CHAPTER

4

LANDFILL GAS AND LEACHATE MANAGEMENT FOR REHABILITATED SITES

4.1. Introduction

Waste often contains organic matter whose molecules are decomposed by specialized bacteria once disposed in landfill. This decomposition process releases a gaseous mixture called **biogas** or landfill gas (LFG) and a liquid, rich in pollutants, mainly deriving from the leaching of waste by water meteoric infiltration.

Landfill gas is generated by the chemical and biological degradation of organic material present in the waste itself. The specific composition of landfill gas changes continuously and depends on many factors among them:

- waste composition;
- environmental conditions of the waste;
- time and conditions in which waste is stored.

Obviously, different kind of waste (organic, plastic, inert, etc.) will greatly influence the type of landfill gas produced. A huge presence of organic matter will result in high productivity, while the content of inert material or inhibitory chemicals will severely limit it. The **size** of the material plays an important role; If a reduced size increases the bio-reactive surface of the materials- with consequent better conditions of landfill gas productivity- in the opposite situation, it also leads to a greater compaction of waste, a reduction of the void ratio and to an increase in the density of the mass, resulting in a reduced possibility of spreading moisture, bacteria and the transmissibility of landfill gas itself. Size is strongly influenced by any pre-treatments that the waste undergoes before being disposed; shredding activity for example reduces the size and mixes the material.

Leachate is the *liquid that has seeped through solid waste in a landfill and has extracted soluble dissolved or suspended materials in the process*. Solid waste landfills may cause severe environmental impacts if leachate and gas emissions are not controlled. Leachate generated in municipal landfill contains large amounts of organic and inorganic contaminants which can percolate into the ground.

As a consequence, landfill management will focus on minimizing leachate production in the first place and on the leachate collection and removal system after.

Generally, leachate seepage is controlled by low-permeability mechanical barriers working with a drainage system which also removes the end products of biodegradation. The barriers are made of layers of compacted on-site clay soil. Alternatively, it's possible to comply with the regulations thorough the use of synthetic geomembranes which can be paired with clay soil or used as stand-alone elements.

4.2 Landfill gas management

4.2.1 Landfill gas composition and main components

Among the environmental factors, **moisture** plays a pivotal role; when the percentage of moisture increases (within certain limits), as well an increase in landfill gas production is registered.
In fact, a greater availability of water is resulted into beneficial effects on the process of biological degradation, for many reasons:

- it increases the activity of microorganisms;
- it improves the solid-liquid interface and acts as a vector to better spread microorganisms and nutrients.

Low humidity (30-40%) does not ensure adequate conditions for the biochemical reactions to degrade organic matter, while conditions of saturation (or worse "flooding") hinder both the gas production and the ability to move it. The presence of water in the waste comes from:

- an endogenous factor (for example, the presence of water in kitchen and garden waste is very high);
- storm water percolation/ leachate;
- flow of surface and underground waters;
- leachate recirculation treatment (if needed)

The first statement concerns the waste composition and its methods of collection. Usually, waste going to landfill are unsaturated and are able to absorb water until capillary saturation, beyond which leachate is formed.

External inputs are strongly influenced by landfill management methods, such as daily covering of the waste and proper removal of surface runoff water.

As mentioned above, the first stage of waste degradation process in the landfill, is **the biological degradation**- the breakdown of organic matter by microorganisms, such as bacteria.

The bio-degradation consists of three stages:

- aerobic stage
- anaerobic acidic stage
- anaerobic methanogenic stage

The aerobic phase is the initial phase and is the breakdown of organic contaminants by microorganisms when oxygen is present; oxygen is taken from the atmosphere, from the air incorporated during storage, from the one that penetrates after closing and from the one dissolved in infiltration water. This process actually begins during the waste collection and (eventual) pre-treatment phase, and in any case, it goes ahead until oxygen is available.

It is the same process used to produce compost at the household level, from kitchen and garden waste, and at the agricultural/industrial level from agricultural waste or organic waste. The aerobic process has a highly exothermic reaction, it can be reached even 70°C.

If the waste is stored and compacted, this process can last few hours/days, otherwise, if the deposit of waste is uncontrolled and the air keeps circulating, the same process can last several months. This oxidation stage includes a relevant production and emissions of CO_2.

Anaerobic (acidic) stage: this occurs when the availability of oxygen is reduced and an aerobic process is no longer possible. In this context, aerobic microorganisms prefer to use other oxygen compounds. In this stage, the production of carbon dioxide takes place. There is less generation of thermal energy compared to the aerobic process and a considerable production of partially degraded organic substance. Most of the partially degraded organic substance consists of organic acids. These acids are found in the leachate. A relevant production (emission) of CO_2 is registered at this stage which can last a few weeks or months.

Anaerobic methanogenic stage: Finally, the anaerobic phase, is activated when the oxygen has been completely consumed and favourable conditions are created for the action of bacteria that work in an anaerobic environment, so-called methanogenic bacteria, as they continue the action of degradation, converting organic matter into methane and CO_2.

When the right conditions are met, the percentage of methane can be as high as 60% of the LFG. Also this stage has a highly exothermic reaction that is however lower than that occurs during the aerobic stage. Generally, this stage starts a few months after the storage of waste and can last for decades, with a maximum production in the first years and a slow reduction until the complete degradation of organic matter. Obviously, this phase can continue until the chemical-physical conditions- that can guarantee the biochemical processes- exist. It can be completely reduced to zero. Sometimes, after many years from the waste storage- it can happen that the waste is still intact or little degraded, for example because of the lack of moisture.

In Figure 4.1, you can still recognize a paper ticket after 30 years from its storage due to moisture deficiency.

Figure 4.1. Paper Waste after 30 years of deposition. Source: ASET Spa, October 2016

Waste degradation stages are strongly influenced by different management methods; for example, when a huge quantity of collected and unprocessed waste is not adequately covered in uncontrolled waste dumps, the conditions for the following stages of the aerobic process, risk no to be longer met.

The graph below, proposed in an article by A. Damiani and M. Gandolla in 1992, represents a milestone in describing the (indicative) trend in the composition of gas mixture produced during the various stages of waste "fermentation" in a managed and controlled landfill.

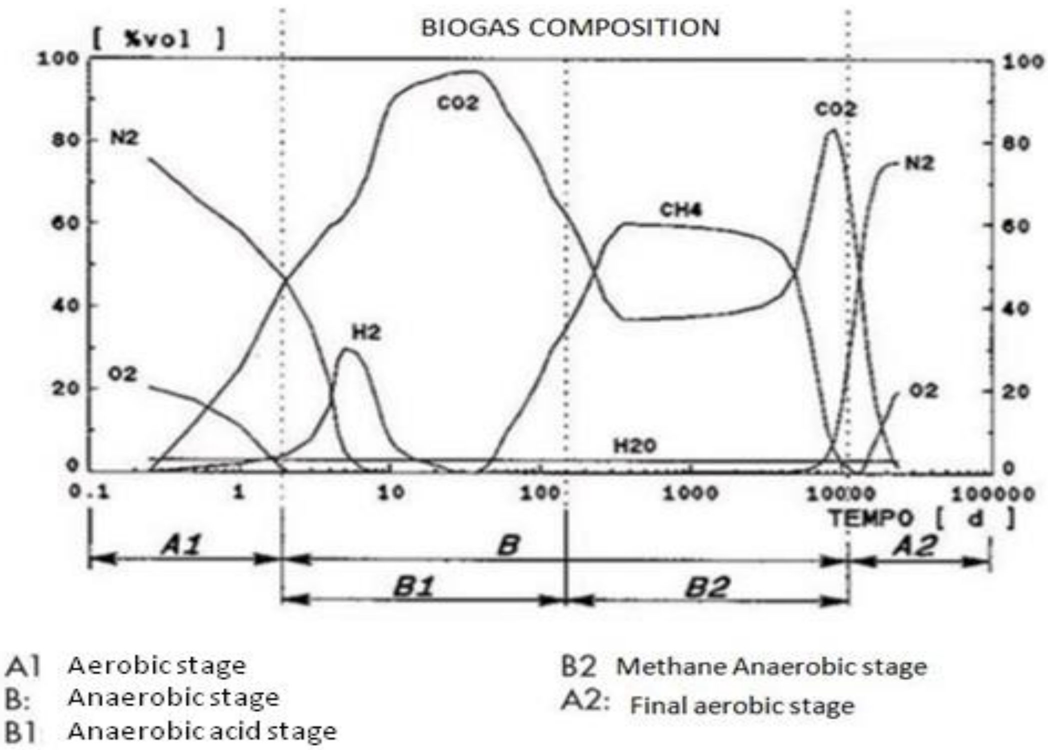

Figure 4.2. Composition process of biogas in a Landfill. Source: Damiani L., Gandolla M., 1992, Biogas management in controlled landfills, Istituto per l'Ambiente.

