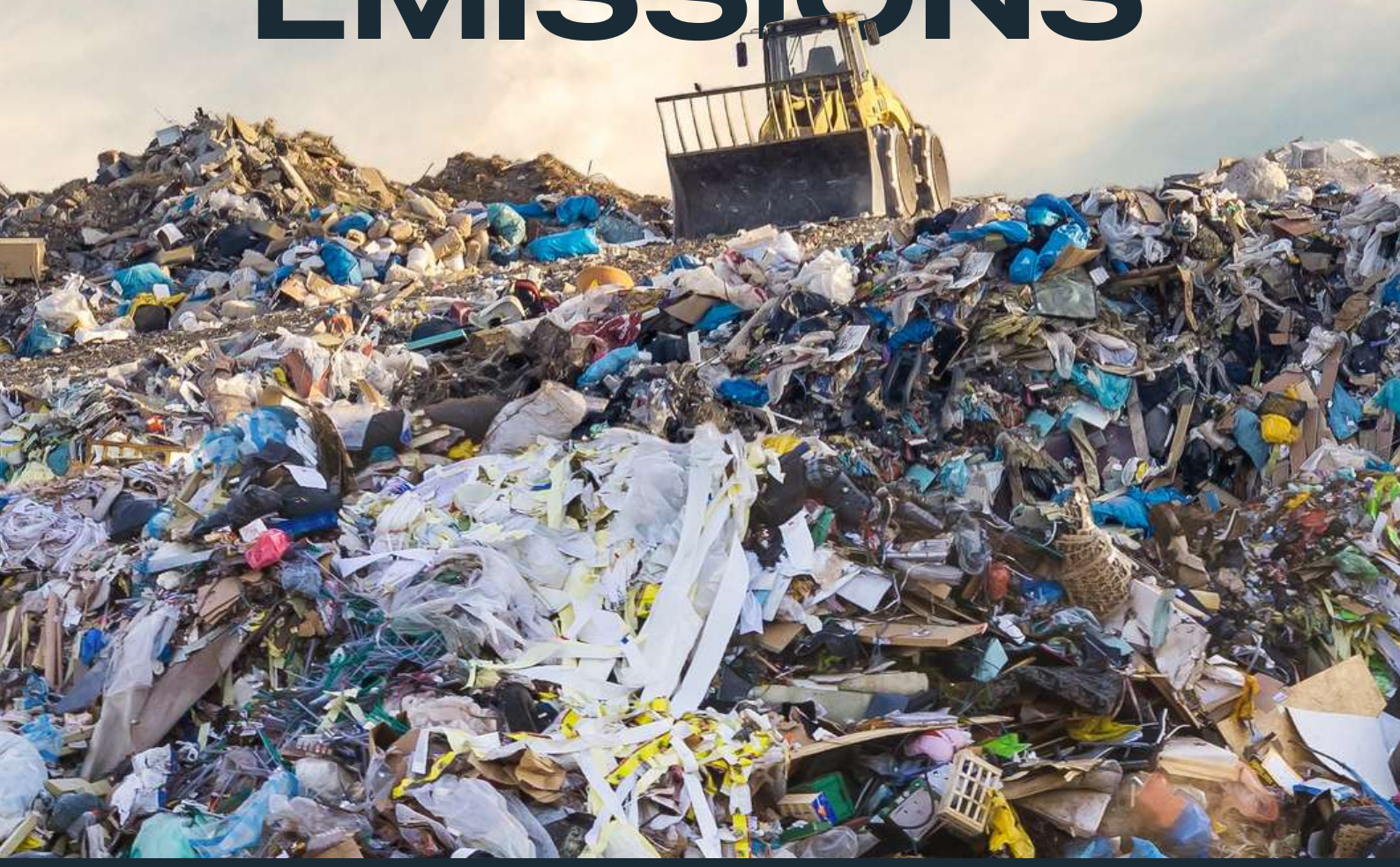
ISWA

THE IMPACT OF MANAGEMENT CHOICES ON LANDFILL METHANE EMISSIONS



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Abstract

The ISWA Working Group on Landfill (WGL) carried out a project to quantify the impact of different landfill management choices on gas capture at landfills. The goal of this project is to compile factual arguments in a white paper to illustrate and clarify, to both regulators and operators, which realistic management choices during landfill operation provide the best options to minimize greenhouse gas (GHG) emissions from landfills over their lifetime.

A literature review or a comparison of (pilot) projects was not considered feasible. The landfill operational conditions are usually poorly described and make comparison a challenge. The project team chose to model plausible and realistic scenarios for the different continents. In order to harmonize the approach for different continents it was decided to use the same model for all continents and to apply as much as possible IPCC recommended input parameters. In order to draft scenarios as realistic and plausible as possible two online seminars were organized. These were attended by many ISWA members, both of the WGL and even outside, and provided valuable input.

The scenarios for the different continents are very different. Nevertheless, the modelling exercise indicates that on all continents the two most important aspects for landfill methane emission reduction are:

- **Early gas recovery:**
  This is especially important under warm and wet climate conditions with high degradation rates. Most of the landfill gas is generated shortly after disposal. Early gas recovery entails that gas recovery systems are built up with increasing waste height. Such an approach allows gas recovery to start during disposal. It is likely that the initial quality of the gas will be poor. Flaring or even low calorific flaring could temporarily be the only methane destruction options.
- **Reduction of degradable organic carbon input:**
  This can significantly reduce the landfill methane emissions, but only if it is a strong carbon input reduction that is not limited to food waste, and includes yard waste and especially paper and cardboard containing wastes. It also requires that alternative waste treatment/beneficiation methods are available for these waste streams. Drafting new waste management policy, drafting, accepting and implementing new waste management regulations, (public) funding, site selection, planning, permitting and realization of alternative waste treatment methods is a process that takes many years. State-of-the-art technology for separate collection, mechanical separation, composting, fermentation and/or incineration is expensive. It is likely that almost 60% of all nations cannot afford state-of-the-art alternatives for landfill. In many cases it will be necessary to look for incremental steps with appropriate technology. It is not realistic to assume that deviation of degradable organic carbon from landfills will provide serious methane emission reduction on short notice.

Contrary to common belief, the additional benefit of energy recovery in terms of avoided fossil fuel is very limited. That benefit will decline further with progress towards a more sustainable energy mix. Larger methane emission reduction on landfills seems possible without energy recovery by means of more aggressive gas recovery, leading to lower gas quality, and consequently requiring destruction of methane in (low calorific) flares.

Early construction of a landfill capping layer or surface sealing layer increases recovery efficiency. But there may be drawbacks in terms of settlement induced sealing damage and costs for replacement before final closure. Improvement of passive oxidation (when active recovery becomes difficult) has a negligible impact on the overall methane emissions from a landfill over a 100-year period.

Contents

1. Introduction

It seems that concerning greenhouse gas (GHG) emissions from landfills often relatively bold statements are communicated. There are statements claiming that landfills are large sources of methane emissions and also statements claiming that proper landfill management results in low methane emissions. Both categories of statements allow very little room for nuance, and do not reflect the changes in gas control during a landfill's operation life. Often a generic gas recovery efficiency is applied in Life Cycle Assessments (LCA) or National Inventory Reports (NIR). During the lifetime of a landfill however, periods with very different conditions result in very different recovery efficiencies, and consequently in very different greenhouse gas capture and destruction and consequent climate benefits.

A review article (Oonk, 2012) concludes the following. "Recovery efficiency depends on the phase of the landfill. During operation, a large part of the methane potential is generated. In the absence of a collection system, most is released to the atmosphere. In many cases, landfill gas collection only starts after closure and in this period collection efficiencies generally increase. High efficiencies are achieved, when the site is capped with an impermeable liner. For landfills with state-of-the-art liners, collection efficiencies can be 90–100%. For closed landfills, reported efficiencies range from 10–90%. For landfills in operation, efficiencies are 10 to 80%."

The above-mentioned recovery efficiencies consider moments in time. Real life landfills go through different phases, in different portions of the landfill, often at the same time. The impact of management choices on landfill gas (LFG) capture during the landfill life is therefore poorly described in literature. The practitioners among the ISWA Working Group on Landfill (WGL) members have valuable insights about management choices based on their experience. They can make a difference, fill in the knowledge gap and identify the management options that deliver the largest climate benefits. The ISWA WGL therefore started a project to quantify the impact of different management choices on landfill gas capture at landfills. The goal of this project is to compile factual arguments, in a white paper, to illustrate and clarify to both regulators and operators which realistic management choices during landfill operation provide the best options to minimize greenhouse gas (GHG) emissions from landfills over their lifetime.

2. Background

In a landfill organic matter is degraded by microbes to form landfill gas. Although fats and protein are present in waste, the bulk of the organic matter that is degraded consists of carbohydrates. The degradation formula can be simplified to:

$$(C_6H_{12}O_6)_n \rightarrow 3nCH_4 + 3nCO_2$$

Consequently, the two main components in landfill gas are methane and carbon dioxide. But landfill gas can contain other greenhouse gases than methane and carbon dioxide. The IPCC considers the amount of nitrous oxide in landfill gas negligible (IPCC, 2006). There are landfills where the concentration of chlorofluorocarbons (CFC's) is relatively high and can contribute up to 10% of the landfill's GHG emissions. This is rare and cannot be considered in a generic modelling approach. CFC's have been phased out via the Montreal Protocol that entered into force on 1st January 1989. They will therefore constitute a decreasing proportion in landfill gas. Recently more information has become available on carbon black (soot) as GHG (Paul, 2021). Carbon black is emitted A.O. from landfill fires. ISWA discourages landfill fires and open waste burning. Carbon black was therefore excluded from the project approach.

Only biogenic carbon degrades under landfill conditions. The NIRs and most waste LCAs consider biogenic CO_2 emissions to have a global warming potential (GWP) of zero (Wang et al., 2020). Biogenic CO_2 is considered part of the short-term carbon cycle and is being returned to the atmosphere relatively quickly. Under this assumption, the storage of biogenic carbon is considered a net benefit since it removes CO_2 from the short-term carbon cycle. Should the biogenic carbon be assumed to already be stored in the waste material before it is disposed in a landfill, then CO_2-biogenic and CO_2-fossil emissions should be treated as equivalent. That implies there are no benefits attributable to keeping biogenic carbon stored in the landfill. For NIRs UNFCCC and IPCC still adhere to the GWP zero for biogenic CO_2.

The choice will change the numbers, but it will not change the ranking of scenarios and management options. Only biogenic carbon is microbially degraded under landfill conditions. In this paper GWP zero was adopted for carbon dioxide and the focus was on methane in the landfill gas:

Methane Emission = (Generation – Recovery) – Oxidation

Methane has an estimated mean half-life of 9.1 years in the atmosphere (Stocker, 2013). Therefore, it has a large effect for a relatively brief period. Methane has a GWP 28 times greater than CO_2 for a 100-year time frame (IPCC, 2013 and UNFCCC, 2021). But taken over a 20-year time frame the GWP is approximately 84 (values of 72 to 105 are reported) times greater than CO_2 (Wedderburn-Bishop et al., 2015). This implies that reducing methane emissions has a large and immediate impact on reducing global radiative forcing.

The 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019) include a higher fraction of Degradable Organic Carbon (DOCf) for easily degradable carbon and lower DOCf for less degradable carbon. The IPCC has made this amendment in response to strong indications that methane generation is higher (than previously assumed) shortly after landfilling and lower (than previously assumed) in later years. This implies that a large methane reduction potential can be expected, even more than before, in the years immediately following disposal, if LFG extraction systems are in place.

At COP 26 in November 2021 in Glasgow 112 nations launched the Global Methane Pledge (2021). 'Participants joining the Pledge agree to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least 30 percent from 2020 levels by 2030.'

The latest estimation of IPCC (2021) is that the total global anthropogenic methane emission is 356 Tg methane per year. With GWP = 25 (UNFCCC convention for years prior to 2021) this is equivalent to 8.9 Pg CO_2-equivalent. Landfills and waste management globally emit 64 Tg methane per year. Landfills and waste management thus constitute the third largest anthropogenic source of methane emissions after fossil fuels and enteric fermentation & manure. It amounts to 18% of the total global anthropogenic methane emission and (with GWP=25) to 1.6 Pg CO_2-equivalent and therefore to 3.8% of the total global GHG emissions and (IPCC, 2021).

Globally two thirds of municipal solid waste (MSW) is landfilled (World Bank, 2018). Composting, incineration and recycling do not generate significant amounts of methane. It is safe to assume that most of the global methane emissions from waste management originate from landfills and therefore that there is significant methane emission reduction potential on landfills.

With respect to methane emission mitigation options for landfills and waste management the IPCC (2022) mainly points at food loss reduction, food waste reduction and use and recycling of organic waste. Landfill management options are not mentioned.

3. Method

3.1. General

A literature review or a comparison of landfill (pilot) projects was not considered feasible. The landfill operational conditions are usually poorly described and make comparison a challenge. The project team aims to illustrate and not to demonstrate or validate the impact of management choices. For this paper plausible scenarios for each continent were drafted. By means of modelling, these scenarios illustrate the GHG impact of realistic management choices for the different continents.

3.2. Model

There are numerous landfill gas generation models around. Not all models are accessible or transparent. In Europe a protocol for GHG accounting by waste management companies was developed (EpE) and approved by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI). With respect to modelling the GHG emission of landfills, the EpE-protocol states six requirements with respect to the models that can be used:

1. The model has to be based on a first order degradation equation.

2. It should not resort to direct emission factors that would be applied to waste tonnages.

3. It should consider waste composition.

4. It should clearly specify the rules followed for diffuse emissions and oxidation factors.

5. It should be published, accepted and available in scientific and technical papers.

6. The methane content of recovered gas should be based on specific analysis.

Requirement (5) specifically limits the number of acceptable models. The IPCC model, the US-EPA model, GasSim, the Afvalzorg simple landfill gas model and the Afvalzorg multiphase model can comply with that requirement.

The IPCC model is used by nations for NIRs to report the GHG emissions of the landfills present in that nation to UNFCCC. Therefore, the model itself is less suited for the WGL purpose, although the IPCC recommendations have the highest authority and credibility. It was decided to use the Afvalzorg simple landfill gas model (Afvalzorg, 2021). This free model follows IPCC recommendations as much as possible, and is updated for the IPCC 2019 refinement.

3.3. Typical Landfill Scenario(s)

A landfill scenario typically consists of an annual amount of waste landfilled, the number of years that amount is landfilled, the typical waste composition, the climatic conditions, and the level of gas control. It was estimated that while in 2018, 55% of the world population lives in an urban environment, this will grow to 60% in 2030 and 70% in 2050 (United Nations, 2018). This implies that the main landfill GHG impact (as well as hazards and nuisance) comes from urban, and increasingly less from rural situations. It was therefore decided to focus on urban situations only. The intention is to compare typical scenarios for each continent, but not necessarily all scenarios imaginable. The aim of the study is to illustrate. For reasons of comparability it was decided to model a waste input of 500,000 metric tons per year for a period of 30 years for all scenarios. For Africa a 40-year period was chosen. Waste composition and climatic conditions are discussed in the paragraph Modelling parameters for each continent. The level of gas control is discussed in the paragraph Landfill management choices for each continent.

3.4. Modelling Parameters

The model that was selected is a so-called single-phase model. The calculations are executed with one single (weighted average) waste type and consequently with one Degradable Organic Carbon (DOC) value. In reality landfills receive different wastes with different DOC content and different fractions (DOCf) of the DOC that actually degrade. The model input is DOC * DOCf.

In order to both accommodate the typical waste mixture for each continent and the calculation of impact due to landfill diversion policy weighted averages of DOC * DOCf and k-values (degradation rates) were calculated with IPCC default values and recommendations based on waste composition.

The rate at which DOC decomposes varies with temperature and moisture. The IPCC (2006) distinguishes between four different climate conditions:

- Boreal and temperate (mean annual temperature < 20ºC), with a mean annual precipitation larger than the potential evapotranspiration (in this paper called temperate/wet).
- Boreal and temperate (mean annual temperature < 20ºC), with a mean annual precipitation smaller than the potential evapotranspiration (in this paper called temperate/dry).
- Tropical (mean annual temperature > 20ºC), with a mean annual precipitation larger than the potential evapotranspiration (in this paper called tropical/wet).
- Tropical (mean annual temperature > 20ºC), with a mean annual precipitation smaller than the potential evapotranspiration (in this paper called tropical/dry).

