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Landfilling of waste: accounting of greenhouse gases and global warming contributions

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Accounting of greenhouse gas (GHG) emissions from waste landfilling is summarized with the focus on processes and technical data for a number of different landfilling technologies: open dump (which was included as the worst-case-scenario), conventional landfills with flares and with energy recovery, and landfills receiving low-organic-carbon waste. The results showed that direct emissions of GHG from the landfill systems (primarily dispersive release of methane) are the major contributions to the GHG accounting, up to about 1000 kg CO_2-eq. tonne^{-1} for the open dump, 300 kg CO_2-eq. tonne^{-1} for conventional landfilling of mixed waste and 70 kg CO_2-eq. tonne^{-1} for low-organic-carbon waste landfills. The load caused by indirect, upstream emissions from provision of energy and materials to the landfill was low, here estimated to be up to 16 kg CO_2-eq. tonne^{-1}. On the other hand, utilization of landfill gas for electricity generation contributed to major savings, in most cases, corresponding to about half of the load caused by direct GHG emission from the landfill. However, this saving can vary significantly depending on what the generated electricity substitutes for. Significant amounts of biogenic carbon may still be stored within the landfill body after 100 years, which here is counted as a saved GHG emission. With respect to landfilling of mixed waste with energy recovery, the net, average GHG accounting ranged from about –70 to 30 kg CO_2-eq. tonne^{-1}, obtained by summing the direct and indirect (upstream and downstream) emissions and accounting for stored biogenic carbon as a saving. However, if binding of biogenic carbon was not accounted for, the overall GHG load would be in the range of 60 to 300 kg CO_2-eq. tonne^{-1}. This paper clearly shows that electricity generation as well as accounting of stored biogenic carbon are crucial to the accounting of GHG of waste landfilling.

Keywords: Global warming, GHG accounting, waste landfilling, LFG utilization, biogenic carbon

Introduction

Landfilling is the most common waste disposal method throughout the world. In a global warming (GW) context, the landfill is a complex unit because so many aspects must be included when counting greenhouse gases (GHGs). Methane is a major emission from landfills caused by degradation of organic matter, but methane may also be converted prior to discharge or recovered and used for energy purposes thereby potentially off-setting energy based on fossil fuels. Within the foreseeable future, for example, 100 years, not all biogenic carbon in a landfill will be released, and bound biogenic carbon may be considered a sink of carbon and the landfill should potentially be credited for this.

Landfilling technologies have developed dramatically during the last few decades, although this development has not yet been implemented in all parts of the world. Landfills range from dumps to highly engineered facilities as bioreactor landfills, flushing-bioreactor landfills and semi-aerobic landfills (Manfredi & Christensen 2009). The engineered landfills may have a range of landfill gas utilization and control systems leading to dramatically reduced emissions of methane and recovery of energy.

Most of our current knowledge on landfills stems from mixed municipal solid waste (MSW) landfills, but in many countries in Europe landfilling of organic waste is being reduced, and in

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the future, landfills with less organic matter will become common. These landfills will generate less gas, but they may also contribute to GW because the landfill gas recovery is likely to be less efficient (Manfredi *et al.* 2009).

The main purpose of this paper is to describe landfilling of waste from a GW point of view and to provide information about data that is useful in accounting for GHG emissions including the energy recovery by landfill gas (LFG) utilization and sequestering of biogenic carbon in the landfill body. The GHG accounting is done as suggested by Gentil *et al.* (2009), distinguishing between direct and indirect contributions and between fossil and biogenic CO_2. Biogenic CO_2 is considered neutral with respect to GW when emitted but biogenic carbon bound in the landfill is considered a saving according to Christensen *et al.* (2009).

According to the Kyoto protocol, GHG emissions should for each nation be reported annually, and the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (Eggleston *et al.* 2006) provides detailed guidelines on how annual GHG emissions from landfills can be estimated. The current annual landfill emissions on a national scale consists of contributions from many different landfills of different ages and for the individual landfill from waste of different ages and levels of degradation. Much of the waste that currently contributes to GHG emissions from landfills originates from a time where data on waste amounts and composition was rudimentary. Therefore, the IPCC provides guidance on how estimates can be made on a sparse level of actual data. In the current paper we take a more generic approach and assume that data is available on the waste entering the landfill and that the degradation of organic carbon follows our current general understanding of landfill processes. Furthermore, the current paper focuses on 1 tonne of waste and accumulates the emissions that are expected for a 100-year period into a time-integrated value. The aim of the paper thus is to provide insight into the individual contributions to GHG emissions from waste landfilling and provide likely ranges for the contributions from the technology point of view. This approach is in particular valuable when comparing landfilling with other waste management options. For the purpose of the annual national accounting reference should be made to the IPCC (Bogner *et al.* 2007) and for the annual accounting of a single landfill guidance can be found, for example, in Scharff & Jacobs (2006).

Overview of solid waste landfilling technologies

The following sections provide a general description of the key characteristics of the principal waste landfilling technologies, from dump to modern engineered facilities. The main focus is on the issues that are considered important with respect to GW and GHG accounting.

Dump

The dump here refers to a landfill where many different kinds of waste are disposed of with little or no benefit of an engineering plan the waste is not compacted, no measures exist to prevent gas and leachate emissions to the environment, and the waste is not covered. The dump is today not considered good landfilling technology, but has, however, been included as a worst-case reference, since dumps are still used in developing countries. Infiltrating rainwater results in leachate that migrates into the soil and aquifer below the landfill. The LFG generated from degradation of organic matter is assumed to be emitted directly to the atmosphere. Carbon losses are by way of dissolved carbon in leachate and methane and carbon dioxide in LFG. Volatile organic compounds in LFG might also contribute to GW; for example, chlorofluorocarbons (CFCs).

Conventional landfill

A conventional landfill, as typically defined, is a landfill that implements technical measures to collect and manage the leachate and gas generated. With regard to leachate handling, these measures usually included bottom and side liners, a leachate collection system and leachate treatment prior to discharge to surface water bodies. With regard to gas handling, these measures include a gas collection system, gas treatment in flares and maybe top soil cover for mitigation of emissions of uncollected gas. This type of landfill is referred to as 'conventional' because active measures to enhance the waste degradation (e.g. leachate recirculation, water addition, air injection, etc.) are not taken (Manfredi & Christensen 2009). The organic waste content is significant and waste degradation may be taking place over long periods, ranging from a few years to decades for the most biodegradable compounds to more than a century for the less degradable materials.