As can be seen from the graph, the macro-components of a **typical landfill gas** and its volume concentrations are:

- methane (**CH_4**) 30÷50 %
- carbon dioxide (**CO_2**) 35÷70 %
- Oxygen (**O_2**) 3÷5 %
- Nitrogen (**N_2**) 10÷15 %
- water vapour 0÷5 %

All these gasses are odourless. Components in a lower percentage (that can be measured in ppm or mg/m^3) are hydrogen sulphide (**H_2S**) and ammonia (**NH_3**) that have distinct and specific odorous aspects.

Landfill gas is a mixture of gases in different percentages that change according to the kind of waste collected, plant management and time of waste deposition. For convenience, reference is always being made- in case of landfill management- to a LFG with a Methane content of 50% (**LFG_{50}**).

Numerous other gases (including VOC, PAH, non-methane hydrocarbons), also present in the landfill gas, are generated by the biochemical reactions that take place inside the waste or which come directly from the synthetic substances contained in the waste itself. Some of these gases are toxic and therefore must be adequately monitored, both for the protection of the personnel working in the plant and for their environmental and health impact.

Particular attention should be paid to the methane that is a flammable gas. Since methane is a fuel, in the presence of an oxidizer (the oxygen present in the air) and a trigger, a combustion can be generated. For the combustion to take place, however, there must be a precise proportion between the gases in the mixture. In the case of methane in air, there is:

- lower limit equal to 5% of the **LEL** (Lower Explosive Limit);
- upper limit equal to 15% of the **UEL** (Upper Explosive Limit)

The methane "flammable range" in air is between 5 and 15%. For concentrations of less than 5% there is insufficient fuel, while for concentrations of more than 15% there is insufficient oxidizing.

It is clear that, due to the effect of landfill gas dilutions (with high % of methane), there always will be areas that enter the flammability field; it is necessary to be very careful, especially where a accumulation of landfill gas can be created (in confined areas): in this case, the risk of fire is added to that of explosion.

The flammable range in air of the biogas is different from that of pure methane, due to the presence of inert gases (such CO_2 e N_2) that can saturate the mixture; in fact, with percentages of inert gases higher than 20%, the product enters the non-flammability range due to excess of inert gases. For a better evaluation of these aspects, please refer to the flammability diagrams in the flammable gas management manuals. (e.g. G. Zebetakis 1959 US *Bureau of mines*).

4.2.2 Production and risks

As we will see in the following paragraphs, calculating (or rather estimating) the amount of landfill gas that will be produced over time by the waste itself, is a fundamental activity for the design and sizing of the various plant components. This is also pivotal for the next management and monitoring stages of a landfill gas collection system and treatment plant.

The calculation models consider the landfill as a **bioreactor** where the various biochemical phases described are developed, in particular the anaerobic one. An assumed production curve is obtained, adding together the effects produced over time by each individual ton of waste, through the overlapping of individual contributions; two trends (the best and the worst case) are often proposed within which the actual production curve may be estimated. Different calculation models are available, from empirical to theoretical models, based on the biochemical dynamics of organic matter transformation. In any case, it is clear that the production of landfill gas is strongly influenced by the kind of waste collected and by the chemical-physical conditions of waste showed over time. One tonne of kitchen waste will have a qualitative and quantitative production other than one tonne of textiles, glass and metals one. Considering that at least 50% of organic matter can be converted to landfill gas under anaerobic conditions, it is estimated that one ton of organic material can produce, over time, even more than 200 m^3 of landfill gas.

Thus, for example, a medium-sized landfill that receives 30,000 tons of municipal waste (with a high organic component) over a period of 10 years, will manage at least 50 million m^3 of landfill gas over time.

Whatever the calculation model used, to have a consistent estimate of landfill gas production over time it is essential to know:

- quantity, composition and evolution over time of the waste collected (especially in the last 10 years);
- the possible presence of special (industrial) waste that may contain substances that inhibit biochemical reactions;
- any pre-treatment of the waste (e.g., bio stabilization);
- the management forms (or not) of the plant over time (compaction, coverage, possible modalities of landfill gas collection, leachate management, etc.);
- the configuration of the tank and the external water inputs (groundwater, thermo-rainfall, etc.) in order to assess the humidity conditions in the waste.

As showed through the qualitative and quantitative description of landfill gas, the lack of bio gas control and management over time, involves a series of risks and negative impacts that must be well taken into consideration. Among these, there is certainly that of **fire and explosion risk**; the strong presence in biogas of a combustible gas, such as methane, its wide flammability range and its high mobility (both in air and in the ground) can generate many serious risk situations, even hundreds of meters from the plant. In fact, especially in poorly managed landfills, fires and landslides generated by explosions (due to internal combustion or in confined areas) are not uncommon and have caused extensive damage to people and property.

Among the environmental and health impacts of landfill gas, these can be highlighted: the impact of the odorous emissions and air quality impact, the emission of greenhouse gases and phytotoxicity. The most common **environmental impact** caused by the landfills, is the bad odour-stench generated by certain substances (e.g., mercaptans, H2S, amines, PAHs, etc.) present in landfill gas, sometimes only in traces; but rather the macro components (methane, CO_2, air, water vapour) are odourless. The landfill gas, besides being the source of odours, is also the means of transport when the gas- generated by the fermentation of disposed waste - goes up towards the surface layers, collecting other substances originating from the just deposited waste, and from there towards the outside.

As mentioned above, methane is a powerful "greenhouse gas", having a global warming potential (so-called GWP100) of 28 times higher than that of carbon dioxide; lack of its remediation and recovery, contributes greatly to global warming. Waste landfills are the second/third largest contributor (at least 15%) of uncontrolled methane emissions (of anthropogenic origin) after the oil industry and animal husbandry.

The presence of an efficient landfill gas collection and remediation system, avoiding overpressures in the waste and uncontrolled emissions from it, is fundamental to reduce risks and negative impacts on human being safety and environment.

4.2.3 The collection and transport

The **landfill gas collection activity** consists of the development and management of products that, once placed in direct contact with waste, are able to recognize the gas just produced by their fermentation.

These elements will obviously be connected to the intake system and to the treatment of the gas itself (see next paragraphs). Without these elements, the gas, due to the overpressure within the waste, would disperse into the atmosphere in an uncontrolled manner, reaching the surface of the landfill or the surrounding soil through the walls of the tank (if not adequately waterproofed).

The collection system must be designed from the beginning of the landfill life cycle, because, landfill gas starts to be generated immediately, although with different characteristics than those at full capacity. The more efficient collection elements are, the larger is the surface area in contact with the waste. Generally, they consist of vertical wells or horizontal drainage trenches.

In the case of open dump rehabilitation, the landfill gas collection system will be built afterwards, following the same criteria applied to new landfills.

A typical element of the gas collection system is the **vertical well**, consisting of a circular column and a central probe (slotted pipe) (Fig. 4.3). The gravel column ensures the drainage surface of the gas, while the slotted probe ensures the possibility of surface connection to the intake and transport network of landfill gas.

