# Influence of landfill cap cover characteristics on the mitigation of GHG emissions

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ABSTRACT: Landfill cap covers are one of the key components of modern landfills as they prevent uncontrolled water infiltration and diffuse biogas emissions. The role of the landfill cover in mitigating greenhouse gas (GHG) emissions from landfills is essential. In this paper, an assessment of the GHG emissions from a typical French landfill sub-cell is made. Different scenarios of cap cover characteristics (semi-permeable and impermeable covers) are simulated. Landfill gas (LFG) production, energy recovery from LFG, the oxidation of diffuse emissions and the related substituted emissions are also discussed. The sensitivity of the environmental performance of landfills on the LFG collection and recovery system as well as on the cap barrier characteristics is highlighted. Appropriate cap covers may clearly mitigate landfill emissions, and there is a demand for innovative cap cover systems with long-term efficiency.

## 1 INTRODUCTION

### 1.1. *Landfill design and the use of geosynthetics*

Landfilling remains presently the first treatment option for Municipal solid waste (MSW) and other non-hazardous wastes in France (FNADE, 2007). Landfill gas (LFG, also referred to as biogas) emissions are, along with potential leachate breakouts, one of the major environmental issues related to sanitary landfills.

The key components of modern landfills include a bottom liner, gas and leachate collection systems, a surface water management system, and a final cap cover. The final cover system of a non-hazardous waste landfill is designed to minimize exposure of the waste, control gas emissions, and prevent the uncontrolled infiltration of water into the waste which could potentially result in the bottom leakage of contaminated leachate. These features have to be maintained over time despite potential important differential settlements inducing potential damage to the cap cover. This is why the cap cover for the cells usually evolves with the operation process of the landfill. Often, a temporary cover is installed after the end of the cell fill to enable high settlement rates before the final geocomposite cover is placed. Figure 1a illustrates a typical MSW landfill with its final cover system.

Generally, the final cap cover of non-hazardous waste landfills is composed of a composite material (soil and geosynthetics). In France, for non-hazardous and degradable materials, it is specified that a semi-permeable cover should be used, in order to promote passive humidification through rain water (Figure 1b). New barriers especially designed for bioreactor landfills, in which the natural biodegradation processes are enhanced through controlled moisture addition, are under development. A proposed system could be (Gourc and Staub, 2009; Figure 1c) composed of a drainage layer above the waste materials to collect biogas and to integrate the leachate injection system, an impervious layer (fine soil and geomembrane or geosynthetic clay liner (GCL)), and finally a drainage layer for runoff water, with a soil layer at its top.

### 1.2. *Landfills and global warming*

LFG is composed of 60% Methane ($CH_4$), 40% Carbon dioxide ($CO_2$) (by volume) and trace compounds (Arigala et al., 1995; Reinhart and Townsend, 1997). Methane and Carbon dioxide are both Greenhouse gases (GHG). The effects of Methane, which has a shorter lifetime than Carbon dioxide, have to be considered on a certain time span to be compared to the effects of Carbon dioxide. Atmospheric Methane absorbs infrared rays reemitted by the earth in a far more effective way than Carbon dioxide, hence having a higher Global warming potential (GWP). This effect is especially strong on the short term.

