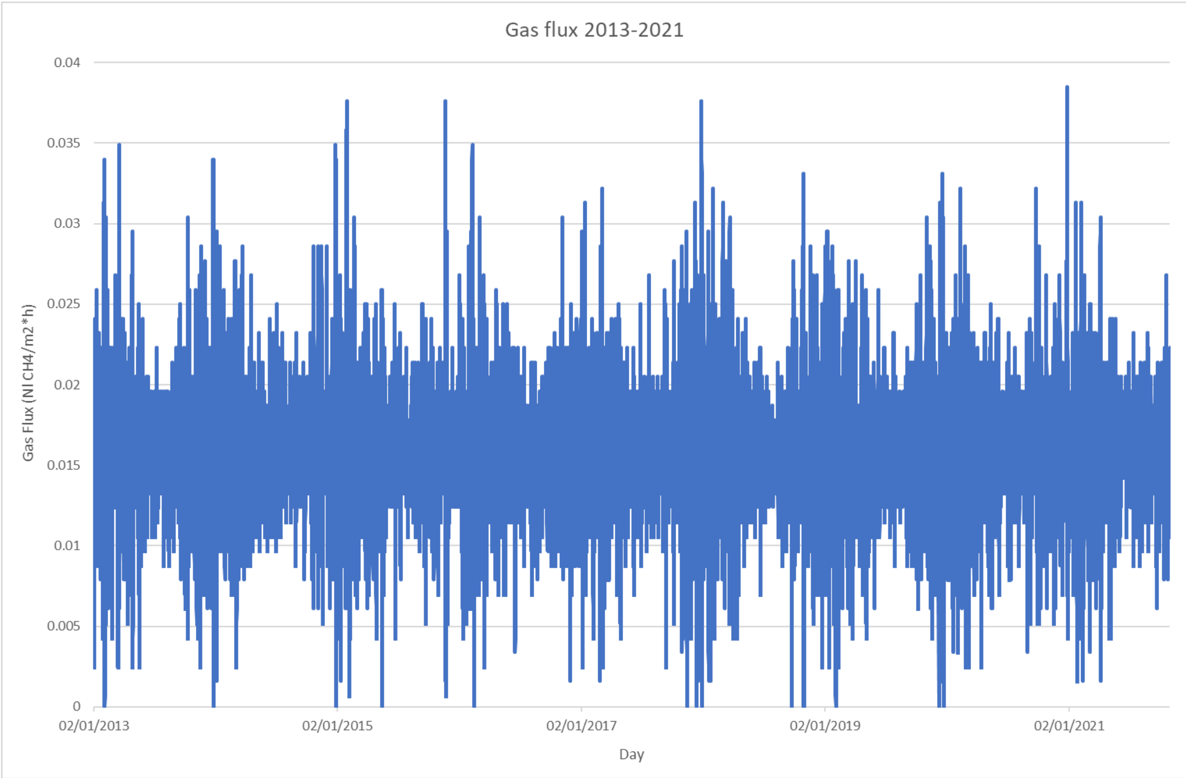
At this point, the resulting parameters from the Young equation correspond ,respectively, to α = 0.0159 and β = -0.0009. Thus, in order to compute the whole gas flux related to the Site , the new parameters are combined with the pressure gradient which was already used in Graph P21.

In this regard, a graph showing the overall gas flux was created by considering only the last monitoring period between 2018-2021 [Graph P22].



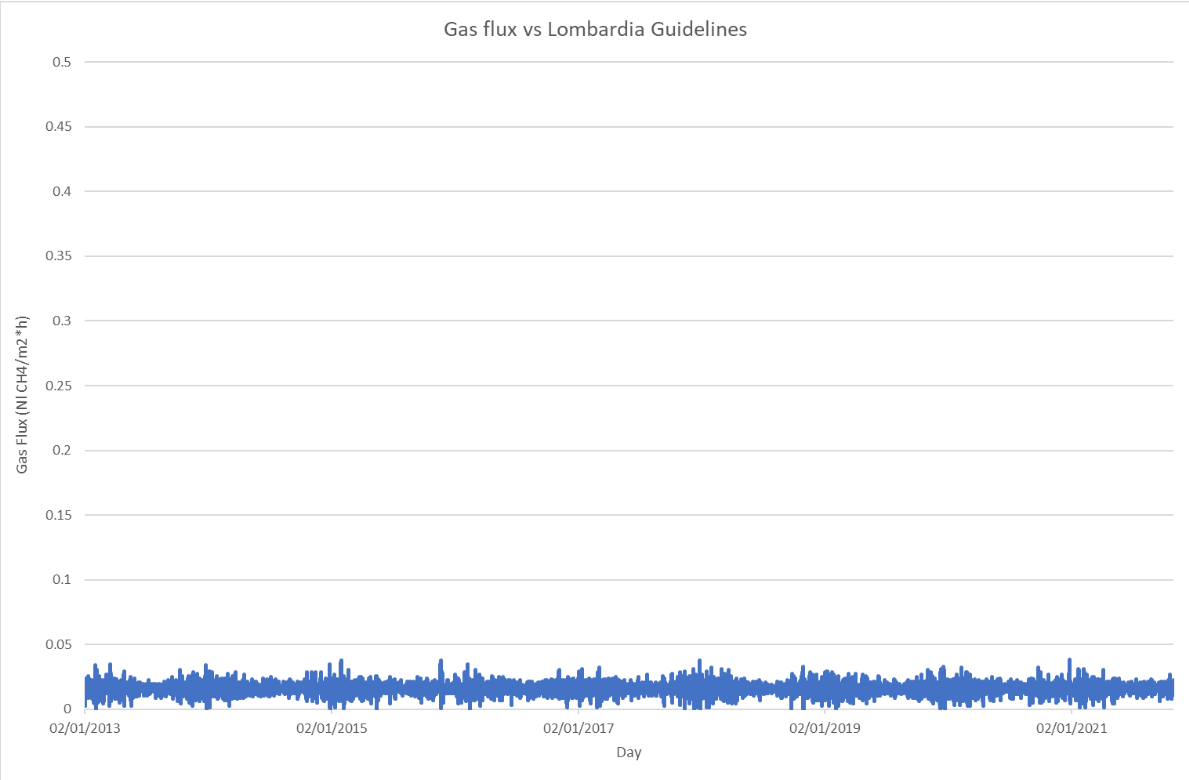
Graph P22, Gas Flux in 2018-2021.

Subsequently, it was decided to extend the Young equation to the whole monitoring period beginning from January 2013. The refence trend is shown in Graph P23 by taking only the positive values because they are more representative for the data analysis. In this regard, average and maximum values set at respectively 0.015 and 0.038 $\mathrm{Nl\,CH_4/m^2h}$. In particular the maximum value will be taken into account when deciding the technology for the treatment plant.



Graph P23, Gas Flux in 2013-2021.

To conclude with this paragraph, it can be interesting to evaluate how the site emissions set with respect to the current legislation. In this regard, gas emissions were compared to the regional guidelines carried out by region Lombardia ('Guidelines from Lombardia region', no date)where the maximum value for the biogas emission sets at 0.5 $\mathrm{Nl\,CH_4/m^2h}$. Graph P24 clearly shows how the law limit is largely respected as the average value corresponds to 0.015 $\mathrm{Nl\,CH_4/m^2h}$, while the maximum value sets at 0.038 $\mathrm{Nl\,CH_4/m^2h}$.



Graph P24, Gas Flux vs Lombardia Guidelines.

5.7 COMPARISON BETWEEN THE SITE AND THE PIEDMONT LANDFILLS

The aim of the this part of the work was to compare the different CH_4 emissions between all the Piedmont landfills, including the Site subject of the thesis. In this regard, after performing a formal request addressed to Arpa Piemonte it was possible to obtain the emissions data needed for the aim of this work. Year 2019 was chosen as the reference period because most of the CH_4 emissions values relate to this year. A specific table (Table 5.1) was created in order to hold the information needed for the comparison.

Table 5.1, Piedmont landfill sites and respective emissions

Landfill	CH_4 emissions (t/year)
Novi Ligure	1,378.95
Tortona	938.12
Pinerolo	788
Cerro Tanaro	550.29
Cambiano	457.24
Barengo	231.99
Cavaglià (ASRAB)	139.84
Villafalletto	97.22
Vinovo	66.07
Cavaglià (A2A)	36.78
Riva presso Chieri	17.26
Bairo	14.97
Strambino	9.49
Roasio	4.50

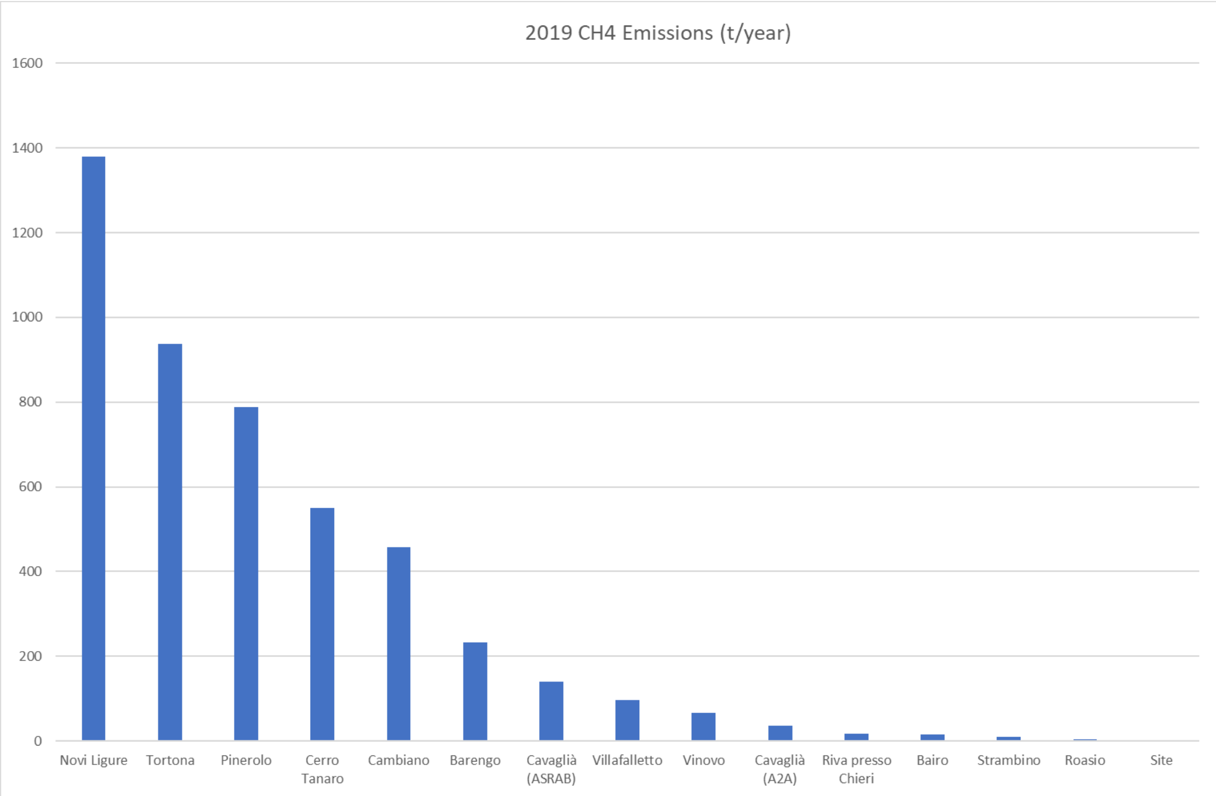
At this point, landfill gas emission from the Site was calculated. The reference values are then summarized in Table 5.2 starting from the maximum gas flux which is equal to $0.028\ \mathrm{Nl\,CH_4/m^2h}$ evaluated in 2019.

Table 5.2, Gas flux related to the Site.

2019	Site
Max flux Nl CH_4/(m^2*h)	0.028
Site southern area (m^2)	8,060
Yearly hours (h)	8,760
Tot Flux (Nl CH_4/year)	1,057,726.70
Tot Flux (Nm3/year CH_4)	1,057.73
Tot Flux (Kg/year CH_4)	740.409
Tot Flux (t/year CH_4)	0.740

Among all landfills, the site under investigation holds the lowest value of CH_4 total emissions, however, in order to better carry out a complete comparison, it needs to know the area of each site and the amount of waste treated as well. Unfortunately, it was difficult to obtain such a kind of information from the other Piedmont sites. A final histogram (Graph P25) was realized to observe the number of gas emissions showing the differences between each site.

In this analysis, the site under investigation shows the lowest values in terms of CH_4 emissions, while on the other hand, the highest value belongs to Novi Ligure landfill: the difference between them is signified by more than three orders of magnitude, testifying the scarce gas flux encountered in the site covered by the thesis work.



Graph P25, CH_4 emissions in Piedmont landfills.

6. TREATMENT PLANT: DESIGN AND DIMENSIONING CRITERIA

6.1 REGULATORY ASPECTS

After computing the amount of biogas emissions coming from the Site, it needs to evaluate how the these emissions can be treated in order to reduce the methane release on the environment. In this regard, the Italian regulatory to be studied refers to the legislative Decree n.121/20 -Attachment 1, Par.2.5- (Gazzetta Ufficiale, 2020) in terms of landfill gas monitoring where all the possible abatement technologies are mentioned. Actually, the site under investigation is not classified as "landfill", however, it is worth to follow the current legislation in order to know how the gas flux should be treated. According to the biogas composition and to the economical availability of the landfill owners, three different solutions can be considered to reach the ultimate scope, namely:

- Energy recovery
- Flare combustion
- Bio-oxidation

From a general point of view, the Italian regulations highlight how "landfills which can accept biodegradable waste must be equipped with gas extraction facilities that ensure the maximum collection efficiency and the consequent energy use". Of course, such a kind of condition is not ensured anywhere, it depends on the landfill and biogas features which will be described in the following paragraphs. Furthermore, when managing the biogas extraction system, it needs to consider the natural settlement of the waste mass. In fact, it can damage the structure of the system itself, thus a maintenance plan should be drawn up. In this scenario, it is useful to understand the main characteristics belonging to each of the three technologies. After evaluating the main features related to each solution, it will result easier to decide the best method to apply at the Site.
However, regardless of the technology used it needs to carry out a safety treatment of the biogas as it is underlined by the current law. In fact, the legislation highlights as "biogas management must be conducted in such a way as to minimise the risk to the environment and human health".

6.1.1 Energy recovery

As it is mentioned by the Italian regulation, the energy recovery represents the best final goal when facing out the landfill biogas emissions. Whenever it is viable, the energy recovery should be performed, also because of its dual effect in terms of biogas treatment. On one hand, it allows to trap the landfill gas emissions by avoiding that they can spread over into the environment and, on the other hand, it results in owning an economical earn which can be obtained by the landfill owners. The current legislation points out how the energy recovery can take place, with regard to the normative text "the actual energy reuse is subordinate to the minimum biogas production which can be extracted, it has to be greater than 100 Nm^3CH_4 / h with a flow duration provided for, at least, five years ". Furthermore, "the biogas extraction and treatment system must be kept active for as long as the landfill presents gas formations". It means that the power plant should work for the time required to capture all the biogas emissions, taking into account also the economic issue to make it work. Looking at the previous legislations and in particular referring to the Legislative Decree n. 36/2003, another parameter was considered in order to treat the biogas emissions. In this case, as the final aim is to convert biogas into energy a great percentage of methane is required, it should be greater than 40%. Now, by comparing these parameters with the Site, subject of the thesis, it results how the energy recovery cannot be used, first of all for the low methane percentages. In fact, in paragraph 3.3.2, Table 3.5 shows the amount of biogas extracted which sets at 85 m^3/h for the southern area of the Site. Moreover, the maximum methane percentage belongs to well Pb04 which is equal to 15 %. The Italian legislation, definitely, requires higher values to perform the energy recovery.

