CENTER FOR A COMPETITIVE WASTE INDUSTRY

Effective Mitigation of Methane Emissions from Ontario Landfills

Technical assumptions and control practices

a Report to the Environmental Commissioner of Ontario
from the Center for a Competitive Waste Industry

June 2010

CONTENTS

EXECUTIVE SUMMARY. 1

PURPOSE OF REPORT. 3

1. BACKGROUND. 4
    1.1. Landfill's importance to climate change 4
    1.2. Methane's key role 6
    1.3. Gas collection efficiency 8

2. THE ONTARIO CONTEXT. 10
    2.1. Landfill methane emissions in Canada 10
    2.2. Landfills in Ontario 10
    2.3. Ontario's waste plans 11

3. ANALYSIS OF ONTARIO'S INVENTORY. 12
    3.1. Landfills' responsibility for climate change 12
        3.1.1. Wrong Model 14
            3.1.1.1. Second wave of gas generation 15
            3.1.1.2. Variable methane concentrations 16
            3.1.1.3. Different precipitation rates 18
            3.1.1.4. Moisture omitted 19
        3.1.2. Questionable inputs 20
            3.1.2.1. Total Gas Potential (L_o) 20
            3.1.2.2. Annual gas generation rate (k) 21
            3.1.2.3. Carbon sequestration 22
            3.1.2.4. Oxidation 22
        3.1.3. Invalid time period to measure gas capture 23
    3.2. Landfill-gas-to-energy impacts 26
        3.2.1. New discards 27
        3.2.2. Existing waste-in-place 29
            3.2.2.1. Methane levels increased 29
            3.2.2.2. Collection efficiency degraded 30
    3.3. Impacts of lower gas collection threshold 33

4. CONCLUSIONS. 37

FIGURES

Figure 1 P Diagram of Typical Landfill Profile. 4
Figure 2 P Landfill Carbon Mass Balance. 5
Figure 3 P CO_2 and Methane Warming Effects: Long-Term vs. Short-Term 7
Figure 4 P Greenhouse Gas Emissions by Type of Gas 2006. 10
Figure 5 P Canadian Methane Emissions by Source of Gas 2006. 10
Figure 6 P Ontario Sector Responsibility for Greenhouse Gas Emissions in 2005. 10
Figure 7 P Landfill Decomposition. 13
Figure8 P Bi-model Distribution of Future Methane Emissions. 16
Figure 9 P Diversion’s Advantage Over LFGTE in Long-Term. 27
Figure 10 P Diversion’s Advantage Over LFGTE in Short-Term. 28
Figure 11 P Energy v. Flaring at Existing Landfills in the Long-Term. 31
Figure 12 P Energy v. Flaring at Existing Landfills in the Short-Term. 32

◆

TABLES

Table 1 P Characteristics of Greenhouse Gases. 6
Table 2 P Major Landfills in Ontario. 34

◆

APPENDIX

Appendix A P Summary of Recommendations. 39

ABBREVIATIONS

CAAA	U.S. Clean Air Act Amendments of 1990
CO_2	Carbon dioxide
CO_2-E	Carbon dioxide-equivalent
CDM	Clean Development Mechanism
CH_4	Methane
DOC	Degradable organic carbon
DOC_f	The fraction of DOC dissimilated
EC	Environment Canada
ECO	Environmental Commissioner of Ontario
EU	European Union
GHG	Greenhouse gas emissions from anthropogenic activity
GCS	Gas collection system
GWP	Global warming potential
ICE	Internal combustion engine
ICF	ICF Consulting (authors of EC report)
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
LFGTE	Landfill-gas-to-energy
m^3	Cubic meters
MACT	Maximum achievable control technology
MOE	Ontario Ministry of the Environment
MSW	Municipal solid waste
MT CO_2E	Million tonnes of carbon dioxide-equivalent
NO_x	Nitrous oxides
ppm	Parts per million
UNFCCC	UN Framework Convention on Climate Change
U.S.	United States
EPA	U.S. Environmental Protection Agency
W m^2	Units of radiative forcing (warming per square meter)
WTE	Waste-to-energy (or incineration)

ACKNOWLEDGMENTS

We would like to express our appreciation to Craig Palmer of Environment Canada and James Hiraishi of the Ontario Ministry of the Environment for providing the data and context necessary to understand the present regulatory structures in Ontario and protocols for evaluating gas emissions from landfills. We would also like to thank for their peer review comments Mr. Hiraishi along with David Picard of Clearstone Engineering, and Dr. Shirley Thompson of the University of Manitoba. Their involvement in reviewing the draft, of course, does not imply endorsement of the final product. Finally, the kind patience and advice of Mr. Chris Gates from the Commissioner's staff, was invaluable.

EXECUTIVE SUMMARY

This report examines the current protocols and assumptions that underpin the Province of Ontario's landfill gas collection and control practices. Recent changes to *Ontario Regulation 232/98 – Landfilling Sites* now require smaller landfills to design and install gas collection systems, to either flare methane or burn it to generate electricity (landfill-gas-to-energy or LFGTE). However, there does not appear to have been any critical evaluation of the industry assumptions underlying this change in regulatory requirements.

The report concludes that sources of methane from landfills are an important factor in any *short*-term climate change response strategy. This conclusion is derived from observations regarding methane's relatively short (~12 yr) lifetime in the atmosphere, which translates into a global warming potential (GWP) up to three times higher than previously considered (i.e., a GWP on a 20-year time frame of 72 vs. a GWP of 25 if based on a 100-year time frame).

The report also concludes that gas collection efficiency, previously assumed to be 75% based on U.S. Environmental Protection Agency (US EPA) data, has never been validated through field measurements and may, according to the Intergovernmental Panel on Climate Change (IPCC), be as low as 20%. Further, the report notes that after the site is closed and postclosure maintenance ends, the cover may fail permitting rainfall to reenter the waste body and produce further gas generation at a time when there are no controls.

For existing waste-in-place facilities, where there are no alternatives, the report concludes that LFGTE may release two or more times as much greenhouse gases (GHG) compared to flaring (notwithstanding its ability to avoid CO2 emissions from power plants). This is because LFGTE requires major modifications to how a landfill is operated and maintained to ensure an economical supply of methane to produce power – modifications that increase the volume of methane generated and the proportion that escapes as fugitive emissions.

With regard to new discards, the report concludes that alternatives to landfills are, on average, 16 times more effective in reducing GHGs than LFGTE, largely as a function of diversion's effectiveness in preventing organics from entering landfills in the first place. However, the regulatory changes noted above are sending mixed and conflicting signals to Ontario municipalities and landfill operators.

On the one hand, Ontario's municipalities are responding to the dual concerns about GHGs and threats to groundwater from landfill leachate contamination by accelerating their organics diversion efforts. But, the requirement for installing landfill gas capture systems in smaller capacity landfill sites, at considerable cost, may prompt operators to seek an increased stream of organics to feed their landfill gas collection systems to generate electricity.

The report recognizes the need to capture landfill gases in existing landfills but questions the underlying assumptions regarding the environmental efficacy of gas collection systems where methane gas production is accelerated. The contradictory messaging to municipalities underscores the need for a broader waste management strategy in Ontario.

PURPOSE OF REPORT

The Office of the Environmental Commissioner of Ontario (ECO) contracted the Center for a Competitive Waste Industry to evaluate the current protocols and assumptions that underpin greenhouse gas (GHG) mitigation plans in the waste sector in Ontario, with a specific focus on landfill gas collection and control practices. The intent was to produce a report providing the baseline for effective mitigation of climate change and related GHG impacts in the waste sector based upon reliable data and systems and correct tools for measurement. This independent review updates data and assumptions regarding landfill practices to reflect the best scientific knowledge currently available to better evaluate whether the Province is maximizing opportunities for waste sector climate action plans.

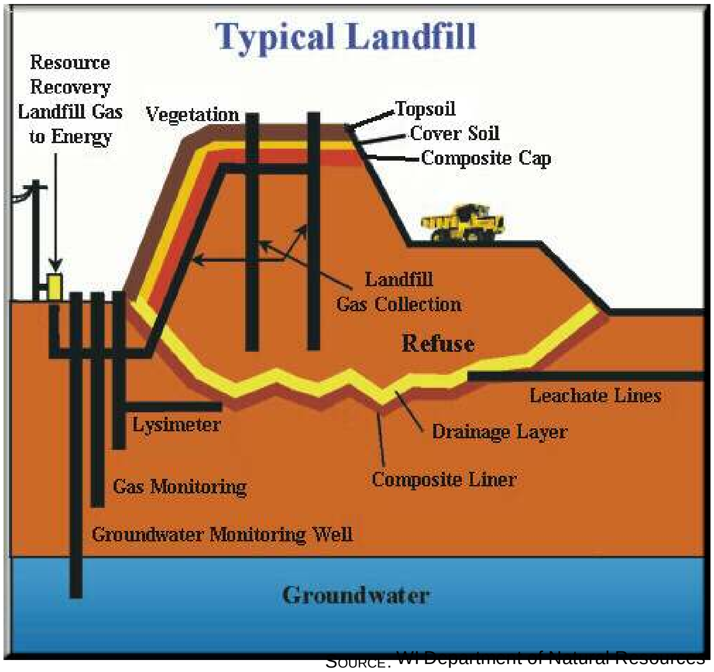
1. BACKGROUND

Prerequisite to understanding this report's response to the Commissioner is an appreciation of landfills' relationship to global warming; the especial importance of uncontrolled methane generated in landfills to climate change; and how this gas escapes from landfills.

1.1. Landfill's importance to climate change.

The vast majority of municipal solid waste is disposed of in landfills. Half or more of the wastes consist of organic discards, such as food scraps, soiled paper and yard trimmings, that generates gases as a byproduct of decomposition. About half of the gases generated by decomposing wastes that are buried is carbon dioxide. Because the source of that carbon, as a part of the carbon cycle, comes from and returns to plants and trees without adding new carbon, it is considered biogenic. Such biogenic carbon is not generally counted as anthropogenic, or manmade, which means it is not considered as a contributor to global warming.[1]

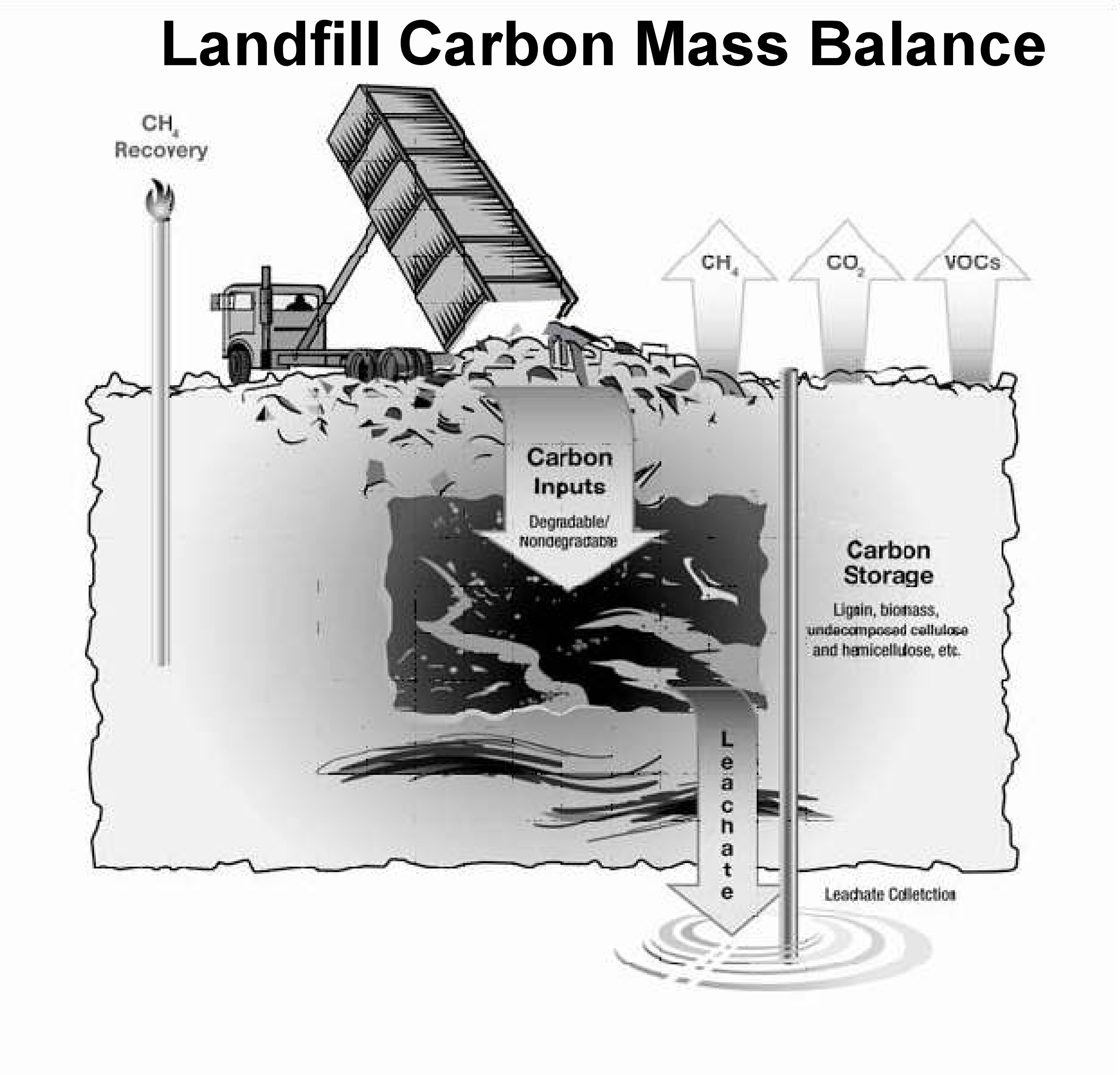
However, when we bury our wastes, along with their organic constituents, anaerobic (or oxygen-starved) conditions are created in which methanogenic microbes thrive. Consequently, in addition to CO_2 and water, major volumes of methane, a greenhouse gas, are also produced as a byproduct of rotting garbage. The methane generated in landfills strips out volatile organic chemicals that can contribute to ground level ozone, a constituent of smog and release hazardous air pollutants into the atmosphere. To reduce the impact of landfill gases on global warming, smog and human health, gas collection systems are usually required.[2] FIGURE 1 shows a typical landfill profile.