The construction and operation of the landfill contribute to GW by the use of materials (e.g. liner materials), fuels used in machinery for soil moving and waste compaction, and electricity used on-site (e.g. administration facilities, light on-site, leachate treatment, and gas pumps). Mitigation of GHG emissions is typically carried out in conventional landfills through combustion of LFG in flares and maybe passive oxidation of methane in top covers. A key factor is the LFG collection system. The effectiveness of these measures is highly variable due to the many technical and environmental factors involved. In addition, the duration of the active gas management in conventional landfills may not be enough to reach sufficiently low gas generation rates that a merely passive oxidation in the top cover can mitigate efficiently.

Engineered landfills with energy recovery

During recent decades new engineered landfilling technologies have been developed, including bioreactor, flushing-bioreactors and semi-aerobic landfills. In addition to the technical measures implemented in conventional landfills, these technologies adopt active measures to enhance the waste degradation process, in order to make it faster and more efficient. This leads to high gas generation rates early in the life of the landfill (higher than experienced in conventional landfills), which makes it more valuable to ensure an efficient gas collection system and undertake gas utilization schemes, such as electricity or combined heat and power (CHP) generation. The level of on-site construction and operation needed, however, increases accordingly (Manfredi & Christensen 2009).

Bioreactors landfills typically recirculate collected leachate through the waste mass; this keeps the waste moisture content close to field capacity and provides a continuous supply of moisture and nutrients, resulting in an enhancement of the microbial anaerobic environment. Flushing-bioreactor landfills recirculate the leachate together with additional amounts of water in order to flush-out the soluble waste constituents. This is often combined with measures to prevent excessive leachate ammonia, such as leachate nitrification–denitrification. Semi-aerobic landfills rely on a hybrid anaerobic/aerobic degradation sequence. The anaerobic phase comes first and it is stopped by air injection when the methane yield becomes too low to justify LFG utilization (typically after 5 to 10 years). The aerobic degradation phase will then quickly stabilize the waste, blocking, at least in theory, residual methane generation.

Engineered landfill for low organic waste

Landfilling of organic waste in Europe has progressively been reduced due to the implementation of the EU Landfill Directive (CEC 1999). A number of well established technologies are available for treatment of organic waste, but still in many countries landfilling of waste with low organic content is unavoidable. Similar to engineered landfills, these landfills adopt technical measures to collect and treat the generated leachate. The gas management, however, is typically rather simple, as degradation of low organic waste does not lead to a significant methane yield (typically below 10 to 15 m^3 CH_4 $tonne^{-1}$ wet low-organic waste, compared to 60–90 m^3 CH_4 $tonne^{-1}$ wet household waste) and thus does not always justify investment in gas utilization technologies. Low-organic waste landfills are expected to rely on gas flaring in combination with passive oxidation of methane in the top soil cover. A gas utilization scheme may, however, be successfully implemented at low-organic waste landfills, although on a reduced scale compared to high-organic waste landfills. An example is the Nauerna landfill (The Netherlands), where part of the collected gas is used internally to heat and cool the office and to warm up the biological reactor of the leachate treatment plant (LTP) (Manfredi *et al.* 2009a).

Defining landfill technology and related greenhouse gas emissions

Greenhouse gas emissions are defined in terms of the types listed here.

- Direct emissions, which are emissions or avoided emissions directly linked to activities at the landfill site and the degradation of the waste.
- Indirect emissions, which are emissions or avoided emissions associated with the landfill but actually taking place outside the landfill site. These are here divided into two groups.
  - Upstream emissions, which are related to activities such as production of materials and electricity used at the site, the provision of fuels used on the site and the construction of the facilities.
  - Downstream emissions, which are related to activities such as the off-set of energy production substituted by the energy recovered at the site, for example, in terms of electricity, maybe heat or clean biogas delivered and converted at other facilities outside the landfill.

A number of emission factors have been used in the calculations as listed in Table 1.

Direct emissions

The prime GHG from landfilling is methane generated by anaerobic degradation of the waste inside the landfill body. The volume of methane generated depends not only on the biogenic carbon content of the waste landfilled but also on which material fractions contain the carbon. Organic kitchen waste has a high degree of degradability, whereas paper and in particular wood have a low degree of degradability within the landfill (Table 2) (Camobreco *et al.* 1999, Barlaz 2005). The global warming contribution of the LFG depends on any conversion of methane to carbon dioxide by combustion in flares or gas engines or by microbial oxidation in the soil top cover of the landfill. CH_4 converted to CO_2 has no global warming potential since we assume biogenic CO_2 to be neutral with respect to global warming. Considering biogenic CO_2 emitted as neutral with respect to global warming also dictates that non-biogenic carbon (e.g. in plastic and rubber) left in the landfill is neutral with respect to GW (Christensen *et al.* 2008). These issues are quantified below for the individual landfill technologies. Biogenic carbon that is not released within the 100-year period equals an avoided emission of biogenic carbon dioxide and must mathematically be considered a saving with respect to GW (Christensen *et al.* 2008).

The losses of carbon are by gas (see above) and to a minor extent by leaching of dissolved organic C. The latter is for a typical landfill of the order of 1–4% of the carbon in the

Table 1: Emission factors relevant in GHG accounting for landfilling.

Type of process/emission	Emission factor	Reference
Provision of diesel fuel	0.4–0.5 kg CO_2-eq. L^{-1} diesel	Fruergaard *et al.* (2009)
Combustion of diesel fuel	2.7 kg CO_2-eq. L^{-1} diesel	Fruergaard *et al.* (2009)
Provision of electricity	0.1–0.9 kg CO_2-eq. kWh^{-1}	Fruergaard *et al.* (2009)
Provision of HDPE for synthetic liner	1.85 kg CO_2-eq. kg^{-1} HDPE	EASEWASTE database
Provision of gravel	1.4 kg CO_2-eq. $tonne^{-1}$ wet waste	EASEWASTE database

Table 2: Typical ranges of biogenic carbon contents of various waste fractions. (Eleazer *et al.* 1997.; Barlaz 1998, Eggleston *et al.* 2006, Riber *et al.* 2009, US EPA 2006, Manfredi *et al.* 2009).

Material fraction	Biogenic carbon content (kg C tonne^{-1} wet fraction)	Dissimilation factor of biogenic carbon as LFG (D_{LFG})
Household waste (all fractions)	160–200	0.50
Kitchen organics	100–120	0.64
Newspapers	360–440	0.2
Office paper	300–360	0.88
Cardboard	300–380	0.45
Wood	400–450	0.23
Plastic	0 (650–750 of C fossil)	0
Glass	0	0
Metals	0	0
Predominantly mineral waste	15–25	0

waste (based on simulation with the EASEWASTE model). The leaching of biogenic carbon has no direct effect on GW, but must be accounted when calculating the amount of biogenic carbon left in the landfill. Neglecting the loss of C by leaching will overestimate the carbon binding in the landfill when based on a carbon mass balance of the landfill. Organic carbon in the leachate calls for treatment of the leachate and thereby electricity consumption may increase.