6.1.2 Flare combustion

Whether the energy recovery cannot be implemented, the second option refers to the flare combustion. In this case, the biogas can be disposed by controlled combustion where the methane is burnt in oxygen excess:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$

At this point, by studying the regulatory aspect (L.D. n. 121/20), flaring can be carried out only in a "suitable combustion chamber a temperature T > 850°C, with an oxygen presence greater than 3 % by volume and a retention time greater than 0.3 s." The last sentence outlines how the flare combustion should be performed but it does not explain when it could be developed. Thus, it needs to deal with Legislative Decree n. 36/2003 by mentioning another key parameter. In particular, it corresponds to the methane percentage in the gas flow which should own values greater than 25 %. Looking at these conditions, flare combustion needs specific requirements to be performed, thus it cannot be implemented in each landfill site. Nowadays, there are two types of gas flare to control biogas, they are subdivided in opened and enclosed torches. The main difference between them concerns the working temperature which is usually higher for the first category (T > 1000°C). In the recent past, landfill gases are valorised through the production of electricity or the production of renewable natural gas. In this scenario, enclosed flame flares are used for emergency conditions and for excess gas situation and they do not represent the first option in terms of biogas treatment. The last sentence confirms that the energy recovery is considered the first solution (whenever it is viable) to treat the biogas emissions.

However, the flare combustion cannot be assumed suitable for the site under investigation because of the methane percentages required. Methane average concentrations present low values also for this kind of technology as it is shown once again in Table 3.5. The Italian regulatory refers about self-powered torches, it means that the flare combustion works only by using the landfill gas to be treated and the plant does not need any other source to make it work. The second option consists in working with flares powered by other gases in order to reach the amount of methane percentage required by the regulatory parameters. Nevertheless , this method must to be rejected because it requires additional costs to be incurred.

6.1.3 Bio-oxidation in situ

The last method mentioned by the Italian legislation refers to the bio-oxidation or biofiltration. This technique represents the most recent solution in terms of landfill biogas treatment and there are not specific guide lines aimed to the plant design. The current Italian legislation allows the application of biofiltration systems, in particular it tells how "because of a methane production lower than 0.001 $Nm^3 CH_4$ / $m^2 h$, it will be possible to implement the bio-oxidation method in situ". In this text, it is also declared that "bio-oxidation can be carried out by the use biofilters or the installation of bio-oxidative roofing". Biofiltration (or bio-oxidation) consists in oxidizing the methane which is present in the biogas flow into carbon dioxide.

The landfill gas flows throughout a filter medium, which is usually made up of compost. With regard to the material composition, it can be said that it is usually reach in methanotrophic organisms which can transform CH_4 in CO_2.

As the biogas parameters related to the site under investigation respect the rules previously mentioned, the biofiltration represents the best solution for treating this kind of landfill gas flux.

For this reason, the plant design for this Site will face out the application of a possible biofiltration system which aim consists in the methane reduction.

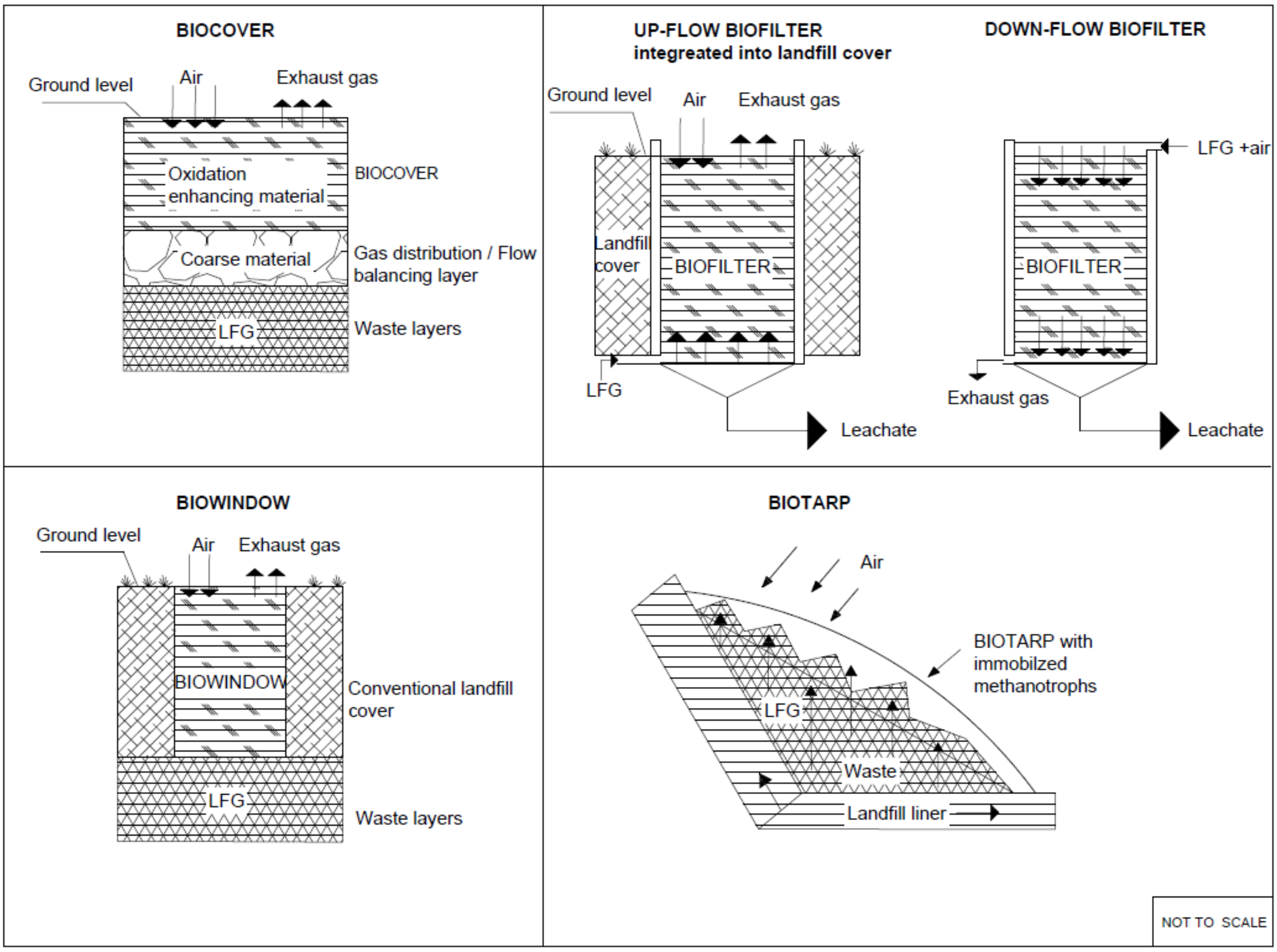
6.2 ANALYSIS OF THE BIO-OXIDATIVE METHODS

Bio-oxidation processes carried out in landfill sites is an emerging technology. In recent years several pilot projects were conducted, considering four different technologies: biotarps, biocovers, biowindows and biofilters. In this regard, Table 6.1 describes all the main characteristics belonging to each one of these technologies. Furthermore, a graphic representation is illustrated in Drawing 6.1 in order to look at a conceptual scheme about the four technologies. The greatest difference between them concerns the use of an active gas extraction system, so they can be distinguished in active and passive methods (Huber-Humer, Gebert and Hilger, 2008). The first three technologies do not require any active gas collection systems such as pumps or blowers. In this case, the gas flux naturally flows throughout the filter medium which is usually placed into the landfill cover. On the other hand, the biofilter acts by conveying the gas flux towards the filter medium which is installed in a box over the ground level.

All these technologies are described in the following paragraphs by listing the main characteristics and by explaining their reliability with respect to the site under investigation.

Table 6.1, Features of the biofiltration technologies.

	BIOFILTRATION TECHNOLOGIES			
	BIOCOVER	BIOWINDOW	BIOFILTER	BIOTARP
Collection system	Passive	Passive	Active	Passive
Description	Drainage layers and biofiltering material are included in the final or provisional coverage package	Small biocovers applied to limited landfill areas	Self-contained, fixed-bed reactors containing a packing material supporting a population of methane oxidizers	Removable tarp impregnated with methanotrophs
Methane oxidation layer	Mature and porous compost	Compost characterized by a permeability to the gas greater than that of the covering layer	Wood chips, bark mulch or peat; inorganic materials such as glass beads, bottom ash or porous clay pellets, sands and soils	Waste materials: sewage sludge or paper and water Commercial products: foams and canvas slurries
Aim and Functioning	Designing a cover to enhance biotic methane removal	Landfill gases migrate from the body of the landfill inside the biowindow for spreading, mainly due to pressure gradients	The gas to be treated is fed to the filtering unit by exploiting an extraction system	It is designed to cover the waste at the end of each working day
Methane oxidation capacity	95–99%, depending on the kind of compost applied	-	-	16% to 32 % by adding compost material
Advanatges	The high removal ratedue to teh installation of a gravel distribution layer	Useful when biocover is not warranted or economically feasible and when no gas collection system is present	Enclosed biofilters: capable to control methane and oxygen fluxes and maintain optimum temperature and moisture conditions	The support matrix is inert and not subject to biochemical degradation over time
Critical issues	Reulatory issues. Final capping can not be removed (L.D. 36/2003)	-	High capital and operating costs	-
Technology proposed by authors	Huber-Humer et al. (2008)	Kjeldsen et al. (2007)	-	Hilger et al. (2007)



Drawing 6.1, Scheme of the biofiltration technologies.

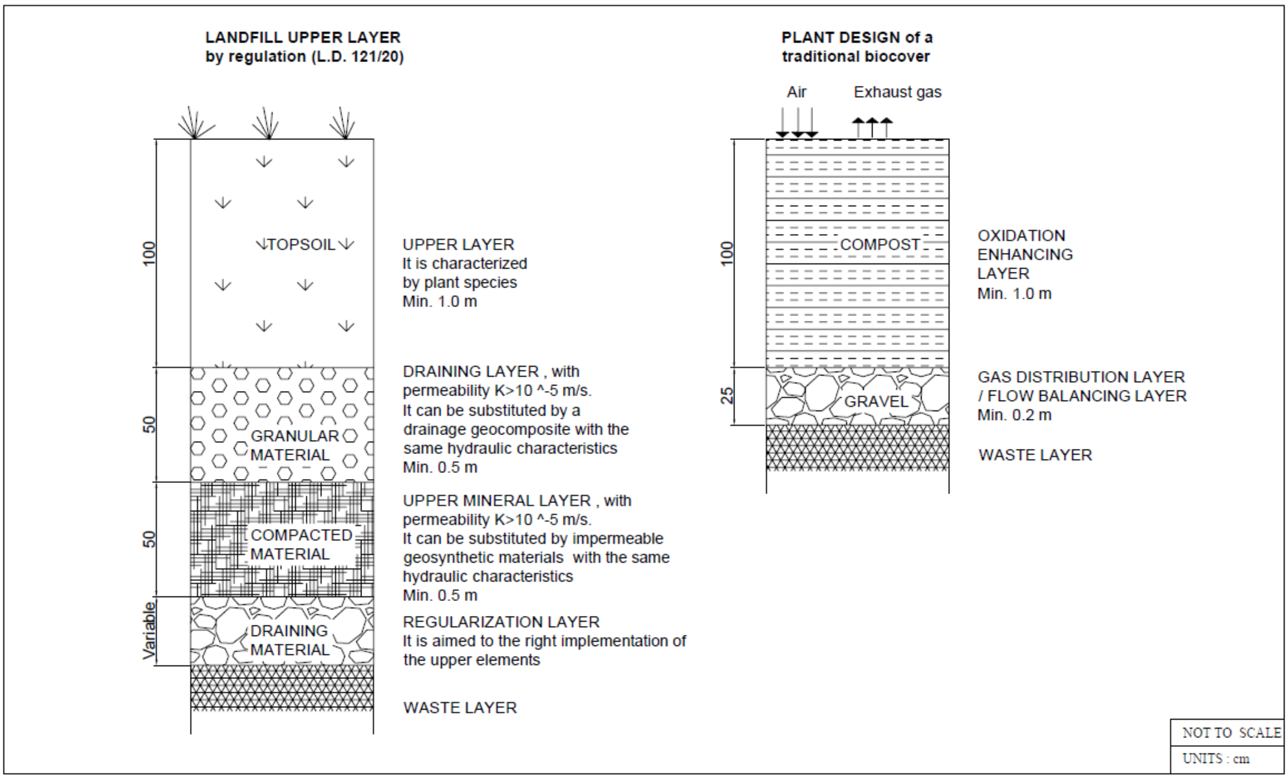
6.2.1 Biotarp

The first methodology to be analysed is the "biotarp". It consists in a removable sheet usually made up of immobilized methanotrophs. At the end of each working day, after the waste disposal, it is placed over the waste body in order to mitigate the methane emissions. Then, the following morning it is removed to allow the new waste placement. Because of its use conditions, biotarp needs to be managed day-by-day. In order to obtain a good methane oxidation, it is necessary to provide enough moisture and light during its activity. Dealing with all the biofiltration systems, the most important parameters refer to the moisture holding capacity and the porosity. Focusing on the biotarp, the surface area of the available matrix for the colonization plays an important role, as well as the mass/volume density of the cloth material. Most of the used elements for the methane oxidation leads to waste material such as sewage sludge or paper and water slurries, otherwise commercial products such as foams and canvas covers can be employed.

Biotarp is considered as a passive biofiltration system although it requires daily working operations. However, with regard to the site under investigation this technology cannot be implemented. In fact, as the cultivation of the landfill site was completed, it is no longer convenient to use such a kind of technology. For this reason, no further research was carried out about this topic.

6.2.2 Biocover

Biocovers represent one of the first attempts to mitigate the methane emissions from landfill covers. They consist in great landfill covers which are inserted into the landfill surface, in particular they are designed to cover all or most of landfill surface, so they can be applied only by removing the original landfill capping. A graphic pattern of a typical biocover is shown in Drawing 6.2 as well as the conceptual scheme of the final landfill capping foreseen by the Italian legislation.



Drawing 6.2, Biocovers: Plant design vs Regulations.

A traditional biocover structure is made up of two layers. From the bottom to the landfill surface, the first sheet to be encountered consists in the gas distribution layer. It is usually made up of a coarse gravel to obtain a more uniform supply and a decreasing rate of gas fluxes. It is usually 0.3-0.5 m thick to provide a high gas permeability. After the gas passes through this draining layer, it will be "trapped" by the compost layer where the methane oxidation takes place. Usually, it refers to a mature compost signified by about 1.2 m thick. Mature compost is used because it is preferred to avoid interference by heterotrophs competing for oxygen supplies. Another characteristic of the mature compost concerns the low trends in the organic mineralization and structural changes. "Long-term studies pointed out that mature compost with high well-stabilized organic matter slowly mineralized with a 10-15 % TOC reduction over more than 5 years" (Huber-Humer, Gebert and Hilger, 2008). However, the compost structure can change over time due to settling and biological activity which can affect the physical properties of the material. In this regard, in order to guarantee a suitable compost functioning, air-filled pore volumes should set at 30-45 % v/v, while moisture contents need to range between 40-50 % w/w water matter (Huber-Humer, Gebert and Hilger, 2008).