SOURCE: WI Department of Natural Resources

FIGURE 1

While CO_2 from decomposing garbage does not add to the overall stock of GHGs, methane is an especially aggressive greenhouse gas with 25 times the warming potential of CO_2, when measured over 100 years, and 72 times over 20 years.[3] Because of the inherent challenges controlling gas in landfills extending more than a hundred hectares, much of it escapes into the atmosphere through the top, bottom and especially the sides.[4] FIGURE 2 on the following page shows the mass balance of carbon moving, and being chemically and biologically transformed, through a landfill.



Source: EPA, Solid Waste Mgt & GHG, p. 81.

FIGURE 2

Landfills' importance to climate change is a function of how much of and when that methane is generated, and, of that, how much of it is captured, oxidized in the overlying layer of dirt, sequestered by lignin or used to generate electricity that offsets fossil-fired power generation on the utility grid.

! *1.2. Methane's key role.*

Climate action plans are often predicated on long-term technology strategies to reduce CO_2, including sequestration of carbon from coal power plants, the substitution of hydrogen for gasoline at the pump and energy efficiency programs such as green buildings. But, for political inertia to be overcome, the clean coal technology to be developed and capital building stock rolled over, decades will pass before sizable CO_2 reductions will be realized, and, thus, they offer little relief for the immediate crisis.

In addition, long-term historic climate trends indicates abrupt shifts repeatedly have occurred due to positive feedback loops running out of control. An example are forces that lead to the unstoppable break up of the massive Greenland glaciers. That has led many climatologists to conclude that we confront a point of no return in the near term, after which those feedback loops may become irreversible. Key tipping points are variously anticipated will be upon us in 10 or 20 years.[5]

Attention, therefore, is turning to a parallel set of alternatives focused directly at that short-term time horizon which can buy the necessary time for those CO_2 reductions to slowly be realized. This has shifted the spotlight to a parallel set of strategies aimed at the short lived and more potent greenhouse gases, where the impacts are concentrated and pronounced in the near term.

Characteristics of Greenhouse Gases

	Percent of GHGs in Atmosphere	Life in Atmosphere	Global Warming Potential Short-Term	Global Warming Potential Long-Term
Carbon Dioxide	99.451231%	100	1	1
Methane	0.464456%	12	72	25
Nitrous Oxide	0.083969%	114	289	298
CFC-11	0.000079%	45	6730	4750
CFC-12	0.000262%	100	11000	10900

SOURCE: Intergovernmental Panel on Climate Change

TABLE 1

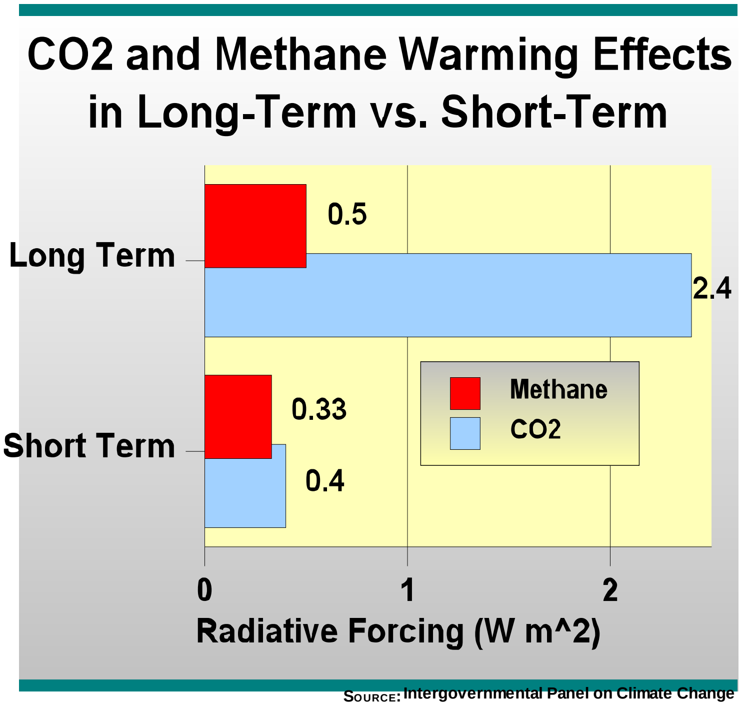
TABLE 1 lists the major greenhouse gases, along with their relative concentration and residence time in the atmosphere, and their global warming potential (GWP) as a multiple of CO_2 when measured in the short-term (20 years) and long-term (100 years).[6] The greenhouse gas with the combination of the greatest prevalence, shortest residence time and highest warming potential leads to methane as a key element in an effective strategy to buy the necessary time and to avoid the tipping point.

While there is 214 times more CO_2 than methane in the atmosphere, methane's global warming potential per molecule is far more significant than CO_2's. For one thing, by weight, methane, which has increased nearly threefold in industrial times, is as much as 72 times more potent. For another, its residence time in the atmosphere is approximately 12 years, compared to CO_2's 50-200 years,[7] thereby concentrating its impact on the present, which is the critical time if we are achieve quick GHG reductions to avert positive feedback loops from becoming irreversible.

The graph along side illustrates the effect of a shift in perspective from the 100 year long-term, when methane has 25 times the warming impact of CO_2, to the near term 20-year time horizon, when methane has 72 times CO_2's. The 20-year time frame, which is the outer bound of the tipping point, dramatically magnifies methane's warming potential. While in the long 100-year time frame carbon dioxide shows approximately five times the warming effect on global climate, in the short run, CO_2 and methane's impacts are almost equal.[8] See FIGURE 3.

Methane's critical role is being increasingly recognized. The Goddard Institute for Space Study's James Hansen confirms –

> "CO_2 increases are the main cause of the increasing anthropogenic greenhouse effect, so efforts to mitigate global warming must focus on CO_2. However, it would be a mistake to infer that non-CO_2 forcings are unimportant relative to CO_2.... Given the difficulty of halting near-term CO_2 growth, the only practical way to avoid dangerous anthropogenic interference with climate may be simultaneous efforts to reverse the growth of some non-CO_2 gases while slowing and eventually halting the growth of CO_2. .... [F]easible reversal of the growth of atmospheric CH_4 and other trace gases would provide a vital contribution toward averting dangerous anthropogenic interference with global climate."[9]



SOURCE: Intergovernmental Panel on Climate Change

FIGURE 3

The U.S. Environmental Protection Agency (US EPA) adds similarly that,

> "[Methane's] relatively short lifetime makes methane an excellent candidate for mitigating the impacts of global warming because emission reductions could lead to stabilization or reduction in methane concentrations within 10-20 years."[10]

1.3. Gas collection efficiency.

How much of the methane generated in landfills escapes into the atmosphere depends primarily upon how much is captured if and when active gas collection systems (GCS) are installed. To reduce these fugitive emissions, a GCS is installed some number of years after the landfill first accepts garbage.[11] The effectiveness of those systems, in turn, depends largely upon many site specific factors.[12]

Unfortunately, there is limited actual field data on how effective any particular landfill's collection system is because landfills are immeasurable non-point sources of emissions.[13] Because the question is probabilistic and the stakes in a carbon constrained world are substantial, there is an extremely wide diversity in opinions about capture rates. At the upper end of official estimates, the US EPA assumes landfill gas collection efficiency is 75%,[14] which is also incorporated indirectly into Ontario and Environment Canada's analysis.[15] However, notwithstanding the widespread adoption of this value in national, provincial and state inventories, there are insufficient field measurements to validate it.[16]

Moreover, there are also two major methodological flaws in US EPA's contemplation. First, the agency's assumption is based upon what the agency imagines the best, and not the average, gas collection systems achieve.[17] Yet, to reflect global atmospheric concentrations of greenhouse gases, the aggregate values are a function of the typical site, not just the best ones.

Second, US EPA's assumption is also predicated upon what the systems can achieve in a limited time period when the efficiency of GCSs are greatest. This is after the final cover is installed and continues for the extended, but finite period, that the cap is maintained. However, very little gas generation occurs when the barriers block moisture. Most gas is generated before and after that time when there is little or no gas collection. That is to say, efficient gas collection is only possible in a dormant period when almost no gas is produced for lack of moisture. Before and after that time is when there is moisture in the landfills and most gases are generated, yet almost none of those gases are captured.[18]

To turn, then, to the lower end of the officially estimated range of estimates for gas collection efficiency lies the Intergovernmental Panel on Climate Change. In its Waste Chapter to the Fourth Assessment Report in 2008, the IPCC found that, even though the best systems at the best times may achieve efficiencies greater than 90%, when an average-lifetime definition is used instead, the capture rate "may be as low as 20%."[19]

The timing mismatch between gas collection and gas generation is accentuated even further in Ontario. Under the Ministry of the Environment's regulatory approach called "controlled precipitation," the owner generally delays installation of the gas collection system and the final cover until the entire site reaches final grade, rather than covering and managing gas collection at the landfill sequentially in stages as each section is built out.[20] This means some gas generation is shifted from the distant future after the cover ultimately fails, when there will be no gas collection, to the present, when there also is no gas collection, but is precisely when there are substantial concerns about our passing a tipping point. If time shifting of gas generation is an objective, moving methane production backward to the present instead of ahead to the distant future carries extremely large adverse implications for crossing a tipping point due to its high GWP.

Wrestling a supportable and reliable best estimate of gas capture to the ground is an important part of any climate action plan. On the correct answer– based upon the correct definition of the terms – lies a proper assessment of landfills' responsibility for greenhouse gas emissions. With actual data, best estimates suggest actual collection efficiencies are several factors lower than commonly assumed.

➥

2. THE ONTARIO CONTEXT

2.1. Landfill methane emissions in Canada.

Estimates of methane's share of total manmade greenhouse gas emissions in Canada is 14%, when each of the different gases is converted into its equivalent as CO_2 and measured over the long-term (100 years).[21] See FIGURE 4. As noted on page 7, in the short-term, according to the IPCC, methane's responsibility would be close to carbon dioxide's.

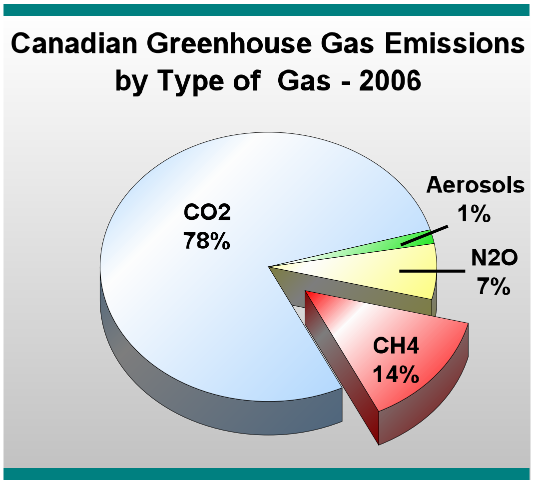


FIGURE 4

Landfills, where 95% of Canada's discards wind up, are a major source of anthropogenic methane releases. However, because gas is released though a plethora of escape routes from landfills, there are no actual measurements of their responsibility. Instead, as discussed below, estimates are made from assumptions that are not grounded in any reliable factual basis.