An example for the calculation of weighted averages of DOC * DOCf and k in a baseline scenario (i.e current waste composition) for a tropical wet climate is presented in Table 3.4.a.

Table 3.4.a. Calculation of Weighted Averages of DOC * DOCf and k for a Tropical Wet Climate

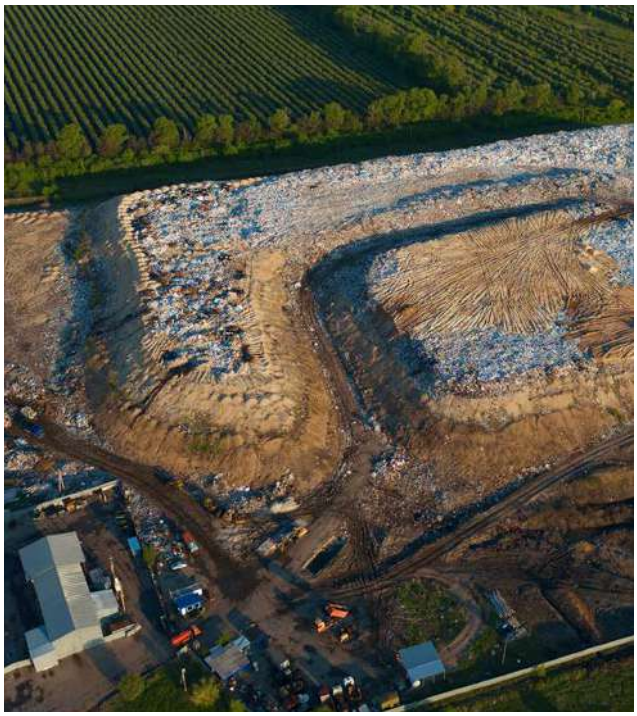
Category		%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
	Food Waste	52%	260,000	0.150	0.7	0.055	0.400	0.208
	Paper & Card	13%	65,000	0.400	0.5	0.026	0.070	0.009
	Wood	1%	5,000	0.430	0.1	0.000	0.035	0.000
	Industrial Waste	15%	75,000	0.150	0.5	0.011	0.170	0.026
	Non-degradables	19%	95,000	0.000	0.0	0.000	0.000	0.000
Total		100%	500,000			0.092		0.243

In Table 3.4.b. the weighted averages of reduced DOC * DOCf and k for a tropical wet climate are presented. Organic waste reduction policy is often the same as a landfill diversion policy. In this example it is assumed that 15% reduction of food waste is achieved. 15% of 260,000 tonnes of food waste per year represent 40,000 tonnes of food waste per year. To account for landfill diversion the total amount of waste landfilled is reduced from 500,000 to 460,000 tonnes per year. The percentage of food waste in the mixture goes down and the percentages of the other waste categories go up.

Table 3.4.b. Calculation of Weighted Averages of Reduced DOC * DOCf and k for a Tropical Wet Climate

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	48%	220,000	0.150	0.7	0.050	0.400	0.191
Paper & Card	14%	65,000	0.400	0.5	0.028	0.070	0.010
Wood	1%	5,000	0.430	0.1	0.000	0.035	0.000
Industrial Waste	16%	75,000	0.150	0.5	0.012	0.170	0.028
Non-degradables	21%	95,000	0.000	0.0	0.000	0.000	0.000
Total	100%	460,000			0.091		0.229

IPCC (IPCC, 2006 & 2019) distinguishes between eight different types of management where a so-called Methane Correction Factor (MCF) is recommended. The common assumption is that on poorly managed landfills a higher portion of DOC is degraded aerobically, and it consequently cannot generate methane. While deliberate open burning of waste cannot be considered in a modelling approach without enormous uncertainties thus the degree of carbon conversion by open burning will always remain unclear. Moreover, burning is not an acceptable waste management for obvious health and safety reasons. That's why landfill fires need to be extinguished quickly. Urban landfills with an annual input of around 500.000 tons are large and are usually a lot higher than 5 m. Therefore, the focus for this modelling exercise is on managed – anaerobic landfills (MCF = 1.0). In addition, for Africa, unmanaged deep landfills are also considered (MCF = 0.8).



3.5. Landfill Management Choices

3.5.a. Reduced Degradable Organic Carbon Content

Lowering the degradable organic carbon of the input to the landfill is presented by IPCC (2022) as the main mitigation option for reducing landfill methane emissions. This is however a waste management choice that is normally made on a national or state regulatory level. Although it is not a choice made by the landfill operator, it was decided to illustrate its impact in this study. Lowering the DOC at landfills is often also a waste diversion from landfill policy. Therefore, it was decided to model 'reduced DOC' scenarios in terms of lowering the actual number of tons of a DOC rich waste category without increasing the other waste categories, so the total annual input in tons also reduces. (See Tables 3.4a and b).

Deviation of organic waste from landfill requires access to alternative treatment/beneficiation methods. These methods can include separate collection, mechanical separation, composting, anaerobic digestion and/or incineration. It should however be considered that drafting new waste management policy, drafting, accepting and implementing new waste management regulations, site selection, planning, permitting, financing and realization of alternative waste treatment methods is a process that takes many years. With respect to financing it should be considered that societies have their limits to what are considered acceptable costs for waste management. Based on an investigation carried out for the WHO, MacFarlane (1996) developed a rule thumb indicating that irrespective of culture societies are not prepared to spend more than 0.5 to 1.0% of their gross domestic product (GDP) on waste management. This rule of thumb indicates that to afford waste treatment such as separate collection, mechanical separation, composting, fermentation and/or incineration, an average GDP per capita of approximately € 20,000 or $ 20,000 per year is required. Wikipedia (2022) lists the GDP at purchasing power parity (GDP-PPP) from 3 different sources: the International Monetary Fund, the World Bank and the CIA World Factbook. Taking the average from these sources indicates that almost 60% of all nations has a GDP-PPP below that level. Consequently, it cannot be considered realistic that these nations can afford state-of-the-art alternatives for landfill. In many cases it will be necessary to look for incremental steps with appropriate, economically sustainable, technology.

3.5.b. Landfill Gas Recovery

The IPCC landfill gas recovery default value for national inventories is 20% of the methane generated. This value allows a nation to include a relatively large number of abandoned landfills without recovery in addition to operational landfills with gas recovery in the NIR. Consequently, this IPCC default value is not appropriate for individual landfills with gas recovery. Landfill operators can make various management choices that influence the methane recovery efficiency and the moment when methane recovery starts. These are aspects like cell size, when to install wells, what type of wells to install, when to start recovery, how to control recovery (gas quality or gas quantity), when to put (or not put) in a capping or surface sealing layers, when to end recovery, what kind of passive treatment to realize, etc. In order to limit the number of options, this modelling exercise distinguished between no gas control, gas control after the total landfill volume has been filled, gas control after each landfill cell is filled and gas control during disposal.

Table 3.5.b.1. Four Typical Modes of Gas Control

Gas Control	% Gas Recovery
Control during filling (from year 1 onwards)	30–90%
Control cell by cell (from year 4 onwards)	50–90%
Control after operation (years 32-100)	50–90%
No Gas Control	0%

Remark: The actual recovery efficiency depends on the gas permeability of the temporary or permanent cover and can vary based on the expert's judgement.

A recovery efficiency of 90% can only be achieved by installing an impermeable surface sealing layer. In some scenarios installing surface sealing layers is considered and explicitly mentioned.

3.5.c. Over-extraction

In some scenarios over-extraction is considered. Over-extraction entails that within the sphere of influence of available gas wells more gas is extracted than is actually generated. This implies that air is introduced ('sucked in') into the waste body. Part of the degradation will be aerobic and some methane might be oxidised to carbon dioxide. This will lower the methane to carbon dioxide ratio in the gas. Due to nitrogen gas intake, it will also reduce the absolute percentages of methane and carbon dioxide in the recovered gas. A so-called low calorific flare will be required to treat the gas (see e.g. Scharff & Jacobs, 2003). The impact on the processes very much depends on the rate of over-extraction. In a mild form it can increase gas recovery or re-activate gas wells. In a more aggressive approach, it can be used to aerate landfills. In all cases, due to larger recovery flow rates, there will be less methane emission than with more traditional gas recovery. In order not to overestimate the impact, the modelling exercise assumes that the recovery efficiencies are 30% during filling of the cell, 50% after temporary capping, 70% after permanent (semi-permeable) capping and 90% after the permanent cap is installed.

3.5.d. End of Landfill Gas Recovery

'End of recovery' is also a management option. In the USA the flare and gas collection system can be turned off 15 years after operations cease, if less than 34 Mg per year of NMOCs (non-methane organic compounds) are being collected (Wang, 2020). In Europe, in some countries active recovery and treatment can be replaced by passive methods when methane generation drops below 25 m^3 CH_4 per hour. Since a landfill with an annual input of 500.000 tonnes waste per year can produce several thousand m^3 CH_4 per hour, it can be anticipated that passive measures after ending active recovery can only be realised very long after the start of operation. Therefore, they can only affect small quantities of methane compared to methane generation over the entire landfill life. Passive recovery and treatment methods do however play a role during landfill aftercare.

3.5.e. Microbial Methane Oxidation

Methane that is not recovered can be partially oxidised by microbes in a suitable capping or cover layer. The IPCC recommends methane oxidation factors of 0.1 for managed landfills covered with methane oxidising material and 0 for other situations. 10% oxidation of the amount of methane that moves through the cover layer implies that oxidation in absolute numbers is higher when generation is higher and/or recovery is lower. In actual fact oxidation is a function of the soil porosity (enabling oxygen diffusion), temperature and moisture content. Oxidation is better expressed in terms of (g) CH_4 per m^2 per day. Literature studies (e.g. Huber-Humer, 2008) have indicated that oxidation of 1 litre CH_4 per m^2 per hour (17.1 g CH_4 per m^2 per day or 6.2 kg CH_4 per m^2 per year) in landfill covers seems realistic in moderate climates. Unfortunately the total surface of the model landfill, and the site soil properties, is not described in the paper. When the residual methane generation is below 25 m^3 CH_4 per hour, it is safe to assume that the load to the cover is less than 0.5 litre CH_4 per m^2 per hour. In a moderate climate 50% oxidation (100% in summer, 0% in winter) is a conservative assumption.

3.5.f. Energy Recovery

Energy recovery is another management choice that can be made by operators. Energy recovery is possible in various ways. Electricity can be generated with e.g. gas engines or gas turbines. Hot water can be generated with boilers and heat exchangers in flares or gas engines. Clients for hot water are however often harder to find and harder to distribute to than clients for electricity through a connection into the electricity grid. In order not to underestimate the impact of electrical energy recovery, it was decided to not take a conservative, but rather an optimistic approach. The most important parameters to calculate the amount of energy produced are presented in Table 3.5.f.1.

Table 3.5.f.1. Parameters for the Calculation of Landfill Gas to Energy

Aspect	Number	Unit
Methane Content of LFG	50%	(50% because the IPCC modelling default is 50%)
Methane	0.714	kg/m^3
Energy Content of Methane	50	MJ/kg methane
Energy Content of LFG	17.85	MJ/m^3 = 4.96 kWh/m^3
Availability of Recovery	95%	
Availability of Utilization	95%	
Total Availability	7906	hours/year
Conversion of Energy Content	40%	to electricity replacing energy from the grid
	50%	to heat replacing thermal energy

Gas engines require a considerable capital investment. In order to improve the return on investment the capacity of gas engines is always chosen to be lower than the actual amount of landfill gas that is available over a longer term period (10-20 years). This means that there is always excess landfill gas available. Strictly speaking this excess landfill gas should be flared. Very often however this is not the case and consequently landfill gas to energy projects do not result in the lowest methane emission that is technically possible.

In Table 3.5.f.1. the most important parameter to calculate the climate impact of avoided fossil fuel for energy from landfill gas is not presented: the so-called grid emission factor. This is the number that indicates how much carbon dioxide is emitted for a kWh of electricity that is distributed through the electricity grid in a specific country or continent. The grid emission factor varies enormously throughout the world. Some examples are presented in Figure 3.5.f.1.

Figure 3.5.f.1. Grid Emission Factors for Electricity in kg CO_2/kWhe in various Places in the World. From the different Sources Average Values and Selected High and Low Values are presented

Canada:
Average - 0.140
Alberta - 0.800
Quebec - 0.001

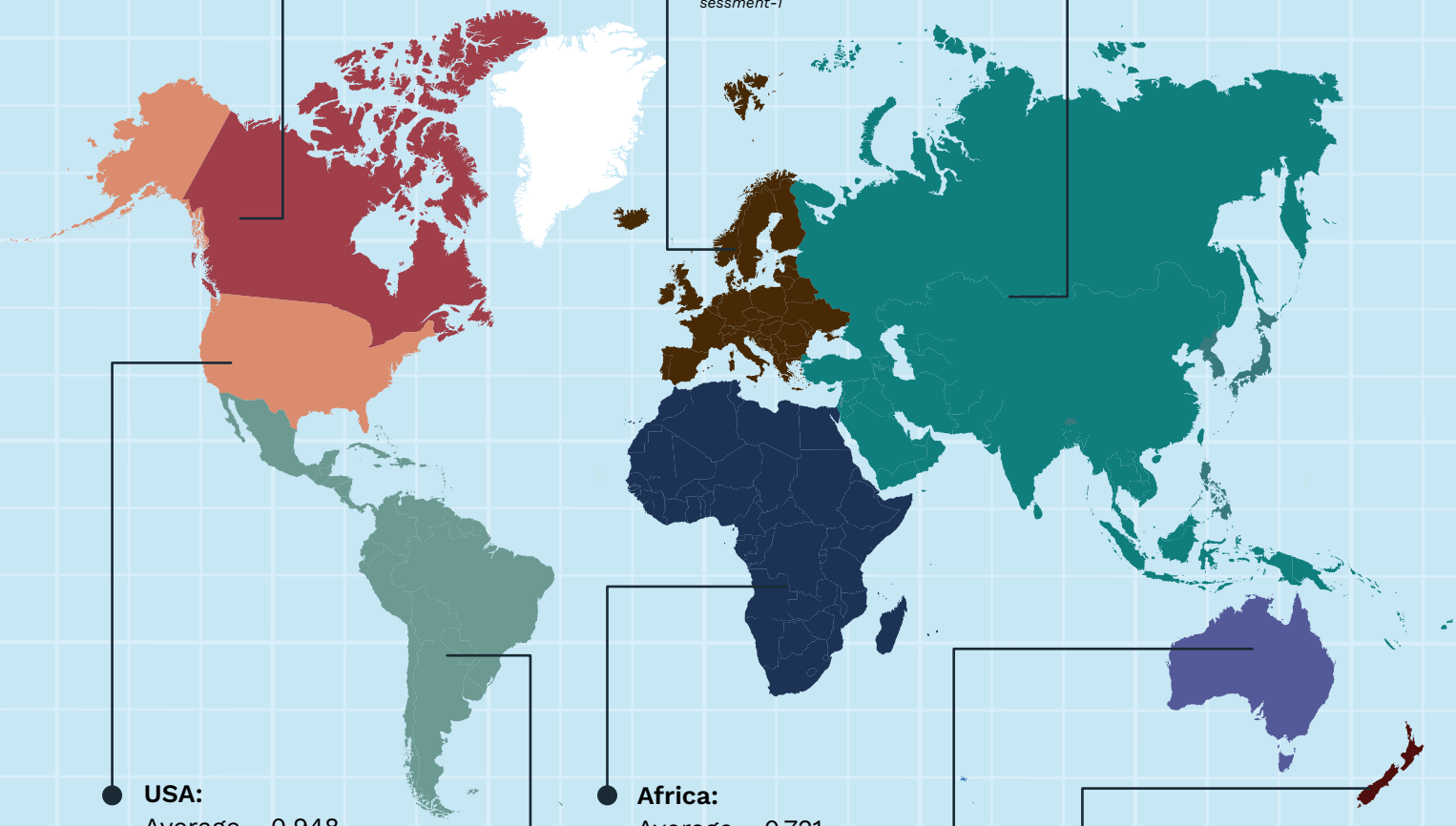
Source: www.carbonfootprint.com

Europe:
EU-28 - 0.255
Poland - 0.751
Sweden - 0.012
Iceland - 0.000

Source: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment-1

Asia:
Average - 0.834
Mongolia - 1.130
Thailand - 0.548

Source: https://www.iges.or.jp/en/pub/list-grid-emission-factor/en



USA:
Average - 0.948
Minnesota - 1.678
Up State New York - 0.253

Source: https://www.epa.gov/sites/production/files/2020-04/documents/ghg-emission-factors-hub.pdf

Africa:
Average - 0.721
South Africa - 0.953
Sudan - 0.305

Source: https://www.iges.or.jp/en/pub/list-grid-emission-factor/en

New Zealand:
Average - 0.100

Source: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/

Latin America:
Average - 0.468
Guyana - 0.948
Costa Rica - 0.281

Source: https://www.iges.or.jp/en/pub/list-grid-emission-factor/en

Australia:
Average - 0.880
Western Australia - 1.260
Tasmania - 0.170

Source: https://www.industry.gov.au/sites/default/files/2020-07/national-greenhouse-accounts-factors-august-2019.pdf

The highest grid emission factors are found in countries or states that rely heavily on coal fired power plants for their electric energy mix. They can be found all over the world, e.g. Western Australia, Mongolia, Poland, Guyana, South Africa, Minnesota, Alberta. Various countries have a more climate neutral energy mix. E.g. New Zealand (hydropower, geothermal and wind power), Sweden (hydro and nuclear power), Iceland (geothermal) and Quebec (hydropower). These countries or states have a low grid emission factor and consequently the avoided fossil fuel contribution of landfill gas to electricity projects is small to almost negligible.