The first case studies carried out in Europe refer to two Austrian landfills between spring 1999 and winter 2002. Biocover design provided for the two layers previously mentioned which consist in a sub-layer aimed to homogenize gas fluxes and the porous upper layer which goal was to supply a good methane oxidation activity.

In this case, a strong decrease in methane oxidation was observed in shallow covers during the winter, however, the methane emission mitigation did not show a drop in methane oxidation referred to this study site. This condition can be due to a good insulation capacity established in the cover design. High removal rate was obtained in one year monitoring period by reaching until 95-99%. In this scenario, a proper cover design represents the most successful way to achieve high percentages in methane removal. In addition to the installation of the gravel distribution layer, it needs to evaluate all the chemical-physical parameters related to the compost material. In this regard, laboratory and field studies (Marlies Hrad, 2010) shown which are the most important elements to get an efficient biocover. These items are listed below:

- A long-term supply of nutrients (N_2 and P)
- A high temperature-insulating capacity
- Good porosity and gas permeability
- High water holding capacity

With regard to methane flux entering into the biocover, in order to obtain a satisfactory methane oxidation, field studies (Marlies Hrad, 2010) demonstrated that biocover system should ensure a minimum methane load equal to 4 $\frac{\mathrm{l\,CH_4}}{\mathrm{m^2d}}$. Finally, biocovers functioning can be also related to a possible sink for atmospheric methane. This phenomenon is most notable when a gas extraction system takes place because it can create negative pressure that conveys air into the landfill through the cover where methane can be oxidized. However, this condition can naturally occur when a greater amount of gas molecules is consumed with respect to the produced one, and it takes place when some of the water product exists as liquid rather than vapour.

Table 6.2 shows other two biocovers implementations in order to visualize the main features belonging to different applications: one in USA, and one in Finland. The greatest difference between these two projects concerns the size of the plant. On the one hand, in USA the biocover was designed to cover a large area of the landfill (but it does not cover the whole surface), on the other hand, in Estonia the biocover methodology was implemented to the entire landfill surface. Methane oxidation efficiencies set at 31 % and 46-84% ,respectively, for the two case studies.

Table 6.2, Biocovers field activities.

	BIOCOVERS FIELD APPLICATIONS		
		USA,2004	Finland,2006
	Landfill	Leon County	Aikkala
Landfill features	Surface [m2]	NA	39000
	Final authorized capacity [m^3]	NA	NA
	Total waste (ton)	NA	200000
Plant dimensioning	Number	2	1
	Size [m]	18 x 32	whole landfill
	Draining layer (gravel) [m]	0.1 (*)	0.5
	Particle size of the gravel layer [mm]	NA	NA
	Methane oxidation layer [m]	0.6	1
Compost features	Material used	Chipped yard waste	Peat and sludge compost (40:60,vol%)
	Moisture content [% ww]	NA	33
	pH	7.5	4.3
Gas flux characteristics	LFG flow [Nl CH_4/(m^2*h)]	NA	0.353
	LFG composition: CH_4 conc. [%]	53	44-63
	CH4 load [g/(m^2*h)]	3.13	0.12-1.11
	CH_4 oxidation capacity [g/(m^2*h)]	0.97	0.08-0.94
Results	CH_4 Oxidation Efficiencies [%]	31	46-84

NA= not available
(*) Crushed fluorescent tube glass

In general, biocover design and dimensioning is related to the local site-specific conditions and they are subject to the climatic conditions, expected gas fluxes, aim of the of the cover (temporary or final), features of the substrate and the expected after use of the site (Marlies Hrad, 2010). However, after studying the different biocovers features jointed with field activities around the world it needs to understand if this technology can be implemented to the piedmont site, subject of the thesis. Actually, by referring to the current Italian legislation, biocover systems cannot be realized in landfill sites because they require to remove the upper landfill capping as it was represented in Drawing 6.2. Because of this reason, the site under investigation cannot host a biocover system.

6.2.3 Biowindow

The third option of methane mitigation refers to the biowindws. Biowindows represent a similar technology with respect to the biocovers in terms of methane removal. The greatest difference consists in the surface occupied by the two oxidative methods, in fact, biowinows are designed to cover only small regions of a landfill surface. This kind of technology is, usually, carried out when biocover design is not economically feasible or it does not ensure great oxidation efficiencies. The principle of operation reflects what it was previously discussed when referring to biocovers. In this regard, the biogas coming from the waste reaches the ground openings by following a preferential route addressed by the draining layer which is made up of coarse gravel.

Subsequently, biogas flow encounters the compost layer where it is subject to the methane oxidation. The main characteristics of the compost material were already described as well as the main controlling parameters which affect the methane oxidation. However, in order to deeply investigate such kind of process it can be said which are the most affecting parameters related to this phenomenon. In particular, they mainly refer to two elements which correspond to moisture content and the organic content and nutrient supply (Marlies Hrad, 2010). On one hand, the methane oxidation is certainly subject to the moisture content. In particular, it can affect both gas permeability and diffusivity of soil. In the previous article named "Quantification of landfill gas emissions in biocovers- An Experimental Simulation in Lysimeters", authors suggested how the "higher performances in methane oxidation correspond to moisture contents setting at 50% of the water holding capacity which support both the activity of methanotrophic bacteria and gas permeability". In this way, higher moisture levels do not allow a successful CH_4 oxidation capacity.

On the other hand, the second parameter to take into account refers to the organic content and nutrient supply. In this regard, the organic matter present in the compost material strongly influences the CH_4 oxidation capacity.

In fact, this item can improve the substrate features like soil structure and aggregation. Furthermore, in order to carry out an efficient methane capacity, the substrate needs methanotrophic bacteria to perform its work. In particular, these micro-organisms can develop only throughout a sufficient nutrient supply. In this scenario, compost used for CH_4 oxidation presents nitrogen and phosphorus values equal to 0.85 – 1.25 % (dry matter) and 0.43 – 3.06 % (dry matter), which percentages are typically higher than those found in traditional soils (Marlies Hrad, 2010). After proposing a general overview about the main characteristics belonging to the filter media, it can be useful to point out the first case studies in terms of biowindows applications. In this regard, German and Danish on-site works characterized the beginning activities about this topic. In particular, after performing a critical search the analysis focused on three main works which were carried out in three different countries: Austria, Italy and Denmark. All these field applications are shown in Table 6.3 as it was realized for biocovers projects.

Table 6.3, Biowindows field applications.

	BIOWINDOWS FIELD APPLICATIONS			
		Austria,2014	Italy,2016	Denmark,2010
	Landfill		Le Fornaci di Monticiano (Siena)	Fakse
Landfill features	Surface [m2]	100,000	25,000	120,000
	Final authorized capacity [m3]	540,000	NA	NA
	Total waste (ton)	NA	29,300	660,000
Plant dimensioning	Number	2	7	10
	Size [m]	8 x 8	2 x 2	50 x 10
	Draining layer (gravel) [m]	0.5	0.2	0.15
	Particle size of the gravel layer [mm]	30-60	15-30	5
	Methane oxidation layer [m]	1.4	1.2	1
Compost features	Material used	Bio-compost/wooden chips (70:30,vol%)	Compost/ Organic fraction of MSW and sand (80:20,vol%)	Composted garden waste
	Moisture content [% ww]	NA	28	NA
	pH	7.6	7.2	NA
Gas flux characteristics	LFG flow [Nl CH_4 /(m^2*h)]	0.03	0.66	0.015
	LFG comp.: CH4 concentration [%]	15-35	26	33
	CH4 load [g/(m2*h)]	4	NA	NA
	CH4 oxidation capacity [g/(m2*h)]	NA	NA	4.5
	Gas flow rate [Nm^3/h]	NA	2.5	NA
Results	CH4 Oxidation Efficiencies [%]	NA	88	41

NA= not available

Unfortunately, regarding the Austrian work, some data are missing, thus it was hard to study how efficient the bio-oxidative method was.
On the other hand, the other two case studies present a more detailed description of the work. In this case, oxidation efficiencies set at 88% and 41%, respectively for the Italian and Danish field applications. To conclude with the biowindows focus, it needs to tell if this kind of project can be feasible for the Site. Because of the small areas required for the biowindows installation, this kind of technology can be implemented as it does not require to remove the whole landfill capping in a given site. Moreover, a biowindow system was already implemented at the Piedmont Site as it was mentioned in paragraph 3.3.1.

6.2.4 Biofilter

Biofilters represent the bio-oxidative technology which mostly differ from the previous methods. In fact, a biofilter works as an active biofiltration system where the gas flux is captured and conveyed to the filter medium. From a designing point of view, it can be intended as an engineered system similar to those implemented for filtering air for odour or organic contaminants. Its main configuration refers to a fixed-bed reactor where a packing material takes place in order to support micro-organisms which aim is to oxidize the methane flux. Biofiltration carried out in biofilters is, usually, implemented when both the energy recovery and flaring are not yet viable. Furthermore, biofilters are not represented by a unique family in terms of external configurations, but they differ into two big categories (Drawing 6.1) :open bed biofilters and fully confined biofilters which are enclosed (Huber-Humer, Gebert and Hilger, 2008). In the first typology, filter medium directly interacts with the atmospheric air, so the amount of oxygen is supplied by the air itself. Furthermore, this kind of technology allows the biofilter realization into the landfill cover; in this case, oxygen can be conveyed to the filter media throughout landfill gas pipe. On the other hand, the opposite method provides for enclosed structures where the oxygen must be supplied only by a gas pipeline. From an engineering point of view, the second option results to be more efficient because of the possibility to control methane and oxygen fluxes. Moreover, the monitoring of temperature and moisture conditions is easier. However, there also some disadvantages in operating with such kind of technology because of the capital and operating costs, which are usually very high.

The biofiltration layer must have the same characteristics as biocovers and biowindows, that is, it must ensure proper environmental conditions or the development of the microbes. In this regard, the filter medium should hold suitable moisture levels ranging between 40-50 % ww and a sufficient organic content and nutrient supply. Moreover, the material must have a high permeability in order to overcome given pressure loss. Laboratory studied suggested a number of suitable materials for the methane oxidation. In particular they refer to in compost of various origins which can be characterized by wood chips, bark mulch or peat. However, inorganic materials can be used too, such as such as glass beads and bottom ash. While, in terms of biofiltration performances it needs to consider the kind of material used for the methane reduction. For example, it was studied (Huber-Humer, Gebert and Hilger, 2008) that by using a mixture of compost and bark or wood chips in a opened bed systems it is possible to achieve more than 90% in the CH_4 removal rates. In this case, the biofiltration plant worked at ambient conditions with CH_4 lowing rates of 1.1-2.5 $\frac{m^3}{hm^3}$. Another biofiltration method refers to a case study in Western Canada where a biofilter made up of compost was integrated into the landfill cover. In addition to the original biofilter, a heat exchanger system was jointed. Results coming from this activity led to the 89% of methane removed from the biogas flow with an input methane flux up to 40 $\frac{gCH_4}{m^2d}$. The previous results witnessed the goodness in operating with such a kind of technology. However, when dealing with open beds biofilters there at least two issues to face out. The first parameter to control refers to the LFG flux input. In fact, whether it occurs in large amounts it can impede the oxygen supply from the atmosphere. On the other hand, the second challenge concerns the presence of exopolymer substances (EPS) which could thicken the filter media by hinder the mass exchange in the bed. In addition to the bibliographic case studies previously mentioned, Table 6.4 shows two other field activities carried out in USA and Italy.

Table 6.4, Biofilter field applications.

	BIOFILTERS FIELD APPLICATIONS		
		USA,2004	Italy,2016
	Landfill	Leon County	Podere il Pero (Arezzo)
Landfill features	Surface [m^2]	NA	92,000
	Final authorized capacity [m^3]	NA	631,000
	Total waste (ton)	NA	660,000
Technology	Methane oxidation system	Biofilter	Biofilter
Plant dimensioning	Number	1	1
	Size [m]	0.9 x 0.58 (diameter)	18 x 15
	Draining layer (gravel) [m]	0.16	0.2
	Particle size of the gravel layer [mm]	NA	15-30
	Methane oxidation layer [m]	0.58	1.5
Compost features	Material used	Chipped yard waste	Compost/ Organic fraction of MSW and sand (80:20,vol%)
	Moisture content [% ww]	NA	28
	pH	7.5	7.2
Gas flux characteristics	LFG flow [Nl CH_4 /(m^2*h)]	NA	2.67
	LFG comp. : CH_4 concentration [%]	50	33
	CH_4 load [g/(m^2*h)]	10.4-20.8	10.9
	CH_4 oxidation capacity [g/(m^2*h)]	10.0	5.7
	Gas flow rate [Nm^3/h]	NA	20
Results	CH_4 Oxidation Efficiencies [%]	69	58

NA=not available

With regard to the USA field activity, the project provided for the same landfill site the realization of both a compost biofilter and the installation of two biocovers which were previously mentioned.

In this case, the biofilter performances settled at 69% of CH_4 removal efficiency signified by a methane oxidation capacity of about 10 $\frac{g}{m^2 h}$. While, referring to the Italian field work, a great biofilter (18 x 15 m) was installed in Tuscany by obtaining an overall efficiency approximately equal to 58%. The work carried out in Italy refers to the “Project Life RE Mida” which lasted for three years from 2016 to 2018. This plan dealt with the biowindows installations previously described too. Finally, focusing on the Site evaluated for the thesis, a biofilter system can be implemented. However, the place under investigation is not equipped with electric power as well as it represents the biggest issue if deciding to realize such kind of plant.

7. BIO-OXIDATIVE METHODS TO BE IMPLEMENTED AT THE SITE

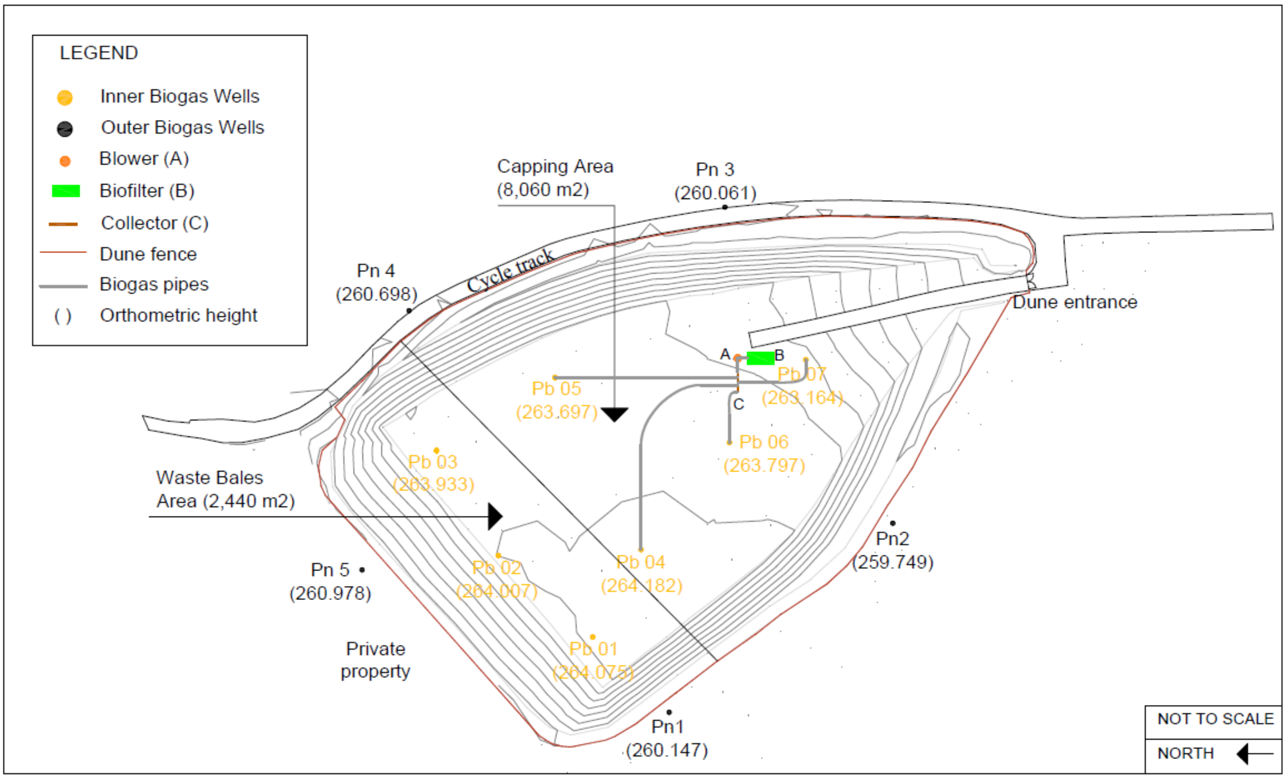
Among the considered technologies, biofilter and biowindows represent the most appropriate methods to treat such a kind of landfill gas emissions.