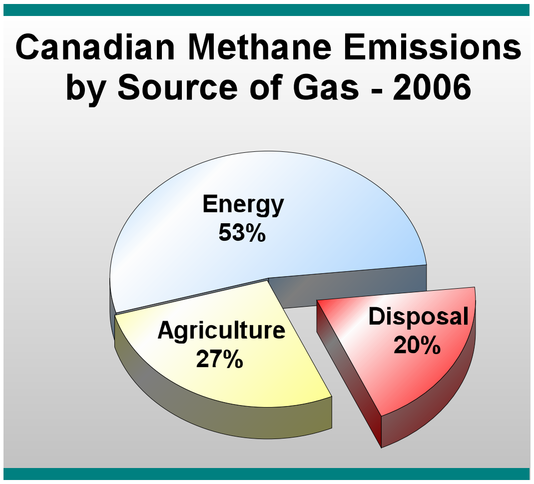


FIGURE 5

Subject to this limitation, but using the protocols for projections established by the United Nations Framework Convention on Climate Change (UNFCCC), Environment Canada estimates that landfills are responsible for about 20 million tons of methane, which is 20% of all the country's anthropogenic methane. See FIGURE 5. Of the whole, and on a basis of its 100-year equivalence to carbon dioxide, landfills are estimated to generate 21 MT CO_2E out of a total of 721 MT CO_2E, or 2.9%.[22]

2.2. Landfills in Ontario.

In Ontario, landfills' responsibility for all GHGs has been pegged slightly higher, at 4.0%, by the Ministry of the Environment (MOE). See FIGURE 6.[23]

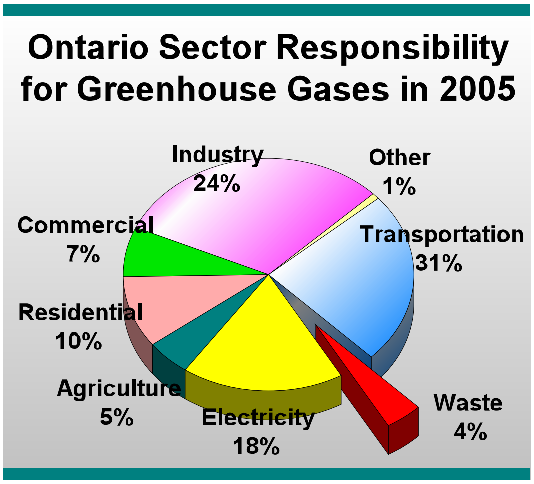


FIGURE 6

2.3. Ontario’s waste plans.

Government efforts to address climate change are reflected in each country and province’s climate action plans. In 2007, Ontario released its plan, which contained many ambitious objectives, such as phasing out coal power plants. It also contains specific recommendations concerning the Province’s 22 landfills.

With regard to the waste sector, Ontario’s Climate Action Plan –

① Concluded that fugitive landfill gas bears a nontrivial, but not decisive responsibility for GHGs.

② Encouraged burning landfill gas to generate electricity, often referred to as landfill-gas-to-energy or LFGTE, which was incorporated into its overall renewable energy goals.

③ Recommended improvement of methane capture at landfills by reducing the minimum size landfill required to install an active gas collection system from three to 1.5 million cubic meters,[24] and offering $10 million in financial assistance for the projects.[25]

Each recommendation is analyzed in turn for its effectiveness in addressing global warming issues.

➥

▲3. ANALYSIS OF ONTARIO’S INVENTORY

As an outgrowth of the United Nations Framework Convention on Climate Change (UNFCCC), each signatory from among the industrial countries annually prepares a national inventory of its estimated greenhouse gas inventories, typically back to 1990 as the base year.[26]

The inventories also breakdown total annual emissions by types of greenhouse gas, such as carbon dioxide, methane, nitrous oxide and aerosols, as well as by sources of each gas by sector, such as electric generation, transportation and landfills. By beginning with a base line, over time, the totals measure how well each country has met the objectives of the 1997 Kyoto Protocols in reducing total emissions, which, by 2012, are intended to be approximately 5.2% less than 1990 levels. These breakdowns lay out a road map indicating where to target reductions to achieve those objectives when climate action plans are developed.

How much attention climate action plans devote to reducing emissions from any particular source of GHGs turns out largely to be a function of its reported significance to the whole, and the ease and cost of achieving those reductions. To the extent that, through measurement error, the inventory significantly understates a source’s true responsibility, the effectiveness of the overall plan would be brought into question, and the capacity of society to avert major climate change, undermined.[27]

! *3.1. Landfills’ responsibility for climate change.*

Using the IPCC’s Guidelines, Environment Canada, and then Ontario’s Environment Ministry, estimate that landfills’ responsibility for GHGs in the country and province in 2007 was 2.9% and 4.0%, respectively.[28] These numbers are not trivial, but, had they been correctly stated, as is explained below, neither would they be so overwhelming as to be on the top tier of issues for attention. The question is how accurate are these reported GHG emissions from landfills.

There is significant difficulty inventorying landfills’ emissions because currently, and for the foreseeable future, it is effectively not possible to take reliable field measurement of their releases. Landfills are typically configured in the shape of a four sided pyramid. They can extend over tens of hectares, and, with their base dug approximately 20 meters into the ground, may be many tens of meters high.[29]

Consequently, landfills’ methane releases are not channeled through a point source where measurement devices can be installed. Instead, gases, which combined are heavier than air, are generated anaerobically from within the decomposing wastes, and follow any number of escape routes. Their tracks are a function of the random location of paths of least resistance and pressure gradients through the heterogeneous waste mass. They flow out into the atmosphere not only through cracks, tears and broken seams at the surface along the sides and top, but also conveyed along the bottom of the facility following leachate collection gravel trenches and piping.[30]

To further complicate matters, methane generated by decomposing wastes buried in the ground is not produced all at once as the wastes are buried, but rather extends over decades, partially resembling a standard decay function.[31] Leachate, which is related evidence of continuing biological activity, is still being generated today from garbage dumps dating back to the Roman Empire.[32]

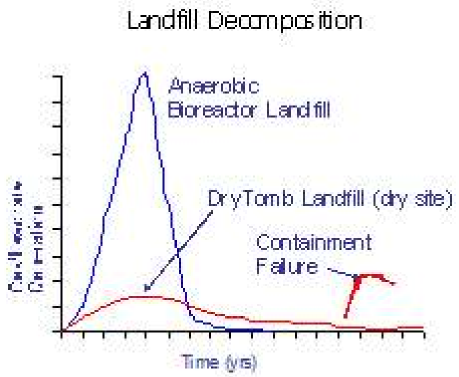


FIGURE 7

This characteristic is of some moment because, like elsewhere, at Ontario's landfills, gas collection is not omnipresent. Extraction wells are often not installed in Ontario until about the time the landfill is closed, 15 to 20 or more years after opening. Then, service is withdrawn after the site's initial wave of gas generation tapers off, perhaps 10 to 20 years following that.[33]

But, after closure and postclosure maintenance eventually winds down, over time the cap on top that blocks incursions will deteriorate and rainfall will re-enter the site. Then, a second wave of gas generation will be re-ignited, and at that future date, there will no longer be any functioning controls.[34] FIGURE 7 shows how the California Integrated Waste Management Board describes the later re-emergence of leachate and gas generation over time, which is denoted on the graph as "containment failure."[35]

Although data is lacking, as subsidence records suggest, conceivably more gas may be generated and released uncontrolled than is produced during the limited time that the collection pipes are installed and fully functioning.

Without actual measurements of emissions to ground the accounting, national inventories of hard-to-quantify sectors have turned to modeling, which in this case attempts to mathematically mimic methane generation patterns inside an actual landfill and fugitive releases from the facility based upon a number of factor inputs. These include such simple things as the number of tonnes of waste-in-place (WIP) to other factors, discussed below, that are essentially unknowable.

With that introduction to the lack of any reliable information about actual landfill emissions, on balance, Environment Canada has done a reasonably diligent job of following the modeling guidelines put forward by the IPCC.[36] However, a careful examination shows that the process laid out in those guidelines are fundamentally flawed. Faced with an almost complete lack of salient data, landfills' purported responsibility for GHGs is based upon a methodology that is predominately, and imperfectly, focused on achieving something that resembles *precision*, with relatively little attention devoted to *accuracy*, notwithstanding IPCC's hope to reduce uncertainty.

In statistics, these are terms of art that have a specific meaning of critical importance. Precision refers to a protocol intended to measure something in a manner that, if done repeatedly, will tend to produce similar results, and preferably do so with a defined degree of variation around the predicted mean value. Thus, as an example, a broken scale that is always 10 kilograms too low or too high may produce consistent results between measurements and therefore be precise, but each result will be wrong in reporting the accurate weight of the person standing on it.[37] Accuracy refers to the correct answer.

In the landfill case, the sites are immeasurable non-point sources. So a model has been constructed that attempts to estimate fugitive methane using a mass balance analysis. Like balancing one's checkbook, this technique attempts to account for all the material entering and leaving a defined system by adding up its discrete parts and tracking where they go. As applied here, it essentially involves attempts to estimate:

① The total gas potential in a landfill over the entire lifetime that gas can be generated (referred to in the equations as L_o);

② The amount of gas that would be generated from that lifetime total in a given year using the Scholl Canyon model, which is an equation that tries to track how much material decays in a landfill each year by multiplying a rate constant (referred to in the equations as k) by the remaining mass; and

③ Of that generated, the amount of gas captured (through gas collection systems), sequestered (in the waste mass) and oxidized (in the overlying dirt cover), to then be subtracted from generation to deduce the net releases.[38]

Among these several parameters, the only known value may be the amount of gas captured. All the other input values are based upon estimation procedures more focused on precision than accuracy. Their value for greenhouse gas inventories are examined below.

Of note, the result cannot even properly be called precise without a questionable leap of faith. For the landfill protocols are only reproducible if, for several key inputs, certain and not other assumptions in the literature – none derived from actual field measurements – are selected, even though there is little factual basis for that choice. A classic example is the assumed gas collection efficiency rate described earlier on page 8, which is indirectly used to estimate total gas generation.

• **3.1.1. Wrong Model**. Canada uses the so-called "Scholl Canyon" equation to model annual methane emissions from landfills. There are three major problems with the model itself, before turning to the inputs used.

. *3.1.1.1. Second wave of gas generation.* The overall model is based on a standard decay function, which is one that represents a natural process in which the original mass decays over time and thus, each year, will release less material than the year before because part of the original mass has been exhausted in the prior period.

In landfills, the relevant waste constituents are food scraps, then soiled paper and later the textiles and wood, which decompose, creating gas and leachate. Those who advocate using a decay model first modify it to reflect the fact that new waste is added each year to the original material until the site is full. To account for that initial uptick, the particular decay function used in the IPCC Guidelines and Canada's protocols resembles a dromedary camel's back – that is a camel with one hump – rising rapidly as new wastes continue to be added. Then, gas generation slowly trails off after the site closes as decomposition continues working on the remaining organic discards that have not previously decayed, for perhaps 100 years on the remaining carbon.

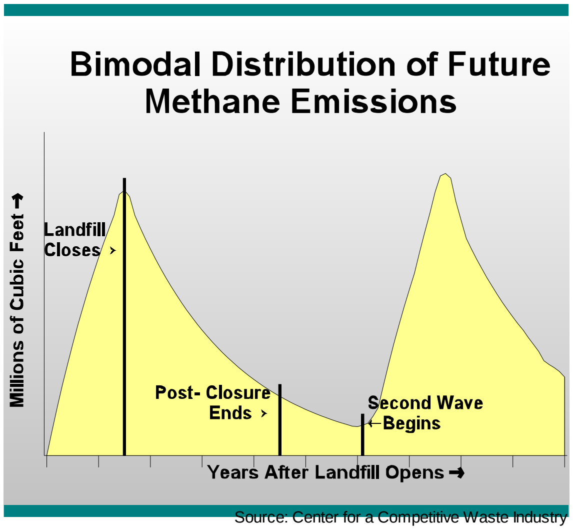
However, this trajectory substantially differs from what actually will happen at landfills over the long-term. In traditional decay functions, there is typically no physical hurdle interposed in the process that impedes its occurrence, such as the continuous declining emissions from the subatomic particles emitted by uranium isotopes. On the other hand, in a landfill, quite the opposite is the case. Along with heat, microbes and pH, which generally are not limiting conditions, decomposition in a landfill cannot comprehensively proceed unless there is a continuing adequate supply of moisture that is evenly distributed.[39] Unfortunately, this prerequisite condition does not exist. The interplay of the discarded organics, barrier performance and time plays out in ways that require a very different equation to describe.