Direct emissions are also from the combustion of the diesel fuel used on-site in dozers, compactors and other landfill vehicles. Combustion of diesel fuel is assumed to lead to an emission of 2.7 kg CO_2 L^{-1} diesel (Fruergaard *et al.* 2009). Fuels combusted by the waste collection trucks while unloading and driving on the site are not included here but ascribed to collection and transport of waste (Eigtved *et al.* 2009). The fuel consumption at the landfill site depends on the degree of compaction and the amount of soil that is excavated and/or moved for daily cover. Only a small amount of data has been found in the literature, but typical values seem to be in the range 1–3 L diesel tonne^{-1} waste landfilled (cumulative amount throughout the entire lifetime of the landfill) (Hunziker & Paterna 1995, Manfredi & Christensen 2009, Niskanen *et al.* 2009).

Indirect emissions

The upstream contributions to GW are for the landfill related to the following items.

- Provision of diesel fuels for soil works at the site for construction of the landfill. Little data are available in the literature but the contribution is considered small, around 0.5–1 L diesel tonne^{-1} wet waste landfilled assuming that about 1 m^3 of soil is moved and transported 5 km tonne^{-1} of landfill capacity. Provision (inclusive of production and transport) of diesel fuel is assumed to lead to emissions of 0.4–0.5 kg CO_2 L^{-1} diesel (Fruergaard *et al.* 2009).
- Provision of diesel fuel for specialized vehicles for daily on-site operations.
- Provision of electricity used for light on the site, administration buildings, pumps and fans. This may amount to 2–12 kWh tonne^{-1} waste landfilled (Hunziker & Paterna 1995, Niskanen *et al.* 2009). Provision of electricity is here counted as 0.1–0.9 kg CO_2-eq. kWh^{-1} electricity (Fruergaard *et al.* 2009): this interval covers a broad variety of electricity mixes, ranging from a mix mostly based on natural gas use to a mix mostly based on coal use.
- Provision of liner materials [here assumed as high-density polyethylene (HDPE)]: a petroleum-based synthetic lining (2 mm thick) of the landfill corresponds to about 1 kg liner tonne^{-1} waste assuming a 20 m landfill depth. The EF for producing HDPE is about 1.85 kg CO_2 kg^{-1} liner based on the EASEWASTE database. This includes the energy used in producing the liner, but does of course not include the fossil carbon contained in the liner material.
- Provision of gravel or crushed rock for construction of the drainage system etc. is assumed to be of the order of 0.1 tonne material tonne^{-1} wet waste (ww) landfilled for a 20 m deep landfill. The EF for producing gravel or crushed rock is about 1.4 kg CO_2 tonne^{-1} of material (estimated from the EASEWASTE database).

The downstream contributions to GW for the landfill are primarily related to the following item.

- Delivery of electricity or maybe heat from conversion of LFG. Conversion of collected gas is efficient: typical values are 25–35% for electricity and maybe 40–50% for heat. Producing electricity only is the most common approach, because the demand for heat may be very low in the vicinity of the landfill. The crediting depends on how these energy deliverables are used and what they substitute for. The main credits are obtained if substituting for energy produced by coal, while no crediting is obtained when substituting for hydro-power, wind-power or other energy based on renewable sources (e.g. biomass) (see Fruergaard *et al.* 2009).

Estimating greenhouse contributions for landfilling

Greenhouse contributions are here accounted for the following types of landfill.

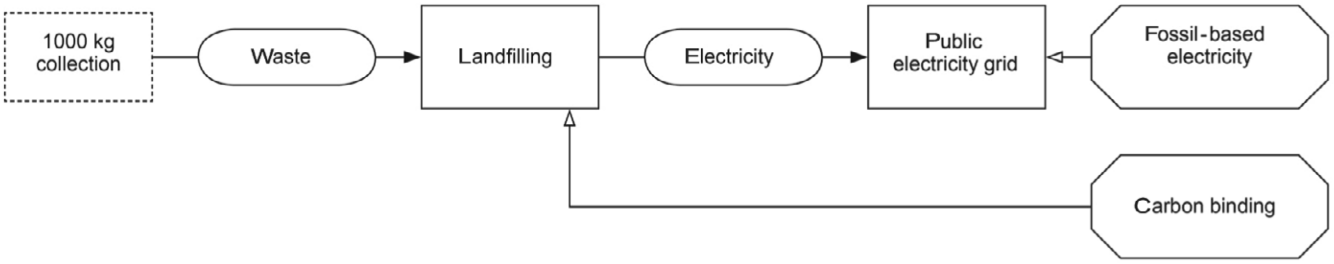

Fig. 1: Illustration of the landfilling systems considered in the study.

Table 3: Biogenic carbon content and dissimilation factors of the different waste types considered (Barlaz 1998, US EPA 2006, Manfredi *et al.* 2009).

Waste type	Biogenic carbon content (kg C tonne^{-1} ww)	Dissimilation factor of biogenic carbon as LFG (D_{LFG})	Dissimilation factors of biogenic carbon as leachate ($D_{Leachate}$)
Mixed waste	75–105	0.50	0.04 (dump) 0.02 (other landfills)
Low-organic waste	30–40	0.33	0.02

- A dump (mixed waste) – primarily representing a worst case reference.
- A conventional landfill (mixed waste) with flaring of collected landfill gas.
- A highly engineered landfill (mixed waste) with extensive gas collection and utilization.
- A low-organic waste landfill as expected to develop in Europe in the future.

A schematic illustration of the general structure of the landfilling systems considered is given in Figure 1, showing that biogenic C left in the landfill after 100 years should be considered as well as the substitutional value of any electricity delivered to the grid as produced by the combustion of LFG as a fuel. The waste degradation process is approached by assuming that the amount of biogenic carbon in the landfilled waste gradually decreases throughout the 100-year time horizon due to emissions of both gas and leachate. This is mathematically accounted for by means of two dissimilation coefficients, D_{LFG} and $D_{Leachate}$ (Table 3), expressing the fractions of biogenic carbon in the landfilled waste input that leaves the waste via emissions of gas and leachate within 100 years, respectively. The dissimilation coefficients used in the calculation are based on IPCC (2006) and Barlaz (2005). It should be mentioned that the dissimilation coefficients used in the modelling represent landfilling conditions where water is constantly available and do not limit the waste degradation process. This might, however, not apply to a landfill located in a water-deficient area. In such an environment, water availability often constitutes the limiting factor for waste degradation and, as a consequence, gas generation and emission are also reduced.