The well can be arranged from the base of the tank that will collect the waste (see Fig. 4.3); in this case, the gravel column will be protected by a cage, usually consisting of a metal frame (the helical steel reinforcements of concrete foundation piles are often used) and a metal containment mesh. As the development of the landfill proceeds, the gravel column and the central probe will be gradually raised to the working level; it is important to maintain the continuity of the draining column, even if vertical deformations of the column should occur.

The metal parts degrade over time, but without causing damage, as the waste body itself will now contain the gravel column.

The gravel (size: 40/70) should preferably be made of siliceous or basaltic materials (typically the basaltic ballast for railway is used), avoiding the use of calcareous rocks that tend to be attacked and disintegrated by the acids contained in the gas and leachate. Perforated high-density polyethylene (HDPE) pipes are typically used for the central probe (see Fig. 4.3.)


Figure 4.3. Horizontal drainage and wells. Source: ASET Spa, April 2019.

Generally, wells have a diameter of 60/120 cm, while the polyethylene probe has an external diameter of 20/60 cm (the larger probes allow the housing of pumps for leachate pumping). Similar techniques can also be used to make oblique wells of semicircular section (Fig. 4.3), on the tanks side.

In a municipal waste landfill, as well as in open dumps, the **"radius of influence"** of the well is considered to be 25 m. For optimal collection, at the design or management stage, it is recommended to stay around 15-20 meters in order to overlap the effects of a mesh of wells.
The wells, rising from the bottom of the landfill, are particularly useful as they can perform the dual function of collecting landfill gas upwards and draining leachate downwards, where it is removed from the drainage of the bottom of the tank.

However, there are many factors that influence this mechanism, such as:

- mechanical action of means of transport and compaction of waste;
- waste settlement (materials to be dragged down by friction)

- differential thrusts (within the wells, e.g.);
- materials degradation (due to acid actions);
- pressures and physical conditions (the temperature in the waste can reach up to 70°C, with consequent "softening" of the polyethylene);
- clogging of drains; etc.

All these actions lead to a progressive loss of functionality of these components, until they become unusable. In the cycle life of a landfill, it is therefore necessary to provide a periodic renewal of these technical elements, since maintenance of the same is not possible.

Figure 4.4. Drilling of a new well and table of data collected to build new wells. Source: ASET Spa, July 2021.

When the need of introducing new collection elements arises, it is necessary to plan a building campaign of new wells to be drilled on the waste body (Figure 4.4). This is also valid in case of rehabilitation of an open dump.

This operation must be carried out by specialized firms because there are several risks in the activity’s implementation: chance of falling into the drilling hole, exhalation of landfill gas with risk of entering the field of flammability, incorrect realization of the drainage column, etc. However, during the assessment stage before the drilling, it is possible to collect a lot of information on the chemical-physical condition of the waste body. During this stage it can be observed the following factors: humidity, temperature, hydraulic head, state of mineralization of the waste, etc.; Representative samples of waste can also be collected for laboratory testing: dynamic respirometry index, residual carbon content, any bio methanation tests, etc., which can also provide further useful information by comparing data between the various wells. (See Fig. 4.4)

During the cultivation phase, it is always useful to create sub-horizontal drains that act as additional collection elements (see Fig. 4.3); they are created, at various heights, through the excavation of simple trenches then filled with gravels; if necessary, slotted pipes can also be inserted to increase the gas flow. By connecting these trenches between one well and another, it is possible to create an underground collection network that exceeds any interruptions that may be generated; the only precaution is to ensure an adequate slope of the trenches towards the wells in order to allow leachate and condensate, which could flood the trench itself, to drain towards the wells.

The top part of a collection system has the function of connecting the main element of the structure to the landfill gas transport network. Without this connecting element, the gas would be dispersed in the atmosphere, nullifying the efforts made to implement and manage the collection system. Well heads can be realized in two ways:

- the probe inserted in the well can be connected to a blind pipe (for a depth of at least 2/3 meters flat) of the same diameter as the probe;
- through a **"bell" structure** that encloses the entire upper part of the draining column, generating a sort of chamber on which the leachate intake and pumping pipes can be connected; this method is preferred.

In any case, in order to avoid air being drawn from the surface of the landfill, it is essential to ensure a perfect seal between the well and the landfill cover itself.

Considering that these elements are often located in the working area of the operating machines, it is also necessary to guarantee their adequate protection in order to avoid damages.

The pipe system that connects the individual collection elements with the extraction and treatment plant constitutes **the landfill gas transport system**.

For its flexibility, lightness, resistance to chemical aggression and functionality of management, the transport system is usually made of high-density polyethylene (HDPE) pipes of various diameters.

When there are dozens of wells, in order to ensure proper regulation, it is necessary to collect the lines of individual wells, making them converge in intermediate stations; in these points are also inserted the devices for regulation and control of the collection; they are also called **Control Stations.**

The transport system can be divided into:

• **primary lines** (usually with diameters 180/250 mm) that connect the Control Stations with the Extraction Station;

• **secondary lines** (it is generally suggested not to go below 90 mm in diameter) that connect the individual wells with the **Regulating Stations.**

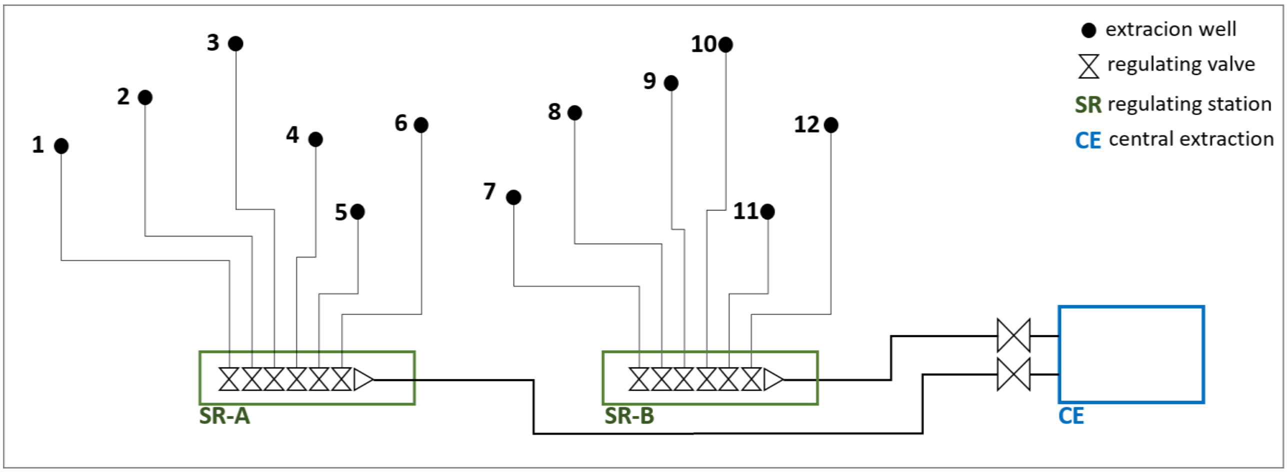

Figure 4.5. Typical framework of a landfill gas transport system. Source: adapted from Magnano E., ed. 2010, Landfill Biogas, EPC.

Figure 4.5 shows a landfill gas transport system with two kinds of lines highlighted (primary lines in bold). The gas moves inside the pipes for two reasons: the (natural) pressure exerted inside the waste body (as a result of its fermentation) and the (artificial) depression of the intake system; the effects of the two actions are coexistent and add up, but the intake action is the most predominant one and has the advantage of being able to be regulated.

It should be noted that the landfill gas transport system is depressed; since it is a flammable gas, this aspect is in favor of safety, as in the case of ruptures there is at most an air intake into the network and not an uncontrolled release of biogas.

Since landfill gas is a hot and often saturated fluid of water vapor, one of the main problems of the management of landfill gas transport lines is that of the creation of condensation inside the pipes, due to the change in temperature (cooling) that may occur along the lines that run externally (especially in cold periods).

The **condensation** reduces or blocks the flow of landfill gas inside the pipes; however, since it is not possible to avoid their development, it is necessary to provide a solution for their purge; the depressions applied on the line are generally not able to aspirate all the liquids collected.