In a landfill, the first thing of note is that there is an initial wave of gas generation while it is open, continuing for a few years after closure, that is incomplete. For one thing, liquids are not evenly distributed in landfills. Municipal solid waste is highly heterogeneous, heavily compacted, interspersed with daily cover, and often confined in splayed open plastic bags, all of which creates preferred paths of flow. Estimates are that liquids only reach 23% to 34% of the mass.[40]

More important, there is inadequate moisture for complete decomposition. While complete biological conversion requires 60%-80% moisture, the moisture entrained in the incoming wastes is usually not much more than 20%, and even the controlled precipitation used in Ontario is unlikely to raise that to levels sufficient to complete decomposition.

Even bioreactors, which also recirculate leachate and add outside liquids in addition to delaying installation of a final cover, have not demonstrated adequate moisture to fully stabilize organic material in a landfill. Though they do achieve substantial subsidence of 15%-25%, a substantial part of that apparently is due to compressive forces, not decomposition.[41]

Thus, the likelihood is not high that the same thing happens in controlled precipitation landfills, except in high precipitation regions such as the Pacific Northwest. Pending hard data being compiled, a best guess from discussions with practitioners is that controlled precipitation landfills achieve an increase in moisture to, perhaps, 35%, and even that would not be evenly distributed.[42]



Source: Center for a Competitive Waste Industry

FIGURE 8

Therefore, Ontario landfills can be expected to also trace their biological activity in a bi-model function similar to, but to a slightly lesser extent than, dry tomb landfills. FIGURE 8 illustrates the bi-model form that an equation would have to track in order to begin to accurately model landfill gas emissions over time.

. 3.1.1.2. Variable methane concentrations. The other problem with the Scholl Canyon model that Canada uses is that, in most cases, it will precisely compute an incorrect value for methane emissions that can be highly inaccurate.

Scholl Canyon makes the following error with its equation:[43]

$$\text{EQ. 1:}\quad L_t = K \times L_o \times \overset{n}{\underset{t=1}{}} M_t \exp^{-(K\times t)}$$

where L_o is the lifetime methane potential and k is the annual methane generation rate

As derived, the equation Environment Canada uses implicitly assumes that landfill gas consists of equal fractions of carbon dioxide and methane.

This is a common error in the literature usually arising out of an oversimplified transposition from chemistry textbooks that fails to account for what actually happens in landfills. The standard chemical postulate that describes decomposition of the carbon in organic material such as cellulose in the presence of methanogens is:[44]

$$\text{EQ. 2:}\quad (C_6H_{10}O_5) + n\ H_2O \rightarrow 3\ CH_4 + 3\ CO_2$$

But, this textbook depiction is the denouement of a long chain of complex chemical reactions that is really based upon a tendency of gas composition from among many observations. It masks a wide diversity among the individual data points seen in the real world and is not an immutable fact that falls out of mathematical equations.[45]

Thus, first order decay models, such as Scholl Canyon, not only are incorrectly applied to landfills that exhibit a bi-model instead of a continuous decay function, but also, they make an arbitrary assumption that methane is fixed, when their basis shows no such thing.

The incorrect equality between CO_2 and CH_4 is carried through into the models in this way. In the first order decay function used in Scholl Canyon and other such models, the mathematical solution to the underlying decay function requires multiplying the product by 2 to derive the quantity of total gas emissions.[46] Since the gas being evaluated, methane, is assumed from the incorrect reading of the chemical conversion to be half of the total, the convention is to drop the 2 when solving for methane rather than total gas. This is what was done in Equation 1.

However, the obvious experiential problem with this formulation, which considers methane to always be precisely one-half of total gas generation, is that it not only misapplies the chemistry. It is also contradicted by the data – actual field data, not assumptions – which often shows landfill gas measured with 55%-60% methane concentration ratios. This is most often the case in landfills that accelerate decomposition, such as by controlled precipitation and leachate recirculation. In contrast, dry tomb landfills minimize liquid incursions, and the data shows that then methane ratios are observed to fall as low as 35% after the landfill is closed with a low permeable cover.

Overall, observed methane ratios in landfill gas are reported to range from 35% to 60%.[47] Environment Canada later notes that the range of methane is from 40% to 60%,[48] but, again, does not incorporate that recognition as a correction to the Scholl Canyon first order equation. EC may have adhered to the IPCC protocols, but, if so, it has done so without independently considering whether those guidelines produce reasonable results as applied.

The low methane concentration ratios occur in dry tomb landfills in part because there is inadequate moisture to complete methanogenesis or too much oxygen infiltration for viable colonies of methanogens. For, in order to maximize gas capture, the dry tomb system operator exerts maximum vacuum pressures through the collection wells until oxygen intrusions approach 5% when flammable conditions could be created.[49] By way of comparison, when managing for energy recovery, air infiltration must be limited to 0.05% – one hundred times less – to prevent poisoning the methanogens that require anaerobic environments. This means dry tomb landfills will tend to exhibit low methane ratios and high collection efficiency, while landfills that accelerate decomposition, and recover energy, will produce high Btu gas at the price of low capture rates.

Together, this suggests that there may be a 50% variation in methane ratios from the low to the high end of the range, depending upon whether immediate gas control or other energy related objectives are pursued. All of these issues are simply ignored by the 50%/50% convention used in the Scholl Canyon and most other first order decay models. Without a correct statement of the amount of methane – the key parameter that drives the output – the study conclusions cannot be relied upon.

For most critical for these climate studies is the fact this degree of uncertainty is magnified between 25 (when methane's warming equivalence to CO_2 is measured over 100 years) and 72 times (when measured over 20 years), because methane has so much more warming potential than carbon dioxide.[50] Thus, the 50% range of unaccounted for variation in methane concentrations equates on a carbon dioxide-equivalent basis to 13 times to 36 times the reported methane quantities in the equations.

Any non-trivial change in methane concentration, which is ignored by the unsupported assumption that methane is always 50%, virtually overwhelms almost the other factors.

. *3.1.1.3. Different precipitation rates*. Finally, there are, at last count, at least 11 different models intended to estimate annual gas emissions from landfills, of which many were developed in relation to observations at individual landfills, and the others synthesized from among the landfill-specific ones.[51] In addition to the fact that none of them use a bi-model function to account for fluctuating moisture levels, discussed on page 15, the selection process among first order decay models was flawed, as well.

By way of background about these models, the values assumed for the lifetime gas potential and the annual decay rate is not a geometric proof or an observed set of data points, and therefore does not represent intrinsic truth. Rather, the selection of one variant of a negative exponential function over another is little more than a tweaking process to find a curve that best seems to match the observed data for total annual gas generation in a given application. In the case of landfills, however, there are no observations of total annual gas generation, because all that is known is the amount of gas captured, while, on average, a non-trivial fraction escapes.

In place of actual observations, the typical method of estimating yearly gas generation, in order to match with an infinite array of possible curves, is to divide the gas that was captured by an assumed 75% instantaneous capture rate,[52] per the equation below:

EQ. 3: $\text{Gas Captured} = \text{Total Gas Generation} \times \text{Assumed Capture Rate}$

solving for Total Gas Generation

$$\text{Total Gas Generation} = \frac{\text{Gas Captured}}{\text{Assumed Capture Rate}}$$

But, this is a tautological methodology that brings its validity back to the accuracy of the assumed capture rate, which is unknown, and which, based upon competing official estimates, the range of reasonableness varies by nearly a factor of 4 times from 20% to approximately 80%.[53]

Environment Canada indicates it selected Scholl Canyon because that model, unlike many of the others, does not insert a lag factor delaying the predicted onset of methane production after first waste emplacement. Its consultant found the data suggests that, in Canada, there is no significant lag.[54]

In non-arid climates, there is evidence that microbial action commences within weeks immediately after food scraps are buried. But, that is just one factor relevant to the selection of an equation that accurately tracks the trace of emissions from landfills in Ontario. Unlike Canada, the Scholl Canyon Landfill, whose gas behavior was used to deduce its model, is located in Los Angeles County. It experiences near arid conditions that severely constrain methanogenesis, and it falls under the US EPA's tighter cover requirements that further restrict moisture additions.

Ontario's continental climate, on the other hand, has ample rainfall. While Los Angeles' average annual precipitation is approximately 46 centimeters, Ontario's rainfall averages about 84 centimeters – almost twice as much. Also, Canadian landfills are operated in ways that maximize infiltration of precipitation, and do so in areas with approximately twice as much rain. Those differences suggest that the Scholl Canyon's base equation would under-predict methane emissions from Ontario's landfills in the early years.

To a limited extent, differences in rainfall might be very crudely controlled for in the model by the use of different inputs than Los Angeles landfills use for the "*k*" factor (see EQUATION 1). This is the methane generation rate, which is a parameter intended to relate to how much of the remaining carbon in a landfill is converted to gas in each year. A high assumed value for "*k*" will tend to increase near term and decrease out-year emissions, somewhat, but not entirely similar to, the impact of higher rainfall.

However, as discussed in more detail later at page 21, the methodology used to derive the adjustment to "*k*" fails to correlate that change to the differences between moisture levels in Los Angeles and Ontario landfills. Moreover, there is no way to know whether, and the extent to which, the use of any specific "*k*" factor will also adequately compensate for the underlying base equation at the heart of the model that was derived from matching observations to various curves in arid conditions.

. *3.1.1.4. Moisture omitted.* As noted previously, the presence of substantial moisture in the range of 60% to 80% is needed to fully optimize methanogenesis in the landfills' anaerobic environment, while traditional dry tomb landfills have approximately 20% moisture. Even facilities that aggressively encourage moisture additions may achieve only 30% to 40% moisture content.[55] Environment Canada agrees that moisture in the "60%-80% range" is necessary for optimized methanogenesis, "because its presence is essential for bacteria growth, metabolism, and nutrient transport."[56]

However, neither the selected Scholl Canyon first order decay model, nor any of the other ten, have any coefficient in their equations for the level of moisture inside the waste mass.[57] Without one, the equation is useless.

Again, as noted, US EPA attempted to substitute an adjustment to the value for "*k*", the annual methane generation rate, to compensate for that omission. The validity of that proxy is discussed in the next section at p. 21 as part of the discussion of the value of the input factors to the model.

• **3.1.2. Questionable inputs.** In addition to the foregoing selection problems for the base model that estimates annual methane emissions, there are also serious questions about the inputs used to run the model, many of which are also recognized by Environment Canada.

In first order decay models, the main inputs are L_o and k. The L_o factor is an estimate of the total amount of latent gas potential remaining in the landfill from the time the analysis begins. *K* is the amount of gas estimated to be produced from the remaining potential gas generation in each year. To simplify the calculation, the amount of material that was decomposed in the prior year is subtracted from the original mass, and the annual methane generation rate is multiplied by the amount remaining. Each of Canada's key estimates raise significant questions.

. *3.1.2.1. Total Gas Potential (L_o).* The total gas potential used in Canada's model is a theoretical calculation. It attempts to count the mass of unsequestered carbon atoms in the landfilled wastes in order to run the IPCC's equation that converts that total into the quantity of gases that can be generated over time. But, that is an artificial and unproven mathematical artifice, not an observed value, nor even one derived from laboratory experiments.

Previous attempts to chemically specify a methane potential from MSW, incidently, have not been overwhelmingly successful. They have ranged from 400 to 520 m^3 CH_4/Mg of MSW. Even more sophisticated efforts to do so after eliminating the large variability in waste composition by isolating the degradable organic fraction for further analysis have only narrowed that to 100 to 310 m^3 CH_4/Mg.[58] That is still by a factor of more than 300%.