The input waste considered in the GHG accounting varies across the different landfilling scenarios. Dump and conventional landfill receive an input of mixed waste; engineered landfills can instead receive either mixed waste or low-organic waste (Tables 2 and 3). Mixed waste is here defined assuming that, on a mass base, half of the waste is predominantly inert and half is household waste. Based on the content of biogenic carbon specific of these two fractions (Table 2), the overall biogenic carbon content of the mixed waste type is estimated to be 75–105 kg tonne^{-1} ww landfilled. The quality of low-organic waste does not reflect a specific composition and therefore the waste carbon content is based on average values from existing landfills of this type (Manfredi *et al.* 2009).

Based on the content of biogenic carbon (C, in kg tonne^{-1} ww) and assuming that on a mass base 55% of the carbon becomes CH_4 and 45% becomes CO_2, the overall amount of methane and carbon dioxide generated within 100 years of degradation (G_{CH4}, in m^3 CH_4 tonne^{-1} wet waste; G_{CO2} in m^3 CO_2 tonne^{-1} ww) is estimated by:

$$G_{CH4} = \mathrm{C} \times D_{LFG} \times \frac{55}{100} \times \frac{16}{12} \times 1.40 \tag{1}$$

$$G_{CO2} = \frac{45}{55} \times G_{CH4} \tag{2}$$

where 1.40 is the volume (m^3) occupied by 1 kg methane at standard temperature and pressure (STP: $T = 0$ °C, $P = 101.3$ kPa). For a landfill where the generated LFG is not collected, the overall emission of methane ($CH_{4\mathrm{Emitted}}$, in m^3 CH_4 tonne^{-1} ww) and carbon dioxide ($CO_{2\mathrm{Emitted}}$, in m^3 CO_2 tonne^{-1} ww) to the atmosphere is equal to the amount of methane and carbon dioxide generated, respectively (assuming zero attenuation):

$$CO_{2\mathrm{Emitted}} = G_{CO2} \tag{3}$$

$$CH_{4\mathrm{Emitted}} = G_{CH4} \tag{4}$$

For a landfill where, instead, the generated LFG is collected (collection efficiency is defined by the parameter ε) and treated in flares (or utilized for electricity generation at a power plant) the overall emission of methane ($CH_{4\mathrm{Emitted}}$, in m^3 CH$_4$ tonne^{-1} ww) within 100 years is given by dispersive emission from the landfill surface ($CH_{4\mathrm{Dispersive}}$, in m^3 CH$_4$ tonne^{-1} ww) and emission of unoxidized methane from flares ($CH_{4\mathrm{Flares}}$, in m^3 CH$_4$ tonne^{-1} ww) or from the power plant ($CH_{4\mathrm{PowerPlant}}$, in m^3 CH$_4$ tonne^{-1} ww). $CH_{4\mathrm{Dispersive}}$ and $CH_{4\mathrm{Flares}}$ or $CH_{4\mathrm{PowerPlant}}$ therefore depend on the average methane oxidation efficiency provided by the top cover (defined by the parameter β) and by the treatment in flares or the power plant (defined by the parameter η):

$$CH_{4\mathrm{Dispersive}} = G_{\mathrm{CH4}} \times (1 - \varepsilon) \times (1 - \beta) \tag{5}$$

$$CH_{4\mathrm{Flares/PowerPlant}} = G_{\mathrm{CH4}} \times \varepsilon \times (1 - \eta) \tag{6}$$

Likewise, the overall emission of carbon dioxide ($CO_{2\mathrm{Emitted}}$, in m^3 CO$_2$ tonne^{-1} ww) within 100 years is given by dispersive emission from landfill top cover ($CO_{2\mathrm{Dispersive}}$, in m^3 CO$_2$ tonne^{-1} ww) and emission from flares ($CO_{2\mathrm{Flares}}$, in m^3 CO$_2$ tonne^{-1} ww) or from the power plant ($CO_{2\mathrm{PowerPlant}}$, in m^3 CO$_2$ tonne^{-1} ww). $CO_{2\mathrm{Dispersive}}$ accounts for the direct emission of the generated carbon dioxide and for the carbon dioxide generated from methane oxidation in top cover. $CO_{2\mathrm{Flares}}$ accounts for direct emission from flares (or power plant) and from conversion of methane in flares (or power plant):

$$\begin{aligned} CO_{2\mathrm{Dispersive}} &= G_{\mathrm{CO2}} \times (1 - \varepsilon) + G_{\mathrm{CH4}} \times (1 - \varepsilon) \times \beta \\ &= (1 - \varepsilon) \times (G_{\mathrm{CO2}} + G_{\mathrm{CH4}} \times \beta) \end{aligned} \tag{7}$$

$$\begin{aligned} CO_{2\mathrm{Flares/PowerPlant}} &= G_{\mathrm{CO2}} \times \varepsilon + G_{\mathrm{CH}} \times \varepsilon \times \eta \\ &= \varepsilon \times (G_{\mathrm{CO2}} + G_{\mathrm{CH4}} \times \eta) \end{aligned} \tag{8}$$

Biogenic carbon left in the landfill (C_{left}, in kg C tonne^{-1} ww) and its related global warming factor ($GWP(C_{\mathrm{left}})$, in kg CO$_2$-eq. kg^{-1} of wet waste) are estimated by:

$$C_{\mathrm{left}} = C - C \times (D_{\mathrm{LFG}} + D_{\mathrm{Leachate}}) \tag{9}$$

$$GWF(C_{\mathrm{left}}) = -\frac{44}{12} \times C_{\mathrm{left}} \tag{10}$$

The global warming factor from emissions of landfill gas ($GWF(LFG)$, in kg CO$_2$-eq. tonne^{-1} ww) is estimated considering only methane by a factor of 25 (1 kg of CH$_4$ = 25 kg of CO$_2$):

$$GWF(LFG) = 25 \times CH_{4\mathrm{Emitted}} \tag{11}$$

Finally, the avoided global warming factor from the utilization of the electricity generated from the landfill gas energy recovery ($GWF(LFG_{\mathrm{utilization}})$, in kg CO$_2$-eq. tonne^{-1} ww) has to be estimated. $GWF(LFG_{\mathrm{utilization}})$ depends on the amount of methane that is actually delivered to the power plant ($G_{\mathrm{CH4}} * \varepsilon$), the energy content of the methane (EC = 37 MJ m^{-3} CH$_4$, which is equal to 10.3 kWh m^{-3} CH$_4$), the specific energy recovery efficiency achieved (here defined by the parameter λ) and the emission of carbon dioxide from electricity provision (EP = 0.1–0.9 kg CO$_2$-eq. kWh^{-1}). The following equation will be used:

$$GWF(LFG_{\mathrm{utilization}}) = - G_{\mathrm{CH4}} \times \varepsilon \times EC \times \lambda \times EP. \tag{12}$$