In this scenario, in order to understand the best technology to be implemented, both the technologies will be examined and a feasibility study will be performed. With regard to the system functioning, the two methodologies refer to different kind of emissions treatment. On one hand, in fact, biofilter signifies an active biofiltration system where gas flow needs to be conveyed into the filter media. In this way, in order to carry out a satisfying procedure, a collector and a blower must to be used for moving the gas from the wells to the biofilter. On the other hand, biowindows do not require any active methods to transport the gas flow. This second kind of technology exploits the upwards gas movement leaving out the subsoil to reduce the methane concentration in the biogas flow.

With regard to the passive biofiltration method, two different solutions will be studied which refer to two different field applications: Danish and Italian works previously mentioned. In particular, both the biowindows patterns will be applied at the Site in order to understand which is the best solution in terms of both oxidation efficiency and implementation costs.

7.1 BIOFILTER

The first technology to be studied refers to the biofilter. Before starting to describe the design parameters and the overall costs related to this bio-oxidative method, it appears useful to understand where the biofilter box can be placed into the Site. In this regard, because of the easiness of approaching, the whole equipment can be installed at the end of the access ramp (Drawing 7.1). Furthermore, it is important to remember both the collector and the aspirator need to be used to allow the biofilter to operate. For this reason, such a kind of system requires a flat plane where all the machines can be located. At the same time, this area should be close to the site entrance as well as it can be easily accessed.



Drawing 7.1, Placement of the active biofiltration system.

Subsequently, after pointing out a possible sitting for the active biofiltration system, the biofilter box can be studied by highlighting its main components. In this regard, in order to understand the key elements constituting the biofilter, six different Italian firms were evaluated by comparing the both the technical characteristics and methane oxidation capacity: the main features belonging to each company are shown in Table 7.1.1 and Table 7.1.2.

Table 7.1.1, Biofilter technical data: 1st section.

Technical Features	COMPANIES Company A		Company B	Company C	Company D	Company E	Company F
Kind of plant	Swap body biofilter		Detachable biofilter	Swap body biofilter	Biofilter with biomodules	One-piece biofilter	Swap body biofilter
Operating temperature	5 to 40 °C			2 to 45°C	T > 10°C		10 to 45 °C
Air flow rate (m^3/h)	100	500	max 2,000	30 to 150		600	
Specific flow rate per m3 of filter medium (m^3/h)	80		80		<= 150	80-110	<= 100
Head loss	< 1000 Pa			10-50 mm H_2O			30-50 mm H_2O
Contact time (air/filter medium)	41 sec		> 45 sec		> 35 sec	> 36 sec	
Operability	Air extraction and pollutant abatement system		Purification of biogas fumes	Air and biogas reduction:low CH4 percentage (< 20%)	Waste-gas treatment	Substances reduction such as dust and micro-polluting acids	Odour and VOCs reduction
External size (m)	Customer needs		2.5 x 6.3 x 2.55	6.0 x 2.5 x 2.55	Customer needs	3.2 x 2.3 x 2.0	Customer needs
Net inner volume m^3	3	7.2	20	20		10	

Table 7.1.2, Biofilter technical data: 2nd section.

Technical Features	COMPANIES Company A	Company B	Company C	Company D	Company E	Company F
Filter medium	Wood chips and coconut fibre	Pine bark, broad-leaved bark and mature compost	Plant mixture from green compost and shredded hardwood bark	Compost, bark and wood chip	BIOPOR: special inert material with porous structure and basic matrix of volcanic origin	Porous solid inorganic and organic material
Filter bed height (m)	1.5	1.6	1.5		1.0-1.5	1.0-2.0
Humidifycation system	Network of nozzles installed above the filter material	Electric pump unit and hydrosphere tank	Drip irrigation system	Scrubber or humidifier	Surface humidification with timing	
Removal efficiency	Odours up to 99 % H2S : 99% NH3 : 95%	Odours up to 92% No CH4 reduction	Odour > 90% CH4 : 67-51 %	Odours > 92% No CH4 reduction	No CH4 reduction	No CH4 reduction
Maintenance			Replacement of the filter medium after two years from the plant starting	30 h/year	Replacement of the filter medium	Check of the filter bed clogging
Advantages	Ready to be used	Water retention capacity	Quick and easy installation	Lower installation timing and uniform air distribution	Installation convenience	

However, most of the approached companies dealt with the removal of the odour substances by neglecting the methane reduction. In this scenario, Company C represents the only firm which technologies are able to face out such kind of operation.

For this reason, the biofilter description refers to this company by considering its proper parameters. From the data sheet provided by Company C, biofilter can treat biogas flow rate ranging from 30 to 150 m^3/h with the reference removal efficiency varying from 67 to 51 %. In this regard, Table 7.2 shows the performance characteristics.

Table 7.2, Biofilter operating performance

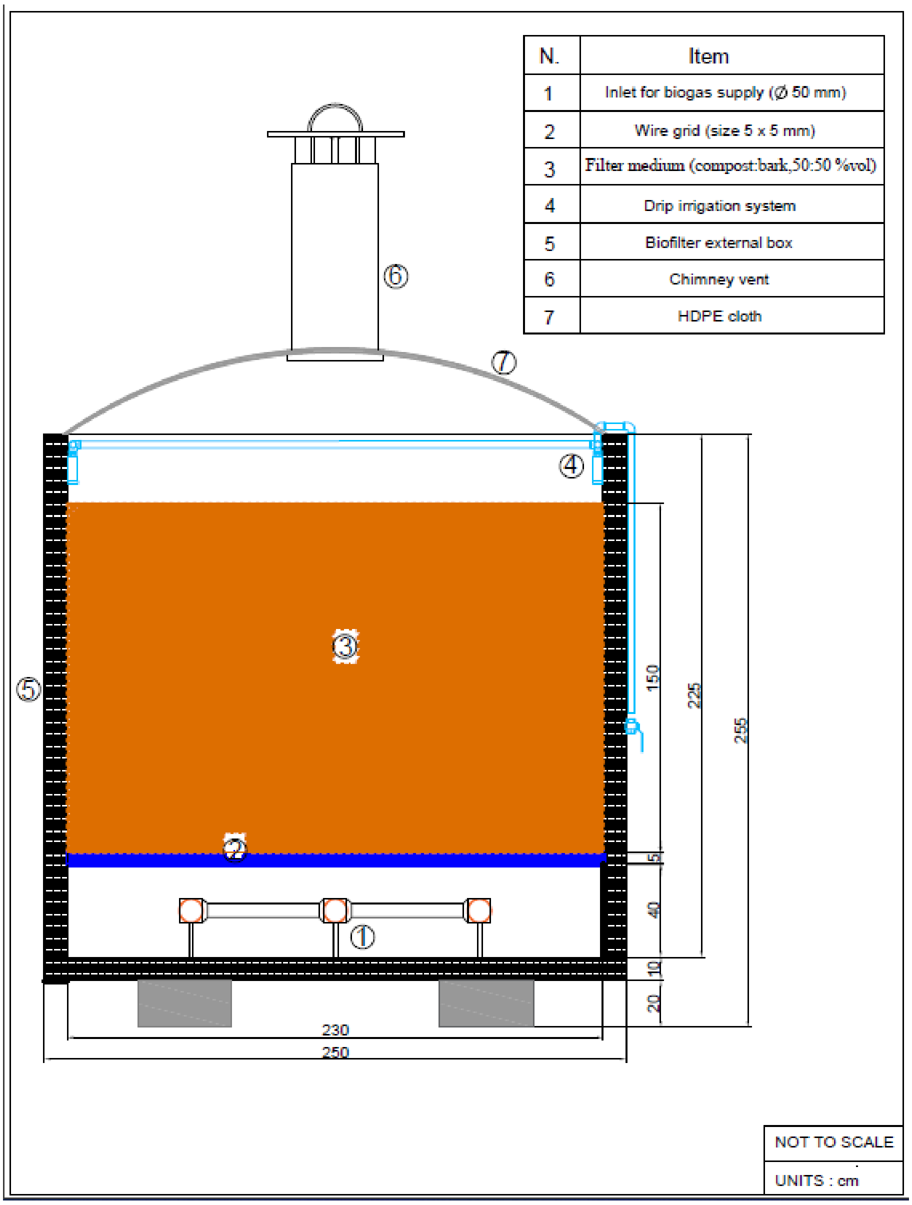
Biogas flow rate input (m^3/h)	Methane concentration input (%)	Methane removal efficiency (%)	Methane concentration output (%)
30	5	67	1.7
30	20	67	6.6
50	5	64	1.8
50	20	64	7
100	5	58	2
100	20	58	8.4
150	5	51	2.4
150	20	51	9.6

After looking at the CH_4 removal efficiencies belonging to the reference biofilter, it needs to evaluate the overall gas flux coming from the wells located in the southern part of the Site where most of the gas emissions take place. With regard to Chapter 6, Table 6.2 highlights how the gas flux to be considered sets at 85 m^3/h characterized by an average methane concentration equal to 7.4%. Therefore, because of the parameters coming from Table 7.2, the most similar value with respect to flow rate of 85 m^3/h appears to be a biogas flow input of 100 m^3/h. In this regard, the biofilter under investigation will own an efficiency equal to 58% in terms of methane reduction.

To conclude with performance study, output methane concentration will result to be around 3.1 % as the input methane flux is equal to 7.4 %.

7.1.1 Biofilter design parameters

Next step regarding the biofilter description concerns the evaluation of the design parameters. Biofilter is intended as an enclosed steel box which size depends on the amount of gas flow rate to be treated. The front section of the biofilter proposed by the Company C is illustrated in Drawing 7.2.



Drawing 7.2, Biofilter front section.

Typically, the internal structure of the biofilter is made up of two main components. On one hand, it is possible to find a wire grid placed in the lower part of the structure characterized by a thickness of few centimetres. Its aim consists in uniformly distributing the gas flow towards the filter media located just above the wire grid. On the other hand, the second element is signified by the filter medium itself.

This second item is known as the gas oxidation layer where the methane reduction takes place. Its characteristic thickness is around 1.5 m to allow a proper oxidation of the gas to be treated. The material used for this purpose, usually, refers to compost or organic substances able to degrade the methane concentration. For example, the filter medium belonging to Company C is obtained by herbal mixture made up of green compost and chopped hardwood bark.

Such a kind of material is considered as a suitable matter in terms of porosity and water retention because of its dry volume weight equal to 400 kg/m^3 (wet weight 800 kg/m^3). In order to achieve good performance in terms of CH_4 removal efficiency, it needs to take into account two physical properties related to the filter media. The first one refers to the pH belonging to the compost. In this case, pH values should set at around neutral number to ensure a proper oxidation activity carried out by the micro-organisms present in the organic matter. On the other hand, the second feature to be considered leads to the humidity percentage. In this regard, moisture levels should set at around 50-60 % w/w water matter. Both pH values and humidity percentages refer to the same quantities which were already encountered during the biocover and biowindow description in the bibliographic search. This common characteristic is explained because of the same substances used for the oxidation capacity which mainly refer to compost or organic matter. In particular, in order to guarantee a proper humidity level in a biofilter media, it is necessary to provide an irrigation system to the structure itself. In this regard, concerning the biofilter of the Company C, the humidification procedure of the filter bed is ensured through a planned drip irrigation system. In addition to the irrigation system, it needs to provide a water withdrawal hub close to the biofilter as well as a water drainage station for the excess water. Finally, the last thing to consider about biofilter design refers to the biofilter coverage which is realized in propylene geotextile. On top of the coverage, a HDPE chimney is built in order to check the emission characteristics.

Once the design parameters have been described, the maintenance procedures should be evaluated. The following maintenance activities are suggested by the same Company supplying the biofilter :

- It is recommended to replace the filter material two years later the start-up of the plant.
- Verifying the height of the filter material. In case of compost reduction, it is required to add new material in order to restore the original level.
- It is suggested to substituting the filter cloth every two years from the date of system start-up.

- Checking periodically that every nozzle emits an homogenous spray by forming a well-defined cone.
- Visually checking the preferential pore gas routes every three months. Whether preferential routes occur, emanations of concentrated vapor may be noted.

All technical features belonging to the biofilter are summarized in Table 7.3.

Table 7.3, Biofilter design features.

BIOFILTER FEATURES	
Type of plant	Swap body biofilter
Functioning	Air and biogas treatment with low CH_4 concentration (< 20%)
Operating Temperature	2°C to 45°C
Gas flow rate (m3/h)	100
Avg methane percentage (%)	7.4
Pressure loss (mm H2O)	10 to 50
External dimensions (m)	4,0 x 2.50 x 2.55
Internal dimensions (m)	3.7 x 2.3 x 2.25
Inside volume (m3)	20
Filter bed	1.5
Filter material	Herbal mixture made up of green compost and chopped hardwood bark
Humidification system	Planned drip irrigation system
Utilities	Well filtered water
Water consumption (m3/day)	0.07
Efficiency (%)	58
Maintenance	Filter material replacement after two years from the start of the plant. Replacement of filter sheet every two years from the start of the plant
Cost	18,690.00 €

7.1.2 Economic assessment

The economical estimate of the biofilter implementation must include both the costs of the biofilter cost and of two machines which allow the biofilter to operate.

As it was previously mentioned, the first technology refers to the collector. In this regard, it is intended as 1.5 m tube which receives four different pipes, each one from the four wells related to the biogas extraction. Furthermore, another pipe is linked to the collector which aim is to convey clean air to be mixed to the biogas flow. On the opposite side of clean air pipe, there is another pipe linking the collector with the blower.

Once the biogas flow reaches the collector, it is conveyed towards an aspirator through a depression work created by the blower itself. Finally, the gas flow is forced to move into the biofilter by entering in the bottom part.