The grid emission factor for the production of thermal energy (hot water) is less well described in literature. For several fossil fuels a theoretical emission factor was calculated and is presented in Table 3.5.f.2. In this case in order not to overestimate the impact of thermal energy recovery, a conservative approach was followed. During transport and distribution of thermal energy compared to local production some losses occur. The conversion efficiencies of 90% and 80% can therefore be considered high. But this in turn means that emission factors for the avoided fossil fuel can be considered low. Many households and industries use diesel or coal to generate hot water and steam. Again, in order to not overestimate the impact in the modelling, natural gas is chosen as the replacement fuel.

Table 3.5.f.2. Calculated Emission Factors for Thermal Energy Production in kg CO_2/kWh_{th}

Feul	Energy Content MJ/kg	Combustion Emission* $kgCO_2/kg$	Conversion to Heat %	Emission Factor $kgCO_2/kWh_{th}$
Methane	50	2.75	90%	0.220
Natural Gas	44	2.75	90%	0.250
Petrol	50	3.33	90%	0.267
Diesel	45	3.18	90%	0.282
Coal	35	3.66	80%	0.471

** excluding exploration, production, refining, transport and storage (which can be 20-25% extra)*

3.5.g. Emerging Landfill Management Technologies

Emerging landfill technologies such as leachate recirculation and landfill aeration have not been considered. The IPCC in 2019 has introduced MCF's for aerated landfills. The MCF is an overall factor that does not allow for calculations of management changes during the operational life of the landfill. It is not possible to model the impact of leachate recirculation or landfill aeration during different phases of operation, if the changes in reaction rate constants and DOCf are unknown. To date insufficient data on this aspect is available to allow for its inclusion.

3.5.h. Uncertainties

Uncertainties of parameters have not been included in this paper. The IPCC default values and recommendations were followed as much as possible. If uncertainties would have been considered, they would have been based on uncertainties described in IPCC recommendations. They would therefore likely have a similar outcome for all scenarios. The more important factor is that it would not impact the ranking of management choices, and the intention of this paper is to illustrate the relative importance of the different management choices. Therefore an uncertainty analysis was not deemed necessary.

4. Results

4.1. General

In this chapter all scenarios, management options and results are described and presented per continent. All the underlying calculation spreadsheet for methane generation, recovery, oxidation, emission, energy recovery and comparison of results per continent are available in <PM: repository>.

4.2. Results - Oceania

The Oceania scenarios were split between New Zealand and Australia to emphasize the impact of existing and future policy and legislation on the quantity of landfill gas methane captured and destroyed through the operational and post closure phases of a landfill. The focus of the comparison was on large cities in populated areas which generally have engineered landfills, operated to sanitary landfill standards in both countries. Based on the Köppen climate classification (Kottek et al, 2006), and focusing on the east coast of Australia which is generally the more populated area of the country, this allows for a similar climatic classification to be used for the two countries, that of Temperate and Boreal wet.

The New Zealand input parameters in terms of waste composition is as per the Climate Change (Unique Emissions Factors) Amendment Regulations 2018. The Unique Emissions Factors Regulations: 2009 stipulates that all operating landfills are liable for their greenhouse gas emissions from 1 January 2013. These liabilities are based on the theoretical methane production from a tonne of waste with a prescribed organic content. They are calculated to account for all methane expected to be generated by the waste and are applied at the time of placement to every tonne of waste that enters the landfill. The Australian input parameters in terms of waste composition is as per the National Greenhouse and Energy Reporting (Measurement) Determination 2008, Compilation No. 12 2020. The DOC, DOCf (the fraction of DOC that actually degrades) and k-values (degradation rates) for both countries were calculated with IPCC default values and recommendations and based on waste composition.

Landfills in large metropolitan cities generally have landfill gas extraction systems to flare, to power generation, or more commonly to both. In New Zealand any landfill that will contain > 1 million tonnes of waste, must after it has >200,000 tonnes of waste placed, install gas extraction wells and either send that to flare or to power generating engines, as per the national air quality regulations. This is typically achieved by vertically extendable gas wells installed into the placed waste and extended as the landfill is filled. The top of the well is formed by a large diameter steel casing that is progressively raised, while the inside smaller diameter perforated extraction well casing and drainage aggregate backfill is progressively extended/filled.

In Australia, there is no fixed guidance on when wells are to be installed, other than LFG action levels, like >1% methane in monitoring wells on the perimeter of the landfill or when methane exceeds surface emission levels. There is some early LFG collection using sacrificial horizontal wells, largely driven to manage odour.

There is no nationally legislated diversion of organics from landfill yet in either country, but these are being recommended by the respective governments.

4.2.a. New Zealand Baseline Scenario

The New Zealand baseline scenario is current waste composition, as per the current national legislation, and early extraction, also driven by current legislation. Recovery efficiency was assumed to be 30% during filling of the first cell, except year 1 which was 0 as the initial layer of waste is still being placed. Each cell was assumed to take 3 years to fill. The recovery efficiency was increased to 50% after installing intermediate cover soil (4 years after start of cell operation) and 70% 7 years after start of cell operation when the cover soil has matured and is densely vegetated. It was assumed that progressive final capping would take place after a further 10 years, which would increase the recovery efficiency to 90%. The methane oxidation factor was set at 10% throughout the life of the landfill.

4.2.b. New Zealand Reduced Organics Scenario

The Climate Change Commission report for New Zealand, May 2021, advised that organic waste to landfill must be reduced, by 50% by 2035. The reduction is calculated in Table 4.2.f.2. as a reduction of 50% of the waste streams contributing to the organic load going into the landfill. This results in 150,500 tonnes of waste being removed from the landfill annually. The recovery efficiency assumptions and methane oxidation assumptions were kept the same as for the baseline scenario.

4.2.c. Australia Baseline Scenario

The Australia baseline scenario is current waste composition, as per the current national legislation, and gas extraction commencing once the landfill is full and gas wells are installed after the entire landfill has reached its final height. Recovery efficiency was assumed to be 70% after intermediate closure, while final capping was being installed. This process was assumed to take 3 years, after which recovery efficiency was increased to 90%.

4.2.d. Australia Early Extraction Scenario

This scenario was included in order to model the impact of gas recovery during waste placement. Gas recovery during waste placement can be done by means of horizontal gas extraction wells or vertical extendable wells as used in New Zealand. Recovery efficiency was assumed to be 30% during filling of the first cell, except year 1 which was 0 as the initial layer of waste is still being placed. Each cell was assumed to take 3 years to fill. The recovery efficiency was increased to 50% after installing intermediate cover soil (4 years after start of cell operation) and 70% 7 years after start of cell operation when the cover soil has matured and is densely vegetated. It was assumed that progressive final capping would take place after a further 10 years, which would increase the recovery efficiency to 90%. The methane oxidation factor was set at 10% throughout the life of the landfill.

4.2.e. Australia Early Extraction & Reduced Organics Scenario

Australia has released a National Waste Policy Action Plan, 2019, which advises a 50% diversion of organics from landfill by 2030. The early extraction baseline was used to model this additional scenario, in order to demonstrate what the lowest possible methane generation scenario could look like. The reduction is calculated in Table 4.2.f.4. as a reduction of 50% of the waste streams contributing to the organic load going into the landfill. This results in 166,750 tonnes of waste being removed from the landfill annually. The recovery efficiency assumptions and methane oxidation assumptions were kept the same as for the early extraction scenario.

4.2.f. Calculated Modelling Parameters

The calculated modelling parameters DOC, DOCf and k are presented in Tables 4.2.f.1. and 2 for the New Zealand baseline and reduced organics scenarios respectively. The calculated modelling parameters DOC, DOCf and k are presented in Tables 4.2.f.3. and d for the Australia baseline and reduced organics scenarios respectively.

Table 4.2.f.1. Calculated Parameters for the New Zealand Baseline Scenario

Category		%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
	Food Waste	17%	84,000	0.150	0.7	0.018	0.185	0.031
	Garden Waste	8%	41,500	0.200	0.7	0.012	0.100	0.008
	Paper	11%	53,500	0.400	0.5	0.021	0.060	0.006
	Wood	12%	59,500	0.430	0.1	0.005	0.030	0.004
	Textile Waste	6%	28,000	0.240	0.5	0.007	0.060	0.003
	Nappies	3%	15,000	0.240	0.5	0.004	0.100	0.003
	Sewage Sludge	4%	19,500	0.050	0.7	0.001	0.185	0.007
	Other	40%	199,000	0.000	0.0	0.000	0.000	0.000
Total		100%	500,000			0.067		0.063

Table 4.2.f.2. Calculated Parameters for the New Zealand Reduced Organics Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	8%	42,000	0.150	0.7	0.009	0.185	0.016
Garden Waste	4%	20,750	0.200	0.7	0.006	0.100	0.004
Paper	5%	26,750	0.400	0.5	0.011	0.060	0.003
Wood	6%	29,750	0.430	0.1	0.003	0.030	0.002
Textile Waste	6%	14,000	0.240	0.5	0.007	0.060	0.003
Nappies	2%	7,500	0.240	0.5	0.002	0.100	0.002
Sewage Sludge	2%	9,750	0.050	0.7	0.001	0.185	0.004
Other	68%	199,000	0.000	0.0	0.000	0.000	0.000
Total	100%	349,500			0.037		0.033

Table 4.2.f.3. Calculated Parameters for the Australia Baseline Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	40%	201,500	0.150	0.7	0.042	0.185	0.075
Garden Waste	4%	19,500	0.200	0.7	0.005	0.100	0.004
Paper	15%	75,000	0.400	0.5	0.030	0.060	0.009
Wood	1%	6,000	0.430	0.1	0.001	0.030	0.004
Textile Waste	2%	8,500	0.240	0.5	0.002	0.060	0.001
Nappies	5%	23,000	0.240	0.5	0.006	0.100	0.005
Sewage Sludge	0%	-	0.050	0.7	0.000	0.185	0.000
Rubber & Leather	1%	6,000	0.390	0.0	0.000	0.000	0.000
Inert	32%	160,500	0.000	0.0	0.000	0.000	0.000
Total	100%	500,000			0.086		0.093

Table 4.2.f.4. Calculated Parameters for the Australia Reduced Organics Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	20%	100,750	0.150	0.7	0.021	0.185	0.037
Garden Waste	2%	9,750	0.200	0.7	0.003	0.100	0.002
Paper	8%	37,500	0.400	0.5	0.015	0.060	0.005
Wood	1%	3,000	0.430	0.1	0.000	0.030	0.000
Textile Waste	2%	4,250	0.240	0.5	0.002	0.060	0.001
Nappies	2%	11,500	0.240	0.5	0.003	0.100	0.002
Sewage Sludge	0%	-	0.050	0.7	0.000	0.185	0.000
Rubber & Leather	1%	6,000	0.390	0.0	0.000	0.000	0.000
Inert	65%	160,500	0.000	0.0	0.000	0.000	0.000
Total	100%	333,250			0.044		0.047

4.2.g. Summary of Results for Oceania

The results for Oceania are summarized in Figure 4.2.g.1 and Table 4.2.g.1.

Figure 4.2.g.1. Calculated Methane Emission for 100 years for Oceania Scenarios

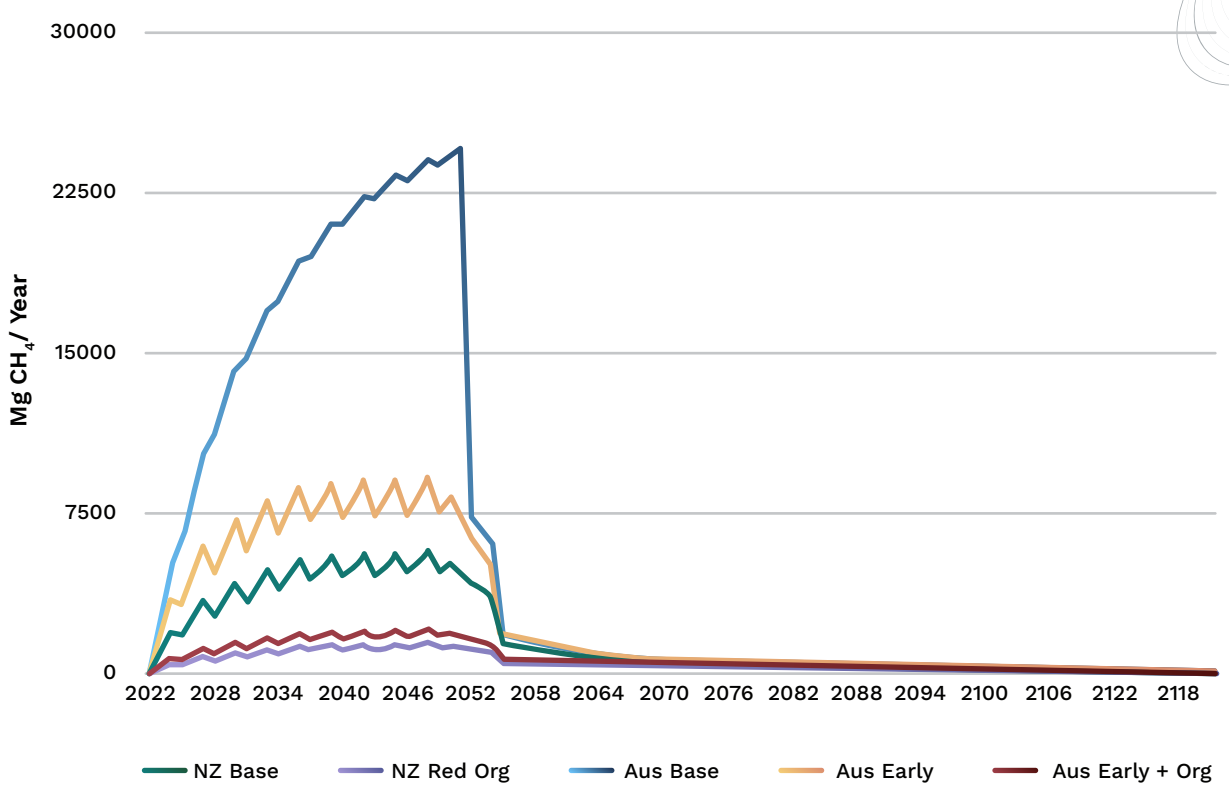


Table 4.2.g.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for Oceania Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
New Zealand Baseline	666,226	496,363	155,616	
New Zealand Reduced Organics	238,793	191,389	43,197	72%
Australia Baseline	859,549	257,517	549,238	
Australia Early Recovery	859,549	600,217	238,488	57%
Australia Early Recovery Plus Reduced Organics	284,000	219,878	58,596	89%

The results for New Zealand indicate that compared to the baseline scenario reducing organic waste input according to the target Climate Change Commission report results in a 72% methane emission reduction, with both scenarios benefitting from early capture and destruction of the landfill gas with progressive welling and capping of the waste.