Condensate is removed by gravity, taking care to ensure that the lines always have profiles sloping towards the wells or the Regulating Stations; where this is not possible, **special condensate drains** must be provided to guarantee the continuity of the depression (see Fig. 4.6).

The pipes, which generally run on the surface of the landfill, face continuous displacements caused by waste settling, thermal expansion of the pipes, etc., the lines can therefore lose the slope necessary to ensure the draining of condensation. Slopes control and pipes integrity can be optimized by positioning them on a scaffolding with adjustable joints.

Figure 4.6. Secondary landfill gas lines laid on supports of metal pipes - in the foreground a condensate discharger - in the background a Regulation Station. Source: ASET Spa, Nov.2020.

As mentioned in the previous paragraphs, landfill gas -inside a well- faces continuous qualitative and quantitative changes, being conditioned by several factors: waste characteristics, chemical and physical conditions (affected by precipitation and atmospheric pressure), sealing, interaction with other wells, etc.

An efficient collection must take into account these changes (which occur several times in a day) and must put in place a **system of regulation** of the intake- suction rate; this activity is usually carried out manually.

The modalities of regulation will depend also on the objectives to be reached: if one aims at maximizing the energy recovery or if wants to collect as much landfill gas as possible; it is obvious that such activity results quite complex to realize; where possible it is preferable to entrust it to modern **automated regulation systems** (see Case Study 8 -Italy).

4.2.4 Landfill gas Recovery/remediation

As highlighted in the previous paragraphs, the collected biogas cannot be released into the atmosphere, however must be treated to reduce as much as possible the negative effects it has on the environment.

Generally, the activities of landfill gas recovery/remediation occur in a single site, the so-called **Central Extraction.**

Figure 4.7. Extraction Plant and energy recovery for landfill gas. Source: ASET Spa, 2005.

The conveyance of the landfill gas is guaranteed by an intake and compression system, which has the double function of ensuring a sufficient depression on the entire network of capture and transport and that of compressing the gas towards the treatment organs (see below).

Figure 4.8. A turbo blower -Centrifugal fans. Source: ASWM Srl, 2020. All rights reserved.

This work is carried out by machines, *Centrifugal fans or* centrifugal blower, that extract gas and convey the aspirated gas towards the treatment systems.

For the dynamics of the fluids, these equipments must guarantee (relatively) low ventilation pressures but with high capacities; they must be adequately dimensioned, taking into account the production peaks.

In the suction stage, it is necessary to guarantee a vacuum of at least 10÷20 mbar to the farthest collector while in compression it is necessary to sustain a thrust of about 1 bar. As to flow rates, it is necessary to consider machines able to intake/compress from a few hundred to a few thousand

Nm^3/h of landfill gas. These machines are the driving force of the entire system, working continuously (24h 365 days/year). For this reason, It is important to size them correctly in order to meet the needs of the project and to consider the time and its possible variations that occur throughout the life of the landfill.

In general, it is preferred to equip the plant with more machines (perhaps with lower flow rates than peak ones) that can work simultaneously, to ensure the variability of the flow rates and to guarantee the system working even in the case of maintenance of one of them. Considering that the Centrifugal fans are very energy-intensive and work 24 hours, it is possible to use machines equipped with inverters that guarantee a reduction in electricity consumption.

It is available on the market a wide range of machines with different characteristics (in recent years also with Atex protection), to cover all design needs.

The treatment of landfill gas mostly depends on the quality and flow rates of the biogas itself.

When the methane content is greater than 25 30 %, it is possible to perform a thermal treatment by combustion; but rather, lower methane content cannot guarantee an adequate heating/thermal value for combustion.

Higher levels of methane allow more advanced and efficient treatment opportunities to ensure the recovery of the energy within landfill gas, while for landfill gas with low percentage of methane, biofiltration is the only possible treatment.

The following landfill gas treatments, listed in increasing order of methane percentage, can be applied:

- (0÷25 %) biofiltration;
- (> 25%) static or flame torches;
- (> 30%) high temperature torches;
- (> 35%) microturbine;
- (> 35÷40 %) combustion engines.

In case of:

- open-dumps with not widely compacted and/or uncovered waste, where therefore the anaerobic phase is not activated in the waste itself;
- in the first stages of landfill management;
- or in landfills closed for many years;

the “quality” of landfill gas can’t guarantee the combustion treatment.

In these cases, it may be useful to provide the plant with **biofilters** that can oxidize and biodegrade many organic and inorganic substances contained in landfill gas.

Figure 4.9. Examples of container biofilters with organic material (detail). Source: ASWM Srl, 2021.

The biofilters are tank-shaped containers filled with organic material (usually wood bark) with great porosity (Fig. 4.9). They can be static or mobile (modular biofilters).

Within this organic mass, a wide range of micro-organisms (bacteria, fungi, etc.), able to decompose many substances through a series of biological reactions, is activated.

The substances within the landfill gas (methane, hydrogen sulfide, ammonia, mercaptans, hydrocarbons, carbon monoxide, etc.) are largely adsorbed through the biofilter and then metabolized by microorganisms.

The abatement efficiency of these substances is generally very high, for methane oxidation it can exceed 80%.

This technology has been successfully used for the treatment of areas damaged by composting plants and for the treatment of sewage for many years.

Reactions can only occur if there are specific chemical and physical conditions (temperature, humidity, pH, gas contact time, etc.); however, they can be easily controlled. Attention should be paid when methane/oxygen mixture enters the explosive range (5÷15 % methane in air). The flow rate of the gas mixture will provide the sizing of the tanks that are characterized by great modularity; also the costs and the management activities are very limited and they include: maintenance of the chemical and physical conditions of the plant material, its replacement (usually lasts years) and the control of incoming gases and emissions.

Therefore, through a simple and economic system, it is possible to effectively treat even large volumes of landfill gas with low energy content.

When methane is present in landfill gas with a percentage higher than 25 %, the most adequate treatment becomes **combustion**: methane and other substances (e.g. H_2S) are oxidized, producing carbon dioxide that has a reduced impact (see paragraph 1).

Combustion (without energy recovery) usually takes place in a **torch** where the methane, present in the landfill gas, acts as fuel and the oxygen, present in the air, as an oxidizer (while the inert nitrogen remains unchanged); the main reactions are:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$$

$$2CO + 2O_2 \rightarrow 2CO_2$$

If the landfill gas contains fluorinated, chlorinated or sulfur compounds, hydrofluoric acid (HF), hydrochloric acid (HCl) and sulfur dioxide (SO_2) are also inevitably produced.

The presence of nitrogen obviously also leads to extensive production of oxides of nitrogen (NOx), especially if combustion temperatures are high (> 1,200 °C).

Low temperature combustion, “low Residence time of flaming combustion” and poor gas mixing lead to the development of dangerous compounds such as dioxins and furans.

The monitoring of combustion conditions has a great influence on the chemical reactions and determine the quality of the exhaust fumes.

In order to guarantee an effective combustion, the following elements and actions are necessary:

- combustion temperatures between 850 and 1,100 °C;
- a gas retention time > 0.3 seconds;
- adequate gas mixing;
- avoid sudden cooling of the flame.

The simplest devices are **static or open flame torches.**

These are usually fed directly by the overpressure of the gas generated by the fermentation of the organic matter in the waste; often they consist of one or more torches positioned directly on the collection elements within the waste itself.

This represents an economical solution of landfill gas recovery; however, 2 main negative aspects should be outlined, namely the flammable conditions created by waste, and their impossibility of ensuring proper combustion and control of exhaust fumes.

High temperature torches are highly-performing mechanism because they keep the heat of the flame inside.

The presence of combustion chambers, refractory coatings and other devices, ensure optimal combustion conditions that compliance with the gas emission limits in many countries.

It is necessary to refer to the maximum production rates of the landfill gas to be treated, both if the landfill biogas recovery is generated exclusively through combustion in the torch or whether this is used only when the energy-using device (see below) is in maintenance.