Moreover, there are many serious problems with EC's calculation, including the lack of reliable waste composition and sequestration data. As the IPCC's 1996 Guidelines state:

> "The degradable organic content of the waste has a large impact on the potential methane generation value. Small variations in the DOC inputs can result in large variations in the overall methane estimates."[59]

Yet, notwithstanding the extreme sensitivity of the results to even small inaccuracies in the estimates of organics in landfilled waste, the references to the data that was used suggests that point estimates hide very wide uncertainty bands. Apparently, visual audits and elaborate estimation procedures were used to supplement the limited composition data that did exist for the decomposable organic fraction (DOC), and within that the fraction dissimilated (DOC_f), as the basis to calculate how much total methane is generated in landfills.[60]

The report suggests that statistically valid waste composition studies to characterize all three waste streams (residential, and industrial, commercial and institutional sectors) were not the basis for the organic estimates for the total population. A waste composition study involves taking random samples that are carefully designed to be representative of the population, including each sector, and then physically sorting a sufficient number of samples by type of material necessary to achieve a desired level of reliability by sector for a level of significance. Statistical results provide an estimated mean value for each component's share in the population, and a defined uncertainty band around that mean.[61] Without knowing the degree of uncertainty around the mean, there is no way to know whether the process has sufficiently sharpened the estimate of organics' share in order to overcome IPCC's concern that "small variations in the DOC inputs can result in large variations in the overall methane estimates."

As such, the results for the estimate of the total gas potential from landfill gas is not usable inasmuch as it was calculated from highly sensitive factors deemed critical to methane emissions that were not reliable.

Presumably, EC is not oblivious of this fact, but is working with the best information that it has available, within the confines of its budget that does not include undertaking actual waste composition studies. Such studies for just Ontario could easily cost 450 million CAD. However, while the reasons for the inadequate analysis is understandable, as is the need to comply with the IPCC protocols, that does not mean the result can be used to inform the effective mitigation of methane emissions from landfill operations as part of a comprehensive climate action plan. Instead, all it shows is that the agency has generally followed the guidelines the IPCC has laid out. Again, we have the appearance of precision, but that has little to nothing to do with accuracy.

. *3.1.2.2. Annual gas generation rate (k).* The estimates of year-by-year gas generation are calculated from the assumption of the annual methane generation rate, referred to in the equations as "*k*." In recognition of the fact that the first order decay model neglects to account for the critical need for moisture, Environment Canada, following US EPA, attempts to adjust the "*k*" value to account for different moisture conditions using arid (< 580mm average annual precipitation) and non-arid (>580 mm) environments as a dummy variable.[62]

This fails to rectify the serious problem because the extent of precipitation is not a proxy for the moisture in the waste mass and its uneven distribution. Also, the analysis seeking to establish a statistical basis between precipitation and a value for k is not sound. Finally, regional precipitation is specified as a constant value while the actual pattern of moisture in the waste mass fluctuates wildly. For these reasons, EC's adjustment to k to account for three levels of precipitation does nothing to rectify the failure of the model to account for large variations in the amount and distribution of moisture levels.[63]

. *3.1.2.3. Carbon sequestration.* Before estimating the quantity of gas latent in the remaining mass of wastes, another adjustment must be made for sequestration. Part of the constituents of paper is cellulose, that does decompose, but it also includes lignin, which is the trees sticky sap that supports the branches, and which tends to resist anaerobic decomposition in a landfill. How much and to what extent the lignin protects carbon, and for how long, however, is entirely a matter of speculation, notwithstanding the meretricious science attached to values commonly assigned to this factor.

The EC's report and supporting documents do not indicate the specific parameters it used for carbon storage. US EPA uses a single laboratory test from a sample from one local program by Dr. Morton Barlaz that reported a 10% sequestration figure from its desk top analyses. That number has been widely used by other jurisdictions because of its pedigree, even though the agency did caution against attaching great import to one test.[64]

However, a closer examination of this single lab test shows so many errors described in the note that no useful conclusion can yet be reached as to the appropriate value to use for sequestration. The existing literature runs the gambit from 0.8% to 9.4%.[65]

Some sequestration likely does occur due to the presence of lignin, although its significance and duration is not at all clear. Any attempt at this juncture to quantify carbon storage in landfills with a point estimate, or even a usable range, is speculative, premature, and not yet ready to be included in a credible analysis.[66]

. *3.1.2.4. Oxidation.* Like US EPA, ICF, whose work Ontario ultimately relies upon to complete its calculations, assumes that 10% of the methane is oxidized in the overlying soil layer on top of a closed landfill.[67] US EPA's assumption was based upon a 1994 study by Czepiel, which found in field and laboratory studies that 10% of the methane generated in a landfill was oxidized in the cover soil over the course of a year.[68]

When landfill gases are truly diffused throughout an overlying soil blanket of adequate porosity and depth, as would tend to have been the case with properly maintained dirt or clay-only covers as they were typically constructed in the 1970s and 1980s, this study could be partially applicable. However, in the U.S., gases are usually not diffused at the surface throughout that earthen layer, because, in most cases, since 1991 a composite cap has been required under that soil blanket as part of the final cover. In practice, this usually includes a 60-mil (or $^{1}/_{16}$") high density polyethylene plastic membrane that effectively impedes the passage of gases from the waste into that cover soil.[69]

That fact is key. It means that, in the U.S. experience from which ICF borrows,[70] methane is not diffused throughout the topsoil for maximum oxidizing effect. Instead, the gases are concentrated in high fluxes at a handful of cracks and tears in the plastic sheet. The few high flux emissions quickly overwhelm the capacity of the topsoil to oxidize the escaping methane through these hot spots. Czepiel expressly stated that not only was his study not done at a landfill with a synthetic geomembrane, but also, "[p]eriodic maintenance of the cover materials has minimized significant surface cracks" in the clay layer, as well.[71]

Under Ontario's controlled precipitation approach, however, Czepiel's study might have some application to the extended period prior to installation of a final cover, if there is a properly maintained intermediate soil cover as part of the controlled precipitation protocols, as applied. However, even that circumstance would only pertain in the more temperate climate zones south of Canada, though even there not in winter. Without more temperature-specific correlation data, the summertime temperate experience does not *ipso facto* apply in real world operation to the colder continental climatic conditions in Canada, which could constrain oxidation in the exposed cover for part of the year. No field study of oxidation in actual conditions of colder temperatures has been cited in Canada's or Ontario's reports. Until it is supported by real world and not idealized tests, wholesale importation of the U.S. 10% oxidation rate into Canada's colder climes may well overstate the effect north of the border, even in landfills with properly maintained covers, and underlying diffusion layers. Some lower value may well be more appropriate here.

• **3.1.3. Invalid time period to measure gas capture.** After estimating the quantity of methane annually generated from each province's landfills, EC's mass balance equation subtracts the amount observed to be collected and assumed to be sequestered in that year (described in a simplified form at p. 14).

The problem with this formulation, which is a part of the IPCC Guidelines, is that it ignores the fact that the gas generated from buried wastes does not all occur in that year, but rather, as the agency states, extends "for up to eighty years,"[72] and quite possibly longer in some cases. Thus, using this estimate, as much as 79 years of gas emissions can be ignored by a protocol that restricts its field of view to just a single year.

This constricted view ignores the other years over which gas will continue to be generated, including much of the time when there will be no functioning gas collection and unfettered gas generation. It is like assessing a person's dose absorption of a 24-hour time release pill in the first hour after its being swallowed, and ignoring the further uptake in the following 23 hours. The effect in climate strategy is to significantly de-emphasize GHG source whose warming impacts continue in the future from actions taken today.

Although the UNFCCC's original intent in the inventories may only have been intended to show annual emissions to compare with targeted reductions for that year, that contemplation fails to fully account for long-lived emissions on cumulative emissions. Also, the actual use to which they have been put is to prioritize the sectors of major concern for the long term challenge.

To reflect their intended use as well as contemporary practice, the Guidelines need to be updated. Thus, the problem with utility of the EC's and MOE's reports lies more in Geneva than Ottawa.

This inappropriate methodology as applied to the waste sector has been challenged in the literature for at least 15 years, which points out that the use of an "instantaneous" (or point in time) instead of an "integrated" (or lifetime) rate improperly ignores the majority of emissions. Most of the emissions occurs prior to or after active gas collection systems are installed and properly functioning.[73] Unfortunately, the proponents of an instantaneous rate have yet to produce any argument to support their position for an analysis that seeks to reflect threats to the planet's long term climate.

The IPCC's Fourth Assessment Report's Waste Chapter did reference Prof. Oonk, who has been the leading expert calling for an integrated analysis over a landfill's landfill, including his conclusion that, even though instantaneous capture rates by the best systems may be more than 90%, on an average lifetime basis, they are "as low as 20%."[74]

Continued reliance on an instantaneous rate also flies in the face of its internal inconsistencies. Elsewhere, the IPCC specifically states that the inventory "should be based on the effects of the greenhouse gases over a 100-year time horizon."[75] US EPA's own life-cycle study states that "it does not matter whether [methane] is released virtually instantaneously or over a period of a few decades."[76]

Moreover, the use of an instantaneous rate for the capture rate – which makes collection efficiency seem substantially larger than it really is – is also contradicted by the convention to use a 100-year time period to compute the equivalent warming effects of other greenhouse gases to CO_2 – where the effect is to reduce landfills' responsibility for the gases.[77] A mass balance analysis cannot be properly predicated on internally inconsistent data, which here tends to undercount landfills' responsibility for greenhouse gases.

As to the complaint that those future years' emissions have not yet occurred and therefore cannot properly be accounted for in the inventory, there is a well-trod analogous mechanism to do this. Investment decisions routinely incorporates into the present a future stream of income flows that derive from an outlay made today to best pick from various options. That technique is the net present value analysis, long used in economic planning and decision-making.

!

For these reasons, estimates of methane emissions from landfills are effectively meaningless. Those reasons include: the selection of any first order decay model that incorporates neither a bi-model function, nor a variable for moisture; the choice of the Scholl Canyon first order decay model in particular; the use of incorrectly derived inputs for L_o and k; the assumptions for sequestration and oxidation; and the use of an implied high instantaneous capture. Together, these create a recurring tendency to systematically undercount fugitive emissions from landfills. The end result of these choices are not useful for evaluating the importance of the waste sector for developing climate action plans, especially ones directed at avoiding the near term tipping point. To turn a phrase, accuracy has been sacrificed on the alter of precision.

Obviously, much of the reason for these problems stem from limited budgets and international protocols. But, while that may explain the reasons for the compromises made in the process, it does not make the results usable for decision-making. Some other way of envisioning the process needs to be contemplated if the waste component of Ontario’s climate action plan is to achieve its intended purpose. All that the present waste inventory can be used for is showing compliance with IPCC Guidelines, not effective strategies to combat global warming. The Guidelines expressly acknowledge the possible need for countries to supplement their reports with different time horizons,[78] and, to the extent that Ontario’s intent is to provide useful information for the public and decision-makers, this explicit recognition should be acted upon.

3.2. Landfill-gas-to-energy impacts.

As to what Ontario's plan does recommend, it first encourages landfill owners with landfill gas collection systems to install generators that can recover the energy in landfill gas to produce electricity. Landfill-gas-to-energy facilities are made eligible for 20-year power purchase agreements through the Renewable Energy Standard Offer Program. The output from that projected source of power is included as part of 2,600 MW of planned renewable power component of the Province's climate action plan.[79] It also, as discussed in the next section, requires small, as well as large, landfills to install some gas collection.

At the time this report was written, the Ontario Power Authority had announced that, in anticipation of the proposed Green Energy Act's being enacted, it would offer long-term contracts for LFGTE in the range of 8¢ to 44.3¢ CAN per kWh,[80] which compares to a likely cost for landfill owners to produce power of approximately 5¢/kWh. Based upon the U.S. experience in the last year and a half in which long-term LFGTE contracts have been reported to be 8¢ to 9¢/kWh CAN, the effect would likely very significantly increase energy projects at landfills.

The benefits from LFGTE consist of the reductions in CO_2 emissions from power plants, a small part of whose output is displaced by the electricity produced from landfill gas.[81] Although the fact of this offset is conceptually correct, by itself it does not provide sufficient information to answer the broader fundamental question: After accounting for all relevant factors including increases in methane generation, some part of which escapes, does LFGTE increase or decrease *net* greenhouse gas emissions? That is, are the benefits in lower CO_2 generation greater or less than the costs, which are in the form of higher methane emissions, with their substantially greater warming potential 25 to 72 times greater than carbon dioxide?

In order to answer these wider question, the issue should be distinguished as between –

① New discards, and

② Existing waste-in-place.

This distinction is necessary because there are well-trod alternatives to landfills for new discards which do not create uncontrolled methane – namely diversion for composting as well as conversion technologies and incineration – but no practical ones for garbage that is already buried in the ground.