The results for Australia indicate that compared to the baseline scenario of no extraction during operation, installing early landfill gas extraction and destruction systems results in a 57% methane emission reduction. If this is further enhanced by reducing organic waste input according to the target National Waste Policy Action Plan report, this results in a 89% methane emission reduction.

Comparing the New Zealand to Australia scenarios shows that once early extraction and reduced organics are implemented, methane emissions for the same assumed landfill size and annual waste inputs are comparable. The significant impact of early landfill gas extraction is however very evident in the results for Australia, highlighting the impact proactive legislative measures can have on methane emissions from landfills.

4.3. Results - Asia

4.3.a. Asian Baseline Scenario

The landfill trend in Asia varies from conventional open dump to advanced engineered landfill. In under-developed nations particularly Central/ Western Asia, the majority of the landfill types are open dumps, while some developing nations in the Southeast Asian region have begun to make progress of transforming from conventional landfill to engineered landfill. The advanced nations in East Asia, such as Japan and South Korea, are predominantly operating engineered landfills in parallel to recycling programs (WBG, 2018). The waste policies in the region differ greatly from one nation to another however, which dictate how the landfill operators devise management plans and disposal options. The local climate condition is also a factor that can gave a significant impact on the choice of management option. The baseline scenario (As 0) is focused on a tropical wet region, particularly Southeastern Asia, in which engineered landfills have gained momentum in a few Association of Southeast Asian Nations (ASEAN) countries which have developed different approaches to cater to local issues. The awareness of recycling has been improved over the years, but nationwide implementation of recycling policies remains a major challenge. Consequently, the organic contents in waste streams to be disposed in municipal landfills remain high. Construction and demolition waste is also expected to be mixed in MSW. Waste policy that mandates a reduction of food waste has been explored by local authorities with different degrees of requirements, however this will be a lengthy process for full enforcement to take place due to unequal development at municipal level (UNEP, 2017). Energy recovery from the landfill gas at advanced landfills in the region has become a trend which is highly supported by government, with incentives to promote green energy. In the baseline scenario (As 0) there is initially no recovery of landfill gas, cell lifespan design is three (3) years, 50% collection efficiency of landfill gas is assumed after the end of each cell (4th year), and the waste composition assumes a waste mixture of 36% MSW, 33% food waste, 19% industrial waste, 5% sewage sludge, 4% garden waste and the remaining 3% as construction and demolition waste (University of Technology Mara Malaysa, 2019; Ministry of Housing and Local Government Malaysia, 2012; Ministry of Housing and Local Government Malaysia, 2013).

It is assumed that the total annual waste input will be 500,000 tonnes beginning in 2021 and that the landfill will be receiving the waste input for 30 years. The landfill is assumed to be a well-managed anaerobic landfill where sealing only occurs when waste reaches the final tipping height.

4.3.b. Option 1:

Reduce Degradable Organic Carbon Content (As 1)

Similar to baseline scenario in which the cell lifespan design of three (3) years, and 50% collection efficiency landfill gas extraction after end of each cell (4th year), it is assumed that the Malaysian food waste policy begins to be implemented and enforced with immediate effect to reduce 20% of the food waste in MSW and industrial waste streams. The food (As 3)waste input will drop from 200,000 tonnes to 160,000 tonnes. The reaction rate constant k exhibits decrement as degradable organic content reduces. The reduction is calculated in Table 4.3.e.2. as a reduction of 20% of 200,000 tonnes of food waste annually.

4.3.c. Option 2:

Gas Control Cell by Cell and Energy Recovery (As 2)

There is an incentive to recover the landfill gas for renewable energy generation. The piping for extraction wells will be installed concurrently with the tipping of waste. The extraction operation will be commenced on tipping cell where the target height is reached and covered with a soil capping layer while the tipping operation advance to a subsequent cell that is demarcated from the previous cell. New pipes will be laid in the new cell as waste is filled up and so on until the final cell. It is assumed that the cell lifespan design of three (3) years, early extraction with 30% collection efficiency from year 2 and 3, and 50% collection efficiency landfill gas extraction after end of each cell (year 4 onwards).

4.3.d. Option 3:

Gas Control with Additional Infrastructure (As 3)

The extraction operation will begin on the closed cell which is covered with a soil capping layer. A geomembrane liner will then be installed over all cells after the tipping at the final cell is completed and the cell is covered with a soil capping layer. Booster pumps will be installed to regulate the internal pressure as the extraction operation is in process. It is assumed that the cell lifespan design of three (3) years, final cover and geomembrane liner with booster blowers, and 90% collection efficiency landfill gas extraction after end of each cell (year 4 onwards).

4.3.e. Calculated Modelling Parameters

The calculated modelling parameters DOC * DOCf and k are presented in Table 4.3.e.1. for the baseline scenario (As 0) under tropical wet climate.

Table 4.3.e.1. Calculated Parameters for the Baseline Scenario under Tropical Wet Climate

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	36%	180,000	0.170	0.5	0.031	0.170	0.061
Industrial Waste	16%	80,000	0.150	0.5	0.012	0.170	0.027
Sewage Sludge	1%	5,000	0.050	0.7	0.000	0.400	0.004
Garden Waste	4%	20,000	0.200	0.7	0.006	0.170	0.007
Food Waste	40%	200,000	0.150	0.7	0.042	0.400	0.160
C&D Waste	3%	15,000	0.043	0.1	0.000	0.070	0.002
Total	100%	500,000			0.091		0.261

Table 4.3.e.2. Calculated parameters for Option 1: Reduce Food Waste

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	39%	180,000	0.170	0.5	0.033	0.170	0.067
Industrial Waste	17%	80,000	0.150	0.5	0.013	0.170	0.030
Sewage Sludge	1%	5,000	0.050	0.7	0.000	0.400	0.004
Garden Waste	4%	20,000	0.200	0.7	0.006	0.170	0.007
Food Waste	35%	160,000	0.150	0.7	0.037	0.400	0.139
C&D Waste	3%	15,000	0.043	0.1	0.000	0.070	0.002
Total	100%	460,000			0.089		0.249

In Table 4.3.e.2. the food waste reduction target (20%) results in a reduction of the total amount of food waste landfilled from 200,000 tonnes to 160,000 tonnes. The new food waste composition for option 1 is 35% of total new waste composition.

4.3.f. Summary of Results for Asia

The outcome of management options is compared to the baseline scenario. The methane emission of the different scenarios is presented in Figure 4.3.f.1. Table 4.3.f.1. shows the estimation of generation, recovery and emission in baseline scenario (BAU) and results from three (3) different management options.

Figure 4.3.f.1. Calculated Methane Emission for 100 years for Asia Scenarios

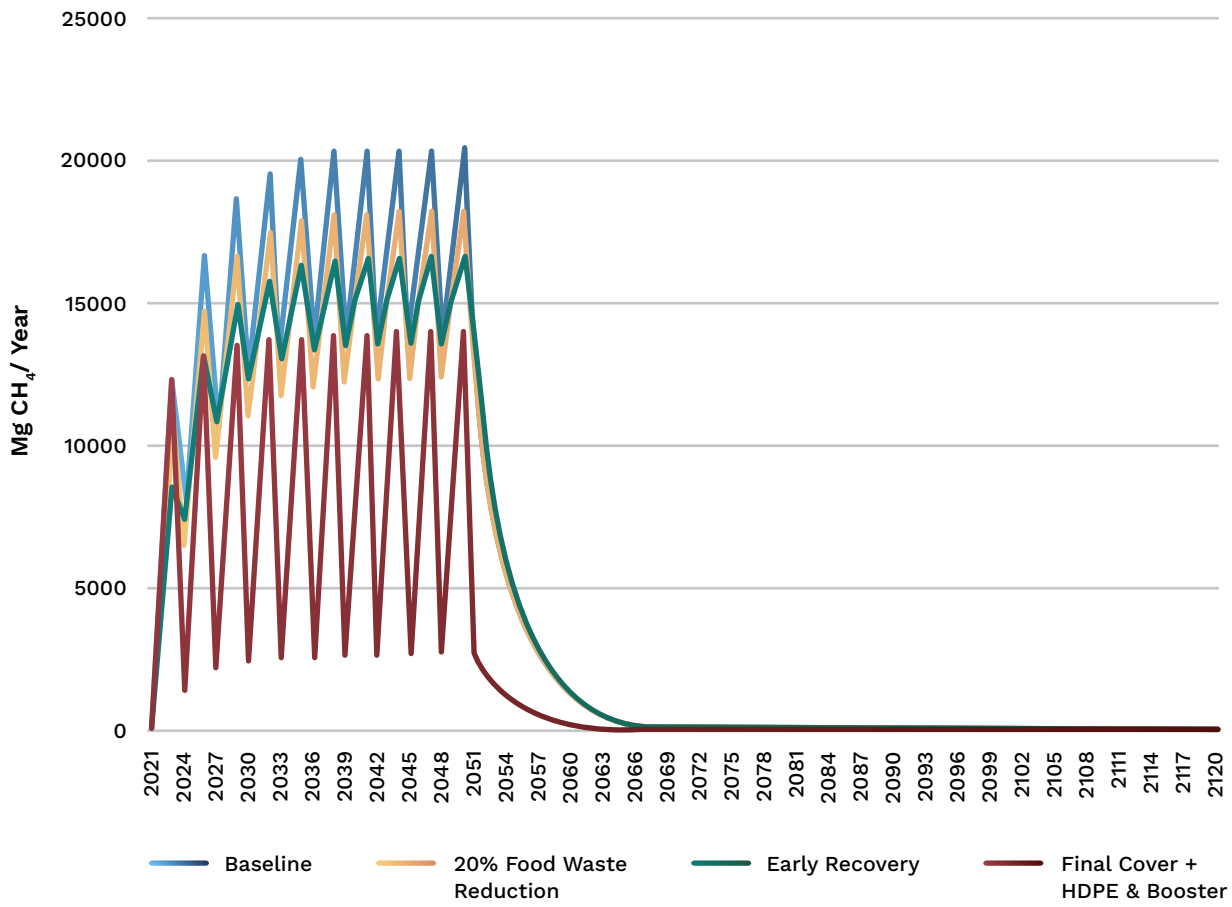


Table 4.3.f.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for Asian Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
As 0: Baseline, Business as Usual	908,572	358,119	514,641	
As 1: 20% Food Waste Reduction	824,721	328,080	463,832	10%
As 2: Early Recovery	908,572	415,819	456,941	11%
As 3: Final Cover, HDPE and Booster	908,572	644,614	256,795	50%

Reduction of organic content (DOC) of the landfill by 20% of food waste input reduction decreases the generation of methane by 10% and the overall emission is also cut down by 10%.

The implementation of gas control and recovery at an early stage (after the final height of a cell is reached and closed with soil capping) does not affect generation but increases the recovery of methane by 16% and thereby cuts down overall fugitive emission by 11%.

The early construction of an HDPE liner and the application of booster blowers in Option As 3 as compared to Option As 0 shows the improvement of recovery of methane and the overall GHG emission is cut down approximately by 50%.

4.4. Results - Europe

4.4.a. European Baseline Scenario

Europe either falls in the IPCC climate category temperate/wet or temperate/dry (SAGE, 2022). The landfill trend in Europe is towards predominantly inorganic waste landfills. Landfill operators tend to diversify to recycling activities on the landfill. European waste policy is focusing more and more on recycling and recovery. Not only for MSW, but also for packaging, construction and demolition waste, contaminated soils, etc. The different European Member States do however progress at a very a different pace towards the goals. The European Landfill Directive (European Commission, 1999) contains biodegradable MSW targets. Member States (with some derogations) were required to reduce the amount of biodegradable MSW (bMSW) by 2014 to less than 35% of the bMSW that was landfilled in the baseline year 1995. The baseline scenario (EU0) therefore assumes a waste mixture of 35% bMSW, 35% industrial waste and 30% construction and demolition waste is landfilled on a typical landfill. In Tables 4.4.h.1. and 4.4.h.2. it is assumed that the total annual input of 500,000 tonnes corresponds to the amount of bMSW that was landfilled in 1995. Although several Member States have already moved beyond this target, it is a hypothetical but plausible scenario for many parts in Europe.

4.4.b. Option 1:
Reduce Degradable Organic Carbon Content

In 2018 the biodegradable MSW targets in the European Landfill Directive were amended (European Commission, 2018). The new target to be achieved in 2035 is to reduce landfill to less than 10% of the bMSW that was landfilled in the baseline year 1995. Since this is already regulated in the legislation, it is selected as management option 1. The reduction is calculated in Table 4.4.h.3. as a reduction of 25% of 500,000 tonnes or 125,000 tonnes of bMSW annually. It should be noted that with the current EU targets the goals of the Global Methane Pledge, also supported by the EU, are unlikely to be met.

4.4.c. Option 2:
Gas Control Cell by Cell

Landfill gas control is mandatory all over Europe since 2001, i.e., two years after the implementation of the

European Landfill Directive in 1999. Some European Member States already had national landfill gas control legislation in place. In the European Landfill Directive landfill gas control is described in four sentences in an annex. The wording does not specify what exactly is required and enforcement in many Member States is weak. In order to provide more clarity, the European Commission in 2014 provided a guidance document. This guidance document is however non-committal. Consequently, in many European Member States, it is still common practice that gas wells are only installed after the entire landfill has reached its final height. Gas control after operation is therefore considered in the baseline scenario (EU 0) and in option 1 (EU 1). In option 2 gas control on a cell by cell basis is introduced. Both in EU 0 and in EU 1 the recovery percentage is assumed to be 50% (4 years after start of cell operation) corresponding with a semi-permeable cover soil.

4.4.d. Option 3:
Gas Control during Filling

Only a few European Member States enforce gas recovery during waste placement. Gas recovery during waste placement can be done by means of horizontal gas drains or by regularly extended vertical wells. Wells and piping are more prone to damage of settlement and vehicles. But it has been practiced widely and proven feasible. Therefore, it is considered in option 3 (EU 3). It is assumed that in order to reduce the amount of air taken in during filling the well spacing is reduced compared to traditional gas control. It is furthermore assumed that this allows for 30% recovery during filling, 50% recovery after installing the cover soil (4 years after start of cell operation) and 70% 7 years after start of cell operation when the cover soil has matured and is densely vegetated.

4.4.e. Option 4:
Over-extraction and Low-calorific Flaring

As explained in par. 3.5.3 over-extraction results in a gas quality that doesn't enable conversion in a gas engine or standard flare. In many cases a so-called low-calorific flare is required. In order not to overestimate the impact, for this modelling exercise it assumed that the recovery efficiencies are 30% during filling of the cell, 50% after temporary capping, 70% after permanent (semi-permeable) capping and 90% 20 years after the permanent cap is installed. This is considered in option 4 (EU 4).

4.4.f. Option 5:
Improved Oxidation

Once filling in a cell ceases a semi-permeable cover soil is typically installed, and the oxidation rate is assumed to be the 10% IPCC default value for managed landfills covered with methane oxidising material. In many European countries competent authorities allow ending active recovery and treatment when the residual gas generation is below 25 m^3 CH_4 per hour or 50 m^3 landfill gas per hour. In most countries it is then required that passive recovery and treatment is installed.

As explained in par. 3.5.e. in a temperate climate 50% oxidation (100% in summer, 0% in winter) is a conservative assumption. In the IPCC recommendations for degradation rate constants Europe has two climate zones: boreal & temperate dry and boreal & temperate wet. With a waste input of 500,000 tonnes per year for 30 years and the degradation rate constants for boreal and temperate dry, the methane generation doesn't drop below 25 m^3 CH_4 per hour within the 100 year's timeframe of the modelling. For illustration of the emission impact of improved oxidation in the baseline scenario the reaction rate constants for boreal & temperate wet were used (EU0/w). In the option EU0/wio the improved oxidation was considered.