Dump

A dump is characterized by the lack of controls of landfill gas emissions and of leachate emissions. Regarding global warming potential, it is assumed that all generated methane escapes to the atmosphere and that no oxidation occurs. The waste input to the dump is assumed to be "mixed waste", as defined in Table 3. The biogenic carbon content (C = 75–105 kg tonne^{-1} ww) is dissimilated by 50% by emission of landfill gas (D_{LFG} = 0.5) and by 4% by emission of leachate (D_{Leachate} = 0.04). The biogenic carbon not converted into gas or washed out is assumed to stay in the landfill. By using equations (1) to (4) and (7) to (11), the following estimates are found:

$G_{\mathrm{CH4}} = CH_{4\mathrm{Emitted}}$ = 38.5–53.9 m^3 CH$_4$ tonne^{-1} ww

(at STP equal to 27.5–38.5 kg CH$_4$ tonne^{-1} ww)

$G_{\mathrm{CO2}} = CO_{2\mathrm{Emitted}}$ = 31.5–44.1 m^3 CO$_2$ tonne^{-1} ww

(at STP 61.9–86.6 kg CO$_2$ tonne^{-1} ww)

C_{left} = 34.5–48.3 kg of biogenic C tonne^{-1} ww

or about 46% of the original biogenic

C content in the waste.

$GWF(C_{\mathrm{left}})$ = –126.5 to –177.1 kg CO$_2$-eq. tonne^{-1} ww

$GWF(LFG)$ = 687.5–962.5 kg CO$_2$-eq. tonne^{-1} ww

The overall GHG accounting is given in Table 4.

Conventional landfill with flares

The waste input to the conventional landfill is assumed to be 'mixed waste', as defined in Table 3. The biogenic carbon content (C = 75–105 kg tonne^{-1} ww) is dissimilated by 50% by emission of landfill gas (D_{LFG} = 0.5) and by 2% by emission of leachate (D_{Leachate} = 0.02). The biogenic carbon not converted into gas or washed out is assumed to stay in the landfill. The landfill gas is collected, and the average collection efficiency over 100 years is ε = 50–80%, inclusive of the post-closure lifetime of the landfill during which time LFG collection may or may not be practised. The collected gas fraction is

Table 4: Greenhouse gas account and global warming factors (GWF) for a dump (values are expressed per tonne of wet waste (ww) landfilled).

Waste type: mixed waste – water content: 30%		
Indirect: upstream	Direct: waste management	Indirect: downstream
GWF (kg CO_2-eq. tonne^{-1} ww): 0	GWF (kg CO_2-eq. tonne^{-1} ww): 561 to 786	GWF (kg CO_2-eq. tonne^{-1} ww): 0
CO_2- equivalents (kg tonne^{-1}):	CO_2-equivalents (kg tonne^{-1}): • CH_4 emission: 688 to 963 (GWP = 25) • CO_2 emission: 0 (GWP = 0) • C left: –127 to –177 (GWP = –44/12)	CO_2-equivalents (kg tonne^{-1}):
Accounted:	Accounted (unit tonne^{-1}): • CH_4 dispersive: 28 to 39 kg • CO_2 biogenic dispersive: 62 to 87 kg • C left: 35 to 48 kg	Accounted:
Not accounted: • Fuel combustion in the waste collection trucks while unloading and driving on the site	Not accounted: • Any trace gas release	Not accounted:

treated in flares, where methane is oxidized into (biogenic) carbon dioxide with an efficiency defined by the parameter η = 95–99%. The uncollected gas fraction is subject to oxidation in the top cover and, with respect to methane, the oxidation efficiency is defined by the parameter β = 40–60%. By using equations (1), (3), (5)–(11), the following estimates are found:

$$G_{CH4} = 38.5\text{–}53.9 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } (T = 0\ °\text{C}, P = 101.3 \text{ kPa})$$

$$\text{equal to } 27.5\text{–}38.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww})$$

$$G_{CO2} = 31.5\text{–}44.1 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 61.9\text{–}86.6 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww})$$

$$CH_{4\text{Dispersive}} = 3.1\text{–}16.2 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 2.2\text{–}11.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww})$$

$$CH_{4\text{Flares}} = 0.2\text{–}2.2 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 0.1\text{–}1.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww})$$

$$CH_{4\text{Emitted}} = CH_{4\text{Dispersive}} + CH_{4\text{Flares}}$$

$$= 3.3\text{–}18.3 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 2.3\text{–}13.1 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww})$$

$$CO_{2\text{Dispersive}} = 9.4\text{–}38.2 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 18.4\text{–}75.1 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww})$$

$$CO_{2\text{Flares}} = 34.1\text{–}78.0 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 66.8\text{–}153.1 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww})$$

$$CO_{2\text{Emitted}} = CO_{2\text{Dispersive}} + CO_{2\text{Flares}}$$

$$= 43.4\text{–}116.2 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$(\text{at STP } 85.3\text{–}228.2 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww})$$

$$C_{\text{left}} = 36.0\text{–}50.4 \text{ kg C tonne}^{-1} \text{ ww or about } 48\%$$

$$\text{of the original biogenic C content in the waste.}$$

$$GWF(C_{\text{left}}) = -132.0 \text{ to } -184.8 \text{ kg CO}_2\text{-eq. tonne}^{-1} \text{ ww}$$

$$GWF(LFG) = 58.4\text{–}327.3 \text{ kg CO}_2\text{-eq. tonne}^{-1} \text{ ww}$$

The overall GHG accounting is given in Table 5.

Engineered landfill (mixed waste) with extensive gas utilization

The waste input to the highly engineered landfill is assumed to be ‘mixed waste’, as defined in Table 3. The biogenic carbon content (C = 75–105 kg tonne^{-1} ww) is dissimilated by 50% by emission of landfill gas (D_{LFG} = 0.5) and by 2% by emission of leachate (D_{Leachate} = 0.02). The biogenic carbon not converted into gas or washed out is assumed to stay in the landfill. The landfill gas is collected, and the average collection efficiency over 100 years is ε = 50–80%, inclusive of the post-closure lifetime of the landfill where collection may or may not be practised. The collected gas fraction is utilized for electricity generation. At the power plant the gas energy recovery efficiency is λ = 25–35% and the methane is converted into (biogenic) carbon dioxide with an efficiency defined by the parameter η = 95–99%. The electricity generated is assumed to substitute for the same electricity mix used as input to the landfill. The uncollected gas fraction is partially oxidized in the top cover and, with respect to methane, the oxidation efficiency is defined by the parameter β = 40–60%. By using equations (1), (3), (5)–(12), the following estimates are found:

Table 5: Greenhouse gas account and global warming factors (GWF) for a conventional landfill (values are expressed per tonne of wet waste (ww) landfilled).