Therefore, in order to carry out a complete cost analysis, it needs to evaluate the costs for every single item constituting the active biofiltration system. In particular, a formal requirement for a cost estimate was addressed to two different Italian companies in order to receive effective prices from both collector and blower. Actually, regarding the economic requirement for the biofilter estimate, Company C provided its economic assessment for the biogas suction unit. In this way, the economic estimate from both the biofilter and the blower refer to the same company. At this point, it was possible to add the respective prices belonging to each machine. Furthermore, in order to guarantee a proper confining of these buildings from the ground surface, a concrete platform will be realized next to the ramp access. In this way, additional costs need to be added to the overall economic assessment. With regard to all components constituting the whole plant, the respective materials and installation works were taken from the 2021 Piedmont regional pricelist.

Regarding the cost analysis a further table was created (Table 7.4) in order to evaluate the overall cost of the biofiltration active system.

Table 7.4, Biofilter implementation costs.

	BIOFILTER IMPLEMENTATION COSTS							
	CODE	DESCRIPTION	U.M.	EURO (€)	NUMBER	COST	LABOUR (%)	LABOUR (€)
TOOLS	10.A04.A10.010	HDPE pipes DN 50	m	2.42	6	325.05 €	31.07%	100.99 €
	1.P01.A42.010	HDPE ball valve, De 50	-	177.81	5	889.05 €	-	-
COLLECTOR	Market Price	HDPE Collector	-	-	1	1,675.00 €	-	-
	Market Price	Steam Trap	-	-	1	385.00 €	-	-
	Market Price	Transport	-	-	1	420.00 €	-	-
BIOFILTER COMPONENTS	Company C	Suction unit including control panel	-	-	1	33,690.00 €	-	-
	Company C	Biofilter	-	-	1	18,690.00 €	-	-
	Company C	Flow meter	-	-	1	included	-	-
	Company C	Condensate pan with pump	-	-	1	3,960.00 €	-	-
	Company C	Transport	-	-	1	1,000.00 €	-	-
PLATFORM TO SUPPORT	01.A04.B27.005	Concrete material: minimum compressive strength class C35 / 45	m^3	109.92	1	1,868.64 €	-	-
	01.A04.C30.005	Concrete: installation in foundation stuctures	m^3	20.95	1	356.15 €	31.64%	112.69 €
	01.A04.E00.005	Concrete vibrance	m^3	8.98	1	152.66 €	71.35%	108.92 €
	01.A04.F00.015	Iron: bars for reinforce concrete and installation	kg	1.60	-	2,720.00 €	55.07%	1,497.90 €
	01.A04.H30.005	Formwork in lumber	m^2	32.39	1	2,720.76 €	92.81%	2,525.14 €
TOTAL						68,852.31 €		4,345.64 €
						73,197.96 €		

To conclude with the feasibility study of the active biofiltration plant, it needs to tell that such a kind of bio-oxidative system leads to the realization of an expensive treatment plant which cost sets at around 73,000 € by excluding the maintenance costs.

However, the high economic cost does not represent the only critical issue related to the biofilter installation. With regard to its implementation, it is possible to mention several disadvantageous aspects which will be discussed in the following paragraph.

7.1.3 Challenges referred to the biofilter implementation

The economic assessment rising up from the biofilter description suggested to refuse its realization with respect to the site under investigation. Furthermore, in addition to the high installation costs, there are other critical issues to be taken into account. First of all, an active biofiltration system requires suitable facilities which can supply the electric energy to the treatment plant. In particular, the blower needs the electricity to allow the biogas conveying from the collector to the biofilter box. Currently, the area is not equipped with an electric energy plant, thus the biofilter installation would not be easy to implement. The second issue to be faced out refers to the biofilter working in terms of water supply for the irrigation system. in this regard, the filter media needs to be periodically watered to maintain a successful humidity level to allow the methane oxidation. Thus, it results to bring a water tank close to the biofilter to allow such kind of operation. The water aimed to supply the drip irrigation system can be withdrawn from both the main and the piezometer wells according to the Site availability. Focusing on the Site, piezometer wells can be used for this purpose although a further pump is required to convey the water collected towards the water tank. Referring to the irrigation system, it needs also to consider a water discharge point to allow the leakage of the leachate. In this regard, the resulting outflow is addressed to another tank close to the biofilter throughout the installation of a connecting pipe.

Therefore, further costs need to be considered when performing the overall economic assessment to allow an effective functioning of the biofiltration system.

Because of these reasons, biofilter does not appear as the best technology to be implemented to the site, subject of the thesis.

7.2 BIOWINDOWS BASED ON THE DANISH PATTERN

7.2.1 Design parameters and performance from Danish field activity

As it was previously mentioned at the beginning of Chapter 7, two different biowindows case studies were examined in order to evaluate which kind of biowindow pattern can be realized into the Site. In particular, the first field application refers to the biowindow concept that was implemented at Fakse landfill, in Denmark. The works date from 2007 to be concluded in 2010 with the ultimate monitoring activity. Landfill waste was mainly made up of soil fill (26%), household refuse (23%), and mixed waste (21%) and no LFG extraction system was installed at the Danish landfill (Scheutz *et al.*, 2011). In this scenario, in order to face out the biogas emissions coming from the waste mass, it was decided to build a biowindows system by placing it into the existing, low permeable soil cover. However, before the biowindows installation, two operations needed to be carried out. The first one dealt with the computing of the CH_4 flow passing through the surface. In this regard, the surface gas flux was determined through static flux chambers by obtaining an average value equal to 740 $\frac{\mathrm{kg\ CH_4}}{\mathrm{d}}$. Referring to the biowindow construction, instead, it followed the rules previously described in the literature paragraph, where two overlaying layers were detected. On one hand, the lower part consists in the gas distribution layer to allow the gas transport towards the upper one. On the other hand, top layer is characterized by organic matter where the actual CH_4 oxidation occurs. In this case, an untreated composted garden waste was used because of its large amount which was already present in the landfill site. The second action to be performed referred to the evaluation of the overall surface aimed to the passive biofiltration system. In this regard, column tests were accomplished on a laboratory scale by sampling the same material used for the biowindow construction. Results coming from laboratory experiences shown average and maximum oxidation capacity equal to 108 and 147 $\frac{\mathrm{g\ CH_4}}{\mathrm{m^2 d}}$, respectively. To conclude with this first design section, the maximum oxidation capacity was chosen to calculate the total area for the biowindows installation. Thus, the reference area appeared to be around 5000 m^2, because of the ratio 740 $\frac{\mathrm{kg\ CH_4}}{\mathrm{d}}$ / 0.15 $\frac{\mathrm{kg\ CH_4}}{\mathrm{m^2 d}}$.

Following the biowindows installation, the next step concerned the evaluation of the system performance. In this regard, emissions flux carried out before and after the entry into service of the system was compared for two years monitoring period. Last results highlighted a CH_4 flux reduction settled at around 28 % with the maximum oxidation efficiency equal to 41 % related to the last monitoring activity.

7.2.2 Biowindows design

Based on the studies experienced at the Danish landfill, a similar solution in terms of biowindows implementation was suggested for the site subject of the thesis. The starting point for the plant design concerns the evaluation of the maximum value related to the methane flux. In this regard, it needs to consider the gas flow which was previously computed during the data processing which refers to $0.038 \text{ Nl } CH_4/m^2h$. This number represents the maximum gas flux related to the overall monitoring period by considering only the southern area of the Site. In more detail, it was analytically computed through the application of the Young equation: Gas flux = $\alpha + \beta \left(\frac{dPatm}{dt}\right)$.

After obtaining the computed gas flux, it needs to understand the main design parameters to know the total area of the biowindows. With regard to the Danish field application, the same oxidation capacity was considered. Thus, it was thought to build a similar biowindow system characterized by the same properties belonging to the actual case study carried out in Denmark. In this regard, the filter medium results to be made up of composted garden waste which thickness sets at 1.5 m. In this way, it is possible to follow the same design path which was already described in the previous paragraph. Table 7.5 illustrates the main design features which were considered before achieving the total surface covered by the biowindows.

Thus, by evaluating the methane flux leaving out the southern area of the site expressed as $\frac{kg\ CH_4}{h}$ and by considering the oxidation capacity (evaluated according to the lab experience) the whole area was obtained which value sets at 36 m^2.

After computing the total area related to the biofiltration system, it is necessary to evaluate the biowindows size and consequently their definite number. Actually, the current site already owns six biowindows characterized by 1 m^2 surface each one. Thus, the effective area to be covered sets at 30 m^2. In order to guarantee such kind of surface, eight circular biowindows are implemented which are detected by 1 m radius.

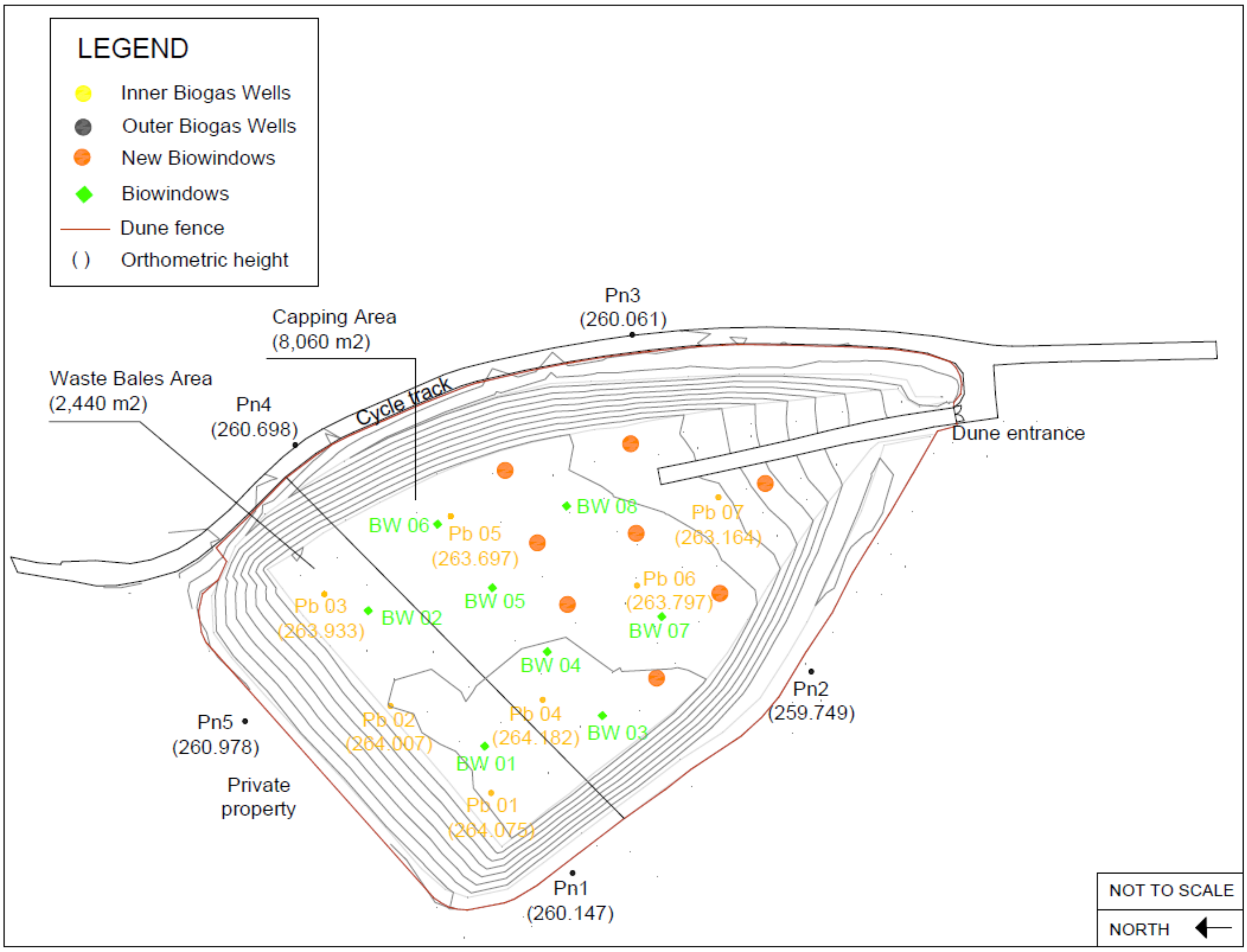
Table 7.5, Biowindows technical features: Danish Pattern.

BIOWINDOWS -DANISH PATTERN		
SITE FEATURES	Methane flux Input (Nl CH_4/m^2*h)	0.038
	Site area (m^2)	8,060
	Methane density (N kg/m^3)	0.71
	Methane flux Input (Kg CH_4/h)	0.217
	Oxidation capacity: Danish lab (Kg CH_4/m^2*h)	0.006
	Biowindows area (m^2)	36 (30)
PLANT DESIGN	Number	10
	Size (m^2)	3.14
	Filter material	Composted garden waste
	Filter bed (m)	1.5
	Draining layer (m)	0.5
	Efficiency: Danish experience (%)	41
	Methane flux Output (Nl CH_4/m^2*h)	0.022
LOMBARDIA GUIDELINES 2014	Law limit (Nl CH_4/m^2*h)	0.50

At this point, by adding the methane flux output for every biofiltration device (10 biowindows), the definite number sets at around 0.22 $\mathrm{Nl\,CH_4/m^2h}$. This value conforms with the law limit subscribed by the Lombardia Guidelines in 2014.

However, regarding the Danish experience, some differences in the biowindows realization take place. The first one consists in the circular size of the device as the Danish field work provided for a squared area. This choice does not hold a technical feature, however, the circular size with 1 m radius was preferred because it better approached the area required for the biofiltration system. Subsequently, the other two parameters to be different from the Danish work are signified by the gravel distribution layer and the filter medium, respectively. On one hand, the first variable shows a greater height (0.5 m with respect to 0.15 m) because of the Italian Legislative Decree n.121/20 which imposes to realize the distribution layer with a minimum thickness of 0.5 m. On the other hand, the filter bed presents a 1.5 m thick (greater than 1 m related to the Danish experience) to allow a better methane oxidation.

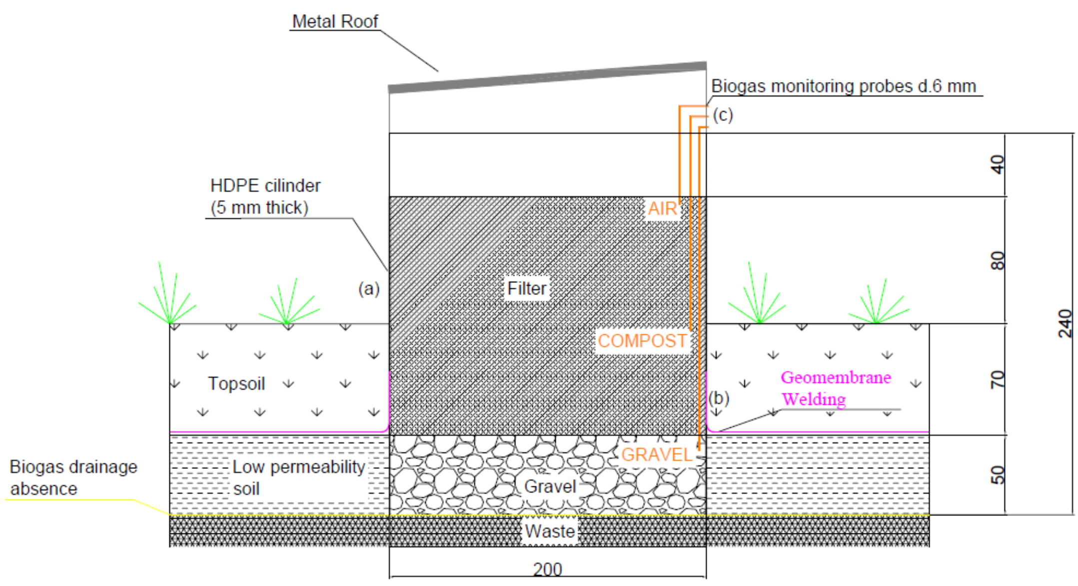
Subsequently, as it occurred for the biofilter description, it needs to evaluate a possible placement for every biofiltration device within the area under investigation. In this regard, Drawing 7.3 shows a possible solution for their placement by trying to keep them some meters apart from the current biowindows to ensure a uniform distribution.