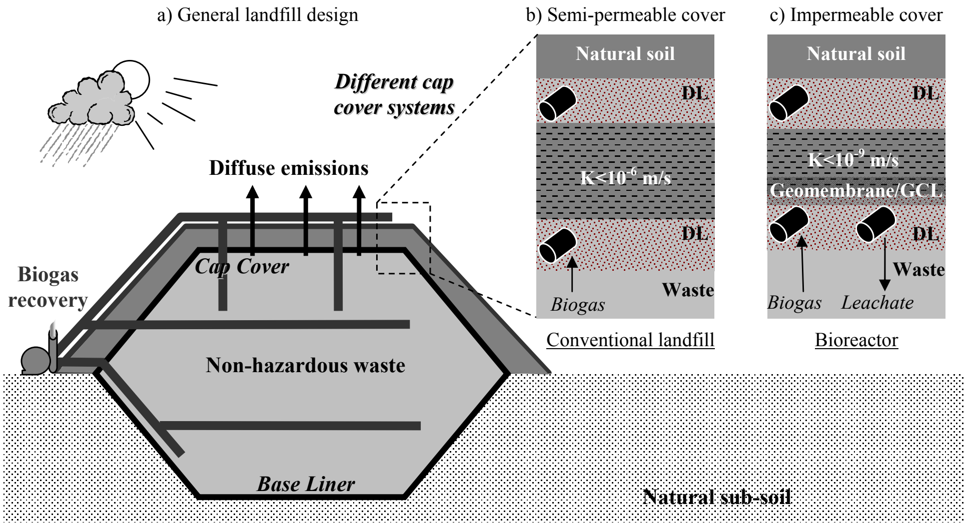


Figure 1: typical landfill design and cover systems for non-hazardous waste. DL=drainage layer.

In France, 3 Tg of Methane were emitted in 2004 from which 16% were emitted from municipal landfill sites. In contrast, 22 Tg of Methane were emitted in the U.S. in 2003 (USEPA, 2006), from which a fourth came from landfills. Worldwide landfill emissions are difficult to quantify due to the absence of data for numerous countries, but estimations range from 3% to 4% of the overall Methane emissions (Spokas et al., 2006). The requirement to control and mitigate Methane emissions is clearly highlighted by these figures. In the field of landfill operation techniques, recent research efforts targeting better recovery rates for LFG or in-situ oxidation of $CH_4$ may reach this objective.

### 1.3. *Calculation of greenhouse gas emissions*

To compare different GHG, the notion of GWP was introduced by the Intergovernmental Panel on Climate Change (IPCC, 2007). By definition, the GWP of Carbon dioxide is equal to 1 for every time horizon. For all the other gases, the GWP is calculated for a given time horizon, even though this information is frequently omitted. The GWP of Methane is 25 at a time horizon of 100 years. This value is recommended by the IPCC since its last report (IPCC 2007). In other terms, 1 kg $CH_4$ is accounted for 25 kg $CO_2$ equivalent (at a time horizon of 100 years). The GWP of Methane is much higher in the short term, as it is 101 for a time horizon of 5 years, and 50 for 40 years for instance.

The general calculation principle used by the IPCC is here followed: Carbon dioxide that is emitted from biogenic sources (i.e. emitted during the aerobic degradation phase as well as oxidized Methane from the methanogenesis) is not included in Carbon dioxide emissions. Finally, Methane emissions, even though they are of biogenic origin, are included in the calculation of emissions, due to the high GWP of Methane, 25, which is considered in the following.

It must be noticed that this study is not a life-cycle analysis. The sequestration of Carbon in landfills is not taken into consideration hereafter, as its importance is still questionable in the Carbon cycle analysis (Staub and Gourc, 2008).

## 2 THEORY AND METHODOLOGY

### 2.1. *Biodegradation and related emissions*

The production of LFG is a consequence of biodegradation of organic MSW that is caused by the action of bacteria and other micro-organisms in wet conditions. At the time of waste deposition in a landfill, oxygen is present in the void space, and this aerobic phase (phase I on Figure 2) is responsible for $CO_2$ emissions from the organic solids during the exothermic aerobic reaction. Oxygen depletion within the landfill (during phases I and II) marks the onset of the anaerobic decomposition phase, methanogenesis (phases III and IV, stable methanogenesis), which mainly results in $CH_4$ and $CO_2$ production.