Waste type: mixed waste – water content: 30%		
Indirect: upstream	Direct: waste management	Indirect: downstream
GWF (kg CO_2-eq. tonne^{-1} ww): • Low electricity: 2 to 6 • High electricity: 9 to 12	GWF (kg CO_2-eq. tonne^{-1} ww): –71 to 150	GWF (kg CO_2-eq. tonne^{-1} ww): 0
CO_2-equivalents (kg tonne^{-1}): • Diesel fuel: 0.6 to 2.0 (GWP = 1) • Synthetic liner (HDPE): 0.9 to 2.8 (GWP = 1) • Gravel: 0.1 to 0.2 (GWP = 1) • Electricity: low = 0.5; high = 7.2 (GWP = 1)	CO_2-equivalents (kg tonne^{-1}): • CO_2 fossil from use of diesel for on-site operations: 3 to 8 (GWP = 1) • CH_4 emission: 58 to 327 (GWP = 25) • CO_2 emission: 0 (GWP = 0) • C left: –132 to –185 (GWP = –44/12)	CO_2-equivalents (kg tonne^{-1}):
Accounted (unit tonne^{-1}): • Provision of diesel for soil excavation works: 0.5 to 1 L • Provision of diesel for on-site daily operations 1–3 L • Provision of HDPE for liner material: 0.5 to 1.5 kg • Provision of gravel: 80 to 120 kg • Provision of electricity: 5 to 8 kWh	Accounted (unit tonne^{-1}): • CO_2 fossil from use of diesel for on-site operations: 1 to 3 L diesel • Use of electricity: 5 to 8 kWh • CH_4 dispersive: 2 to 12 kg • CH_4 flares: 0.1 to 1.5 kg • CO_2 biogenic dispersive: 18 to 75 kg • CO_2 biogenic flares: 67 to 153 kg • C left: 36 to 50 kg	Accounted:
Not accounted: • Fuel combustion in the waste collection trucks while unloading and driving on the site • Use of diesel fuel for soil works at the site for the construction of the landfill	Not accounted: • Any trace gas release	Not accounted:

$$G_{CH4} = 38.5\text{–}53.9 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } (T = 0\text{ °C}, P = 101.3 \text{ kPa)}$$

$$\text{equal to } 27.5\text{–}38.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww)}$$

$$G_{CO2} = 31.5\text{–}44.1 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 61.9\text{–}86.6 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww)}$$

$$CH_{4\text{Dispersive}} = 3.1\text{–}16.2 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 2.2\text{–}11.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww)}$$

$$CH_{4\text{PowerPlants}} = 0.2\text{–}2.2 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 0.1\text{–}1.5 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww)}$$

$$CH_{4\text{Emitted}} = CH_{4\text{Dispersive}} + CH_{4\text{PowerPlant}}$$

$$= 3.3\text{–}18.3 \text{ m}^3 \text{ CH}_4 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 2.3\text{–}13.1 \text{ kg CH}_4 \text{ tonne}^{-1} \text{ ww)}$$

$$CO_{2\text{Dispersive}} = 9.4\text{–}38.2 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 18.4\text{–}75.1 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww)}$$

$$CO_{2\text{PowerPlant}} = 34.1\text{–}78.0 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 66.8\text{–}153.1 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww)}$$

$$CO_{2\text{Emitted}} = CO_{2\text{Dispersive}} + CO_{2\text{PowerPlant}}$$

$$= 43.4\text{–}116.2 \text{ m}^3 \text{ CO}_2 \text{ tonne}^{-1} \text{ ww}$$

$$\text{(at STP } 85.3\text{–}228.2 \text{ kg CO}_2 \text{ tonne}^{-1} \text{ ww)}$$

$$C_{\text{left}} = 36.0\text{–}50.4 \text{ kg C tonne}^{-1} \text{ ww or about 48\% of the}$$

$$\text{original biogenic C content in the waste.}$$

$$GWF(C_{\text{left}}) = -132.0 \text{ to } -184.8 \text{ kg CO}_2\text{-eq. tonne}^{-1} \text{ ww}$$

$$GWF(LFG) = 58.4\text{–}327.3 \text{ kg CO}_2\text{-eq. tonne}^{-1} \text{ ww}$$

$$GWF(LFG_{\text{utilization}}) = -5.0 \text{ to } -140 \text{ kg CO}_2\text{-eq. tonne}^{-1} \text{ ww}$$

The overall GHG accounting is given in Table 6.

Low organic waste landfill

The waste input to the low-organic waste landfill is assumed to be of the ‘low-organic’ type, as defined in Table 3. The biogenic carbon content (C = 30–45 kg tonne^{-1} ww) is dissimilated by 33% by emission of landfill gas (D_{LFG} = 0.33) and by 2% by emission of leachate (D_{Leachate} = 0.02). The biogenic carbon not converted into gas or washed out is assumed to stay in the landfill. The landfill gas is collected, and the average collection efficiency over 100 years is ε = 30–50%, inclusive of the post-closure lifetime of the landfill where collection may or may not be practised. The collected gas fraction is treated in flares, where methane is oxidized into (biogenic) carbon dioxide with an efficiency defined by the parameter

Table 6: Greenhouse gas account and global warming factors (GWF) for a engineered landfill with extensive gas utilization (values are expressed per tonne of wet waste (ww) landfilled).

Waste type: mixed waste – water content: 30%		
Indirect: upstream	Direct: waste management	Indirect: downstream
GWF (kg CO_2-eq. tonne^{-1} ww): • Low electricity: 2 to 6 • High electricity: 12 to 16	GWF (kg CO_2-eq. tonne^{-1} ww): –71 to 150	GWF (kg CO_2-eq. tonne^{-1} ww): –5 to –140
CO_2-equivalents (kg tonne^{-1}): • Diesel fuel: 0.6 to 2.0 (GWP = 1) • Synthetic liner (HDPE): 0.9 to 2.8 (GWP = 1) • Gravel: 0.1 to 0.2 (GWP = 1) • Electricity: low = 0.8; high = 10.8 (GWP = 1)	CO_2-equivalents (kg tonne^{-1}): • CO_2 fossil from use of diesel for on-site operations: 3 to 8 (GWP = 1) • CH_4 emission: 58 to 327 (GWP = 25) • CO_2 emission: 0 (GWP = 0) • C left: –132 to –185 (GWP = –44/12)	CO_2-equivalents (kg tonne^{-1}): • Saved emission of CO_2 due to electricity generation from LFG utilization: –5 to –140 (GWP = –1)
Accounted (unit tonne^{-1}): • Provision of diesel for soil excavation works: 0.5 to 1 L • Provision of diesel for on-site daily operations 1–3 L • Provision of HDPE for liner material: 0.5 to 1.5 kg • Provision of gravel: 80 to 120 kg • Provision of electricity: 8 to 12 kWh	Accounted (unit tonne^{-1}): • CO_2 fossil from use of diesel for on-site operations: 1 to 3 L diesel • Use of electricity: 5 to 8 kWh • CH_4 dispersive: 2 to 12 kg • CH_4 flares: 0.1 to 1.5 kg • CO_2 biogenic dispersive: 18 to 75 kg • CO_2 biogenic flares: 67 to 153 kg • C left: 36 to 50 kg	Accounted (unit tonne^{-1}): • Electricity produced from LFG utilization: 50 to 156 kWh
Not accounted: • Fuel combustion in the waste collection trucks while unloading and driving on the site • Use of diesel fuel for soil works at the site for the construction of the landfill	Not accounted: • Any trace gas release	Not accounted:

η = 95–99%. The uncollected gas fraction is oxidized in the landfill's top cover and, with respect to methane, the oxidation efficiency is defined by the parameter β = 60–80%. By using equations (1), (3), (5)–(11), the following estimates are found:

$$G_{\mathrm{CH4}} = 10.2\text{–}13.6\ \mathrm{m^3\ CH_4\ tonne^{-1}\ ww}$$

$$(\text{at STP } 7.3\text{–}9.7\ \mathrm{kg\ CH_4\ tonne^{-1}\ ww})$$

$$G_{\mathrm{CO2}} = 8.3\text{–}11.1\ \mathrm{m^3\ CO_2\ tonne^{-1}\ ww}$$

$$(\text{at STP } 16.3\text{–}21.8\ \mathrm{kg\ CO_2\ tonne^{-1}\ ww})$$

$$CH_{4\mathrm{Dispersive}} = 1.0\text{–}3.8\ \mathrm{m^3\ CH_4\ tonne^{-1}\ ww}$$

$$(\text{at STP } 0.7\text{–}2.7\ \mathrm{kg\ CH_4\ tonne^{-1}\ ww})$$

$$CH_{4\mathrm{Flares}} = 0.03\text{–}0.3\ \mathrm{m^3\ CH_4\ tonne^{-1}\ ww}$$

$$(\text{at STP } 0.02\text{–}0.24\ \mathrm{kg\ CH_4\ tonne^{-1}\ ww})$$

$$CH_{4\mathrm{Emitted}} = CH_{4\mathrm{Flares}} + CH_{4\mathrm{Dispersive}}$$

$$= 1.1\text{–}4.1\ \mathrm{m^3\ CH_4\ tonne^{-1}\ ww}$$

$$(\text{at STP } 0.8\text{–}3.0\ \mathrm{kg\ CH_4\ tonne^{-1}\ ww})$$

$$CO_{2\mathrm{Dispersive}} = 7.2\text{–}15.4\ \mathrm{m^3\ CO_2\ tonne^{-1}\ ww}$$

$$(\text{at STP } 14.2\text{–}30.2\ \mathrm{kg\ CO_2\ tonne^{-1}\ ww})$$

$$CO_{2\mathrm{Flares}} = 5.4\text{–}12.3\ \mathrm{m^3\ CO_2\ tonne^{-1}\ ww}$$

$$(\text{at STP } 10.6\text{–}24.1\ \mathrm{kg\ CO_2\ tonne^{-1}\ ww})$$

$$CO_{2\mathrm{Emitted}} = CO_{2\mathrm{Dispersive}} + CO_{2\mathrm{Flares}}$$

$$= 12.6\text{–}27.6\ \mathrm{m^3\ CO_2\ tonne^{-1}\ ww}$$

$$(\text{at STP } 24.7\text{–}54.2\ \mathrm{kg\ CO_2\ tonne^{-1}\ ww}$$

$$C_{\mathrm{left}} = 19.5\text{–}26.0\ \mathrm{kg\ C\ tonne^{-1}\ ww} \text{ or about 65\% of the}$$

$$\text{original biogenic C content in the waste.}$$

$$GWF(C_{\mathrm{left}}) = -71.5 \text{ to } -95.3\ \mathrm{kg\ CO_2\text{-}eq.\ tonne^{-1}\ ww}$$

$$GWF(LFG) = 18.7\text{–}73.8\ \mathrm{kg\ CO_2\text{-}eq.\ tonne^{-1}\ ww}$$

The overall GHG accounting is given in Table 7.

Results and discussion

A number of different landfilling approaches, from dump to highly engineered landfills, have been considered with regard to GHG accounting and carbon binding. Tables 4 to 7 give the results found for each landfilling scenario, distinguishing between direct and indirect (upstream and downstream) contributions. Table 8 gives an overview of the GHG accounting for all the landfilling scenarios considered.

Results show that direct GHG emissions from dispersive methane releases always are the major contribution to the

Table 7: Greenhouse gas account and Global Warming Factors (GWF) for low organic waste landfill with gas flaring (values are expressed per tonne of wet waste (ww) landfilled).

Waste type: low organic waste – water content: 20%		
Indirect: upstream	Direct: waste management	Indirect: downstream
GWF (kg CO_2-eq. tonne^{-1} ww): - Low electricity: 2 to 5 - High electricity: 7 to 10	GWF (kg CO_2-eq. tonne^{-1} ww): –50 to –13	GWF (kg CO_2-eq. tonne^{-1} ww): 0
CO_2-equivalents (kg tonne^{-1}): - Diesel fuel: 0.6 to 2.0 (GWP = 1) - Synthetic liner (HDPE): 0.9 to 2.8 (GWP = 1) - Gravel: 0.1 to 0.2 (GWP = 1) - Electricity: low = 0.3; high = 5.4 (GWP = 1)	CO_2-equivalents (kg tonne^{-1}): - CO_2 fossil from use of diesel for on-site operations: 3 to 8 (GWP = 1) - CH_4 emission: 19 to 74 (GWP = 25) - CO_2 emission: 0 (GWP = 0) - C left: –72 to –95 (GWP = –44/12)	CO_2-equivalents (kg tonne^{-1}):
Accounted (unit tonne^{-1}): - Provision of diesel for soil excavation works: 0.5 to 1 L - Provision of diesel for on-site daily operations 1–3 L - Provision of HDPE for liner material: 0.5 to 1.5 kg - Provision of gravel: 80 to 120 kg - Provision of electricity: 3 to 6 kWh	Accounted (unit tonne^{-1}): - CO_2 fossil from use of diesel for on-site operations: 1 to 3 L diesel - Use of electricity: 3 to 6 kWh - CH_4 dispersive: 0.7 to 2.7 kg - CH_4 flares: 0.02 to 0.2 kg - CO_2 biogenic dispersive: 14 to 30 kg - CO_2 biogenic flares: 11 to 24 kg - C left: 20 to 26 kg	Accounted:
Not accounted: - Fuel combustion in the waste collection trucks while unloading and driving on the site - Use of diesel fuel for soil works at the site for the construction of the landfill	Not accounted: - Any trace gas release	Not accounted:

Table 8: Overview of greenhouse gas accounting for all landfilling scenarios included in the assessment (values are given as kg CO_2-eq. tonne^{-1} wet waste).