4.4.g. Energy Recovery

The impact of avoided fossil fuel was calculated for EU2/d, EU3/d and EU4/d. The average European grid emission factor of 0.255 $kgCO_{2eq}$ per kWhe (European Environment Agency, 2021) was applied. For EU2/d and EU3/d it was assumed that only electricity is produced with gas engines of 400kW. It was assumed that gas engines were placed or removed whenever the gas recovery would allow or demand that. This doesn't always coincide with standard amortization periods used in reality. For EU4/d it was assumed that a heat exchanger with a relatively low efficiency of 60% was installed in the low calorific flare. Due to this arrangement practically all recovered gas can be utilized. It was assumed that the thermal energy replaces thermal energy obtained with natural gas with an emission factor of 0.250 $kgCO_{2eq}$ per kWh_{th}.

4.4.h. Calculated Modelling Parameters

The calculated modelling parameters DOC * DOCf and k are presented in Tables 4.4.h.1. and 4.4.h.2. for a boreal & temperate wet climate and a boreal & temperate dry climate respectively.

Table 4.4.h.1. Calculated Parameters for the Europe Temperate & Boreal Wet Baseline Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	35%	175,000	0.190	0.5	0.033	0.090	0.032
Industrial Waste	35%	175,000	0.150	0.5	0.026	0.090	0.032
C&D Waste	30%	150,000	0.043	0.1	0.001	0.060	0.018
Total	100%	500,000			0.061		0.081

Table 4.4.h.2. Calculated Parameters for the Europe Temperate & Boreal Dry Baseline Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	35%	175,000	0.190	0.5	0.033	0.050	0.018
Industrial	35%	175,000	0.150	0.5	0.026	0.050	0.018
C&D Waste	30%	150,000	0.043	0.1	0.001	0.040	0.012
Total	100%	375,000			0.061		0.047

In Tables 4.4.h.3. and 4.4.h.4. the MSW reduction target results in a reduction of the total amount landfilled. Please note that the reduction target is in absolute tonnes. The percentage of the amount of MSW (13%) in the waste mix landfilled results from the reduction in tonnes and is not equal to the percentage of the reduction target itself (10% of the amount landfilled in 1995).

Table 4.4.h.3. Calculated Parameters for the 2035 European Waste Reduction Targets in the Temperate/Wet Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	13%	50,000	0.190	0.5	0.013	0.090	0.012
Industrial Waste	47%	175,000	0.150	0.5	0.035	0.090	0.042
C&D Waste	40%	150,000	0.043	0.1	0.002	0.060	0.024
Total	100%	375,000			0.049		0.078

Table 4.4.h.4. Calculated Parameters for the 2035 European Waste Reduction Targets in the Temperate/Dry Scenario

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	13%	50,000	0.190	0.5	0.013	0.050	0.007
Industrial	47%	175,000	0.150	0.5	0.035	0.050	0.023
C&D Waste	40%	150,000	0.043	0.1	0.002	0.040	0.016
Total	100%	375,000			0.049		0.046

4.4.i. Summary of Results for Europe

Except for improved methane oxidation as explained in 4.4.f. the options have been compared to the baseline scenario in a boreal and temperate dry climate EU 0/d. The options have therefore been given the acronym EU 1/d, EU 2/d, EU 3/d and EU 4/d. Improved oxidation (EU 0/wio) was compared to the baseline scenario in a boreal and temperate wet climate (EU 0/w). The results for Europe are summarized in Table 4.4.i.1. and Figure 4.4.i.1.

Figure 4.4.i.1. Calculated Methane Emission for 100 years for Europe Scenarios
(EU 0/w is overlain by EU 5/w and therefore not visible)

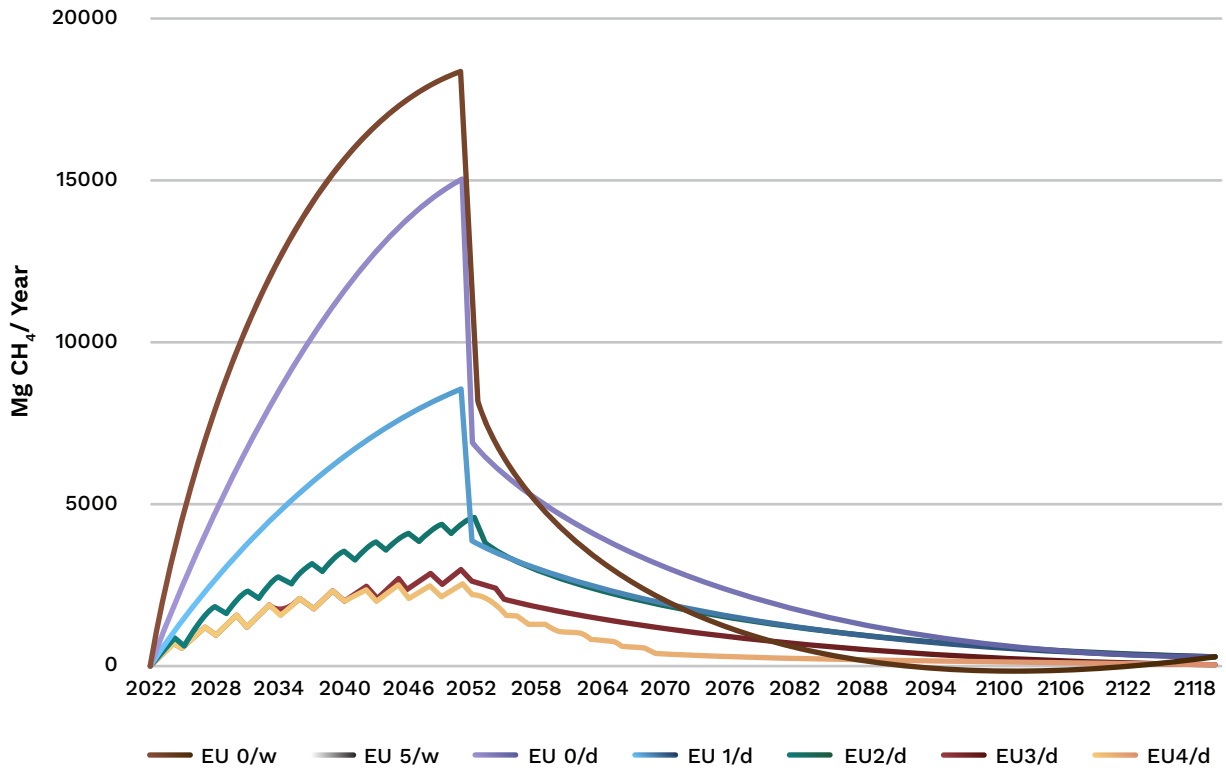


Table 4.4.i.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for Asian Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
EU 0/w: current, wet, late recovery	607,201	118,367	476,998	
EU 5/w: current, wet, improved oxidation	607,201	118,367	476,762	0.05%
EU 0/d: current, dry, late recovery	595,590	160,615	418,913	
EU 1/d: reduced DOC, dry, late recovery	361,816	98,561	253,399	40%
EU 2/d: red. DOC, dry, average recovery	361,816	165,561	178,168	57%
EU 3/d: red. DOC, dry, early recovery	361,816	237,323	113,130	73%
EU 4/d: red. DOC, dry, early rec., lowcall	361,816	268,316	85,277	80%

The results indicate that compared to the baseline scenario (EU 0/d):

- Reducing organic waste input (EU 1/d) according to European legislation provides 40% methane emission reduction. Given the fact that other wastes (especially industrial wastes; see Table 4.4.8c) also contain DOC, there is potential for further methane emission reduction.
- Gas recovery per filled cell (EU 2/d) provides 57% methane emission reduction. This number includes the DOC reduction from EU 1/d to EU 2/d.
- Gas recovery during filling (EU 3/d) provides 73% methane emission reduction.
- Low calorific flaring & over-extraction (EU 4/d) provides 80% methane emission reduction.

The EU 0/w scenario results in 14% more methane emission that the EU 0/d scenario . Under wet conditions the degradation proceeds faster. Consequently, more methane has already escaped before recovery measures become effective. Improved oxidation (EU 5/w) hardly has any impact on the EU scenarios. That is mainly due to the fact that it can only be applied late in the landfill life when methane generation is relatively low.

Energy recovery (electricity only) by means of avoided fossil fuel reduces the overall impact expressed in MgCO2eq of the landfill by 1.5% to 2.5% of the methane generated in scenario EU 2/d and EU 3/d.

Low calorific flaring (EU 4/d) can be combined with thermal energy recovery. By means of avoided fossil fuel it can reduce the overall impact expressed in MgCO2eq of the landfill by another 5%.

Even when low calorific flaring is not combined with energy recovery its overall GHG emission is lower than any other scenario.

4.5. Results - Africa

4.5.a. African Baseline Scenarios Af1 and Af2

Landfilling of solid waste in Africa mainly takes place in uncontrolled dumpsites, without protective groundwater measures and without proper operational management. In densely populated urban areas, these dumpsites are large scale and therefore most relevant in terms of landfill gas emissions. Waste separation or recycling is absent in the majority of the major cities. Mixed MSW, containing large percentages of food waste (up to 50%) are commonly seen being dumped. Moreover, measures to control leachate and landfill gas at these dumpsites are virtually absent.

Regarding the African continent, two major climate zones can be identified (SAGE, 2022), in which the vast majority of relevant dumpsites is situated. The northern and southern parts of the African continent are dominated by a dry and warm climate (desert or savanna). For the selection of methane generation rates these parts qualify as tropical/dry in the IPCC classification. The central part of the continent can predominantly be regarded as tropical/wet.

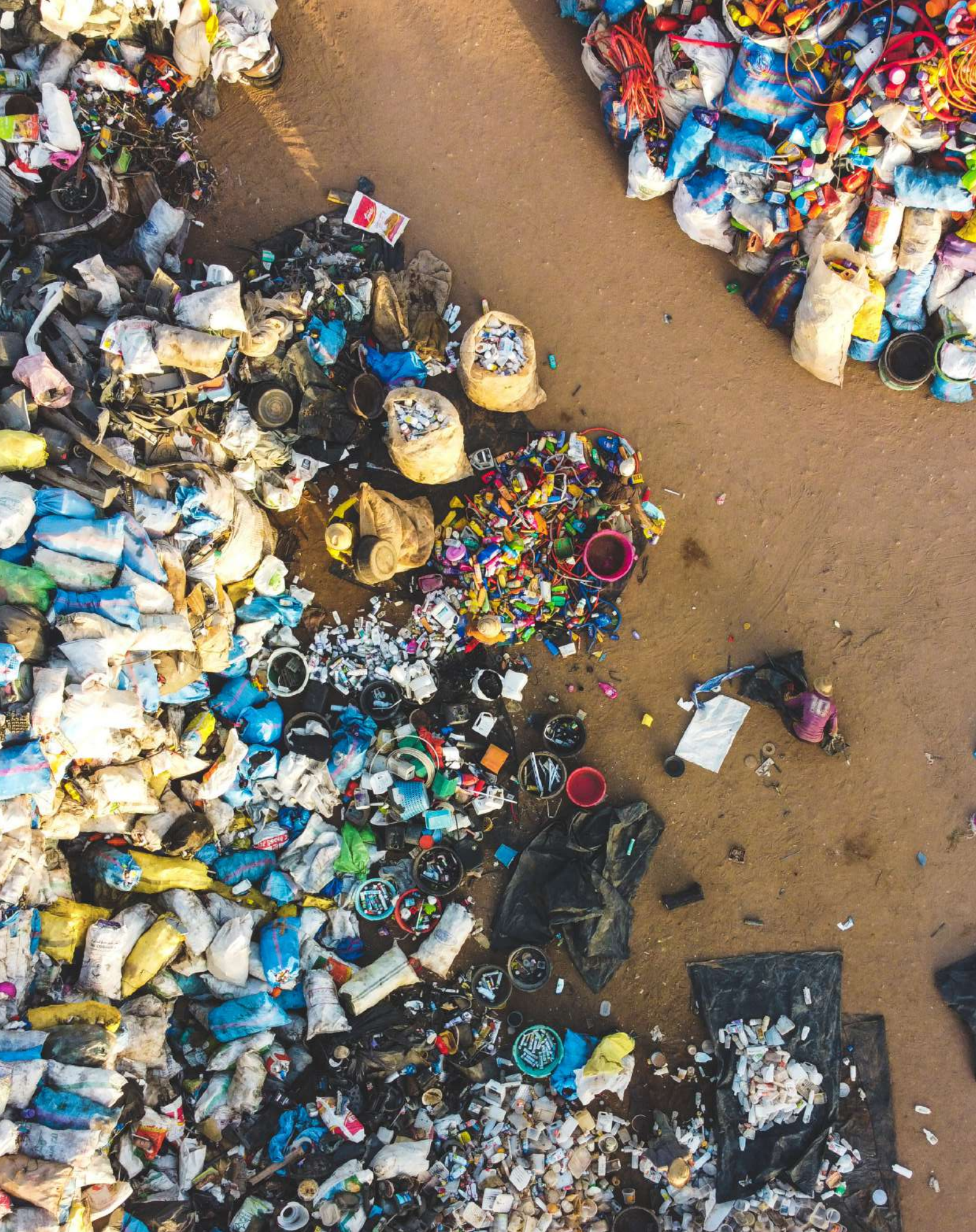
Furthermore, in the baseline scenarios it is assumed that no landfill gas extraction takes place and that the dumpsites are operated as one big waste body, without distinguished landfill cells. Operations are assumed to start in 2021 and last for some 40 years, with a standardized waste input of some 500,000 tonnes of mixed municipal solid waste per year. The dumpsites are assumed to be unmanaged, deep waste bodies with no intermediate covering of the waste, nor final covering at the end of their operational lifetimes. Therefore, the IPCC Methane Correction Factor (MCF) of 0.8 has been applied compared to 1.0, being the MCF for 'managed anaerobic' normally used for sanitary landfills (IPCC, 2019).

Table 4.5.a.1. Calculated Parameters for the Africa Tropical, Dry Baseline Scenario (Af1)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	50%	250,000	0.150	0.7	0.053	0.085	0.043
Green Waste	30%	150,000	0.200	0.5	0.030	0.065	0.020
Industrial Waste	20%	100,000	0.150	0.5	0.015	0.065	0.013
Total	100%	500,000			0.098		0.075

Table 4.5.a.2. Calculated Parameters for the Africa Tropical, Wet Baseline Scenario (Af2)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	50%	250,000	0.150	0.7	0.053	0.400	0.200
Green Waste	30%	150,000	0.200	0.5	0.030	0.170	0.051
Industrial Waste	20%	100,000	0.150	0.5	0.015	0.170	0.034
Total	100%	500,000			0.098		0.285



4.5.b. Scenarios Af1a and Af2a: Reduced Degradable Organic Carbon Content

An often seen attempt to lower the amount of waste that ends up in dumpsites, is the start-up of (small-scale) composting of organic waste. For this purpose, the organic fraction of the mixed MSW is separately collected, or separated from the waste stream after arrival to the waste disposal site. Lowering the amount of organic waste in the waste stream to be dumped, leads to lower potential for landfill gas formation. To formulate realistic scenarios for comparing the effects of these measures, a food waste reduction by 10% was chosen. This mass reduction has been implemented on both baseline scenarios. Interrelated model parameters were calculated and are presented in the Tables 4.5.b.1. and 4.5.b.2.