However, as mentioned in the previous paragraphs, the production of landfill gas varies greatly during the life time of the landfill; thus, it is also important to take into account the minimum level of landfill gas production, ensuring that the torch can handle lower flow rates. The size of the torch must consider the range of work in which it will operate.

Figure 4.10. High temperature torch. Source: CONVECO Srl,2021.

If a single device is not able to cover this range, it is useful to provide two elements- activated individually or in pairs- depending on the system capacities.

When the percentage of methane in landfill gas is further increased (at least 35%), its energy recovery can be considered; in this case there will be two environmental advantages: methane emissions reduction and no CO_2 emissions into the atmosphere that, otherwise, would have been generated by the use of fossil fuels to produce the same amount of energy. For this reason, the energy recovery of biogas from landfill can therefore be considered as a renewable source.

The potential chemical energy present in landfill gas can be easily transformed into **thermal energy** (yields up to 90%) while the yield for **electricity** can reach a maximum of 40%, but it needs an additional mechanical work (engines and alternators). However, in case of thermal energy user's lack near the plant (e.g. a greenhouse), the production of electricity, easily transportable and usable even from remote users, is the most appropriate mean for setting the problem. If thermal energy is recovered from electricity, then Cogeneration process took place (such as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy). A solution for the production of electricity are the **gas micro turbines** which are characterized by a small size and modularity (that allow to bring into use more small machines) but also high initial investment cost.

The most common method to ensure electricity production from landfill gas is the use of **endothermic engine** connected to a current generator. The conversion of landfill gas to electric power by a generator set is much more practical than any other methods.

Landfill gas is used as a fuel in engines that support the use of low-methane fuel (> 35 %) and the presence of inert gases (N_2 and CO_2). The sizes range from a minimum of 100 to a maximum of 1,500 kWe. These engines must be sized according to the amount of landfill gas to be treated and the methane content of the mixture. The efficiency varies, depending on the fuel and workload of the machine (in the range of 30 ÷40%).

The supply pressures are compatible with those generated by *turbo blower* used for landfill gas suction, therefore no additional compressors are needed. It is possible to modify and adapt the engine's carburation in order to control emissions, which must comply with limits, depending on specific national regulations; if this is not possible, it is necessary to combine a afterburner, which further oxidises carbon monoxide and unburnt hydrocarbons.

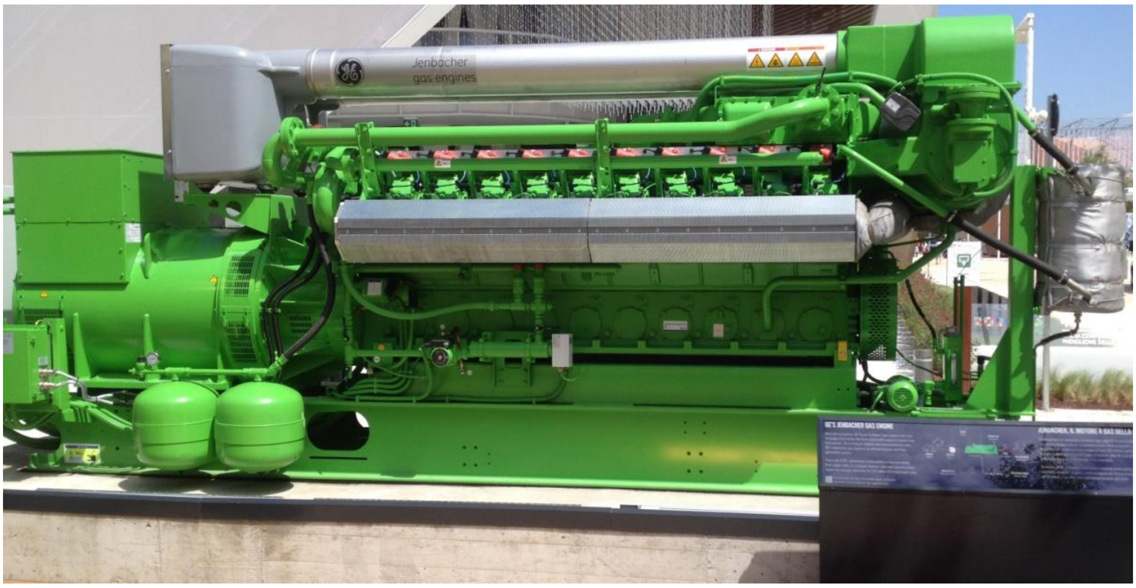

Figure 4.11. GE's Jenbacher gas engine, USA Pavilion, Expo 2015, Milan, Italy. Source: sbamueller, CC BY-SA 2.0 <https://creativecommons.org/licenses/by-sa/2.0>, via Wikimedia Commons.

Generally, it is necessary to foresee also some pre-treatment of the landfill gas before the entrance to the engine. The landfill gas arrives to the plant often saturated with water vapor, therefore it must be dehumidified; this process can also remove other substances (e.g. H_2S) that go into solution.

If the presence of other acids (hydrochloric, hydrofluoric) or siloxanes (organic compounds of silicon) is strong, it will be necessary to provide other forms of pre-treatment.

In general, however, for an initial investment, the use of endothermic engines (and related accessories) guarantees a long working life (even beyond 10 years or 100,000 h) and maintenance costs are gradually increasing but are offset by revenues from the sale of electricity; as mentioned, in fact, this production is considered a renewable source and is often sold at feed-in tariffs.

In this last Figure (4.12) is represented a system of collection, transport, treatment and production of electricity from landfill gas.

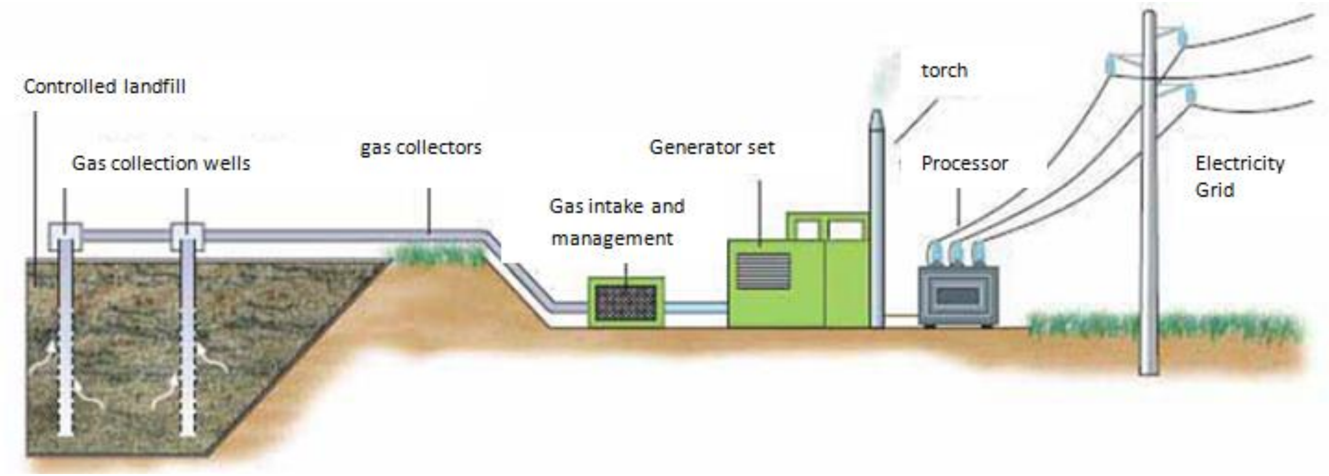

Figure 4.12. Framework of the Landfill gas Collection System and landfill gas Energy exploitation: Source: adapted from Il Gestore Servizi Energetici (Gse) incontra la Regione Emilia-Romagna, regione.emilia-romagna.it, 2011.

4.3 Landfill Leachate Management

4.3.1 Leachate Characteristics

The qualitative and quantitative characteristics of landfill leachate depend on multiple factors, some of which are difficult to control such as as weather conditions, hydrological features, waste composition and age, etc.). All these elements imply critical management issues which led to different systemic approach, both at European and national level.