For waste-in-place, on the other hand, there are no practical alternatives. But, most certainly there is the need to understand whether adding electric generation to a landfill operator's responsibility to minimize emissions changes the way he or she manages the site. Or do all of those other things remain the same?

In the consideration of either new or existing discards that follow, two overriding facts stand out. The first is the fact that methane's warming potential – 25 times CO_2 in the long-term and 72 times in the short run – is so great it drives the result when compared to policies that only offset "mere" carbon dioxide. To better conceptualize methane's power, that extremely large multiplier would, by way of comparison, enable an athlete who can run a four minute mile to do so in three to nine seconds. Second, as noted, of all the alternatives for managing organic discards, only landfilling creates uncontrolled methane, which otherwise would not exist.[82]

- **3.2.1. New discards.** The industry's claim essentially posits that the only issue necessary to determine LFGTE's benefits is how much CO_2 is offset from power production on the utility grid.

However, for a landfill to produce methane requires a decision to bury our organic discards rather than separate them for composting or any of the other alternatives. Every municipality in Ontario successfully separates about a third their residents' bottles, cans and newspapers for recycling. Proven strategies demonstrate that far higher levels of organics diversion are feasible.[83]

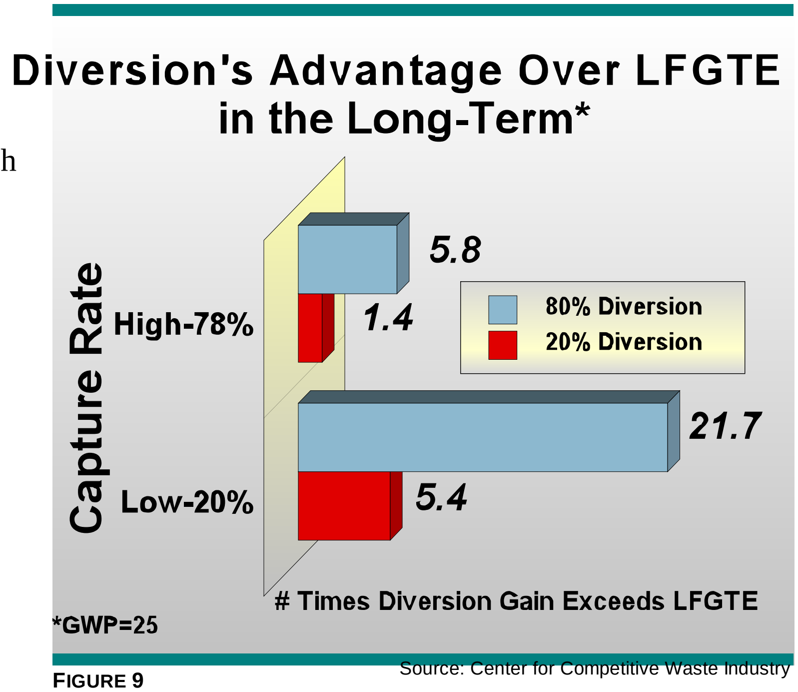
Jurisdictions that have banned yard trimmings from landfills have nearly eliminated all leaves and grass from dumps. Adding the other organics, largely food scraps and soiled paper, to the things we separate is easier than recyclables because most of it is generated in one room: the kitchen. Also, specialized strategies have shown how to improve on that. Collecting organics weekly and trash biweekly, for one, not only reduces the costs of diversion, it also incentivizes unmotivated households to cooperate. Otherwise, their putrescibles will remain in the house another week.

In North America today, there are 124 municipalities now moving aggressively onto this next chapter of diversion efforts, most prominently Greater Toronto. In Europe, its 25 member states are mandated to reduce organics in landfills to 65% of 1995 levels by 2016 because the Union found that palliative efforts to reduce methane's impacts were inadequate to the task.[84]

If organics are diverted from landfills, then the nearly insurmountable challenge of controlling methane released from landfills is eliminated at its source. Methane is not produced in the first instance. Methane's GWP is 25 times CO_2's or more. Diversion's benefits are measured in units of avoided methane, while LFGTE's benefits are measured only in how much CO_2 is offset from the grid. With the force of that GWP multiplier from methane avoidance, there can be no reasonable dispute about the enormous inherent advantage diversion has over CO_2 avoidance-LFGTE.

To show this, FIGURE 9 calculates different scenarios when methane's GWP is calculated over the long-term at the extreme ends of the range of reasonableness. On the one hand, how much landfill gas is captured using the range of government offered assumptions referred to earlier from 20% to 78%, and, on the other, what proportion of organics are diverted from 20% to 80%. No matter which end of either range is selected, diversion is always more effective than LFGTE at reducing GHGs.

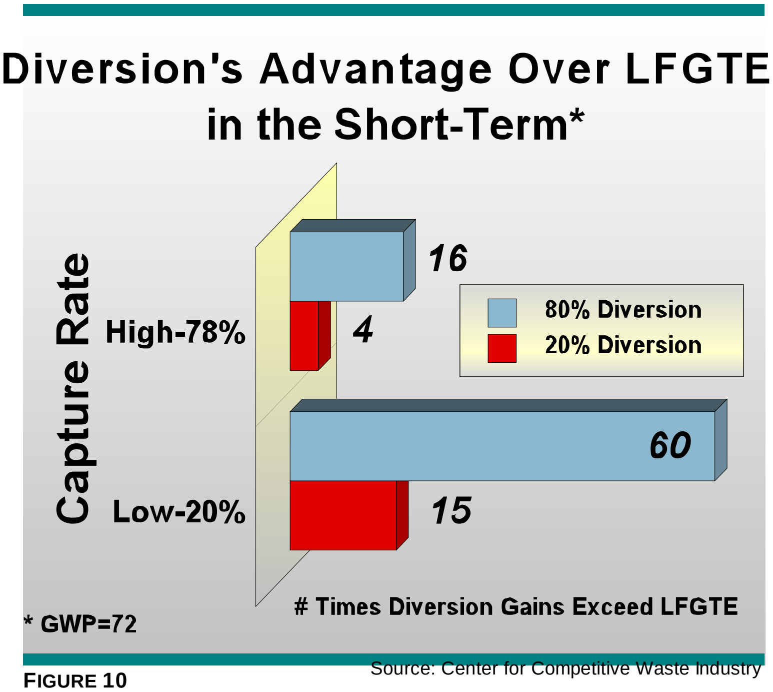
When the question is asked about new discards, the benefits from diversion overwhelm the benefits from LFGTE, by somewhere between 1.4 and 21.7 times as a function of which combination of assumptions are used. Of further note, one organics diversion strategy – anaerobic digesters – also produces substantially more electricity per ton of discards than LFGTE.



Source: Center for Competitive Waste Industry

FIGURE 9

In the short-term when methane's GWP rises from 25× to 72×, diversion's advantage over LFGTE increases dramatically, as shown in FIGURE 10, to between four and 60 times.



Source: Center for Competitive Waste Industry

FIGURE 10

The purpose of these two graphs is to demonstrate that diversion will always produce greater GHG benefits than LFGTE no matter what assumptions – within the range of reasonableness – are used. Inasmuch as the average of these scenarios is a net gain of 16 times, in the more likely case, diversion's advantage will be magnitudes larger than LFGTE.

Therefore, Ontario's brief in support of LFGTE for new discards only exists if one ignores the fact that there are demonstrated, sustainable and significantly less GHG-intensive alternatives.

• **3.2.2. Existing waste-in-place.** Leaving new discards and turning to existing waste-in-place, Ontario's plan presumes that recovering the energy value in landfill gas is inherently preferable than just flaring it, especially since at least here, the garbage has already been buried and can no longer be diverted. So, again, the thesis states, this can reduce the need to generate electricity from power plants, thereby somewhat lowering their emissions of carbon dioxide, and it can do so in this context without losing the opportunity for dramatically lower emissions from alternatives.

That a small part of our electricity needs can be met this way is true, and that will slightly reduce CO_2 emissions. However, as before, the question must again be asked whether it is true, as the Province's argument necessarily assumes, that there will be no changes in the manner landfills are operated necessary to make LFGTE from energy poor landfill gas profitable. For, if that is not the case, and landfill practices are often altered in ways that mean more methane is generated in the near term, and if it is the case that these modifications mean degraded performance of gas collection systems, then the increased methane needs to be accounted for and weighted against those benefits in CO_2 avoidance. For with methane's very high warming potential, even a small increment could overwhelm the benefits from lower CO_2 emissions.

However, nothing in Ontario's plan, or the federal reports on which it relies, suggests that anyone has fact-checked this implied claim that landfill practices do not often change to boost the profitability of LFGTE. Essentially, implicit in the plan's conclusion is an unsupported belief that *ceteris paribus* – that everything else concerning those landfills which exploit their energy potential remains the same in all other respects.

However, this *ceteris paribus* assumption is not correct for two reasons documented below–

① The proportion of methane in landfill gas generated at traditional dry tomb sites would be too low to economically operate the reciprocating engines that typically generate electricity; and

② The same operational changes needed to enhance methane concentration to economic levels degrade gas collection efficiency.

Consequently, only because of the need to maximize revenues from LFGTE, those landfills tend to be operated differently, which otherwise would not happen, in order to generate greater volumes of methane, more of which, unfortunately, escapes.

· *3.2.2.1. Methane levels increased.* The proportion of methane in the landfill gas produced at sites that just flare gas, compared to ones that recover the methane to generate electricity, is not fixed in both at 50%, as the calculation of LFGTE's benefits in the supporting reports state.[85]

In fact, landfills that are properly operated under "dry-tomb" principles strive to minimize infiltration of liquids and maximize gas capture so the wastes remain as close to biologically inactive and immobile as possible and hazardous compounds are not released, thereby posing less of a threat to the environment.

Chief among the means dry tomb principles employ to accomplish this is early installation of a low permeable composite cover as soon as each section reaches capacity. That helps minimize the generation of gas and leachate for the foreseeable future. Moisture levels in the incoming wastes may start out at 20% and quickly drop as gas collection simultaneously sucks much of that residual moisture out with the gas.[86] Moreover, the little that remains is unevenly distributed, leaving substantial swathes of waste completely dry and inactive.[87]

Methane concentrations typically seen for operating dry tomb landfills, regulators indicate, are 40%-45%, while in LFGTE sites, 55%-60%. Presumably, there also will be more total gas volumes from accelerating decomposition due to time-shifting gas production that otherwise would not occur for decades hence, but no data exists on that point.

The base level situation in Ontario, with controlled precipitation, has not been quantified. But, presumably it lies between the dry tomb and LFGTE conditions, and, we expect, most likely closer to dry tomb conditions because the real moisture gains require aggressive liquid additions.

. *3.2.2.2. Collection efficiency degraded.* In addition, gas collection systems at true dry tomb landfills are operated aggressively for the best performance by maximizing the negative pressures through the wells in order to pull as much gas as possible. The only constraint occurs when oxygen from the surface, which is inadvertently pulled at the same time through cracks in the geomembrane, is in the range of 5% to 15% . That is the point the mixture becomes flammable.[88]

While the waste mass in dry tomb landfills may have as little as 10% moisture and as much as 3%-5% oxygen, optimal methane generation, on the other hand, requires as much as 65% moisture – three times the levels in dry cells – and less than 0.1% oxygen. Otherwise, the levels of air that are acceptable in dry tomb landfills, which is approximately 50 times greater, would kill the anaerobic methanogenic microbes. To prevent that from happening, at the first sign of oxygen infiltration, LFGTE operators ramp down the vacuum in the wells to prevent short circuiting.

However, at the same time this reduces the radius of influence and the vacuum forces no longer reach the surface, it also withdraws coverage through much of the surrounding waste field. In addition, because half of the collected gases is water vapor that dries out the surrounding field, LFGTE operators will rotate wells off to give fields time to recharge, possibly 15% at any time.[89]

Then, as well, there are the further baleful influences on collection efficiency beyond delaying installation of the final cover in order to permit controlled precipitation landfills discussed earlier on page 8.

Quantifying the effect of LFGTE's operational changes on capture rates is more difficult than just inferring its significance and requires parsing out the several interrelated factors, starting with the changes in collection efficiency often caused by energy production.

The landfill industry has provided one estimate in a report to the California Air Resources Board that suggests that the impact averages approximately 18%.[90] Presumably, in view of the extent of the degenerative changes in practices, and industry's self-interest in underestimating any effect, the actual impacts are likely to be larger than it concedes. Indeed, an examination of the underlying data suggests that the true extent of deterioration in performance is greater than 50%.[91] By using 18%, the output will be extremely conservative, and one can be reasonably certain the true conclusion will be a even greater erosion in collection efficiency than shown in the charts along side.

