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Review of the IPCC landfill gas emissions model

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Abstract
Almost all developed nations have agreed to report their annual greenhouse gas (GHG) emissions, under the UN Framework Climate Change Convention of 1997. But only a few directly measure their landfill gas emissions. Most use the Intergovernmental Panel on Climate Change (IPCC) landfill gas model to calculate them. This paper examines the accuracy of these default factors, checking references cited by the IPCC for choosing each default factor. It finds that some of these studies were misquoted and several IPCC default factors have no scientific basis. The model is conservative: for example emission inventory compilers are required to avoid underestimation, rather than to find the most accurate possible estimate of emissions. Landfill gas is usually recovered with gas extraction systems, and used to generate electricity. If landfill operators' record-keeping is not good enough, the gas is assumed to be emitted, even if methane was recovered all year. Overall, the model's default factors appear to overstate generation of methane and landfill emissions.

Keywords: Review IPCC landfill gas model

Introduction

There is considerable evidence that the IPCC landfill gas model may, in general, overstate methane generation and emissions.

1. Terraza et al (2007) reviewed six landfill gas recovery projects in developing countries. Operators at the huge Bandeirantes Landfill site in São Paulo, Brazil, used the IPCC model to predict future methane availability before installing a gas recovery system. Actual gas recovery was only 48% of the modelled amount. This may be due to site-specific problems, or alternatively the IPCC's default factors may have overestimated gas generation. Organizers of current landfill gas recovery projects in Brazil comment that the IPCC model still overestimates methane output.

2. De la Cruz et al (2016) measured methane emissions at a newly opened landfill site in Georgia, USA. Measured emissions were compared to emissions predicted by versions of the IPCC model used in the USA. In the first three years after opening of the site, average modeled methane emissions were higher than measured emissions by a factor of 31 in Year 1, 10 in Year 2 and 4 in year 3.

3. Reported methane recovery efficiency in countries that actually measure emissions is much higher than in nations that calculate methane generated using IPCC default factors; then estimate emissions by deducting methane recovered or oxidized. California led the world in directly measuring landfill emissions, using detailed walk-over surveys with Flame Ionization Detectors (FIDs). Other US states now also require conduct regular FID studies. The US EPA (2018) estimates that average national landfill methane recovery is 64.8%; and 78.8% in California.
In contrast, countries relying on IPCC default factors to calculate their emissions - including most EU nations - rarely report more than 45% recovery. The EU's 2021 greenhouse emissions report shows estimated methane recover efficiency for 30 nations. The highest reported recovery figures in continental Europe were 44% for Italy, 42% (France and Greece) and 39% for Belgium. The median was 22%. Several countries started to phase out organic waste deposition in landfill decades ago. These now have very low reported methane recovery. Some examples are Austria (11%); the Netherlands (13%), Denmark (15%) and Malta, (4%). Reported recovery efficiency in these countries was significantly higher in the past, suggesting the IPCC landfill gas model may overestimate both the annual quantity, and the length of time methane is generated at landfill sites.

The model assumes that in temperate or boreal areas, waste continues to produce significant CH_4 emissions decades after it is buried. The decomposition rate is not measured and the emissions may not really occur. Low recovery efficiency in these countries may reflect poor compliance with emission control regulations, but a more likely explanation is that methane generation in their landfills has largely ceased.

Methodology of this study

This study reviews the IPCC's landfill gas default factors, set out in the IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 5. Studies used to establish the default factors were checked to see if they were accurately quoted, and if the landfill model's assumptions are scientifically sound.

The IPCC landfill gas model can be summarized as:
Methane emitted =
W*MCF*DOC*DOCf*F*16/12*(1-R)*(1-ox)
Where
-W is waste deposited, divided into specific types.
-MCF is the Methane Correction Factor. It allows for aerobic decomposition at unmanaged landfill sites.
-DOC is degradable organic carbon in organic wastes.
-DOCf represents DOC that actually decomposes in anaerobic landfill conditions.
-F is the methane content in landfill gas.
-16/12 converts from carbon to methane (CH_4).
- R is methane recovered for energy production or flaring. This must be verified by written site records. It is then deducted from the methane generated.
-Ox is methane oxidized by soil bacteria. Usually 10% of the unrecovered methane is assumed to be oxidized. The remaining methane is assumed to be emitted.