From the **quantitative** point of view, the production of leachate is largely attributed to external inputs (rainwater infiltration, both superficial and underground) and internal inputs such as the level of moisture content waste and the water balances related to the biochemical reactions of waste disposal.

In particular, external inputs relate to:

- Meteorological and hydro geological characteristics on the site, particularly related to *rainfalls*, temperatures, *solar or wind exposition, water body infiltration, both superficial and underground.*
- The landfill management model: *presence of drainage, primary or secondary liner system, daily extension and coverage of the waste tank, possible leachate recirculation*.
- Waste characteristics: composition of waste, *level of moisture content*, *possible pre-treatments, size, level of compactness.*

Leachate composition and strength varies widely from landfill to landfill, even within a given landfill.

It should be noted that, even in absence of external inputs (e.g. a landfill capping system), the anaerobic decomposition of the waste and its leachate production continues even after the end of the landfill life cycle. This means that landfill managers need to keep the drainage and treatment plants operating while ensuring that the surrounding environment is safe from contamination, in conformity with the national laws.

From the **qualitative** point of view, it's impossible to describe a typical landfill leachate composition, being it influenced by different factors that specifically affect the biodegradation process of waste, thus contributing to the seepage of different pollutants.

The main factors affecting the biodegradation progress are:

- *Level of moisture content of disposed wastes*
- *Quantity and nature of organic components (especially if sewage sludge, off-spec compost)*
- *Levels of metals and/or toxic substances from batteries, drugs, solvents, etc.*
- *Levels of separate waste collection* surrounding the landfill plant which can vary the type of waste disposal.

Waste pre-treatments and placement in the landfill are another two important factors which affect the water absorption capacity of the waste mass leading to the migration of pollutants in leachate. Consolidated studies show that the concentration of pollutant inside the leachate is higher within the first operating year of the landfill, progressively decreasing through years. This trend affects organic parameters (COD, BOD, TOC) and the main inorganic salts (heavy metals, sulphates, etc.) These organic parameters are:

- *BOD= biochemical oxygen demand*
- *COD=chemical oxygen demand*
- *TOC= total content of organically bound carbon*

The removal of organic material based on COD, BOD and ammonium from leachate is the usual prerequisite before discharging the leachates into natural waters.

From the microbiological aspect, the proliferation of fungi and bacteria is inhibited by common environmental conditions (high temperatures and pH) during the biodegradation process.

Since the ’70s-80s, the *application of mathematical models* helps to predict leachate characteristics and related implications in relation to the water balance of the landfill. In fact, the waste mass act as an unsaturated element in the landfill which is conceived as a “***bioreactor***”. These models have already proved their efficiency and can be useful in the first phase of the landfill design process together with local data analysis.

4.3.2 Leachate drainage and collection

As mentioned before, leachate seepage and diffusion outside the landfill site is controlled by a protective layer together with the leachate collection and removal system. Obviously, in the case of rehabilitation of open dumps, the use of bottom and ground/wall barriers for leachate is allowed only where it is possible to exploit new waste containment tanks, built on the edge of the sites to be reclaimed.

The engineered barrier system efficiently contains waste and its most common composition is:

- Clay
- Sand-bentonite mixtures
- Sand-cement mixtures
- Geosynthetic membranes

Over approximately the past 20 years, the use of components manufactured from synthetic polymeric materials, termed geosynthetics, has become commonplace in geotechnical engineering. Common geosynthetic materials employed in engineered containment systems include geomembranes, geotextiles, geonets, and geosynthetic clay liners. Recent technological progress made geosynthetic products more appealing to landfill designers because they can perform different functions at the same time (impermeability, drainage, slope stability, etc.).

Moreover, these membranes have certain advantages in terms of the cost-effectiveness of the corresponding quantities of clayey material necessary to achieve the same technical performance, in addition to that of not reducing the storage capacity of the waste disposal tank.

Their main advantages are:

- *Flexibility*
- *Durability, unlike barrier made of natural materials*
- *High resistance to traction and chemical and biological attacks*
- *Economical: they cost less than their natural counterparts*

The combined use of different types of products (natural and synthetic) is becoming increasingly common and its main goal is to optimise the peculiarities of the chosen material.

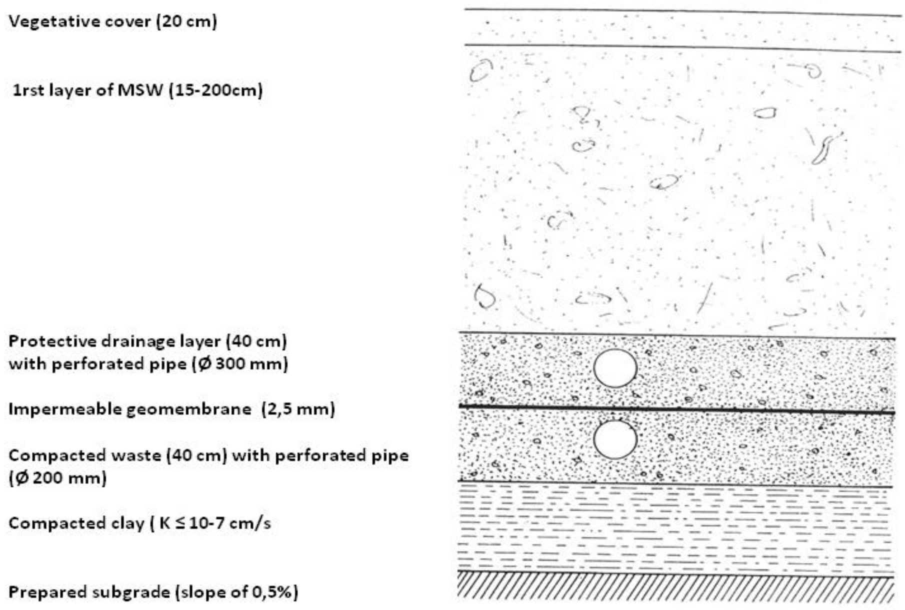

Figure 4.13. A traditional MSWL design cross section. Source: Gervasoni S., ed 2000, The controlled landfills, HOEPLI

Figure 4.13 shows the traditional MSWL (Municipal Solid Waste Landfill) design cross section for sites characterized by a natural clay soil ($K \leq 10^{-7}$ cm/s) or by a generic subgrade before the creation of the barrier.

Over time, the creation of the drainage layers under the waterproof geomembrane was gradually abandoned, due to their tendency to become saturated which lead to the creation of a hydraulic leachate head in direct contact with the mineral barrier, a harbinger of possible dispersions into the subsoil. Moreover, leak detection through the pipes wouldn’t allow to detect it once the waste placement is in its final stage of completion.

Today, bentonite geosynthetics are becoming increasingly widespread among geomembranes. Sodium bentonite chemical properties allows it to increase its volume up to dozen times when in contact with leachate. In this way, it’s able to protect the system from any leaks (Fig. 4.14) and it’s compatible with the underlying mineral barrier.