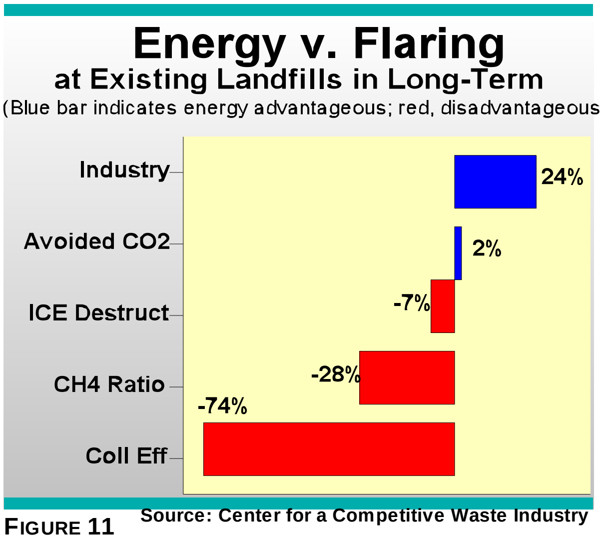


FIGURE 11 Source: Center for a Competitive Waste Industry

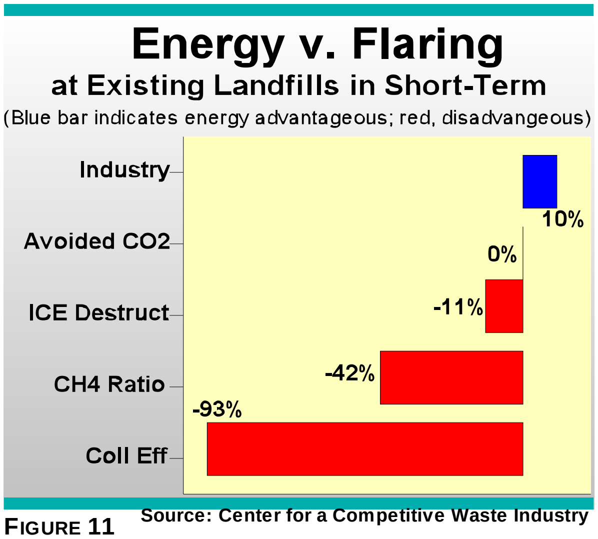
Essentially, properly operated, a dry tomb landfill would be physically incapable of powering generators profitably. LFGTE managers, especially in the private sector, tend to operate their sites fundamentally differently to maximize moisture and minimize air infiltration in order to optimize methane generation – the exact opposite of dry tomb landfills – and diametrically opposite of would be contemplated by anyone motivated to minimize GHGs.[92]

Compounding these operational factors in the landfill itself, the internal combustion engines (ICE) typically used to generate electricity only destroy approximately 94% of the methane they burn, compared to 99% in the flares used in non-energy producing landfills with gas collection.[93]

Adding together all these other factors – which are decidedly not equal between dry tomb and LFGTE landfills – produces a contrarian result. Even in regard to existing waste-in-place, LFGTE results in a net increase in overall GHGs of 74% as shown in FIGURE 12.[94]

FIGURE 11 tracks how LFGTE's relative advantage changes to an increasing disadvantage as the several corrections are cumulatively made to the typical assumptions. Under those made with conventional wisdom, energy recovery will result in 24% less GHGs than flaring at an existing landfill in a long-term analysis when methane's GWP is 25 times CO_2's.

If the amount of avoided CO_2 is corrected, that 24% advantage is reduced to 2%. Adding the correction for worse methane destruction than flares, and LFGTE results in 7% more GHGs than flaring. With the methane ratio conformed to reality, LFGTE releases 28% more; and at a 18 percentage point debit to collection efficiency, LFGTE releases 74% more GHGs than flaring.



Source: Center for a Competitive Waste Industry

FIGURE 11

The next chart, FIGURE 13, shows the same progression in a short-term analysis when methane's GWP is 72 times CO_2's, which worsens LFGTE's comparative relationship with flaring.

As shown in the chart, there is a smaller 10% advantage for LFGTE under the traditional assumptions in the short-term, that, when the same corrections are made to those assumptions, winds up with energy recovery as a disadvantage releasing 93% more GHGs than flaring.

Of import, and just as with the analysis of LFGTE for new discards, the conclusion that energy recovery from existing wastes increases net greenhouse gas emissions is not, within the zone of reasonableness, dependent upon the assumptions used. If any one of the several indicated corrections are made, the outcomes turns negative for LFGTE facilities that change operational practices to boost methane levels.

In the case of new discards, the insensitivity to changes in greater assumed collection efficiencies was previously shown to be the case because the methane avoidance effect is so great. It turns out to overwhelm energy recovery's benefits in lower CO_2 emissions regardless of what reasonable assumptions are used, although the advantage from any of the alternatives to landfilling declines as more favorable assumptions for LFGTE are used.

Ironically, in the case of existing waste-in-place, the greater the assumed base level capture rate, the larger the deficiency that LFGTE labors under compared to just flaring. This happens because increasing the base level capture rate provides an unalloyed gain for the dry tomb (non-energy) landfill. However, for the LFGTE site, the situation is complicated. For LFGTE entails some deterioration in collection efficiency at only energy recovery sites, such as the industry imputed estimate of 18% discussed earlier on page 31. And the larger the base capture rate, the larger the absolute value of that penalty, which is then multiplied by at least 25 times, as shown in the following example. It reflects how the absolute value of the decrease in collection efficiency increases from 0.135 to 0.162 as the capture rate (shown in italics) increases from 75% to 90%, and then is amplified by methane's GWP multiplier from 3.375 to 4.5 –

Standard Capture Rate Greater Capture Rate

Ex. $75\% \times 18\% = 0.135 \times 25 = 3.375 < 90\% \times 18\% = 0.162 \times 25 = 4.5$

3.3. Impacts of lower gas collection threshold.

Finally, Ontario proposes to require smaller landfills along with larger ones to design gas collection systems, and offers financial assistance to do so.[95] In June of 2008, the Ministry adopted this proposal.[96]

In particular, the prior Provincial regulations required the design of some gas collection systems in landfills with permitted capacity greater than three million cubic meters (m^3). The new rules lower that threshold to 1.5 million m^3.[97]

Table 2 on the following page shows the 32 major public and private landfills in Ontario, with 306 million cubic meters of permitted capacity, of which the 22 public sites have 151 million m^3, and the 10 private facilities have 155 million m^3 , for a total of 306 million m^3.[98]

Denoted with an asterisk are the seven landfills with permitted capacities that will bring them within the new regulations reach, Springhill, Lindsay Ops, Tow Howe, Niagara Regional, Humberstone and Merrick – all public facilities – and Richmond, the one privately owned facility. Their total capacity is 16.1 million cm, or 5% of the total. While this change moves in a good direction, by itself, it does not have the potential to achieve significant gains.

Major Landfills in Ontario

	Site	District	Ownership	Capacity (000 cm)
Public	Halton Regional Landfill - Milton	Burlington	Regional Municipality of Halton	7,960
	Cornwall Landfill - Cornwall	Cornwall	City of Cornwall	3,283
	Trail Road - Ottawa (excl Nepean LF)	Ottawa	City of Ottawa	16,988
	**Springhill - Ottawa-Osgoode*	*Ottawa*	*City of Ottawa*	*1,700*
	**Lindsay-Ops - Kawartha Lakes*	*Peterborough*	*City of Kawartha Lakes*	*2,340*
	Bensfort Rd - Peterborough	Peterborough	City of Peterborough	3,827
	Sandy Hollow - Barrie	Barrie	City of Barrie	3,900
	W12A - London	London	City of London	11,700
	Salford - Oxford County	London	County of Oxford	5,900
	Stratford - Stratford	London	City of Stratford	6,470
	EWSWA Regional Landfill	Windsor	Essex Windsor Solid Waste Auth.	12,200
	Erb St. - Waterloo	Guelph	Reg. Municipality of Waterloo	14,722
	Mohawk St. - Brantford	Guelph	City of Brantford	13,371
	Glanbrook - Hamilton	Hamilton	City of Hamilton	11,800
	**Tom Howe - Haldimand*	*Hamilton*	*Counties of Haldimand&Norfolk*	*2,500*
	**Niagara Regional Road 12*	*Ste. Catharines*	*Regional Municipality of Niagara*	*1,851*
	**Humberstone -Niagara Region*	*Ste. Catharines*	*Regional Municipality of Niagara*	*2,000*
	Sudbury Regional Landfill	Sudbury	Greater Sudbury	7,790
	Deloro - Timmins	Timmins	City of Timmins	3275
	John Street - Thunder Bay	Thunder Bay	City of Thunder Bay	8728
	Line 5 Landfill - Sault Ste. Marie	Sault	City of Sault Ste. Marie	9,270
	**Merrick Landfill - North Bay*	*North Bay*	*City of North Bay*	*2,848*
Private	Lafleche (Eastern Ontario LF) Stormont	Cornwall	Lafleche Environmental Inc.	7,400
	Richmond- Napanee	*Kingston*	*Waste Management of Canada*	*2,843*
	West Carlton - Ottawa Carp Rd	Ottawa	Waste Management of Canada	7,300
	WSI - Ottawa - Navan Rd	Ottawa	Waste Services Inc.	4,500
	Green Lane - St. Thomas	London	City of Toronto after transfer	16,750
	Petrolia - Lambton	Sarnia	Waste Management of Canada	4,749
	Warwick - Lambton	Sarnia	Waste Management of Canada	27,000
	Ridge Landfill - Kent	Windsor	BFI Canada	36,800

	Taro E - Stoney Creek	Hamilton	New Alta	6,320
	Walker Bros - Niagara	Ste. Catharines	Walker Brothers	41,200

TABLE 2

An alternative worthy of consideration would be strengthening the regulations that already pertain to most landfills, namely those with the permitted capacity greater than 3 million m^3 that are covered by the existing code.

Specifically: first, controlled precipitation should be repealed because of its significant adverse impacts on greenhouse gas emissions. Instead, its intended objective to reduce long-term liabilities met should be met more effectively by substituting a requirement to phase out landfilling of untreated organic discards. Decomposables are the source of short-term and long-term biological activity before the cover is installed and after it fails. If they are diverted, that reduces long-term landfill liabilities without creating new and significant problems from substantial increases in near-term methane emissions. This is the approach taken by the European Community in its 1999 Landfill Directive.[99]

A focus should be on refining techniques that are most likely to increase rates of household and office participation and capture rates in view of the fact that not everyone exhibits the same commitment to the environment. Toronto has focused on biweekly rubbish collection, because it not only saves money, it also incentivizes otherwise unenthusiastic residents to cooperate (that or their putrescibles will remain uncollected until the following week). Halifax has posited pay-per-throw to achieve the same end. A rigorous review of the most effective strategy in relation to local conditions should be undertaken.

Second, while the existing plan to extend coverage of small landfills with the gas management rule only realizes minor benefits, there are substantive improvements that can be made in what the rule requires of those landfills that are covered.

Currently, the Province's landfill air regulations only require that some plan be submitted. The actual details of what a gas collection system consists of, and when it should be installed, are left to the Ministry staff member's interaction with the applicant. Interviews with the Ministry indicate that this was done because gas management was considered to be site dependent, confounding any effort to impose general prescriptive standards.

The Ministry may want to rethink its belief that effective gas collection designs are too site dependent for general prescriptive standards to be applicable in most cases. For one thing, the ability to conduct individually negotiated site requirements is complicated by staffing shortages and staff turnover, which can result in the final management plan being inadequate.

For another, in fact there is a body of best management practices that are widely adaptable with proven effectiveness in improving efficiency, such as one commissioned by the California Integrated Waste Management Board last year.[100] Even if the Ministry continues to be concerned that there may be individual exceptions to these general best practices, that still can be managed with prescriptive standards. Instead of leaving almost all details to be negotiated in the permit, as is the current practice, the rule can instead prescriptively incorporate those best practices, but with a proviso for case-by-case exceptions when site-specific differences are clearly demonstrated.

APPENDIX A to this report summarizes the specific recommendations that we offer to the Ministry for its consideration. ➥

4. CONCLUSIONS

In conclusion, the Province of Ontario, and in turn Environment Canada, have demonstrated their deep concern about climate change and their determination to establish programs to reduce greenhouse gas emissions from the waste sector.