Table 4.5.b.1. Calculated Parameters for the Africa Tropical, Dry Reduced DOC Scenario (Af1a)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	47%	225,000	0.150	0.7	0.050	0.085	0.040
Green Waste	32%	150,000	0.200	0.5	0.032	0.065	0.021
Industrial Waste	21%	100,000	0.150	0.5	0.016	0.065	0.014
Total	100%	475,000			0.097		0.075

Table 4.5.b.2. Calculated Parameters for the Africa Tropical, Wet Baseline Scenario (Af2)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	47%	225,000	0.150	0.7	0.050	0.400	0.189
Green Waste	32%	150,000	0.200	0.5	0.032	0.170	0.054
Industrial Waste	21%	100,000	0.150	0.5	0.016	0.170	0.036
Total	100%	475,000			0.097		0.285

4.5.c. Scenarios Af1b and Af2b: Energy Recovery from Extracted Landfill Gas

Another realistic management option for the African scenarios to reduce LFG emissions, could be the extraction and utilization of LFG for energy production. For this purpose, realistic, yet conservative parameters were chosen to build 2 additional scenarios in which:

- Gas control during operations of the dumpsite/landfill reaches an efficiency of 30% of the formed LFG.
- Gas control after landfill operations have ceased, sum up to 60% extraction efficiency.

Other model parameters in the baseline scenarios were kept at their original level, as shown in the preceding tables.

4.5.d. Summary of Results for Africa

The model calculations for the African baseline scenarios have been plotted against the scenarios in which the management options "10% food waste reduction" and "LFG extraction and energy production" were implemented. The comparing graphs are shown in Figure 4.5.d.1.

Figure 4.5.d.1. LFG Emissions in the Af1, Af1a & Af1b Scenarios

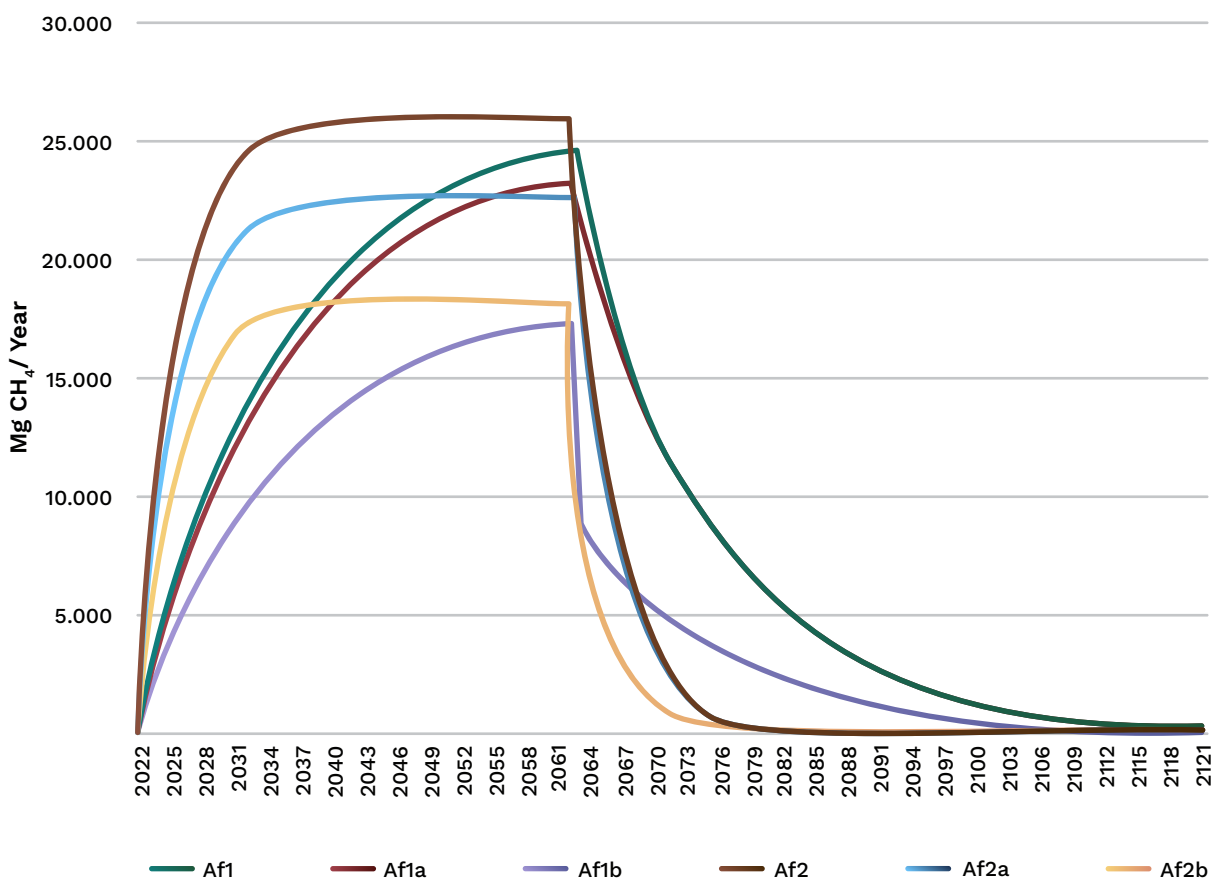


Table 4.5.d.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for Europe Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
Af1: tropical dry, baseline	1,061,890	-	1,027,980	
Af1a: dry, 10% food waste reduction	1,004,566	-	972,310	5%
Af1b: dry, early recovery	1,061,890	420,297	628,030	39%
Af2: tropical wet, baseline	1,066,000	-	1,055,516	
Af2a: wet, 10% food waste reduction	1,008,660	-	998,494	5%
Af2b: wet, early recovery	1,066,000	351,253	710,553	33%

Realistically lowering the DOC of the landfilled waste, by reducing food waste by 10%, leads to an over-all emission reduction of 5%.

LFG extraction at early stage and utilization of the gas for energy production can lead to an overall methane emission reduction of 30 to 40%. Please note that the contribution of avoided fossil fuel is not included in the result for the early recovery scenarios Af1b and Af2b.

4.6. Results - South America and the Caribbean

4.6.a. South America and the Caribbean Baseline Scenario

Both the IPCC and the World Bank consider that there are many similarities between South American and Caribbean countries with respect to waste generation, waste composition and waste treatment. Therefore below, where for the sake of simplicity South America is written, it also applies to Caribbean countries. Most parts of South America and the Caribbean (with the exception of areas on the west coast and in the far south) have mean annual temperatures above 20°C (SAGE, 2022). For that reason this paper focuses on the IPCC climate categories 'tropical, wet' and 'tropical, dry'. The landfill trend in South America is a continuation of predominantly organic waste landfills. Currently 52% of MSW generated is biodegradable (Kaza et al., 2018). All South American countries have high rates of MSW disposal in dumps and controlled landfills (Kaza et al., 2018). Many of those countries have goals to increase waste treatment focusing on the reduction of the amount of waste disposed in landfills. In reality however no pretreatment exists for MSW yet. That said, the intention is that the increase of MSW treatment in the region will only gain scale in long term. The current priority of all South American countries is to close dumpsites and controlled landfills, allied with the construction of new sanitary landfills. In Brazil, for example, currently 60% of MSW is disposed of in sanitary landfills and 40% in dumps and controlled landfills (ABRELPE, 2021). It is also estimated that 2,656 of 5,570 municipalities dispose of their generated MSW in dumps or controlled landfills (ABETRE, 2020). It was established as a goal to eliminate inadequate disposal of waste in dumps and controlled landfills by 2024 (Brasil, 2022). Thus, the baseline scenario for the present study assumes the current South American waste composition (Kaza et al., 2018): a waste mixture of 52% bMSW, 19% non-degradable waste, 15% industrial waste, 13% paper and card and 1% wood is landfilled on a typical sanitary landfill. The SA 0/w scenario is the base scenario for tropical wet climate (Table 4.6.6a), while SA 0/d scenario for tropical dry climate (Table 4.6.6b). In those scenarios, it is assumed that the biogas moves out of the landfill mainly through a passive venting system, without using active mechanical means (the pressure gradient created by gas generation within the landfill that moves the gas toward an internal drainage system of the landfill and conducts it to the surface by vertical drains) and the biogas is burned in a passive flare installed in the top of each vertical drain or directly in the top of the vertical drain, considering a recovery efficiency of 20% in the first 10 years after each cell closure. For all South American scenarios, a 2-year period was considered as lifespan of each landfill cell. All this is typical in South American sanitary landfills.

4.6.b. Option 1:
Reduced Degradable Organic Carbon Content

As described, many South American countries have goals to increase waste treatment and to reduce the amount of waste disposed of in landfills, but the perspective is that this will only gain scale in long term. Brazil, the country with the largest population in the region, has set progressive targets to reduce the amount of bMSW disposed of in sanitary landfills; for example, it has set a target of reducing approximately 8% of total waste disposed of by 2032 (Brazil, 2022). Since this is already stated in some national targets, it is selected as management option 1 (scenarios SA 1/w and SA 1/d, respectively, for tropical wet and tropical dry climates). The reduction is calculated in Tables 4.4.f.3 and d as a reduction of 8% of 500,000 tonnes or 40,000 tonnes of food waste annually since the beginning of the landfill operation. In those scenarios the same gas control is considered as in the baseline scenarios: a passive venting system in the landfill, biogas is burned in a passive flare installed in the top of each vertical drain or directly in the top of the vertical drain, and the same recovery efficiency of 20%.

4.6.c. Option 2:
Gas Control Cell by Cell

Landfill gas control is not mandatory in any South American country, except in São Paulo state (Brazil), where it is a condition for obtaining new environmental licenses, since 2013, exclusively for the new landfill permissions or expansion of existing landfills. However, many big landfills in Brazil receiving more than 500,000 tonnes per year have gas control cell-by-cell through gas recovery during waste placement. Currently, there are 28 on-site facilities in operation generating electric power using LFG as a fuel with internal combustion engines (ANEEL, 2021). There are plans to install dozens of new LFG to energy plants in the next few years. In these landfills it is common practice to connect each cell with the active control system during waste filling in each cell or immediately after each cell has reached its final height. In option 2 (scenarios SA 2/w and SA 2/d, respectively, for tropical wet and tropical dry climates), gas control on a cell-by-cell basis is introduced and it is furthermore assumed that this allows for 30% recovery starting in the second year of operation of each cell, 50% recovery after installing the cover soil (during the first three years of cell closure) and 70% from the fourth year of cell closure when the cover soil has matured and is densely vegetated. As criterion for ending active gas recovery gas generation values lower than 500 m^3 LFG/h (considering 50% methane) was applied.

4.6.d. Option 3:
Gas Control During Filling

Many landfills in South America, especially in Brazil, where annual average rainfall over 3,000 mm can occur, have started to use surface capping or sealing layers on landfills. The main focus was to reduce infiltration of rainwater and minimize excessive leachate generation. But the capping layer also allows for increased landfill gas recovery. In option 3 (scenarios SA 3/w and SA 3/d, respectively, for tropical wet and tropical dry climates), gas control on a cell-by-cell basis is introduced and it is furthermore assumed that this allows for 30% recovery during the second year of operation of each cell, 50% recovery after installing the cover soil (during the first two years of cell closure) and 90% from the third year of cell closure when a surface sealing is installed. As criterion for ending active gas recovery gas generation values lower than 500 m3 LFG/h (considering 50% methane) was applied, the same as for Option 2.

4.6.e. Energy Recovery

The impact of avoided fossil fuel was calculated for SA 2/w, SA 2/d, SA 3/w and SA 3/d. The average South American grid emission factor of 0.468 kgCO2eq per kWhe (Institute for Global Environmental Strategies, 2021) was applied. For all those scenarios it was assumed that only electricity is produced with gas engines of 1 MW and the methane flow needed for operation would be 500 m_3 LFG/h (considering 50% methane). It was assumed that gas engines were placed or removed whenever the gas recovery would allow; and more engines were gradually inserted into each scenario only when there was enough methane to operate the engine for at least 10 years.

4.6.f. Calculated Modelling Parameters

The calculated modelling parameters DOC * DOCf and k are presented in Tables 4.6.f.1. and 2. for a tropical wet climate and a tropical dry climate respectively.

Table 4.6.f.1. Calculated Parameters for the South America Tropical Wet Baseline Scenario, Options 2 and 3

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	52%	260,000	0.150	0.7	0.055	0.400	0.208
Paper & Card	13%	65,000	0.400	0.5	0.026	0.070	0.009
Wood	1%	5,000	0.430	0.1	0.000	0.035	0.000
Industrial Waste	15%	75,000	0.150	0.5	0.011	0.170	0.026
Non-degradables	19%	95,000	0.000	0.0	0.000	0.000	0.000
Total	100%	500,000			0.092		0.243

Table 4.6.f.2. Calculated Parameters for the South America Tropical Dry Baseline Scenario, Options 2 and 3

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	52%	260,000	0.150	0.7	0.055	0.085	0.044
Paper & Card	13%	65,000	0.400	0.5	0.026	0.045	0.006
Wood	1%	5,000	0.430	0.1	0.000	0.025	0.000
Industrial Waste	15%	75,000	0.150	0.5	0.011	0.065	0.010
Non-degradables	19%	95,000	0.000	0.0	0.000	0.000	0.000
Total	100%	500,000			0.092		0.060

Table 4.6.f.3. Calculated Parameters for the South America Tropical Wet Reduced DOC Scenario (Option 1)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	48%	220,000	0.150	0.7	0.055	0.400	0.191
Paper & Card	14%	65,000	0.400	0.5	0.028	0.070	0.010
Wood	1%	5,000	0.430	0.1	0.000	0.035	0.000
Industrial Waste	16%	75,000	0.150	0.5	0.012	0.170	0.028
Non-degradables	21%	95,000	0.000	0.0	0.000	0.000	0.000
Total	100%	460,000			0.091		0.229

Table 4.6.f.4. Calculated Parameters for the South America Tropical Dry Reduced DOC Scenario (Option 1)

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Food Waste	48%	220,000	0.150	0.7	0.050	0.085	0.041
Paper & Card	14%	65,000	0.400	0.5	0.028	0.045	0.006
Wood	1%	5,000	0.430	0.1	0.000	0.025	0.000
Industrial Waste	16%	75,000	0.150	0.5	0.012	0.065	0.011
Non-degradables	21%	95,000	0.000	0.0	0.000	0.000	0.000
Total	100%	460,000			0.091		0.058

4.6.g. Summary of Results for South America

The options 1 (SA 1/w and SA 1/d), 2 (SA 2/w and SA 2/d) and 3 (SA 3/w and SA 3/d) have been compared to the baseline scenario (SA 0/w and SA 0/d) situations. The results for South America are summarized in Figure 4.6.g.1. and Table 4.6.g.1.