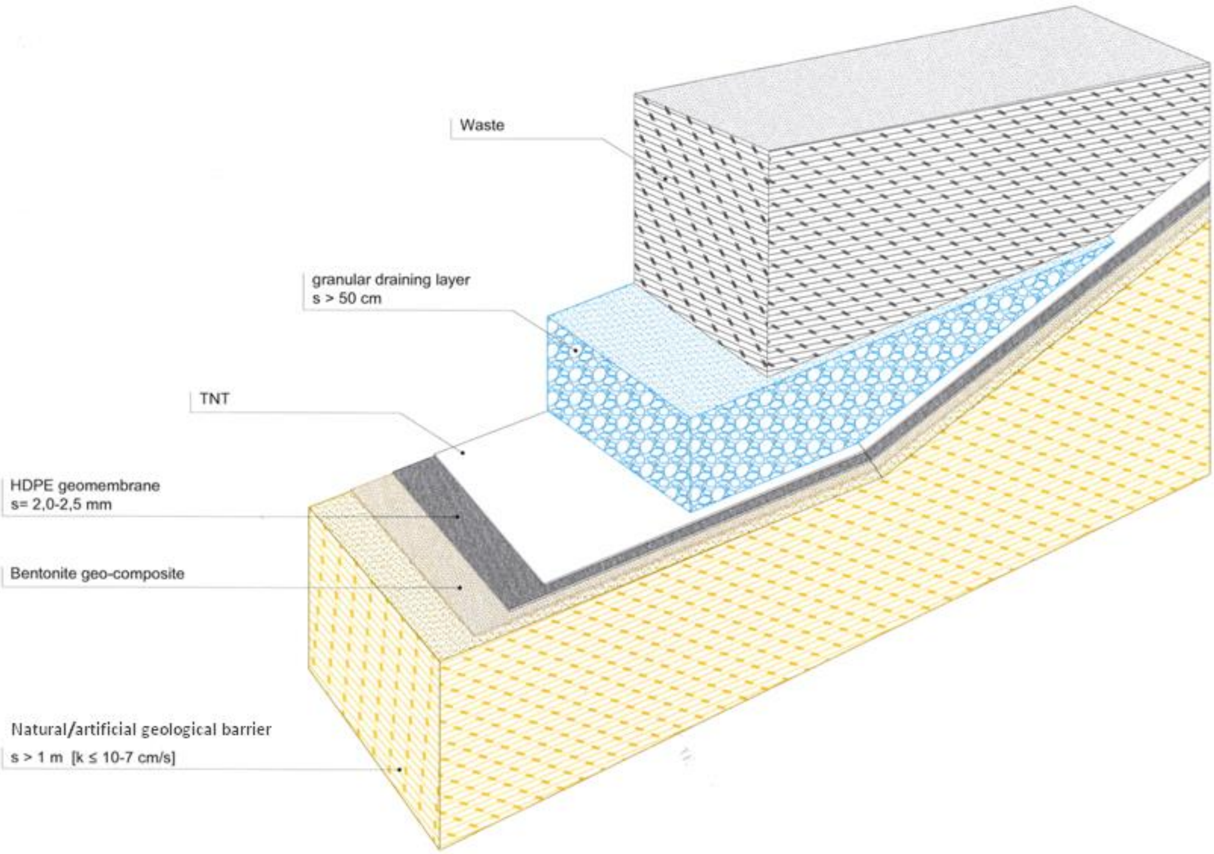

Figure 4.14. Example of different geomembranes associated with geotextile. Source: ASET Spa, 2022.

The most widely used material in the manufacturing of synthetic liners is HDPE geomembrane with a thickness of 2.0–2.5 mm. HDPE geomembranes are supplied as sheet rolls, now available in different thicknesses and also surface finishes, to improve the adhesion capacity and make it more difficult to slip into the bank.

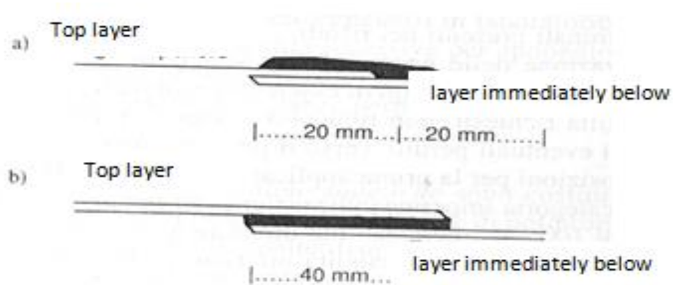

Figure 4.15. Type of HDPE geomembrane seamed on -site: a) overlapping joints (manually), b) interposed joints (automatically).
Source: Gervasoni S., ed 2000, The controlled landfills, HOEPLI

The installation of HDPE sheets, usually supplied in large rolls (e.g. 10x200 m) takes place by laying them side by side with suitable overlap (minimum 200 mm) and thermal welding of the edges whose surfaces should be previously grinded or heated. They are now installed thanks to a special automatic welding machine, ensuring the uniformity of the welding seams (Fig. 4.15). Seams and edges are critical point of detachment of the sheets and may cause the discontinuity of the waterproof barrier. There are two ways of testing the integrity of the geomembrane lining systems, namely through a non-destructive and a destructive testing. The first one is performed on all along the extrusion welds, while the other one is performed by cutting samples of the seams.

Leachate collection is entrusted to the network of micro-fissured pipes located in the drainage layer placed above the waterproof barrier at the bottom; all the collection network is characterized by slopes able to direct the leachate to a point placed at lower geodetic altitude, so that it flows out of gravity (Fig. 4.16). Then, it is will be pumped into collection/equalization waterproof basins and finally treated.

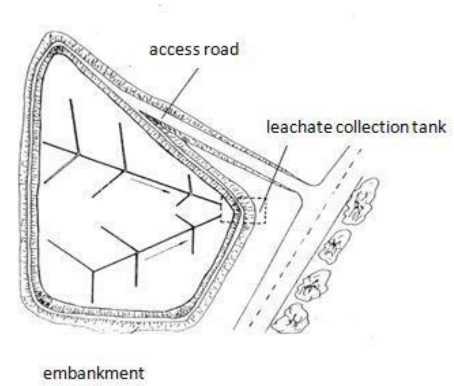

Figure 4.16.Typical scheme for leachate drainage in a controlled. Source: The controlled landfills, Gervasoni S., ed 2000, HOEPLI

As already mentioned, in the case of rehabilitation of open dumps without the possibility of transferring the waste to new waterproofed basins, the collection of the leachate can be entrusted to special wells drilled in the mass already closed. For this purpose, the vertical wells for biogas collection already illustrated can also be adapted (see Fig. 4.3). The gravel column guarantees the drainage of the leachate which - collected by the slotted probe and descending by gravity to the bottom of the well - can be sucked by specific axial pumps suitable for installation within the pipeline.

4.3.3 Minimizing leachate generation

Leachate production is largely attributed to *external inputs* (infiltration of rainwater, surface and/or groundwater) and in the residual fraction to *internal inputs/consumption* such as moisture content and the water balances connected to the biochemical reactions within the waste body., Thus, it's extremely important- especially for the rehabilitation of open dumps – to carefully plan all those interventions aimed at minimizing the production of leachate over time. Subsequently, proper leachate extraction, treatment, and recirculation processes provide a substantial contribution to sustainable landfilling, by controlling biodegradation processes and removing soluble contaminants to achieve, in one generation time, a state of geological storage of inorganic substances and nondegradable organic waste for the landfill.

Predictive models for leachate generation are required to define, design, and size the works, which are connected to all the above-mentioned aspects.

Considering the landfill as a closed and planimetrically defined water basin, leachate quantity is influenced by the mass balance of external and internal water flows surrounding the landfill, as well as by the accumulations and internal production/ consumption.

The following scheme (Fig 4.17*)* summarize the main components of the landfill water balance:

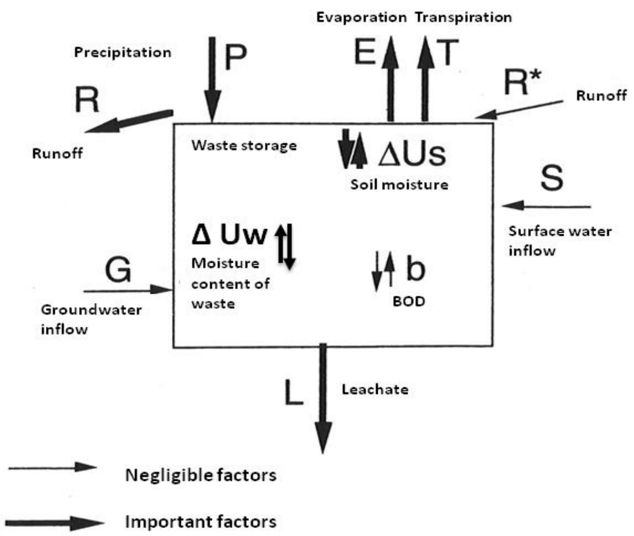

Figure 4.17. Simplified diagram of MSW landfills water balance. Source: Collivignarelli C., ed.1996, Leachate management from Urban Solid Waste Landfill, C.I.P.A

The diagram shows that:

$$Lc = L - Li$$

Where **Lc** (quantity of leachate *collected*) is equal to the total produced (**L**) minus the portion potentially lost due to infiltration (**Li**) at the boundary (hopefully, equal to 0)

Not all elements have the same relevance in the equation. The predominant factors are the precipitations (P) while the BOD (b) factor is negligible. Consequently and in particular in the case of the rehabilitation of open dumps, the minimization of leachate generation must focus on the factors that have a major influence on this process.