Drawing 7.3, Placement of the Biowindows: Danish pattern.

7.2.3 Biowindows realization

Once the placement was estimated, the next step involves the effective realization of the biofiltration structure, so it means to design the different elements constituting the biowindow. A graphic representation of this device can be observed in Drawing 7.4.



CRITICAL ISSUES: Original Biowindow	IMPROVEMENTS
1. Concrete biowindow walls 2. Biogas drainage absence	1. HDPE biowindow walls (a) 2. Geomembrane welding (b) 3. Biogas monitoring probes (c)

NOT TO SCALE
UNITS : cm

Drawing 7.4, Biowindow front section: Danish pattern.

First of all, it needs to carry out an excavation section concerning the place within which the biowindow will be built. The subsoil results to be subdivided into two layers: topsoil which is 0.70 m thick and the bottom soil with low permeability which is 0.5 m thick. Regarding the soil characterization, it was decided to deepen the excavation plane until the end of soil with lower permeability. The lower part of the biowindow where the gas distribution layer takes place was inserted within the bottom layer, so it results to be 0.5 m thick. On the other hand, the overlying filter medium extends for 1.5 m height to allow a suitable methane oxidation. The overall biowindow structure sets at 2.40 m height by exceeding the ground surface of 1.2 m. The device size was established because of safety measures in order to avoid eventual falls inside.

The perimeter of the building is realized by HDPE geomembrane characterized by 5 mm thick. Furthermore, a geomembrane welding is thought to be fixed just around the building for the whole height of the topsoil to prevent potential water infiltration.
Then, a steel roof was installed in order to secure the filter medium from environmental influences. Distance between the top roof and the underlying building sets at around 0.40 m. In this way, the whole device respects the safety measures in order to avoid eventual falls inside. In particular both the HPDE geomembrane walls and geomembrane welding represent two practical improvements with respect to the current biowindows which can be found in the Site. In that figure, it is also possible to notice a biogas drainage layer which is suggested to be implemented between the waste mas and the lower permeability soil to better allow the biogas distribution. Finally, in order to monitor the methane fluxes, three different tubes are inserted in the biowindow section where the gas probes will be placed into. In this regard, they result to be located at the end of the gravel layer, in the middle of the filter media and on top of the filter medium, respectively. Finally, a metal grid will be placed just on top of the biowindow structure which the biogas probes are connected to.
While this paragraph led to understand how the biowindow should be realized, next topic will be focused on the implementation costs to deeper evaluate the feasibility study.

7.2.4 Biowindows implementation costs

In order to carry out a successful feasibility study it needs to take into account the overall costs aimed to implement a complete biowindows system. In this scenario, it is necessary to count every single cost belonging to each stage related to the realization procedure. In this regard, all the operations to be performed can be listed in the following lines:

1. <u>Excavation phase</u>: the excavator activity leads to remove the portion of land aimed to the biowindow installation by realizing a squared section of 2 x 2 m size. The ground removed consists in 1.2 m thick which is made up of both topsoil and soil with lower permeability.
2. <u>Laying of the soil with low permeability</u>: this element could own some waste traces because of its placement just close to the waste mass. In this way, it needs to place this part of land over an impermeable HDPE cloth in order to sweep potential waste traces.
3. <u>Supply and installation of the HDPE well</u>: such a kind of operation will be carried out by an external company which was charged to estimate the cost of the device.

4. Filling the biowindow throughout the gravel and compost arrangement: two skilled workers are needed because of the environmental characteristics where they are forced to work. In this regard, Legislative Decree n. 81/2008 obliges such a kind of workers to be equipped with suitable safety measures in order to face out potential issues related to the gas flammable leakage. In addition to this criticality, the working place is intended as a confined environment where the respective activities result to be harder to be carried out. Once the gravel layer was arranged, the first steel tube will be placed as well as the other two tubes in the middle and at the top of filter medium, respectively.
5. Filling of the empty spaces around the HDPE well: as the biowindow owns a circular size, there are four empty spaces just around it because of the squared original excavation. In this regard, soil with lower permeability will be put into these four spaces in order to seal the whole structure. This kind of work can be performed by one ordinary worker.
6. Placement of the steel roof: the last operation consists in installing the steel roof which will be placed by one ordinary worker. The last object to be realized concerns the metal plate where the biogas probes have to be jointed. It is inserted among the top of the biowindow and the roof.

After this summary related to the main work activities, it is possible to realize a detailed scheme of the implementation costs. With regard to the previous operations, Table 7.6 shows the overall cost related to a single biowindow which will be multiplied by the total number of the devices.
In this regard, the cost required for an individual biowindow sets at around 4,800 €. Thus, the overall cost for such a kind of biofiltration system will be equal to approximately 48,000 € by excluding the maintenance costs.

Table 7.6, Biowindow implementation costs: Danish pattern.

IIMPLEMENTATION COSTS FOR AN INDIVIDUAL BIOWINDOW							
CODE	ACTIVITY	DESCRIPTION	U.M.	EURO	COST (€)	LABOUR (%)	LABOUR (€)
25.P03.A50.010	Excavator-soil removing	Escavator with capcaity 800 L (3.5 h)	h	37.09	129.82 €		
01.P01.A10.005	Excavator driver	Skilled worker (3.5 h)	h	36.91	129.19 €		
01.P01.A30.005	Geotextile removing	Ordinary worker (0.5 h)	h	30.71	15.36 €		
10.A01.A10.010	Placement of the soil with low permeability	Geomembrane thick 2 mm-supply and laying- (4 m²)	m²	9.44	37.76 €	18.83%	7.11 €
Market Price	Supply and installation	HDPE well (Φ = 2000 mm) - 2.40 m	m	1436	3,446.40 €		
01.P03.A90.005	-	Gravel	m³	17.01	26.71 €		
01.P01.A10.005	Gravel placement	Skilled worker (1 h) x2	h	36.91	73.82 €		
Market Price	-	Compost	t	10.00	18.84 €		
01.P01.A10.005	Compost placement	Skilled worker (1 h) x2	h	36.91	73.82 €		
01.P01.A30.005	Sealing the empty space around the cylinder	Ordinary worker (0.5 h)	h	30.71	15.36 €		
11.P01.A30.005	Probe-gravel (1.90 m)	Steel pipe DN 20	m	3.85	7.32 €		
11.P01.A30.005	Probe-compost (1.15 m)	Steel pipe DN 20	m	3.85	4.43 €		
11.P01.A30.005	Probe-air (0.40 m)	Steel pipe DN 20	m	3.85	1.54 €		
25.P05.B35.005	Wired roof	Steel sheet tihck 7,5-50/10	kg	1.16	69.60 €		
01.P01.A10.005	Wired roof realization	Skilled worker	h				700.00 €
25.P05.B35.005	Wired plate-3 holes to be built	Steel sheet tihck 7,5-50/10	kg	1.16	0.22 €		
01.P01.A10.005	Wired plate realization	Skilled worker	h				80.00 €
TOTAL					4,050.16 €		787.11 €
					4,837.27 €		

Prices intended in the cost computing refer to the 2021 Piedmont regional pricelist once again. The cost for the compost supply, on the other hand, refers to the market price proposed by the Italian Composting Association. Although the best efficiencies belonging to the biofilter implementation, biowindows represent best solution from an economical point of view.

7.2.5 Critical issues about the Danish biowindows implementation

The economic assessment of the first kind of biowindow highlighted lower costs with respect to the active biofiltration system. Thus, this favourable condition would suggest realizing the biowindows based on the Danish pattern. However, two criticalities can be detected when facing out the implementation of this kind of system. Both the technical problems were mentioned in the paragraph 7.2.3 when the biowindow realization was described and two possible suggestions were shown. On one hand, the first criticality deals with the lack of the biogas drainage layer between the waste mass and the soli with low permeability. Focusing on this situation, the biogas flow cannot be conveyed towards the biowindows present in the ground surface and it resulted to be dispersed in the subsoil. Such a kind of negative scenario also refers to the site subject of the thesis where no data were detected about the existing 1 m^2 biowindows performances. In this case, in fact, 1 m^2 surface did not allow a proper biogas flow through the filter media.

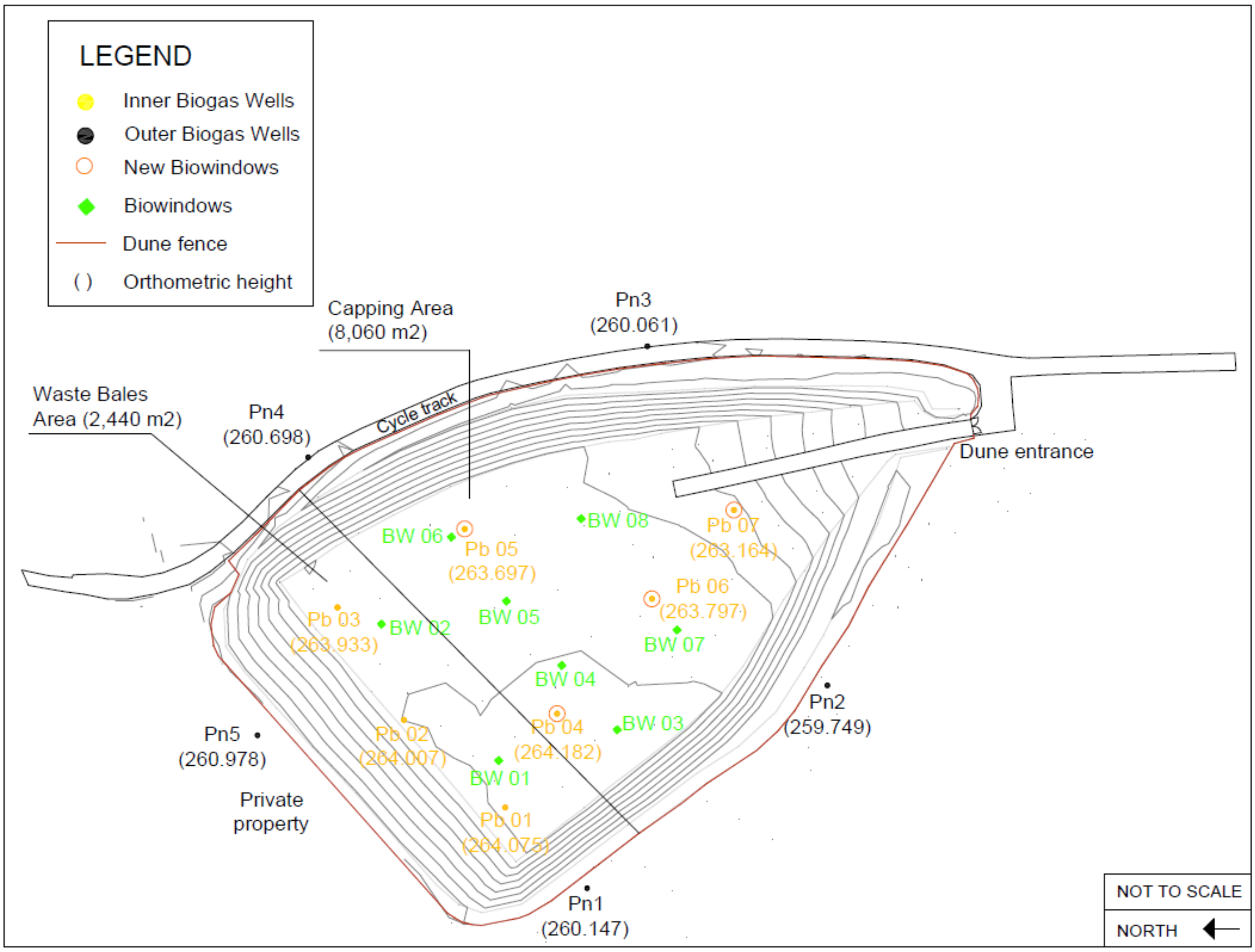
Furthermore, in addition to this disadvantageous condition, the second issue refers to the kind of material used for the biowindows realization. With respect to the Danish device, perimetral walls were built in concrete as well as the biowindows located in the Site. In this case, water can represent serious threats for the system functioning because it can infiltrate in the subsoil, and it can reach the bottom of the biowindow. The lack of data concerning the devices efficiencies related to the Site was also attributed to the water presence inside the biowindow. Because of this reason, it was suggested to realized HDPE walls in case of a possible implementation regarding this kind of biowinodws.

7.3 BIOWINDOWS BASED ON THE ITALIAN PATTERN

7.3.1 Design parameters and performance from Italian field activity

The second field activity to be analysed focussed on the passive biofiltration system which was implemented in Tuscany between 2016 and 2018. The realization of the biowindows and the subsequent monitoring activity were carried out on behalf of the "Project Life RE Mida" promoted by the European Union. The work dealt with the biogas emissions coming from an old landfill of municipal solid waste located at Le Fornaci di Monticiano, close to Siena. The preliminary analysis concerned the assessment of the landfill gas emissions by using the static flux chambers. In 2016, landfill gas emissions were estimated at around 0.66 $\mathrm{Nl\,CH_4/m^2h}$ (Pecorini, Rossi and Iannelli, 2020). Following this operation, passive control systems were realized throughout the installation of seven wells. In particular, they were built next to areas characterized by higher methane emissions which were named "hot-spots". At this point, existing clay soil cover was then removed and the passive biowindows were realized just around the wells. Each one of the seven devices has got a square size of 2 x 2 m and it is made up of three components: a gravel draining layer to allow a homogenous distribution of the gas emission, a filter medium which consists in a mixture of compost and sand and then a geogrid separating the two layers. Distribution and oxidizing layers present 0.20 m and 1.20 m thickness, respectively. In this case, in addition to the compost, sand was added as structuring material in order to avoid an excessive compaction of the filter medium. Furthermore, such a kind of mixture leads to own a sufficient porosity to allow the gas transport. As a result of this composition, the best ratio compost/sand sets at 4:1 in order to guarantee a proper biological oxidation. An external metal formwork enclosed the whole structure, while clay levees are placed just around the building to limit water surface infiltration. Once the biowindows installation ended at the end of 2016, two-years monitoring activity was performed in order to evaluate the methane oxidation efficiency. In this regard, the biofiltration system shown high performance characterized by an average value equal to 88% which values range from 65 to 100 %. Because of the high values in terms of oxidation efficiencies, it was decided to implement a similar model with respect to the Site.

By evaluating the Italian pattern, the plant design focuses only on the biowindows size. In this case, in fact, the number of the biowindows to be realized corresponds to the wells number which are currently located within the Site. As every single biowindow is installed just around each well, their placement refers to the well location as it is shown in Drawing 7.5 .