Figure 4.6.g.1. Calculated Methane Emission for 100 years for South America Scenarios

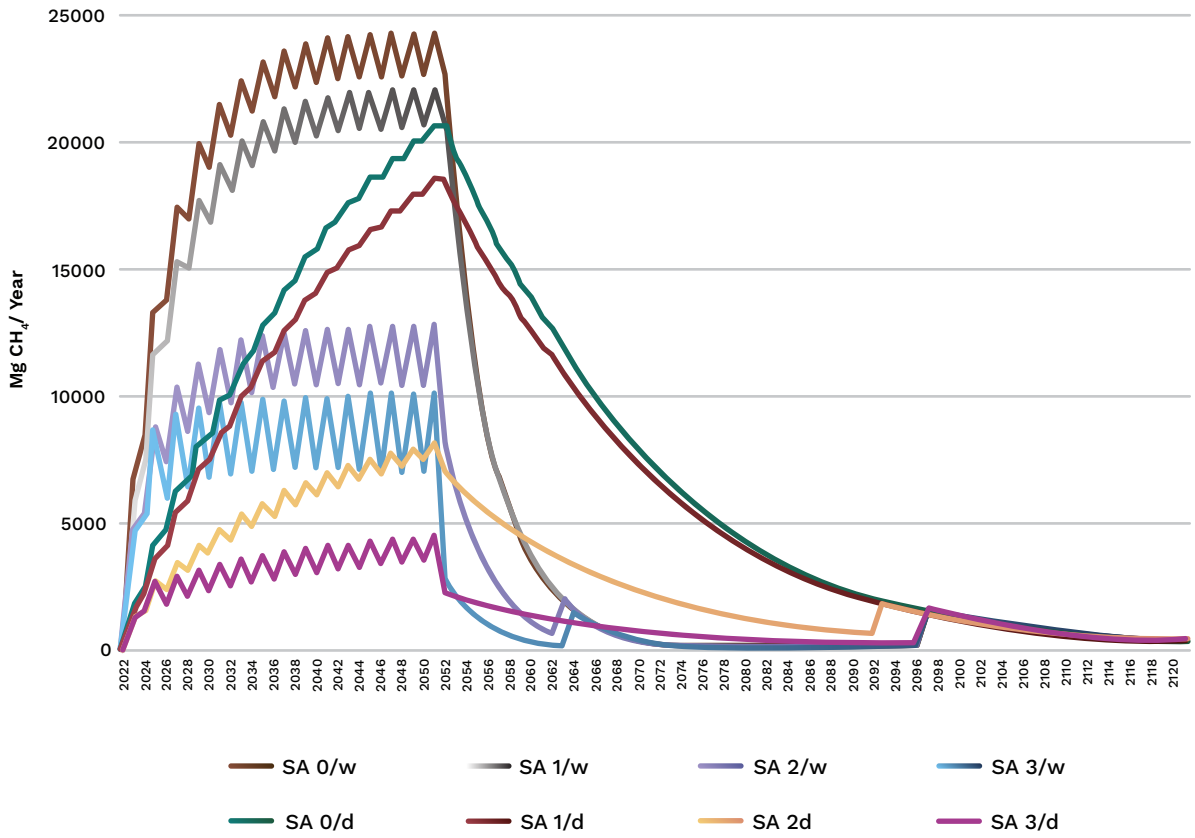


Table 4.6.g.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for South American Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
South America 0/w Tropical Wet, Current (Passive Venting + Open Flare)	922,800	150,153	705,334	
South America 1/w Tropical Wet, Reduce DOC (Passive Venting + Open Flare)	838,800	135,369	641,681	9%
South America 2/w Tropical Wet, Active Control	922,800	540,116	351,382	50%
South America 3/w Tropical Wet, Active Control + Surface Sealing	922,800	645,570	256,473	64%
South America 0/d Tropical Dry, Current (Passive Venting + Open Flare)	916,215	80,894	754,478	
South America 1/d Tropical Dry, Reduce DOC (Passive Venting + Open Flare)	831,675	71,646	686,385	9%
South America 2/d Tropical Dry, Active Control	916,215	589,978	295,496	61%
South America 3/d Tropical Dry, Active Control + Surface Sealing	916,215	749,940	151,530	80%

The results indicate that compared to the baseline scenarios (SA 0/w and SA 0/d):

- Reducing organic waste input (SA 1/w and SA 1/d) by 8% in relation to the total of MSW provides 9% methane emission reduction in both climates. Given the fact that 81% of MSW contain DOC, there is potential for further methane emission reduction.

- Gas recovery per filled cell (SA 2/w and SA 2/d) provides, for tropical/wet and tropical/dry respectively, 50% and 60% methane emission reduction.

- Gas recovery per filled cell including the surface sealing of the landfill (SA 3/w and SA 3/d) provides, for tropical/wet and tropical/dry respectively, 64% and 80% methane emission reduction. When compared to the emission of SA 2/w and SA 2/d, for tropical/wet and tropical/dry respectively, 27% and 49% methane emission reduction.

Energy recovery (electricity only) by means of avoided fossil fuel reduces the overall impact expressed in MgCO2eq of the landfill by 4.3%, 5.2%, 4.8% and 6.3% of the methane generated, respectively in scenario SA 2/w, SA 2/d, SA 3/w and SA 3/d.

Gas recovery per filled cell including the surface sealing of the landfill has an overall GHG emission that is lower than any other scenario.

4.7. Results - North America

4.7.a. North America Baseline Scenario

Throughout the three nations comprising North America (Canada, United States of America, and Mexico), there exists substantial variability in climate conditions, which presents a challenge when attempting to select IPCC climate zones for the modeling scenarios as part of this project that are representative for the vast diversity of large, urban landfills that operate on this continent. In the judgement of the authors, it appeared reasonable that the most universally applicable IPCC climate zones for the most populous portions of these three individual countries are those designated as “temperate, wet” and “temperate, dry”. Accordingly, all modeling scenarios developed for illustrative purposes incorporated one of these two climate conditions.

Similarly, there exists substantial variability in landfilling operational practices at the large, urban solid waste disposal facilities serving metropolitan regions within these three countries, especially those operational practices pertaining to landfill gas collection and control. Examples of typical landfill gas collection and control practices include the timeframe for commencing and terminating landfill gas collection system operations, the comprehensive nature and extent of system infrastructure (wellfield density, collector spacing, collection piping sizing, blower capacity, etc.), liquids management techniques (condensate handling and wellfield dewatering pumps), introduction of interim low-permeability cover and cap system, and much more. The variability in how aggressively landfill operators implement certain strategic landfill gas recovery practices, reflects the different objectives that are imposed on individual landfills to varying degrees, which include regulatory mandates, odor control imposed by public opposition, and landfill gas-to-energy beneficial utilization.

The landfill industry in North America (both public-sector and private-sector facilities) has certainly developed an arsenal of potential landfill gas collection and control “Best Management Practices” that increase the quantity of methane extracted from the landfill and that decrease the fugitive methane emissions.

These Best Management Practices include, but are not limited to:

- Quick setup of comprehensive LFG collection and control system.
- Regular LFG system inspection & update (Annual or Bi-annual).
- Use of vertical wells, horizontal collectors, and leachate cleanouts.
- Dedicated dewatering pumps in most vertical wells.
- Multiple header pipes and blowers for redundancy Automated wellheads for ongoing tuning.
- Frequent surface emissions monitoring by manual and unmanned drones.
- GIS-based remote monitoring with a control dashboard.
- Quality cover material and limited working face size.
- Additional features for bottom liners.
- Optional exposed geomembrane caps in key areas.
- Fast-track final cover system placement (<2 years).

Because the degree to which a particular landfill embraces and implements these Best Management Practices varies according to the particular applicability of the various objectives noted above, and because all three countries have certain large, urban landfills that accomplish and execute mitigation measures for reducing methane emissions in a more robust manner than other facilities, this project evaluated baseline scenarios for three hypothetical landfills as follows:

- **Scenario 1 -**
  Represents a typical landfill that implements nearly all industry Best Management Practices in a rigorous manner.

- **Scenario 2 -**
  Represents a typical landfill that implements some industry Best Management Practices in a limited, casual manner.

- **Scenario 3 -**
  Represents a typical landfill that implements little to no industry Best Management Practices.

4.7.b. Option 1a:
Reduced Degradable Organic Carbon Content

In the Scenario 1 baseline modeling exercise, the DOC*DOCf value is 0.084, which yields an actual amount of degradable carbon for the 500,000 tonnes of waste disposed of annually equal to 41,842 tonnes of carbon/year. Under Scenario 1a, it is assumed that organic waste reductions occur within selected organic waste categories (either imposed by the individual landfill operator or as result of government-mandated organic waste diversion/ prohibition policies) of MSW, garden waste and food waste, which yields a corresponding reduction in the total waste landfilled on an annual basis. Other waste composition categories (including sewage sludge) remain consistent with the baseline scenario. Under Scenario 1a, the DOC*DOCf is decreased to 0.075 and the actual amount of degradable carbon contained in the 315,000 tonnes of waste disposed annually is equal to 23,692 tonnes of carbon/year, which correlates to a 43% reduction.

4.7.c. Option 1b: Earlier Capping

In the Scenario 1 baseline modeling exercise, the lifespan of each cell is established as 4 years, however, no final cap construction or other surface sealing regiment is executed until the conclusion of the full 30-year operational lifespan. Under Scenario 1b, it is assumed that each cell receives an interim exposed geomembrane cap or a final cap installation upon achieving its corresponding design capacity. Thus, the final capping of individual cells on a 4-year interval is anticipated to increase the gas collection efficiencies by an additional 10% in the two relevant stages, which are “upon achieving final height per cell” and “upon termination of disposal operations per cell”.

4.7.d. Options 2a and 3b: Early Recovery

In the Scenario 2 baseline modeling exercise, the lifespan of each cell is established as 4 years, however, no landfill gas collection system is installed or commences operation in each cell until the individual cell achieves its design capacity. Under Scenario 2a, it is assumed that gas collection system components (either shallow vertical wells, a network of horizontal collectors, and/or leachate cleanout connections) are installed in each individual cell while it is undergoing active waste placement operations (i.e., prior to the conclusion of the cell’s 4-year operational life expectancy), This endeavor to install gas extraction infrastructure on an accelerated timeframe is anticipated to increase the gas collection efficiency from zero to 50% in the initial stage, termed “from start of disposal in each cell”, and also increase the efficiency by an additional 15% during the stage identified as “upon achieving final height per cell”.

4.7.e. Option 2b: Extended Recovery

In the Scenario 2 baseline modeling exercise, the criterion for ceasing gas recovery activities coincides with the regulatory threshold outlined in the USA’s federal New Source Performance Standards regulations, which is 34 Mg/yr of NMOC, as well as the RCRA Subtitle D post-closure duration of 30 years. Under Scenario 2b, it is assumed that landfill operators maintain the operational status of gas recovery systems until such time as NMOC flow values decline to less than 15 Mg/yr.

4.7.f. Option 3a: Cell Size Reduction

In the Scenario 3 baseline modeling exercise, the lifespan of each cell is established as 10 years, and no gas recovery is implemented until the termination of disposal operations within each cell. Under Scenario 3a, it is assumed that smaller sized cells with life expectancy of only 5 years are constructed, which will necessitate a more frequent cell construction interval, as the landfill development sequence progresses. This action effectively accelerates the timing that gas recovery efficiency transitions from zero to 70% in the final stage, identified as “upon termination of disposal operations per cell”.

4.7.g. Calculated Modelling Parameters

The calculated modelling parameters DOC * DOCf and k are presented in Tables 4.7.g.1. and 4.7.g.2 for a temperate wet climate and in 4.7.g.3. for a temperate dry climate respectively.

Table 4.7.g.1. Calculated Parameters for North America Scenarios 1, 1b, 2, 2a, 2b, 2a&b

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	60%	300,000	0.190	0.5	0.057	0.090	0.054
Industrial Waste	5%	25,000	0.150	0.5	0.004	0.090	0.005
Sewage Sludge	5%	25,000	0.050	0.7	0.002	0.185	0.009
Garden Waste	5%	25,000	0.200	0.5	0.005	0.100	0.005
Food Waste	15%	75,000	0.150	0.7	0.016	0.185	0.028
C&D Waste	10%	50,000	0.043	0.1	0.000	0.060	0.006
Soil	0%		0.029	0.1	0.000	0.030	0.000
Total	100%	500,000			0.084		0.107

Table 4.7.g.2. Calculated Parameters for North America Scenarios 1a, 1a&b

Category		%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
	Municipal Solid Waste	63%	200,000	0.190	0.5	0.060	0.090	0.057
	Industrial Waste	6%	20,000	0.150	0.5	0.005	0.090	0.005
	Sewage Sludge	8%	25,000	0.050	0.7	0.003	0.185	0.015
	Garden Waste	0%		0.200	0.5	0.000	0.100	0.000
	Food Waste	7%	20,000	0.150	0.7	0.007	0.185	0.013
	C&D Waste	16%	50,000	0.043	0.1	0.001	0.060	0.010
	Soil	0%		0.029	0.1	0.000	0.030	0.000
Total		100%	315,000			0.075		0.099

Table 4.7.g.3. Calculated Parameters for North America Scenarios 3, 3a, 3b, 3a&b

Category	%	Waste Mass (Tonnes/ Year)	DOC (Wet Basis)	DOCf	DOC*DOCf (Per Tonne)	k Tropical/ Wet	Contribution to k
Municipal Solid Waste	63%	300,000	0.190	0.5	0.057	0.050	0.030
Industrial Waste	6%	25,000	0.150	0.5	0.004	0.050	0.003
Sewage Sludge	8%	25,000	0.050	0.7	0.002	0.060	0.003
Garden Waste	0%	25,000	0.200	0.5	0.005	0.050	0.003
Food Waste	7%	75,000	0.150	0.7	0.016	0.185	0.009
C&D Waste	16%	50,000	0.043	0.1	0.000	0.060	0.004
Soil	0%		0.029	0.1	0.000	0.020	0.000
Total	100%	500,000			0.084		0.051

4.7.h. Summary of Results for North America

The results for North America are summarized in Figures 4.7.h.1, 2 and 3 and in Table 4.7.h.1.

Figure 4.7.h.1 Calculated Methane Emission for 100 years for North America 1 Scenarios

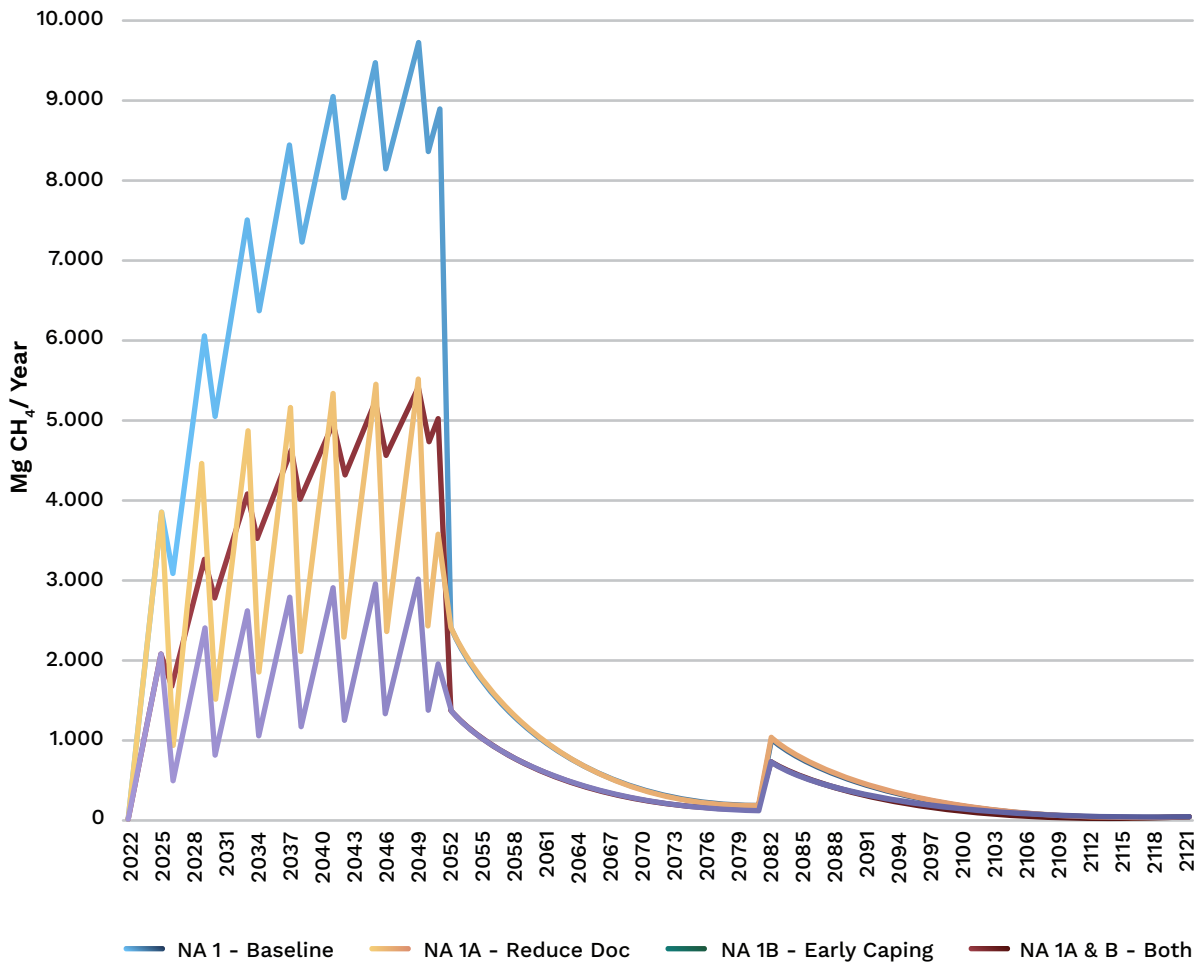


Figure 4.7.h.2. Calculated Methane Emission for 100 years for North America 2 Scenarios