Elements that can be eliminated through drainage and removal operations are:

- *Superficial runoff*
- *Superficial water bodies infiltration*
- *Groundwater aquifers infiltration*

Other elements can only be controlled with efficient technical operations:

- *Covering material*
- *slope of the coverage surface*
- *level of compactness*
- *water managements methods*
- *possible recirculation of leachate.*

Concerning the controllable factors for minimizing leachate generation, the landfill capping system needs special consideration. Capping is a containment technology that forms a barrier between the contaminated waste mass and the surface, thereby shielding humans and the environment from the harmful effects of its contents by limiting their migration. A cap must restrict surface water infiltration into the contaminated subsurface to reduce the potential for contaminants to leach from the site. This operation has both an environmental and economic value due to the high costs of leachate treatment and disposal.

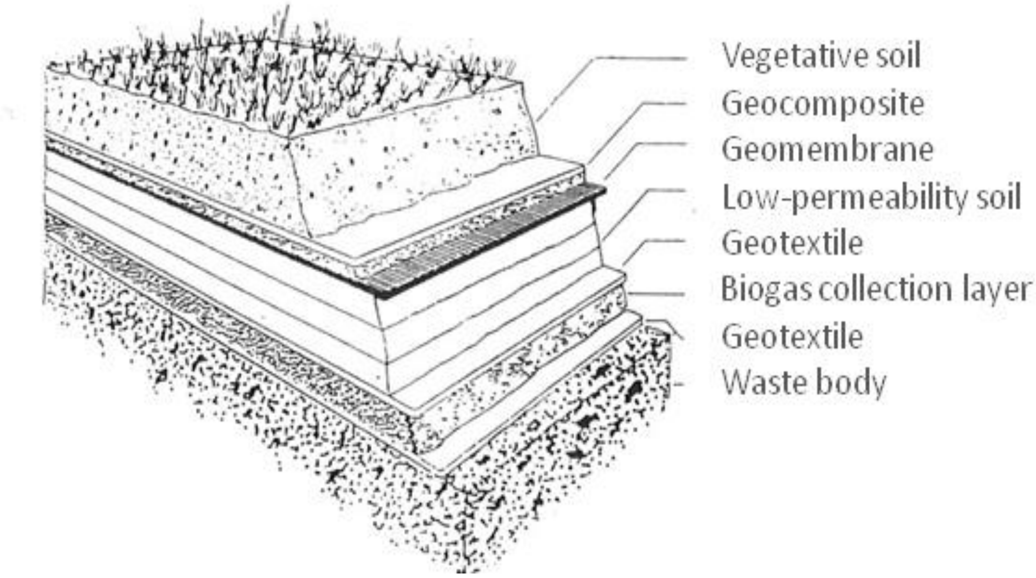

Figure 4.18. Example of landfill capping system. Source: Leachate management from Urban Solid Waste Landfill, Collivignarelli C., C.I.P.A.

Beside minimizing leachate generation, the capping system isolates and prevent the spread of contamination in several ways by:

- *Preventing wind from blowing contaminated material offsite*
- *Controlling releases of gas from wastes containing or producing "volatile" chemical*
- *Keeping people and wildlife from coming into contact with the hazardous material and tacking contaminants offsite.*
- *Growing vegetation*

In this sense, low permeability barriers (LPB) - which aim at limiting the infiltration of meteoric water inside the waste mass - are as important as the bottom liner system and therefore deserve specific design attention for landfill designers and managers.

Today, the most common solution for the LPB is mixing natural and synthetic barriers, namely HDPE sheets and compacted clay soil. Particularly, capillary barriers are an efficient type of sealing system that can be used as a final cover on landfills and remediation sites. This system consist of two sloping layers where fine-grained sand is used in the capillary layer, which overlies a coarse-grained layer (the capillary block). It exploits the fact that a layer of fine sand becomes highly saturated with water from above preventing it from seeping down into the capillary block. Instead, the water is held just above the interface between the two layers and runs off laterally into a ditch containing a drain at the foot of the slope. The engineering approach is fundamental also in this phase because even though it represents the end of the landfill life cycle, it is pivotal to ensure the efficiency of the cap in terms of infiltration minimization over time.

Other controllable factors aimed at minimizing leachate generation are linked to ordinary landfill management activities which are:

- *Limiting the extension of waste tank*; it can reduce the risk of meteoric water infiltration
- *The material used for capping must have absorbent capacity rather than be completely non permeable. Biodegradation is ensured by the presence of water which maintains a certain level of moisture in wastes.* For example, off-specification or other semipermeable sheet which also help in odorous emissions
- *Leachate recirculation* inside the waste body through appropriate diffusion systems can significantly reduce leachate quantities, especially where the landfill characteristics allow higher levels of evapotranspiration (i.e particular weather conditions and vegetative soil).

4.3.4 Leachate treatment

Due the differences of quantity and quality of leachate, it's impossible to provide a general treatment scheme valid for all types of landfills. In fact, there are different approaches to leachate treatment, ranging from chemical-physical to biological treatments, both aerobic and anaerobic. Depending on the regulations in force, landfill managers can chose to implement either one or a combination of the aforementioned types of treatment, according to opportunities available on site.

- Disposal in surface water bodies
- Municipal leachate-treatment plants

One of the most common, but not solution is leachate collection, accumulation and treatment through tanks as it is considered as a "liquid waste". This is due to different legal interpretations of the competent authorities within the Italian national territory.

Similarly, the legal framework regulating leachate recirculation on the waste body depends on the territorial context. For example, it can't be performed where landfill leachate is considered a special type of waste, different from the waste body that generated it. This prevents its re-allocation in the landfill where it has been abstracted.

References

Arecco F., ed. 2012, *Biogas Energy*. Edizioni Ambiente Publisher (Energia da biogas)

ASWM Srl, http://www.aswmsrl.com/

Collivignarelli C., ed.1996, *Leachate management from Urban Solid Waste Landfill*, C.I.P.A. Publisher (*Il trattamento del percolato da discarica RSU*)

CONVECO Srl, https://www.conveco.com/en/home.html

Cossu, R., Grossule, V., Lavagnolo, M.C., 2020. *Sustainable Landfill: Role in the Circular Economy and Regulatory Proposals*. CISA publisher (*La Discarica Sostenibile*)

Damiani L., Gandolla M., 1992, Biogas management in controlled landfills, Istituto per l'Ambiente Publisher (*Gestione del biogas da discariche controllate*)

Gervasoni S., ed *2000, The controlled landfills,* HOEPLI Publisher (*Le discariche controllare*)

Il Gestore Servizi Energetici (Gse) incontra la Regione Emilia-Romagna (2011,November,8th), regione.emilia-romagna.it. Retrieved 11:57, March 28th,2022 from https://energia.regione.emilia-romagna.it/leggi-atti-bandi-1/documenti-e-pubblicazioni/eventi/2010/il-gestore-servizi-energetici-gse-incontra-la-regione-emilia-romagna/CREMONA_GSE.pdf.

Magnano E., ed. 2010, *Landfill Biogas*, EPC Publisher (*Biogas da Discarica*)

Vismara R., Malpei F., Centemero M., ed. 2008, *Biogas from Urban Solid Waste*, Dario Flaccovio Publisher *(Biogas da rifiuti solidi urbani*)