Readily biodegradable materials, including kitchen and garden waste, as well as putrescible materials will mostly degrade promptly during the aerobic phase, whereas other biodegradable materials, including paper and cardboard, part of the textiles and combustible materials etc. will degrade anaerobically. Inert materials including plastics (fossil Carbon), glass, metals and other waste are not degraded in landfills; however, they may contribute to GHG emissions from fossil sources when incinerated.

The biogas produced during aerobic processes is responsible for biogenic $CO_2$ emissions. Consequently, according to the IPCC calculation method, gas emissions of readily biodegradable matter are not considered.

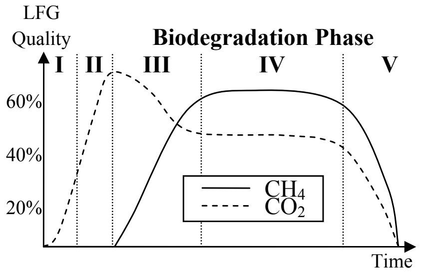


Figure 2: variation of $CH_4$ and $CO_2$ content of LFG.

2.2. *LFG production modelling*

LFG production can be estimated using different production models, a semi-experimental approach is used, basing the calculations of the biogas potential (*BP*, calculated for the methanogenesis) of the waste on the experimental *BP* of its different constituents. This approach differs from the total biodegradable Carbon approach that was considered elsewhere (Staub and Gourc, 2008).

To estimate LFG production, the SWANA model (Cossu et al., 1996) is here considered. This model describes the instantaneous biogas production according to a first-order production rate based on the following equation:

$$Y(t) = BP \cdot k \cdot e^{-k \cdot (t - t_{0B})} \cdot \frac{k + s}{s} \cdot \left(1 - e^{-s(t - t_{0B})}\right)$$

where $Y(t)$ is the LFG yield in $Nm^3$ per tonne dry matter (t DM) per year, $BP$ is the biogas potential during methanogenesis in $Nm^3$/t DM, $k$ is the LFG generation rate, $s$ is the shape parameter of the SWANA model in years$^{-1}$, and $t_{0B}$ is the time when biodegradation starts in years. The value for the LFG generation rate $k$ can be determined using the half-life value $t_{1/2}$ when half of the expected LFG has been produced:

$$k = \frac{\ln(2)}{t_{1/2} - t_{0B}}$$

2.3. *Hypothesis for biogas production*

In France, landfilled waste is composed of approximately 50% Municipal Solid Waste (MSW) and 50% non-hazardous industrial waste. Here, a combination of a typical French MSW and of an average non-hazardous industrial waste is considered. This waste has an estimated biogas potential (*BP*) of 160 $m^3$ LFG/t DM. The composition of this typical waste considered is given on Figure 3 (proportions in dry matter).

To estimate the LFG production, a value of $k$=0.1 years$^{-1}$, i.e. a half-life value $t_{1/2}$=7.5 years were chosen (Cossu et al., 1996). A constant volumetric composition of 60% $CH_4$ and 40% $CO_2$ over the entire biodegradation phase is considered. Biogas production is supposed to start approximately 0.5 years after the first waste layer is disposed in the sub-cell ($t_{0B}$=0.5 years). The results will be displayed as emissions per tonne DM to enable potential emissions of landfills.