Annual decomposition is calculated using climate-specific default decomposition factors, assuming exponential decay.

Results of assessment of IPCC factors

1. Waste deposition data

In most developed countries waste deposition data is based on weighbridge records and is likely quite reliable. However operators are expected to estimate historic data, for at least 50 years (IPCC 2006 Vol. 5 p. 3.6). Most sites would not have accurate data for this period. The IPCC Guidelines state: *"If a shorter time frame is chosen, the inventory compiler should demonstrate that there will be no significant underestimation of the emissions."* To avoid overestimation, operators may instead overestimate past waste deposition, carbon content, site cover etc. This would overstate emissions from "historic" waste.

2. Methane Correction Factor

The IPCC distinguishes between "managed" sites - those with controlled waste deposition and leveling, compaction or cover - and unmanaged or semi-aerobic sites.
Managed sites are given an MCF of 1, meaning that they are assumed to be 100% anaerobic, with no carbon lost to aerobic decomposition. No evidence for this assumption is provided. It is unlikely, as landfill cells or sites are often left open for 2 to 5 years or more. Landfilled waste is known to go through a phase of rapid aerobic decomposition when first deposited, releasing copious CO_2 emissions. Then, fermentation and acidification release hydrogen and CO2. This occurs while the waste is still only lightly covered and gases may escape. Even if sites are leveled and compacted, oxygenated water can penetrate the waste, causing a reversion to aerobic decomposition (Farquhar and Rovers 1973; Mohammadzadeh and Clark 2008).

The IPCC model assumes that carbon will not escape the site as CO_2 in the initial phases of decomposition, before the methanogenic phase is established. This assumption is unrealistic.

3. Degradability factor (DOCf)

In anaerobic landfill conditions, lignin in plant cell walls resists decay, protecting some of the carbon in wood, cardboard, leaves etc. from decomposing. The IPCC landfill model assumes a factor of 0.5 of the degradable organic carbon (DOC) in bulk municipal waste is stored long-term, with the remainder dissimilated to form landfill gas. A study by Bogner & Matthews (2003) is cited.
A check of this reference shows that Bogner and Matthews in fact stated: *"the fraction DOC dissimilated* [DOCf] *is typically much less than 0.50."* They added, *"Optimized laboratory studies of solid waste decomposition from the United States, Germany, and Italy have shown that the dissimilated DOC fraction ranges from negligible to a maximum of 0.25–0.47 (Bogner and Spokas, 1993, Table 4). Methane yields in field settings are lower because landfills do not function as efficiently as anaerobic digesters or laboratory systems… gas generation models may be overestimating gas production, resulting in a lower % recovery when applied to an inflated generation."*
Bogner and Spokas (1993) reviewed a number of studies, concluding that in real landfills, "*One might expect that, in general, more than 75% of the carbon deposited in landfills remains in sedimentary storage."*
This suggests the default carbon storage factor should be 0.75, with a DOCf factor of 0.25.

4. Methane content in landfill gas (F factor)

The IPCC Guidelines provide a default factor of 0.5 for the methane content in landfill gas. They state (Vol 5 p.3.26) that *"The uncertainty in this figure is relatively low, as F depends largely on the stoichiometry of the chemical reaction producing CH4."*
The stoichiometry referred to is an equation used in several models and research papers since the 1990s.
It is set out by Barlaz (2004, pp. 5-8) for cellulose as:

$$(C_6H_{10}O_5)n + nH_2O \rightarrow 3nCO_2 + 3nCH_4 \quad (1)$$

Cellulose + water→ equal molar amounts of CH_4 + CO_2

The assumption that anaerobic decomposition produces equal volumes, or molar masses, of CH_4 and CO_2 can be traced back through several authors to a paper on anaerobic digestion of food and sewage sludges, by Parkin and Owen (1986). The authors comment that when anaerobic digestion is proceeding smoothly the gas produced contains about 50% methane. If methane content falls, this indicates the slurry has become too acidic and decomposition may stall, leaving the sludge only half digested. The authors proposed a complex equation to explain this. When simplified and applied to cellulose, the equation can be reduced to Equation (1) above. Parkin and Owen did not claim that anaerobic digestion always produces equal molar quantities of CO_2 and CH_4 – indeed, they explain that if the digester is overloaded with a rich mix of food waste or sewage sludge, methane output is much lower.
Their equation was simply a wastewater industry rule-of-thumb for methane and CO_2 in gaseous form, not counting CO_2 dissolved in the slurry. CO_2 is much more

soluble than methane, so even if 50-60% of the gas is methane, more than half of the initial carbon may form CO_2 gas or carbonic acid (CO_2 dissolved in liquid).

Mohammadzadeh & Clark (2008) used isotopic analysis of landfill liquids to chart chemical reactions that had occurred within a Canadian landfill site. They found significant evidence of aerobic decomposition following heavy precipitation events in waste deposited up to 4 years earlier. They found several reactions:

Aerobic decomposition
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
Carbohydrates and oxygen form CO_2 and water (2)

Carbohydrates form butyric acid, CO_2 and H_2 (3)
$6CH_2O \rightarrow CH_3CH_2CH_2COOH + 2CO_2 + 2H_2$

Butyric acid forms propionic acid, CO_2 and H_2 (4)
$CH_3CH_2CH_2COOH + 2H_2O \rightarrow CH_3CH_2COOH + CO_2 + 3H_2$

Propionic acid + water → acetic acid, CO_2 and H_2 (5)
$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2$

The synthesis of these reactions is:
$6CH_2O + 4H_2O \rightarrow CH_3COOH + 4CO_2 + 8H_2$ (6)
Carbohydrates and water → acetic acid, CO_2 and H_2
These gases may escape from the site at each reaction.

Hydrogen and CO_2 may form methane and water
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (7)

Acetic acid may cleave to form methane and CO_2
$CH_3COOH \rightarrow CO_2 + CH_4$ (8)

Hydrogen and CO_2 may form acetic acid and water
$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$ (9)
This had occurred in waste buried for up to 28 years, showing that acetic acid does not always go on to form methane and CO_2.

In summary, if no CO_2 or H_2 ever escaped from a landfill site, and landfill never became acidic, then half of the carbon in decomposing waste could form CH_4. But in practice it is unlikely. Fermentation commences as soon as waste is deposited, when sites are unsealed, so gases, especially H_2, are likely to escape. Dugnani et al. (1986) found that hydrogen, like methane, is oxidised by ubiquitous microbes in the soil above landfill sites, forming water. So escaping hydrogen would not be noticed. Loss of CO_2 and H_2 during fermentation would reduce CH_4 output in the methanogenic phase. Overall, less than half the initial DOC is likely to form methane.

5. Leachate loss.

Carbon and hydrogen may also escape in solid, acids, complex compounds, and dissolved CO_2 in landfill leachate The IPCC Guidelines Vol 5 p 3.13 state: "*Generally the amounts of DOC lost with the leachate are less than 1 percent and can be neglected in the calculation"* [of emissions]. No evidence is provided for this claim.. A footnote adds: "*In countries with high precipitation rates the amount of DOC lost through leaching may be higher. In Japan, where the precipitation is high, [sites] with high penetration rate, have been found to leach significant amounts of DOC (sometimes more than 10 percent of the carbon in the SWDS) (Matsufuji et al., 1996).*

A reference check shows that the cited study by Matsufuji et al. does not mention a 10% leachate loss. The study compares degradable carbon "pollutant" loss in two large lysimeters subject to simulated rainfall, over a 700 day period. One lysimeter was designed to be semi-aerobic. It lost 35.5 kg of degradable organic material during this time: 13.1 kg or 36.9% was lost as "leaching pollutants"; the rest was lost as as gases, mainly CO_2.
The second, anaerobic lysimeter lost 33.1 kg of material: 27.2 kg were lost as leachating pollutants, representing 82.2% of the DOC lost – far more than was lost as CO_2 or CH_4. This was a simulation of an anaerobic landfill site – not a real one - but it casts doubt on the claim that "less than 1 percent of DOC" is lost in landfill leachate.