Drawing 7.5, Placement of the biowindows: Italian pattern

7.3.2 Biowindows design

After illustrating where the biowindows take place into the Site, it needs to evaluate the size referred to the biofiltration devices. Methane flows vary from one well to each other as well as the gas flow passing through the four biowindows. In this regard, the methane flux needs to be calculated for each location. The methane values lead to the monitoring activity carried out by Enviars S.r.l from November 2018 to October 2021. As the original emission values referred to the overall area of the Site, it was necessary to focus only on the southern part of the site where the four wells take place. Thus, the land surface under investigation sets at approximately 8,000 m^2 and the respective methane flow values are represented in Table 7.7.

Table 7.7, Methane flux values (South area of the Site).

Gas flux (Nl CH_4 / m^2*h)				
Date	Pb 04	Pb 05	Pb 06	Pb 07
21/11/2018	0.007	0.002	0.002	0.010
23/01/2019	0.006	0.008	0.007	0.004
23/02/2019	0.000	0.004	0.000	0.000
25/03/2019	0.010	0.007	0.003	0.005
22/04/2019	0.006	0.006	0.000	0.004
29/05/2019	0.004	0.004	0.002	0.003
26/06/2019	0.000	0.002	0.005	0.004
30/07/2019	0.000	0.001	0.004	0.005
03/09/2019	0.000	0.000	0.001	0.004
03/10/2019	0.000	0.003	0.004	0.003
04/11/2019	0.005	0.006	0.007	0.004
09/01/2020	0.004	0.008	0.005	0.004
17/03/2020	0.000	0.003	0.001	0.003
19/05/2020	0.006	0.004	0.002	0.005
20/07/2020	0.000	0.004	0.005	0.005
23/09/2020	0.008	0.009	0.005	0.005
24/11/2020	0.005	0.001	0.006	0.005
26/01/2021	0.000	0.001	0.000	0.001
07/04/2021	0.000	0.000	0.000	0.004
14/10/2021	0.000	0.000	0.000	0.003
Max value	0.010	0.009	0.007	0.010

Finally, the maximum value was considered as the methane flux input related to each biowindow.

Moreover, in order to consider the change of CH_4 load entering each device and to avoid eventual overloads related to the treatment unit, some safety measures need to be taken into account. In this regard, Guidelines from "Project Life Re Mida" suggest enhancing the size of the section by 0.5 m each side (Life RE Mida,2018). Thus, the biowindow will be implemented by considering a circular size with the respective diameter of 2.2 m. In this regard, it is worth to remember that the well section was realized by a diameter of 1.2 m with the well radius equal to 0.10 m. With regard to these remarks, in Table 7.8 it is possible to notice how the actual area aimed to the bio-oxidation activity corresponds to a circular area with 1 m radius just around the well tube.

On the other hand, referring to the overall size of the biowindow, both the gravel layer and the filter medium was realized slightly greater than the Italian model. The same decision tree was observed with respect to the Danish pattern. Thus, the gravel distribution layer is 0.5 m thick as foreseen by the Italian Legislative Decree n. 121/20. In this way the gas distribution layer coincides with the soil with low permeability too. Finally, the filter medium results to be 1.5 m thick to allow a better oxidation efficiency.

Table 7.8, Biowindows technical features: Italian pattern.

BIOWINDOW-ITALIAN PATTERN					
WELL		**Pb04**	**Pb05**	**Pb06**	**Pb07**
SITE FEATURES	Methane flux Input (Nl CH_4/m^2*h)	0.010	0.009	0.007	0.010
PLANT DESIGN	Number (circular size)	1	1	1	1
	Diameter Φ (m)	2.2	2.2	2.2	2.2
	Biowindows area (m^2)	3.14	3.14	3.14	3.14
	Filter material	Compost / Organic fraction of MSW and sand (80:20,vol%)			
	Filter bed (m)	1.5	1.5	1.5	1.5
	Filter media (m^3)	4.71	4.71	4.71	4.71
	Draining layer (m)	0.5	0.5	0.5	0.5
	Efficiency: Italian experience (%)	88	88	88	88
	Methane flux output (Nl CH_4/m^2*h)	0.001	0.001	0.001	0.001
LOMBARDIA GUIDELINES 2014	Law limit (Nl CH_4/m^2*h)	0.50			

Furthermore, by looking at the previous table, the efficiency values are illustrated as well as the law limit foreseen by the Lombardia Guidelines. In this regard, by adding the four output flows from every well, the definite number respects the law limits. The output results are obtained by applying the same efficiency values belonging to the Italian biowindows. However, to evaluate the actual field performances, the biowindow construction must be followed by a proper monitoring activity. Monitoring campaign, usually, lasts for several years depending on the site characteristics and the amount of gas emissions. In particular, the monitoring activity as well as the maintenance operations will be deeply discussed in paragraph 7.3.7.
Next paragraph will be focused on the biowindows realization based on the Italian pattern.

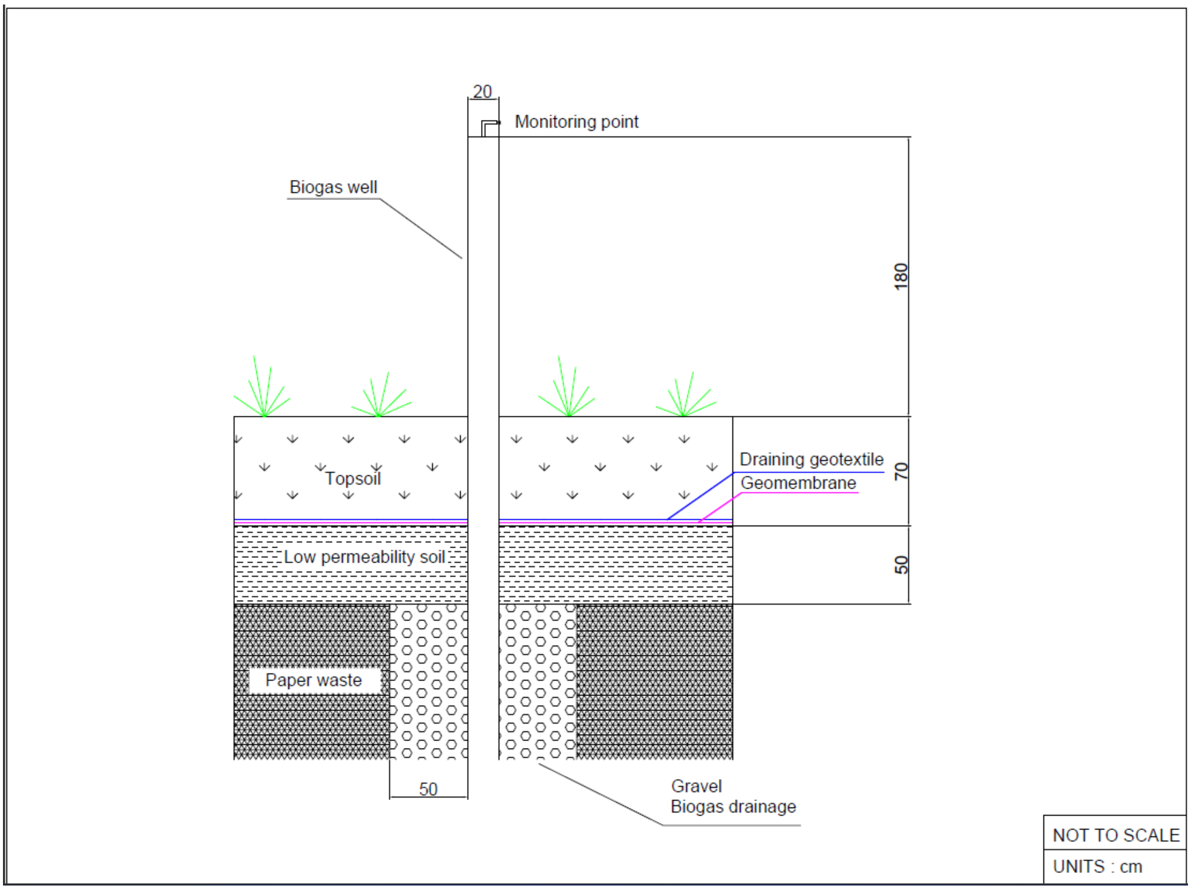
7.3.3 Preliminary tests before the completion

Once the Italian pattern was identified as one of the suitable technologies which purpose is the realization of the biowindows, it needs to carry out preliminary analysis in order to verify the goodness of this choice. The first question to consider refers to the eventual surface gas emissions coming from other sources located inside the Site. The best tool to perform such kind of activity is represented by the static flux chambers. In this regard, it is necessary to place four static flux chambers close to each well to verify if these points signify hot-spot areas where the methane flows are higher. Then, the same number of these device can be arranged some meters apart from the hot-spot areas in order to check other gas emissions sources. Regarding the Site, most of the area is characterized by a lush green vegetation which suggests the lack in the great amount of methane released from the ground surface. However, it is possible to notice the absence in vegetation next to the wells where the biogas flow is evaluated. It means that possible gas emissions can be detected in the areas close the wells. Because of this scenario, it was supposed that most of the gas emissions are linked to the well's presence, thus it can be right to consider the biofiltration devices matching with the hot-spot areas. On the other hand, before realizing the biowindows, it needs to perform another activity. In particular, it deals with the evaluation of the oxidation capacity belonging to the filter medium. With regard to this task, laboratory tests should be carried out by using the same filter medium which will be place into the biowindow. The operation consists in conveying an input gas flux equal to the methane emission monitored *in situ* and then observing the resulting outflow gas. It can be used, for example a 1 m^3 mixture of compost and sand which the gas flow will pass through. Furthermore, the methane load can be varied in order to analyse the variable response of the microorganism in terms of CH_4 oxidation capacity.

In this way, it is possible to verify which CH_4 loads match with the greater oxidation performances by ranging the input gas concentration. Finally, the aim of this work is to collect a certain amount of data in order to understand the effective methane reduction which corresponds to the actual filter medium to be used in the biowindows implementation.

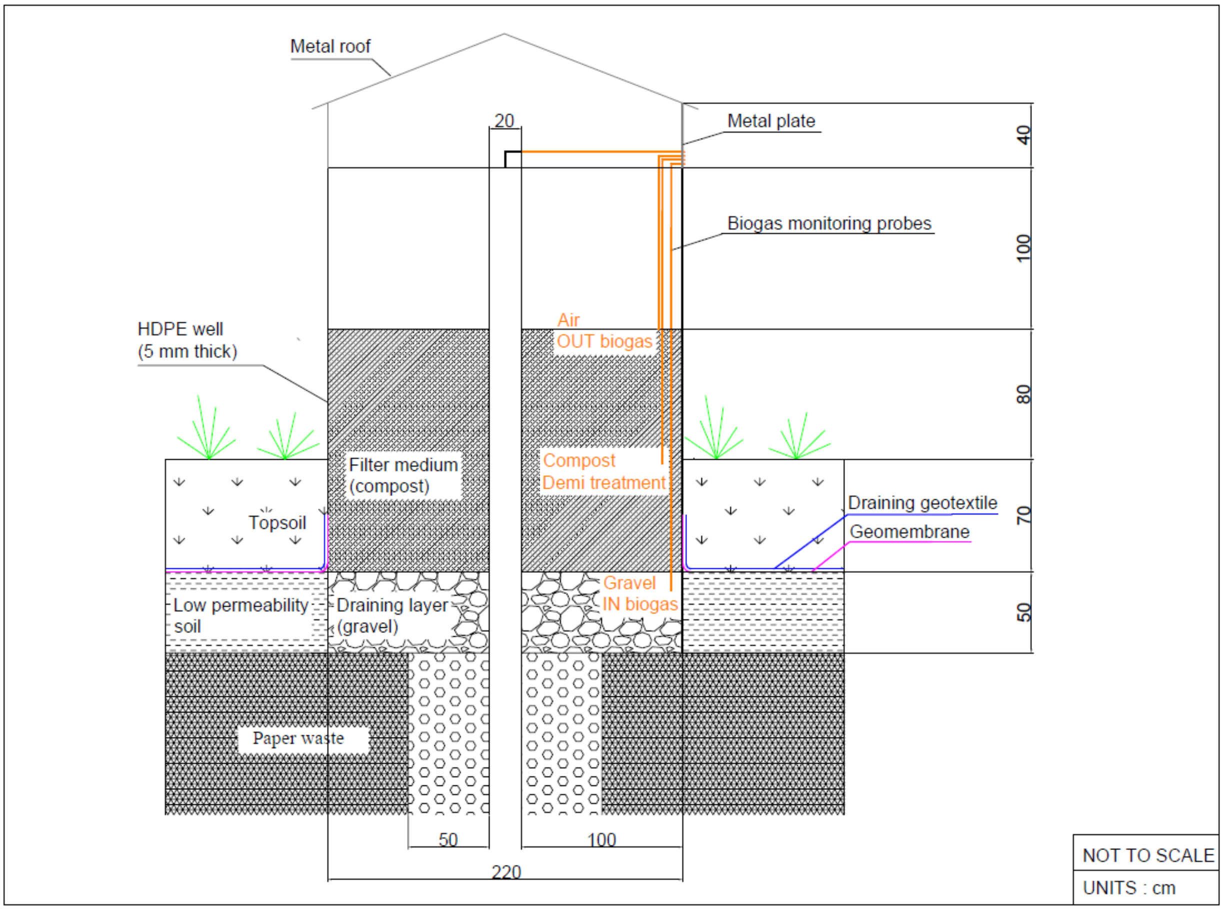
7.3.4 Biowindows realization

Once the design parameters were described and the preliminary test were carried out, it needs to understand how the biowindow results to be realized by highlighting the main components which constitute it. First, it can be useful to remember how the original well takes place. Its graphic representation is illustrated in Drawing 7.6.



Drawing 7.6, Current well configuration.

After representing the current well configuration, the next step leads to show how the biowindow is implemented just around the well. In this regard, all the structural elements can be observed in Drawing 7.7.



Drawing 7.7, Biowindow implementation: Italian pattern.

Before achieving the complete biowindow installation, several activities must to be pursued. The first operation to be carried out refers to the removal of both the soil with lower permeability and the topsoil. Then, the biowindow section is figured out by a circular shape by enlarging the well bucket radius of 0.5 m, as it was previously mentioned.

The whole structure consists in a 5 mm HDPE tube; thus, it signifies that it was used the same element already used for the “Danish” biowindow implementation. Furthermore, in addition to the original geomembrane and the waterproof geotextile placed between the two subsoils layers, these kinds of confining cloths are also arranged along the tube walls. In this way, it was possible to create a successful isolation of the structure with respect to the water infiltration. However, such a kind of device differs from the previous one because of the whole height of the structure. In this case, in fact, a 3 m height was considered in order to cover the whole height of the well. In this regard, the HDPE tube appears to be subdivided in the following way. From the bottom section, the gas distribution layer develops for 0.5 m which is made up of coarse gravel particles. The respective grain size sets at around 15-30 mm.

Over this layer, the filter medium takes place detected by a thickness of 1.5 m. In this case, the methane oxidation layer is formed by compost and sand identified by a ratio 4:1. Therefore, the resulting ratio compost/sand appears to be 80:20 % vol. The nature of the compost used is attributable to the organic matter coming from the municipal solid waste. Finally, the upper part of the biowindow is characterized by an empty space until the top of the well which is about 1.0 m height inside the well. On the other hand, the HDPE well holds a 1.8 m height from the ground level, outside the well. As it occurred for the previous building, the whole structure is topped by a steel roof which preserves the underlying filter medium by the external meteorological agents.
Finally, during the installation of the material within the biowindow, three different probes need to be inserted to allow the methane flow and concentration monitoring. In this way, the monitoring activity will be focused on four total probes as it needs to consider also the original probe used for the evaluation of the biogas flow leaving out the well itself. All these probes will be connected to a metal plate inserted on top of the biowindow structure.