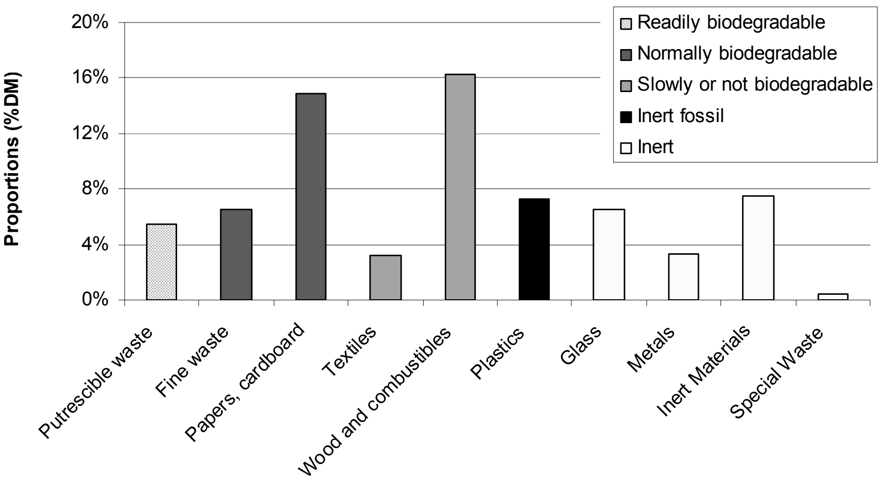


Figure 3: waste composition considered for the evaluation of GHG emissions.

### 2.4. *Considered typical landfill sub-cell*

The theoretical case study is considered for a French landfill of average size (150,000 t waste per year). Landfills are generally composed of hydraulically independent sub-cells. Regulation imposes a sub-cell area of 5000 m² and landfill depths usually reach around 30 meters. The average density considered for the waste is 1 t/m$^3$. For this study, a simple cuboidic design is considered; the sub-cell's volume is calculated by multiplying the area of the sub-cell by its average height. The filling time of the cell hence takes exactly one year with these figures. The reference time ($t$=0) is equal to half the filling time.

### 2.5. *Cap covers and landfill management steps*

Two different case studies will be considered in the following:

- a first scenario (Scenario 1) with a semi-permeable final cover system (Figure 1b);
- a second scenario (Scenario 2) where an impermeable cover is used (Figure 1c).

For both scenarios, 4 different steps are considered (A to D, see Table 1): operation, post-operation, aftercare and long-term custodial care. During the 1-year operation time (Step A), a collection efficiency of 35% is assumed. During post-operation (Step B), the final cover is already placed for Scenario 1 and a temporary cover (generally geosynthetic, see Figure 4) is installed for Scenario 2 with respectively 50% and 65% of LFG collection efficiency. A final cover is placed after 2 more years for Scenario 2 (Step C). Finally, a custodial care phase (Step D) is considered where no active treatment of the emissions is maintained on-site. The values for the capture efficiencies (CE) are taken from the literature (ADEME, 2006; Spokas et al., 2006).

Table 1: steps and gas collection efficiencies (CE) for the considered scenarios. Temp.=Temporary cover.

| Steps | A | B | C | D |
|---|---|---|---|---|
| Period | Operation | Post-operation | Aftercare | Custodial care |
| Duration | 1 year | 2 years | 28 years | 70 years |
| *Scenario 1* | | | | |
| Cover type | None | Final | Final | Permanent |
| CE | 35% | 50% | 50% | ? |
| *Scenario 2* | | | | |
| Cover type | None | Temp. | Final | Permanent |
| CE | 35% | 65% | 90% | ? |

### 2.6. *Biogas treatment*

Once collected, the biogas is either flared or used to generate electricity and/or heat. Flares simply convert Methane to Carbon dioxide and hence reduce drastically potential emissions (see Section 1.3). Here, energy recovery is considered as long as it is technically and economically viable. When the collected biogas is used to generate energy, this energy production can replace a large variety of other methods of energy production. Hence, according to the substitution principle, GHG emissions may be subtracted from the overall GHG balance as a result of energy production from biogas recovery (Camobreco et al., 1999). To account for these substituted emissions, a lower heating value of 21.4 MJ/Nm$^3$ for LFG was considered.

It is considered from that 80% of the collected biogas is used for energy recovery as long as the incoming flow is sufficient for the energy recovery plant (personal communication from operators). The energy recovery plant is supposed to achieve a high performance thanks to cogeneration technology (electricity generated from a turbine as well as heat generation). An efficiency of 60% is considered for the cogeneration plant, taking into account the variability in quality and quantity of the resource (FNADE, 2007).