Landfilling scenarios		Indirect upstream	Direct waste management	Indirect downstream	Net
Dump (mixed waste)	Min	0	561	0	561
	Max	0	786	0	786
Conventional landfill with flares (mixed waste)	Min	2	–71	0	–69
	Max	12	150	0	162
Engineered landfill with extensive gas utilization (mixed waste)	Min	2	–71	–5	–74
	Max	16	150	–140	26
Low organic waste landfill	Min	2	–50	0	–48
	Max	10	–13	0	–3

overall GWF, while indirect upstream GHG emissions from provision of materials, fuel and energy do not contribute significantly. This is particularly true when waste with significant content of organic matter is landfilled. It was also found that the fraction of biogenic carbon that remains stored within the landfills after the selected time horizon of 100 years is significant for all landfilling approaches. For all scenarios where mixed waste was landfilled it was estimated that almost half of the initial carbon content remained stored, while when low organic waste was landfilled this fraction raised to about two-thirds, due to the smaller dissimilation factors assumed for this type of waste. This highlights the fact that landfills, at least within a 100-year time horizon, act as a significant carbon sink. Undeniably, this very much depends upon the dissimilation factors used in the accounting as the higher the dissimilation, the lower the carbon sink. From a GHG-accounting perspective, binding of biogenic carbon brings environmental benefits, because the saved contribution by biogenic carbon left in the landfill is subtracted from the direct contributions from actual GHG emissions.

Results also show that gas utilization for energy generation brings credit to the overall GHG balance. In the GHG accounting it was assumed that the electricity generated from LFG substitutes for the same electricity used as input (provision of electricity). The magnitude of such credits largely depends on how these energy deliverables are used and what they substitute for. With respect to, for instance, 1 tonne of mixed waste in an engineered landfill, the environmental credit brought by LFG utilization was estimated ranging from 5 kg CO_2-eq. (when an electricity mix mostly based on natural gas is substituted) to 140 kg CO_2-eq. (when an electricity mix mostly based on coal is substituted), which can be compared to a load of 58 to 327 kg CO_2-eq. caused by methane emission in the same landfilling scenario. This demonstrates that the environmental relevance of LFG utilization varies widely depending on what energy is substituted (about one-tenth to one-half of the load from methane emission).

With respect to the GHG accounting found for landfilling of mixed waste (half household waste and half inert waste) in conventional landfills with flares and engineered landfills with energy recovery, the middle value of each range found could be chosen as representative of each estimate. This eases the comparison of the results obtained with results found in the literature. For instance, the US EPA (2006) reports emission factors for landfilling of MSW, which do not comprise a significant fraction of inert waste and therefore have higher carbon content and higher methane potential than the 'mixed waste' as defined in Table 3. Keeping that in mind, results can be compared. For a (conventional) landfill with gas collection and flaring, the US EPA (2006) reports an environmental load from LFG-related GHG emissions of 220 kg CO_2-eq. $tonne^{-1}$ wet MSW, compared to about 190 kg CO_2-eq. $tonne^{-1}$ wet mixed waste found in this study. When, instead, the collected gas is utilized for electricity generation, the US EPA (2006) and Fisher *et al*. (2006) report a reduction of approximately 110 and 170 $kgCO_2$-eq. $tonne^{-1}$ wet MSW, respectively. This can be compared to a reduction of about 70 kg CO_2-eq. $tonne^{-1}$ wet mixed waste found in this study. The effect of carbon (biogenic) binding after 100 years is estimated to 367 kg CO_2-eq. $tonne^{-1}$ wet MSW by the US EPA (2006), compared to about 160 kg CO_2-eq. $tonne^{-1}$ wet mixed waste found here.

The fact that with respect to GHG accounting, a 100-year time horizon is assumed for the cumulative emission associated with the degradation of the waste, makes the data needed for the accounting a combination of actual data regarding measurable parameters and model predictions of emissions over time. In particular, the dissimilation factors realized within 100 years, the LFG collection efficiency and the electricity mix that is substituted from the electricity generated from the LFG are uncertain but crucial parameters. Therefore, it must be pointed out that the results given are very uncertain due to the high complexity of the systems assessed and the many assumptions made about the uncertain variables involved in the accounting. Two types of uncertainty affecting the results can be distinguished: scenario uncertainty and parameter uncertainty. Scenario uncertainty is about consistency and correctness of the landfilling scenarios made. Are the chosen gas management options relevant? Should CHP generation have been included? Is the choice of substituted electricity technology appropriate? Parameter uncertainty, instead, applies to all the many parameters involved in the GHG accounting (methane potential, carbon content, LFG collection efficiency, methane oxidation efficiency, etc) and the various waste compositions and landfilling technologies available. These parameters may vary significantly. For the landfill we believe that both scenario uncertainty and parameter uncertainty are significant, suggesting that using only a few generic values for the GHG issues of landfilling may not be useful for assessment of a specific landfill. Clearly, landfill owners must have the opportunity to present their own data for a GHG analysis of a specific landfill.

Conclusion

GHG accounting and reporting in waste landfilling is of crucial importance as landfilling is still the most common waste disposal method world-wide. This is a complex task because several aspects must be taken into consideration, including landfill gas utilization and binding of biogenic carbon within the landfill body.

From the GHG accounting calculation it was found that direct GHG emissions from the landfilling system represent the major contribution, with a load up to almost 1000 kg CO_2-eq. $tonne^{-1}$ wet mixed waste. This mostly comes from dispersive release of methane, as the load caused by on-site operations is estimated to be below 10 kg CO_2-eq. $tonne^{-1}$. Indirect, upstream GHG emissions from provision of energy, fuel and materials are also small and here estimated to be below 20 kg CO_2-eq. $tonne^{-1}$. The latter, however, does not include emissions from soil works for landfill construction, which may increase the estimated load. The study also included the effect of electricity generation from LFG utilization and binding of biogenic carbon, proving that both aspects may have a large influence on the overall GHG accounting. For landfilling of mixed waste (here defined as half household waste and half inert waste) it was found that LFG recovery for electricity generation and binding of biogenic carbon can each save up to about 140 and 180 kg CO_2-eq. $tonne^{-1}$ wet mixed waste, respectively. Some of the results found were compared to aggregated emission factors from other studies, showing a relatively good agreement. Such a comparison, however, could not be extended to all the waste types included in the assessment, due to different approaches towards GHG accounting and also different input waste qualities.

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