7.3.5 Biowindows implementation costs

The last part of feasibility study concerns the assessment of the overall costs related to the passive biofiltration system. The costs computing rises from both the material required and the labour carried out by the specialized workers. In particular, the same execution procedure has to be performed with respect to the first biowindows implementation. With regard to the working activities, next lines summarizes the main operations to be carried out:

1. Excavation phase: the excavator activity leads to remove the portion of land aimed to the biowindow installation by realizing a squared section of 2 x 2 m size. In this case, in contrast with the Danish biowindow installation, the excavator work appears to be harder. In fact, the excavation phase has to consider the presence of the existing well which signifies a warning element to deal with. The ground to be removed holds an overall thickness of 1.2 m which is made up of both topsoil and soil with lower permeability. For this reason, this kind of operation will last for a longer time than the previous biowindows installation. It can be reasonable to think that the "Italian" pattern will require twice the time than "Danish" concept.
2. Laying of the soil with low permeability: this element could own some waste traces because of its placement just close to the waste mass. In this way, it needs to place this part of land over an impermeable HDPE cloth in order to sweep potential waste traces.

3. Supply and installation of the HDPE well: an external company is commissioned to supply and to install the HDPE well. The only difference, in terms of realization costs is signified by the greater length of the HDPE tube as the previous device owned a 2.4 m length.
4. Filling the biowindow throughout the gravel and compost arrangement: two qualified workers are needed to pursue this kind of activity. The presence of the second worker has to be ensured because of the Legislative Decree n. 117/2011 which shows technical updates with respect to the previous Ministerial Decree n.81/2008. In this regard, before the entrance of the specialized worker into the HDPE device, it is necessary to guarantee a gas-free area where no dangerous situations take place. The biogas well must to be closed before the working activity begins. In addition to this criticality, the skilled man which serves into the confined place (pipe depth equal to 3 m) has to be assisted by another worker just outside the respective structure. In this case, the man operating at the bottom of the device must to be equipped with safety belt with rope in such a way to be supported by his fellow.
5. Filling of the empty spaces around the HDPE well: as the biowindow owns a circular size, there are four empty spaces just around it because of the squared original excavation. In this regard, soil with lower permeability will be put into these four spaces in order to seal the whole structure. This kind of work can be performed by one ordinary worker.
6. Placement of the steel roof: the last operation consists in installing the steel roof on top of the biowindow. This operation can be pursued by an ordinary worker. The last object to be realized concerns the metal plate where the biogas probes have to be jointed. It is inserted among the top of the biowindow and the roof.

As it occurred for the previous cost analysis, all the prices submitted are provided by the 2021 Piedmont regional price-list except for the HDPE tube because of its diameter characteristics which are not included in the price-list.

In this case, the price of the two biofiltration devices to be implemented (Danish and Italian biowindows) refers to an Italian company which deals with this work field. Finally, Table 7.9 lists every material used as well as the labour necessary for the definite realization. The whole construction phase is intended to be spread over one working day for each biowindow installation. Therefore the overall cost will be multiplied by the total devices number.

Table 7.9, Biowindow implementation costs: Italian pattern.

IMPLEMENTATION COSTS FOR AN INDIVIDUAL BIOWINDOW							
CODE	ACTIVITY	DESCRIPTION	U.M.	EURO	COST (€)	LABOUR (%)	LABOUR (€)
25.P03.A50.010	Excavator-soil removing	Escavator with capcaity 800 L (3.5 h)	h	37.09	129.82 €		
01.P01.A10.005	Excavator driver	Skilled worker (3.5 h)	h	36.91	129.19 €		
01.P01.A30.005	Geotextile removing	Ordinary worker (0.5 h)	h	30.71	15.36 €		
10.A01.A10.010	Placement of the soil with low permeability	Geomembrane thick 2 mm- supply and laying- (4 m²)	m²	9.44	37.76 €	18.83%	7.11 €
Market Price	Supply and installation	HDPE well (Φ=2200 mm)	m	1820	5,460.00 €		
01.P03.A90.005	Purchase	Gravel just sieved	m³	17.01	26.71 €		
01.P01.A10.005	Gravel placement	Skilled worker (1 h) x2	h	36.91	73.82 €		
Market Price	Purchase	Compost	t	10.00	18.84 €		
01.P01.A10.005	Compost placement	Skilled worker (1 h) x2	h	36.91	73.82 €		
01.P03.A24.005	Purchase	Sand (aggregate for)	q	1.95	34.44 €		
01.P01.A30.005	Sealing the empty space around the cylinder	Ordinary worker (0.5 h)	h	30.71	15.36 €		
11.P01.A30.005	Probe-gravel (2.5 m)	Steel pipe DN 20	m	3.85	9.63 €		
11.P01.A30.005	Probe-compost (1.75 m)	Steel pipe DN 20	m	3.85	6.74 €		
11.P01.A30.005	Probe-air (1.0 m)	Steel pipe DN 20	m	3.85	3.85 €		
25.P05.B35.005	Wired roof	Steel sheet tihck 7,5-50/10	kg	1.16	69.60 €		
01.P01.A10.005	Wired roof realization	Skilled worker	h				700.00 €
25.P05.C85.010	Wired plate-4 holes to be built	Steel sheet tihck 7,5-50/10	kg	1.16	0.22 €		
01.P01.A10.005	Wired plate realization	Skilled metal worker	h				80.00 €
TOTAL					6,105.13 €		787.11 €
					6,892.24 €		

The definite cost for an individual biowindow sets at around 6,900 € by considering also the labour required. Thus, the overall cost for this biofiltration system results to be equal to 27,600 €.

7.3.6 Timing of implementation

The assessment of the overall costs for the biowindows realization also deals with the time required for the whole completion. Each stage of the implementation procedure needs different time windows before completing the work. By considering both the Danish and the Italian pattern, the same timing will be taken into account although the second design faces out half of the biowindows to be realized. This is due to the criticalities in the device installation as it was mentioned in the previous paragraph. By analysing the different operations, the first stage refers to the excavation procedure. In particular, it is supposed to employ four working days in order to realize the excavation section, this procedure concerns the removal of both the topsoil and the soil with low permeability which will be temporary placed over a HDPE cloth .On one hand, the topsoil will be redistributed all over the site surface, on the other hand, the soil with low permeability will result to be stored in the empty spaces between the circular biowindow and the squared excavation section. After carrying out this first phase, it needs to install all the biofiltration devices. In this case, one working day is estimated by regarding also the material backfill through the soil with low permeability.

At this point, two workers are equipped to fill the biowindow with both the gravel and compost. Such a kind of operation requires at least a half a day's work as it needs to install also the rigid tubes where the biogas probes will be inserted into. In this regard, further time will be employed for the metal plate implementation on top of the biowindow walls. Finally, the whole working activity ends with the steel roof installation. One ordinary worker is responsible for the this operation which should last for one day concerning all the wells.

After summarizing the implementation times, it can be easy to understand that the overall timing required for this kind of operations sets at around one working week. In the previous Table 7.7, the reference times are expressed in hours and they help to estimate the overall cost for each working activity.

7.3.7 Maintenance operations and respective costs

Once the realization of the biowindows system was completed, next operation consists in carrying out periodical maintenance operations. This kind of activity focuses on both the biogas flux monitoring and the filter media maintenance. According to the Italian Guidelines proposed by the "Project Life Re Mida" (Life RE Mida, 2018) two different checking activities can be identified: they refer to ordinary maintenance and extra-ordinary maintenance. In particular, it is possible to implement such kind of activities to both the active and passive biofiltration systems, the key-points belonging to each category are here listed.

Ordinary maintenance can be addressed as :

- Returning the thickness of the filtering media to its proper level if lowering occurs because of the compaction of the material;
- Verifying that the layer of drainage gravel does not appear packed and it allows the run off of rainwater in case of a passive biofiltration system and the removal of water for wetting in the case of active biofilters;
- Moving the surface filtering layer whether surface crusts have formed after dry periods, first of all for passive systems;
- Removing eventual weeds that might grow on the filtering bed;
- Verifying no cracks take place in the soil around the biowindow structure. If they occur, it needs to restore by soil cultivation.

On the other hand, extra-ordinary maintenance can be summarized in such a way:

- Reconditioning the filter medium, it means to carry out the homogenization of the material throughout the turning of the filter medium. This operation should be accomplished in case of excessive compaction in certain areas of the filtering matrix that determine the preferential path for the migration of gases.
- Replacing the filtering medium if one of the following issues rise:
  - An excessive fall in the biofilter performance
  - High settling of the material which can cause the porosity reduction leading to the excessive blockage of the filter material.

After listing the main operations related to maintenance activities, it needs to establish the monitoring frequency to be performed as a result of the biowindow implementation.

In particular, with regard to the Site, it is supposed to pursue a five-years monitoring in order to check the biowindow performances.

The mode of the monitoring frequency is carried out in a different way during the respective monitoring period. Every year is characterized by ordinary maintenance operations, while the extra-ordinary activities will be carried out only once during the reference period. In particular, first year is characterized by a monthly maintenance which leads to both the biogas flux monitoring and the filter medium maintenance based on the activities which were previously mentioned. After that, second and third year are signified by a bimonthly frequency in the monitoring task where the same operations with respect to the first year will take place. Subsequently, ordinary maintenance activities will occur during the fourth and fifth year after the biowindow realization. In this case, monitoring operation results to be characterized by a quarterly frequency. At the end of this stage, a five-year report will be drawn up in order to submit all the activities belonging to the maintenance procedure with their respective critical issues. Furthermore, in addition to the ordinary operations it is necessary to pursue an extra-ordinary maintenance which is mainly identified by the reconditioning and the replacing of the filter medium. Before starting with this work, the biowindow roof should be removed in order to better realize all the maintenance operations.

This kind of activities need to be pursued by a specialized team made up of qualified people which are able to work in confined environments. In this regard, one worker comes into the biowindow to recondition/replace the filter medium, while two other workers help him from the top of the ground level. With regard to the filter medium replacement, it deals with disposal of the "old" compost by supplying the biofiltration device with the new compost which is skilful to perform its function.

In this regard, an estimate was made about the overall costs to be sustained for the maintenance operations. The ultimate sum sets at around 60,000 € as it takes into account both the material used for the improvement of the biowindow performance and the people needed to fulfil all the work requirements. The list of the monitoring activities as well as the respective costs are shown in Table 7.10.

Table 7.10, Biowindow maintenance costs: Italian Pattern.

PLANT MAINTENANCE COSTS				
5-YEAR MONITORING		ACTIVITY	FREQUENCY	COST (ESTIMATE)
ORDINARY MAINTENANCE	1 st year	Filter medium maintenance Methane flow monitoring	Monthly	15,000.00 €
	2 nd year	Methane flow monitoring	Bimonthly	6,000.00 €
		Filter medium maintenance	Bimonthly	4,000.00 €
	3 rd year	Methane flow monitoring	Bimonthly	6,000.00 €
		Filter medium maintenance	Bimonthly	4,000.00 €
	4 th year	Methane flow monitoring	Quarterly	8,000.00 €
		Filter medium maintenance	Quarterly	
	5 th year	Methane flow monitoring	Quarterly	8,000.00 €
		Filter medium maintenance	Quarterly	
EXTRA-ORDINARY MAINTENANCE	Once in 5 years	Recondition of the filter medium	Once	2,500.00 €
	Once in 5 years	Replacement of the filter medium	Once	8,000.00 €
TOTAL				61,500.00 €

8. CONCLUSIONS

The study of the thesis focused on the analysis of the biogas emissions leaving out a permanent safety site located in Piedmont. In the first part, the analysis dealt with the main elements affecting the biogas production which can be basically subdivided in the inner characteristics of the site and external parameters such as the meteorological events. In this regard, the result coming from the data processing shown a clear correlation between the biogas emissions and the atmospheric pressure variation. Thus, the highest emissions values rise from a drop in the barometric pressure because of the easiness of gas to go out from the ground surface. Furthermore, in addition to the technical remarks belonging to the data processing, the bibliographic search confirmed the outcomes previously achieved by making the whole work more consistent from a scientific point of view. In this regard, the bibliographic search highlighted an analytical formula studied by A. Young in 1990 which relates the landfill gas flux with the variation in the barometric pressure. The equation is written below in order to take into account its main components:

Gas flux = $\alpha + \beta \left(\frac{dPatm}{dt}\right)$

From the Young work, it appeared how the magnitude of the gas flux value is proportional to the rate at which surface pressure is changing. Clear correlations between these two physical quantities were found during the data processing as it was previously mentioned.

In the second part, on the other hand, the subject of the thesis referred to the description of the biogas treatments. In particular, this topic was aimed to the realization of a feasible treatment plant in order reduce the methane concentration inside the biogas flow. With regard to the biogas emissions treatments, the Legislative Decree n. 121/20 allowed to use the biofiltration technique because of the low value in the methane flux. Thus, different bio-oxidative methods were compared before choosing the best technology to be applied for the emissions treatment. From a bibliographic search, the most widely known biofiltration techniques refer to four different categories: biotarp, biocovers, biowindows and biofilters. After describing the most significant aspects and by listing the advantageous and disadvantageous items belonging to each of them, the best applicable technologies to the Site resulted to be the biofilter and the biowindows.

Therefore, the last part of the thesis faced out three different feasibility studies concerning the respective biofiltration systems. In particular, the study of the biowindows system was subdivided into two field applications because two different case studies were examined. From the bibliographic search, the Danish and the Italian patterns were deeply investigated because they owned the greatest amount of data which were considered useful in order to implement a treatment plant.

The feasibility study realized for each one of the three methods highlighted how the biofilter represents the most expensive solution in terms of the whole plant realization for the methane flow reduction. In fact, as it refers to an active biofiltration system, it needs to consider other tools to successfully design the ultimate treatment plant.

Furthermore, as it was mentioned in paragraph 7.1.3 the site under investigation is not equipped with a power line which signifies the great challenge for such a kind of technology.

Therefore, because of the site features, biowindows represent the best solution to be implemented, also because of the lower realization costs.

After evaluating both the case studies, the Italian pattern was identified as the most feasible technique in order to achieve the highest plant performances. In fact, by filling the "new" biowindows with same material used in the Tuscany implementation work, methane oxidation capacity settled at 88 %. However, as it was described in the previous paragraphs, some preliminary tests have to be carried out in order to verify the effective goodness of the filter media. In this way, it is possible to compare the system performances from the Italian field application with the filter layer which was designed for the Site.

To conclude with the thesis results achieved, the plant design was aimed to reduce the methane flow leaving out the waste mass. Actually, the methane flux does not represent a critical issue with respect to the surrounding environment because of the low methane concentrations as its maximum value sets at $0.038\ \mathrm{Nl\ CH_4/m^2h}$. However, it was decided to implement a treatment plant in order to further reduce the gas emissions into the atmosphere.

In this regard, since the same Italian pattern was pursued and because of its high performances related to the biowindows application, it is expected to achieve about the same CH_4 oxidation efficiencies by contributing to decrease the environmental impacts to the surrounding environment.

Finally, the purpose of the work was to compare several environment-friendly technologies in order to achieve the highest performance in terms of methane flow reduction. Thus, with regard to the plant design similar to the Italian concept, it was preferred because it managed to combine both environmental requirements and the sustainable realization costs.

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