A minimum threshold of 18.75 Nm$^3$ of LFG per hour (164,000 Nm$^3$/year) for one sub-cell as considered here was defined for energy recovery, based on French recommendations and for an average landfill size (INERIS, 2005). Once the LFG flow has reached this limit, a simple flare is maintained on-site until biogas production reaches 10 Nm$^3$ LFG per hour for one sub-cell (87,600 Nm$^3$/year). These thresholds and their effect on the global GHG balance will be discussed in the next section.

Figure 4: photo of a temporary "covertop" system.

## 3 RESULTS

### 3.1 *LFG production and collection*

The simulated LFG productions for the typical sub-cell as well as the collected LFG volume are given on Figure 5 and Figure 6. The different steps A through C with increasing collection efficiencies are clearly visible (see Table 1). Biogas production reaches its maximum 3 years after the start of biogas production. For Scenario 2, it may be noticed that the placement of the final cover 3 years after the beginning of operation seems relevant, the large majority of the biogas being produced after 3 years, as the half-life value for the considered waste type is $t_{1/2}$=7.5 years.

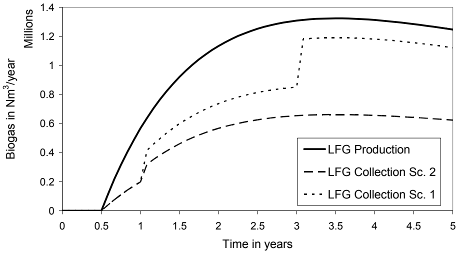


Figure 5: Simulated LFG production and collection for both scenarios for the 5 first years.

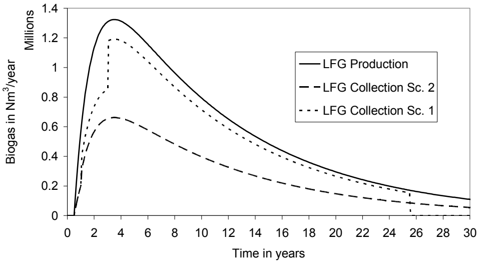


Figure 6: Simulated LFG production and collection for both scenarios for the 30 first years.

## 3.2 *Influence of cap cover type*

It is also remarkable to notice the effect of the cover type scenario on the biogas treatment strategy (Table 2). As the collected flows are substantially higher in Scenario 2 where an impermeable cover is considered, it is possible to maintain an energy recovery plant much longer on-site. Hence, impermeable covers might be seen as incentives for enhanced recovery rates, which, in turn, may benefit financially to the operators as the sale of the generated energy may reduce operation costs on the long-term.

Table 2: time and flow thresholds for one sub-cell for the flare and the energy recovery plant (ERP).

| | Time threshold | Flow threshold |
|---|---|---|
| *Scenario 1* | | |
| Flare deadline | 25.5 years | 10 $Nm^3/h$ |
| ERP deadline | 19 years | 18.75 $Nm^3/h$ |
| *Scenario 2* | | |
| Flare deadline | 31 years | 10 $Nm^3/h$ |
| ERP deadline | 24.75 years | 18.75 $Nm^3/h$ |

## 3.3. *Carbon balance and collection efficiency*

The integrated emissions over the entire lifespan of the landfill (here, 100 years are considered) are given on Figure 7. The use of a biogas collection and treatment system divides potential emissions by a factor 2 when a semi-permeable cover is installed (Scenario 1) and by approx. 5 if an impermeable cover is installed (Scenario 2). The net balance is even better if avoided emissions from energy recovery are considered (reduction of 91% of the potential emissions for Scenario 2).

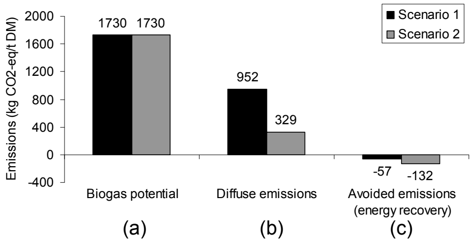


Figure 7: Simulated overall emissions and substitutions for both scenarios (time span is 100 years).