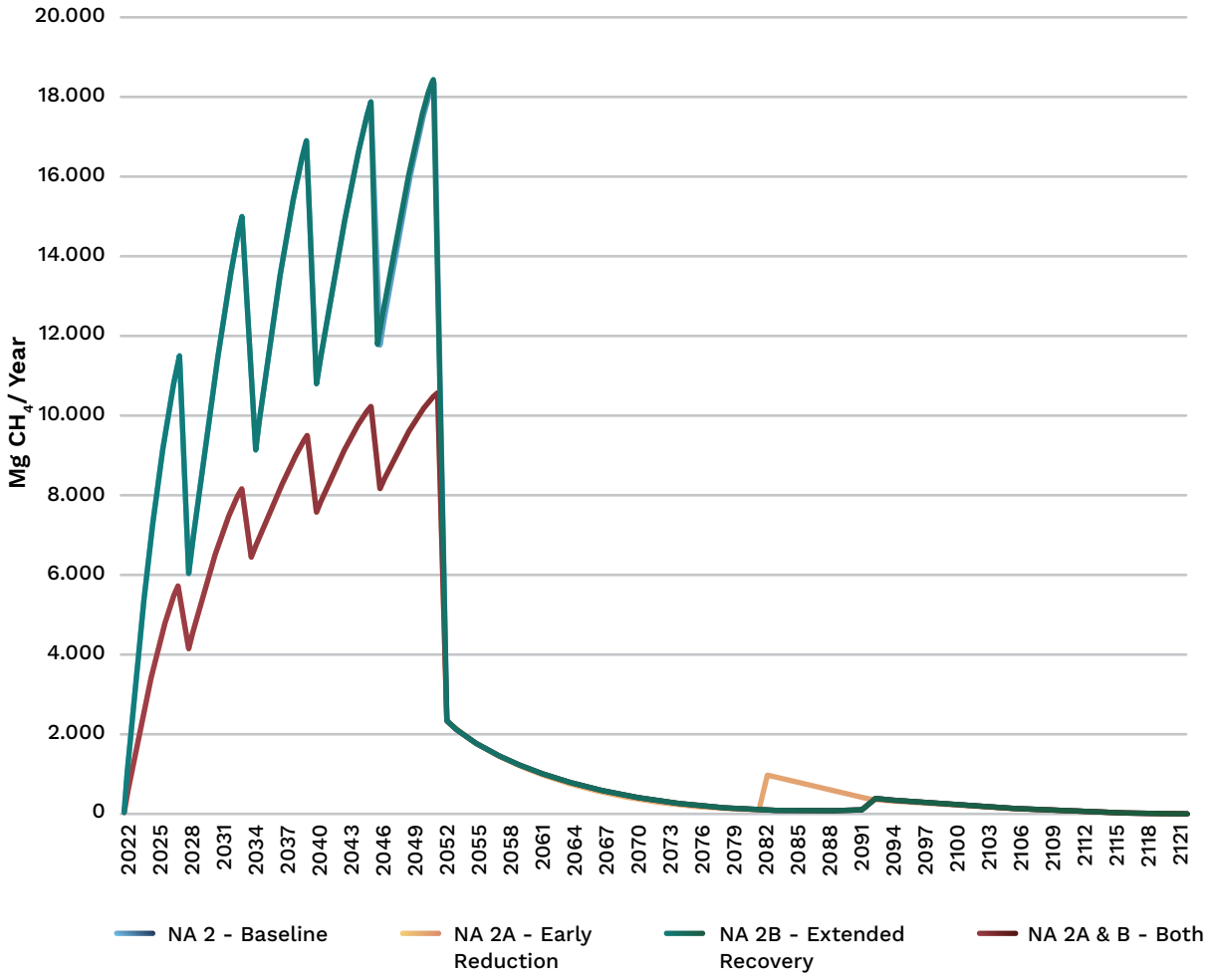


Figure 4.7.h.3. Calculated Methane Emission for 100 years for North America 3 Scenarios

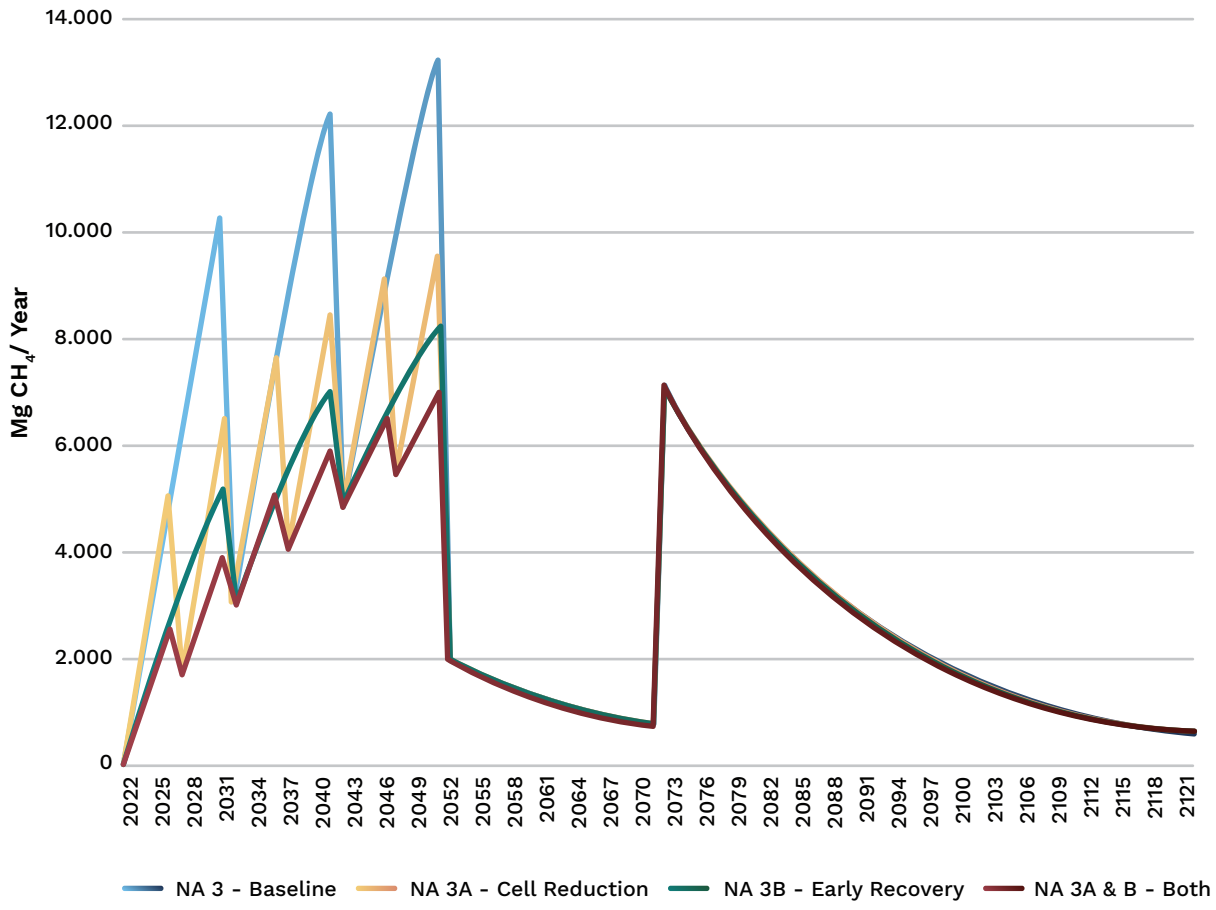


Table 4.7.h.1. Summary of Calculated Methane Generation, Recovery & Emission for 100 years for North American Scenarios

Scenario	Methane Generation Mg/100y	Methane Recovery Mg/100y	Methane Emission Mg/100y	Emission Reduction Due To Mgt. Choices %
NA 1: nearly all BMP	836,687	583,373	233,653	
NA 1a: nearly all BMP, reduced DOC	473,575	331,237	131,125	44%
NA 1b: nearly all BMP, early capping	836,687	698,030	130,461	44%
NA 1a&b: as 1, red. DOC and early cap	473,575	394,974	73,761	68%
NA 2: some BMP	836,687	422,101	391,623	
NA 2a: some BMP, early recovery	836,687	572,640	246,889	37%
NA 2b: some BMP, extended recovery	836,687	428,498	385,865	1%
NA 2a&b: as 2, early & extended recovery	836,687	579,038	241,132	38%
NA 3: little BMP	824,464	415,935	384,122	
NA 3a: little BMP, cell size reduction	824,464	475,623	321,876	16%
NA 3b: little BMP, early recovery	824,464	498,160	301,897	21%
NA 3a&b: as 3, cell size red., early recovery	824,464	515,213	282,285	27%

As depicted in Figure 4.7.h.1., the landfill management choice of reducing quantity of degradable organic carbon being landfilled throughout the facility's life has a profound effect on reducing fugitive methane emissions during the facility's 30-year operational life, with certain years exhibiting reductions of nearly 50% or so. While this strategy may be more economically challenging for individual landfill operators to implement, reducing the degradable organic content of the landfilled waste (in conjunction with decreasing the total waste being landfilled, is one of the most effective techniques for North American landfill operators to achieve dramatic declines in contributions of GHG emissions from their facilities.

Similarly, the landfill management choice of early capping has a profound effect on reducing fugitive methane emissions during the facility's 30-year operational life, with certain years exhibiting reductions of more than 70%. Clearly, earlier capping efforts, such as a cell-by-cell capping protocol, is one of the most powerful tools for North American landfill operators to achieve dramatic declines in contributions of GHG emissions at the most critical period of gas generation. Under Scenario 1a&b, which combines the strategies of reducing the degradable organic carbon content with those of earlier capping, the reductions of fugitive methane emissions are the most substantial of any of the landfill management choices evaluated for North America, with certain years exhibiting reductions as much as 85%.

As depicted in Figure 4.7.h.2., the landfill management choice of early commencement of gas system operation has a noteworthy effect on reducing fugitive methane emissions during the facility's 30-year operational life, with certain years exhibiting reductions of greater than 40%. For those landfills in North America that have already implemented a few Best Management Practices in a more limited and casual manner, early installation of gas recovery system on a cell-by-cell basis represents is one of the most powerful tools to achieve substantial declines in contributions of GHG emissions at the most critical period of gas generation. As depicted in Figure 4.7.h.3., upon juxtaposing the Scenario 3 baseline modeling exercise with results under Scenario 3b, which also addresses early landfill gas recovery technique, similar potential reductions in fugitive methane emissions can be realized at some of the more unsophisticated landfills that have not implemented Best Management Practices. Obviously, this is a landfill management choice that yields significant dividends if these landfill operators can navigate the operational challenges of maintaining landfill gas collection system operations in an active cell.

As depicted in Figure 4.7.h.2., the landfill management choice of extending the operational status of landfill gas collection and control system yields a negligible effect on reducing fugitive methane emissions because the decreases do not occur until 30 years after cessation of waste disposal activities. At this time, the generation of landfill gas has declined to a point where even reductions of 90% compared to the baseline scenario are relatively inconsequential as they pertain to total methane emissions during the facility's active life span.

As depicted in Figure 4.7.h.3., the landfill management choice of reducing the size of individual disposal cells achieves the desired effect on reducing fugitive methane emissions during the facility's 30-year operational life, with certain years exhibiting reductions of approximately 45%, while other years are far less consequential in terms of GHG reductions achieved. Thus, development of smaller cells is demonstrated to serve as a viable strategy for North American landfill operators to achieve substantial reductions in contributions of GHG emissions.

5. Discussion, Conclusions & Recommendations

The goals of the Global Methane Pledge (2021) are very ambitious, and intended to be realized within a relatively short timeframe of 8 years. Waste management (mainly landfill methane emissions) entails 18% of the global methane emissions (IPCC, 2021). The extent of the ambition of the Global Methane Pledge implies that waste management is included in the efforts. Policy making, (public) funding, planning, permitting and realization take many years. As this paper demonstrates, there is no doubt that organic waste reduction on landfills is an effective methane emission mitigation measure. But, due to its lengthy preparation, unfortunately not a measure that is effective immediately. Even after the realization of complete deviation of organic waste from landfills, the waste already deposited continues to generate methane. That methane needs to be captured and destroyed before it can be emitted to the atmosphere. As landfill is a relevant contributor to global methane emissions, landfill management has an almost immediate impact on landfill methane emissions. Focusing on landfill management options provides an important mitigation measure.

Since reduction of methane emissions from landfills involves well-established relatively cheap measures, the planet would benefit if these measures could be stimulated. Until now however only very specific methane emission reduction projects have been stimulated, and those that have mainly through CDM or voluntary trading mechanisms.

Once regulators and operators are more fully aware of the management options, the portfolio of stimulation measures might be reconsidered and enlarged. Although the modelling per continent departs from a different starting point, and has used different parameters, the results show very similar trends.

The modelling exercise indicates that the two most important aspects for landfill methane emission reduction are:

- Early gas recovery provides significant reduction possibilities in the scenarios of all continents. Even if it is considered to be carried out with simple technology resulting in moderate gas recovery efficiency as for instance in the African scenarios. Early gas recovery entails gas recovery systems that are built up with increasing waste height. This is especially important under warm and wet climate conditions with high degradation rates, where most of the landfill gas is generated shortly after disposal. Such an approach allows gas recovery to start during disposal. It is likely that the initial quality of the gas will be poor. Flaring or low calorific flaring could temporarily be the only methane oxidation options.

- Reduction of degradable organic carbon input has a significant impact on landfill methane emissions. The Asian, African and South American scenarios however indicate that, if it is limited to food waste, the impact is also limited. The Oceanian, European and North American scenarios demonstrate that more rigorous reduction of biodegradable organic carbon to landfill (including yard waste and especially paper and cardboard containing wastes) have a much higher impact.

As the Oceanian, European and North American scenarios indicate the combination of rigorous reduction of biodegradable organic carbon and early gas recovery has the largest landfill methane mitigation potential.

Early construction of a landfill capping layer or surface sealing layer increases recovery efficiency. Due to continued settlement howe Fast-track final cover system placement (<2 years) ver it is likely to get damaged and may therefore require replacement or repair before final closure of the landfill.

Improvement of passive oxidation (when active recovery becomes difficult) has a negligible impact on the overall methane emissions from a landfill.

Especially in countries that have regulations in place that do not allow passive treatment as long as it is technically feasible to operate active gas recovery. It may however play an important role during aftercare and after-use of the landfill.

The additional benefit of energy recovery in terms of avoided fossil fuel strongly depends on the energy mix that is avoided in a specific state or country. Only in those situations where it replaces inefficient coal fired power plants can it exceed 10% of the methane generated. But not in countries like Sweden, Iceland and New Zealand that already have a significant proportion of renewable energy supply in the grid. In such countries the climate benefit of landfill gas to energy is negligible. In other countries the benefit will decline with progress towards a more sustainable energy mix. This observation implies that for GHG mitigation it would be beneficial if the focus shifts from 'energy recovery from landfill gas' to 'maximum achievable methane destruction efficiency'. Higher GHG reduction on landfills seems possible without energy recovery by means of more aggressive gas recovery and destruction of methane in low calorific flares.

This paper confirms that the IPCC (2022) recommended methane mitigation measure for waste management (reduction of organic waste to landfill) is effective. Nations are recommended to make an effort to implement it. Practical experience however indicates this will be a long process. In the meantime, methane continues to be emitted from landfills all over the world from waste that is already in place. Landfill gas recovery entails simple, standardized, low-cost technology that can be deployed swiftly. The cost of effective landfill methane recovery and destruction will vary depending on local conditions. In the authors' experience landfill methane recovery projects will rarely exceed € 10 per CO2-equivalent. That is lot less than current 2022 carbon prices of € 60 to 90 in for instance Europe (Carbon Credits, 2022). Nations would benefit both environmentally and financially if, in addition to organic waste to landfill reduction, they would make an effort to stimulate maximum landfill methane recovery and destruction and would reduce the procedural thresholds to realize landfill gas recovery projects.

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