6. Oxidation of methane in the soil cover

The IPCC landfill model has a default factor of zero for methane oxidation by soil microbes. If landfill sites are covered with aerated soil or compost, operators may claim 10% oxidation of unrecovered methane. According to Bogner and Matthews (2003) the 10% value is derived from a study by Czepiel et al (1996), based partly on field data from a New Hampshire landfill site and partly on a model. They comment that 10% methane oxidation is an underestimate.

Methanotrophs are temperature-sensitive, thriving in temperatures of 20-38ºC. New Hampshire has freezing winters with night temperatures falling below zero between November and April. The January minimum is -14ºC. So a study set in New Hampshire is not typical of conditions for most of the world's population. Czepiel et al themselves recognised this, stating: *"the dominance of temperature…and the latitude of the studied landfill imply that annual whole landfill oxidation rates in warmer climates….would be significantly higher than estimates for this site."* They recommended introducing a 'climate factor' when estimating CO_2 oxidation, but the IPCC never did this.

Amini et al. (2013) conducted a major literature search, finding an average 32% methane oxidation in 16 separate studies. Methanotrophs can sometimes oxidise all of the methane available, provided they have adequate oxygen and the methane is emitted slowly, as occurs at sealed sites. Bogner and Matthews (2003) commented that "*At sites with engineered gas recovery resulting in low CH_4 fluxes to the atmosphere, field measurements have demonstrated that methanotrophs can consume all the CH_4 transported upward to cover soils and, additionally, oxidize atmospheric CH_4*". Bogner cites three of her own studies in which this had occurred. Several other authors (e.g. Schroth et al 2012) have noticed the same thing: methane concentrations at the surface of closed sites are sometimes lower than in the surrounding air. This is due to methanotrophs

dwelling near the surface of the site, oxidising the methane coming up from the waste below, and also some of the methane in the air above the site.

Summary

This review of the IPCC landfill model's default factors found that the scientific basis for several factors was not as good as expected at the outset of the study. The IPCC has an impressive reputation for reporting and predicting greenhouse emissions and global warming. Most reports are very well referenced. But the landfill gas model default factors appears to have been chosen without sufficient careful research. The IPCC Guidelines for National Greenhouse Gas Emissions strive to provide accurate estimates of emissions from fossil fuels and other sources. But the landfill gas default factors tend to exaggerate emissions. The IPCC has recognised some of these problems. In 2019 it introduced a "Refinement" to the its 2006 Guidelines. The landfill section was given a new MCF factor for semi-aerobic managed landfill sites, and two new DOCf factors (one for wood and branches and one for other green waste and food waste). Landfill operators were also given permission to claim carbon loss in leachate if they can accurately quantify it – a very difficult thing to do.

Conclusion

The IPCC landfill gas model refinements are welcome but they do not go far enough. The new factor for semi-aerobic managed sites is directed at sites deliberately designed to allow air flow so as to reduce methane output. It does not recognise that even when landfill operators strive to keep oxygen out so as to maximise electricity output, it still penetrates in oxygenated rainwater or air, through pipes, fissures and thin cover. The assumption that most managed sites are 100% anaerobic still strains credulity.

The new default DOCf factor for wood is still too high. For most types of timber in anaerobic conditions, only 1 to 2% of the initial carbon is converted to methane (Wang et al 2011). Wood can certainly decompose in landfill conditions if it is exposed to oxygen before the site is fully sealed. But this is aerobic decomposition : it does not produce methane. The DOCf factor for wood is important because wood is very carbon.-dense. İt has a significant impact on estimated emissions, despite the small amount of wood landfilled in most countries.

Almost all landfill sites lose carbon in leachate – unless all leachate is recycled back into the landfill cells. Further research should be done to find appropriate default factors for leachate loss in various climates, rather than leaving this task to individual landfill operators, with a default factor of zero.

Finally, the default oxidation factor (ox) needs to be revised, and further research is needed on the loss of CO_2 and hydrogen during fermentation.

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