At the end of the aftercare period, current commitments of the operators induce that no flare or energy recovery plant is maintained on-site. From the modelled LFG production (Figure 6), the residual potential Carbon dioxide emissions represent 10% and 6% of the overall emissions for the scenarios 1 and 2 respectively, i.e. 173 and 104 kg $CO_2$-eq. The following section discusses what possible treatment options for these residual emissions exist.

## 3.4. *Discussion: reducing the residual emissions*

Once both the energy recovery plant and the flare are stopped or withdrawn from the landfill for technical or/and economical reasons (see Table 2), a certain amount of the original biogenic Carbon still remains in the landfill. This Carbon may potentially harm the environment on the long term as it may be emitted to the atmosphere without any treatment. The residual fluxes being relatively low, but emitted on a long time scale, oxydizing covers have been chosen to simulate their treatment.

Different options exist for the oxidation of residual methane fluxes: thin biocovers designed to cover the entire surface of the facility, or biofilters that replace the flare, being placed at the end of the biogas drainage system (Cabral et al., 2008; Perdikea et al., 2008).

For Scenario 1, the simulated option is a thin biocover on the entire sub-cell surface, it seems the preferable option as a semi-permeable cover is installed. On the contrary, for Scenario 2, a biofilter is simulated, as the cap cover efficiency is supposed to be far better than for the semi-permeable scenario.

The thin biocover (Sc. 1) is supposed to reach a methane oxidation efficiency of 75% until a maximum flow rate (for a 0.3 m thick 90% compost-10% sawdust cover, according to Perdikea et al., 2008). The biofilter (Sc. 2) is supposed to reach a methane oxidation efficiency of 85% (for a 500 m² large, 0.75 m thick compost biofilter with active LFG collection, according to CSD-Azur-ADEME, 2005).

The capture efficiency of the biogas drainage system (for Sc. 2), set at 90% during the whole after-care and custodial care period, is questionable. It is here hypothesized that this efficiency remains constant, but the durability of geosynthetic liners on the long term under severe conditions is to be validated.

Figure 8 details the residual diffuse emissions, the oxidized emissions and the net balance after all treatment (energy recovery, flaring and methane oxidation barriers). It can be seen that, after all treatments, more than 93% of the initial potential emissions (1730 kg $CO_2$-equivalent) may be mitigated when an impermeable cover is installed (Sc. 2), but this figure drops to only 56% when a semi-permeable cover is present (Sc. 1).

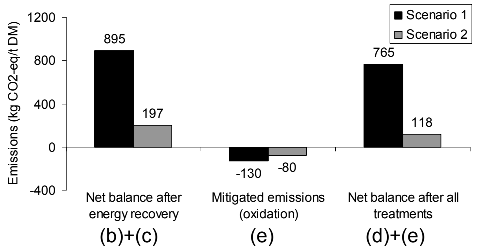


Figure 8: Simulated overall emissions, Mitigated emissions through oxidation and Net balance after all treatments for both scenarios (time span is 100 years).

## 4 CONCLUSIONS AND PERSPECTIVES

In this paper, a typical landfill sub-cell is considered and its LFG emissions are assessed to compare GHG emissions with different types of cap covers. The mitigation of LFG emissions is highly dependent on the nature of the cap cover. Impermeable barriers enable better recovery rates and long-term economic advantages due to the improved associated energy recovery.

However, some questions still remain to be answered, particularly concerning the durability of cap covers. Of course, the long-term environmental performance of landfill sites is highly dependent on the durability of these materials and of the geosynthetic structure of the cover. Another challenge is also to innovate for composite covers designed both for high biogas capture rates and homogeneous leachate recirculation (bioreactor landfills).

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