However, their analysis of the waste sector utilizes the IPCC Guidelines and leans on conventional wisdom, both of which have major shortcomings as applied to the waste sector. They have done so without having cross-checked the adequacy of the procedures that they have recommended. In view of all the competing concerns and their limited resources, this is understandable, but, it is also unfortunate.

By their uncritical reliance on flawed metrics and assumptions, they have failed to reliably inventory landfills' responsibility for greenhouse gas emissions. While the paucity of hard data makes it impossible to demarcate a supportable point estimate, correcting for the errors in the process they followed suggests that methane from landfills generally plays a far more substantial role in climate change than they concluded based upon incorrect assumptions.

In addition, the inadequacy of their procedures also led to a failure to incorporate how certain specific operational practices at landfills today have challenged the most basic element of a rational climate change strategy. This has been the decision to delay installation of a low permeable cover and gas collection system for 10 to 20 years as part of a well-intentioned, but misdirected effort focused on reducing groundwater contamination in the distant future that does not appreciate unintended impacts on the atmosphere today.

An outcome that was not anticipated is a near-term increase in fugitive emissions – possibly more than doubling the total amount of gases that are released. This is a growing area of concern that recognizes methane's short-lived but more aggressive GWP. Despite the Province's best intentions to mitigate the impacts of methane emissions from landfills, a renewed emphasis on LFGTE may, as this report indicates, make matters worse – with the unintended consequence of erecting marketplace barriers to landfill alternatives such as diversion.

The Ministry has demonstrated a commitment to the development of a climate action plan for the waste sector that contributes to the reduction in greenhouse gases. Re-channeling that commitment toward greater diversion of organics from landfills and improved gas collection should better produce a major contribution to that overall effort. APPENDIX A that follows enumerates our specific recommendations. ❐

About the Author

Peter Anderson, an economist in solid waste planning, is Executive Director of the Center for a Competitive Waste Industry. He received his bachelors degree in labor economics from Cornell University, and a masters degree from the Nelson Institute for Environmental Studies at the University of Wisconsin-Madison in solid waste planning. He has been a Senior Lecturer at the University of Wisconsin-Madison Department of Applied Economics on waste systems, and chairperson of the National Recycling Coalition Policy Workgroup and its Landfill Subcommittee, as well as a member of the Sierra Club Landfill-Gas-to-Energy Task Force. He is an consultant for many organizations on landfill issues, including EPA's Landfill Methane Inventory Group, where he has been one of the agency's peer reviewers of their methane estimation models. He is a frequent speaker on landfill issues, including as a plenary speaker at the EPA National Bioreactor Conference, and has published numerous articles on landfills, landfill gas, and other solid waste subjects. He has prepared a major independent evaluation of landfill's long-term liabilities and financial assurance, *Day of Reckoning*, for the California Integrated Waste Management Board, and is currently in the process of completing the first detailed independent analysis of landfills' responsibility for greenhouse gases, *from Beneath the Ground*. It is co-authored with Larry Bingham, an engineer who was part of the team that designed the first landfill gas collection and energy recovery system at the Palos Verdes landfill in 1974.

❖

For more information

CENTER FOR A COMPETITIVE WASTE INDUSTRY
313 Price Place • Suite 14
Madison, WI 53705 USA
(608)231-1100 • Facsimile (608) 233-0011
center@competitivewaste.org
www.competitivewaste.org

APPENDIX A

Summary of Recommendations

A. **OVERALL LANDFILL PRINCIPALS.** Replace controlled precipitation with a requirement to divert organics from landfills modeled on the European Commission’s 1999 Landfill Directive (see APPENDIX A).

B. **DIVERSION STRATEGIES.** Investigate and help develop the most effective and efficient strategies for maximizing organics diversion from the residential and commercial sector in the different local conditions in Ontario.

C. **BEST PRACTICES FOR LANDFILL GAS MANAGEMENT.** Adopt the following landfill gas best practices to maximize the reduction of fugitive gas from landfills during the transition period until organics diversion programs are implemented, and to account for any remaining fraction of the original organic stream that fails to be diverted.

1. **Early Horizontal collectors.** Install horizontal gas collectors in active areas current with lifts prior to installation of vertical gas wells, but delay operation until there is sufficient depth and cover to apply vacuum. Space horizontal collectors to overlap each pipes’ zone of influence when negative pressures are applied under conditions without a low permeable cover. Do not co-utilize horizontal collectors for gas collection and liquid recirculation.

2. **Vertical wells.** As soon thereafter as practicable, but no more than two years after first waste emplacement in the cell, install vertical wells spaced not more than 50 meters apart.

3. **Multiple wells in same bore holes.** For landfills with a depth at final grade greater than 30 meters, install different vertical wells for different depths in same bore hole in order to be able to apply distinct optimal negative pressures at each level as compaction increases with depth but the risk of excess infiltration from the surface diminishes.

4. **Leachate collection system connection.** Connect the leachate collection system (LCS) at the high side on bottom of landfill, which often carries gas that follows the LCS gravel trench or piping, to the active gas collection system (GCS).

5. **Multiple seals around bore holes.** Utilize at least three sets of seals or their equivalent, including bentonite, clay and well bore seal, to connect the collection wells to the final composite cover in order to minimize air infiltration and maximize vacuum forces. Check methane leak rates around the seals at each well head at least monthly during typical atmospheric conditions using an analyzer compliant with Method 21 under US EPA 40 CFR §60.755(c), and if greater

than 500 parts per million above background, repair the seal.

6. **Installation of vertical collectors, maximum slopes and final cover.** Each cell should be designed to reach final grade in not more than two years from first waste emplacement. The active vertical collectors should be installed at that time and connected with headers to a vacuum system. Not more than one year after reaching final grade, a final low permeable cover less than 1×10^{-5} cm/sec. should be installed. If a geomembrane is used to provide a low permeable barrier, exterior side slopes should not exceed 4:1 to facilitate stabilization over a geomembrane. Alternate final covers are incompatible with effective active gas collection and should no longer be allowed.

7. **Delay any recirculation of leachate.** Leachate circulation is not being recommended, but if it is, do not commence recirculation until after an expendable low-permeable cover and active gas collection system has been installed.

8. **De-water flooded vertical wells.** In addition to monitoring each well's performance for oxygen and nitrogen infiltration, monitor gas volumes to detect wells that may be flooded, and pump out flooded wells.

9. **Enhanced monitoring.** At a minimum, based on a standard vapor analyzer or a flame ionization detector measured on a grid spaced approximately 30 meters apart, also specifically check methane leak rates around the seals at each well head at least monthly during typical atmospheric conditions, and if greater than 500 parts per million above background, repair the seal within three days. Use optical remote scanning (ORS-RPM) technologies certified by US EPA to locate hot spots over the surface of the landfill.[101]

ENDNOTES

1. Intergovernmental Panel on Climate Change (IPCC), *1996 Guidelines for National Greenhouse Gas Inventories* (1997).

2. 56 US Federal Register 104, 24473 (May 30, 1991).

3. IPCC, *Fourth Assessment Report: Chapter 2 Changes in Atmospheric Constituents and Radiative Forcing* (2008), at Table 2.14. In the case of calculating national GHG inventories, the IPCC Guidelines provide that a methane GWP of 21 times be used.

4. George Tchobanoglous, *Integrated Solid Waste Management* (McGraw Hill, 1993), at p. 394.

5. Timothy M. Lenton, et al., *Tipping elements in the Earth's climate system*, 105 Proceedings of the National Academy of Sciences 6, at pp. 1786-1793; James Hansen, "Dangerous human-made interference with climate," 7 Atmos. Chem. Phys. 2287-2312 (2007).

6. IPCC, *Fourth Assessment Report*: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (2007), at p. 212, Table 2.14.

7. CO_2's residence in the atmosphere is a much discussed subject, with no firm conclusion as to the appropriate time to assign. The use of 100 years shown in Table 1 is the simplified convention by the IPCC to approximate an average of a wide range in order to be able to calculate Global Warming Potentials of different greenhouse gases in comparison to CO_2, which was set with a GWP of 1, with an underlying assumed average residence time of 100 years. More recent consideration is beginning to emerge that now is concerned CO_2 will remain in the atmosphere effectively forever as historic sinks, such as the capacity of the oceans to dissolve the gas, reach their absorptive limits, and reductions in radiative forcing in the atmosphere are offset by heat slowly re-released from the oceans. Susan Solomon, et. al., *Irreversible climate change due to carbon dioxide emissions*, 106 PNAS 6, p. 1704-1709 (February 10, 2009).

8. Intergovernmental Panel on Climate Change, *Fourth Assessment Report: Chapter 2 Changes in Atmospheric Constituents and in Radiative Forcing* (2008), at p. 206.

9. James Hansen, et. al., *Greenhouse gas growth rates*, 101 Proceedings of the National Academy of Sciences 46 (November 16, 2004), at p. 16111. See also, Benjamin Dessus, et al., "Global Warming: The Significance of Methane," *La Revue Durable* (May-June 2008).

10. US Environmental Protection Agency, *U.S. Methane Emissions 1990 – 2020:Inventories, Projections, and Opportunities for Reductions* (EPA 430-R-99-013) (1999), at p.1-2.

11. George Tchobanoglous, *Integrated Solid Waste Management* (McGraw Hill, 1993), at p. 406. The mechanics of active gas collection systems involve attempts to extract the gas from landfills by creating a applying negative pressure in a vacuum through piping distributed through the waste load covered by a low permeable cover, just as one might use a straw to suck a beverage out of a glass filled with ice cubes. The heart of the systems are generally 15 to 25 cm rigid vertical PVC wells drilled approximately 100 meters apart into the depths of the waste body, stopping about 5 meters from the bottom to insure the pipe does not inadvertently puncture the bottom liner. Perforations are set in the pipe beginning approximately one-third from the surface down so as to not draw air, which, if mixed with methane, would create explosive conditions. In order to maintain paths for gas flow through the holes, the pipes are surrounded by a gravel pack. The array of buried upright pipes are then connected at each well head by horizontal header lines, which are laid above or just below the surface of the landfill, and are interspersed with sampling ports and throttle valves to detect and shut down individual wells operating outside of permissible parameters, and water knockouts to remove moisture condensation. The header lines run to an auxiliary building where a fan or compressor creates negative pressures to draw gas from the fields surrounding each well through the pipe's perforations. The captured gas is then extracted to a flare to destruct, or, after removing the moisture

and impurities, to a turbine or engine to generate power. Of import, for the systems to function properly, either a final low permeable synthetic cover or intermediate dirt cover more than one meter in depth needs to be installed in order to provide a seal for the vacuum system to work properly and to prevent the system's negative forces also pulling oxygen from the surface, and mixing at explosive concentrations with methane from the surrounding wastes.

12. Factors affecting how much landfill gas is collected include:
    ① How long after wastes are installed and gas generation begins that the collection system is installed.
    ② After the GCS is installed, how long before each cell reaches final grade and a low permeable cover is installed, which is essential for the system to function properly.
    ③ How much density and coverage the well placement provides.
    ④ How effectively, and for how long into the future, the GCS is maintained and operated, and also the cover is maintained and, in time replaced, in order to preserve its integrity.
    ⑤ Whether moisture levels are boosted when the site is uncovered by such things as leachate recirculation; whether flexible horizontal piping is used in place of rigid vertical wells, and whether horizontal piping is co-utilized for leachate re-injection and for gas extraction.

13. Memorandum to Brian Guzzone, US EPA, from Chad Leatherwood, Eastern Research Group, Inc., dated November 18, 2002, re: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency. A modern landfill can extend over a hundred hectares and rise almost 100 meters above grade. Gases generated in pockets where liquids accumulate across the waste matrix follow numerous paths of least resistance through the highly heterogeneous and heavily compacted wastes out the top, sides and bottom of site, currently making it impractical to measure how much gas escapes at the time the site is observed. Even if that could be done, far more gas is generated before the gas collection systems are installed or are properly functioning, and, after closure, when maintenance ends, the collection systems are shut down, and the cover fails leading to a second wave of gas generation.

14. US EPA., *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (EPA 530-R-98-013)(September 1998), at p. 106; *Solid Waste Management And Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (EPA530-R-02-006)(June 2002), at p. 108; *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook* (EPA 430-B-96-004(September 1996), at p. 2-8.

15. In Canada, the actual calculation of its national inventory is not directly erected on any specific capture rate assumption in that, in its final analysis, only the amount captured, and that assumed oxidized and sequestered, is subtracted from an estimate of total gas generation. However, collection efficiency is a key building block in making the estimate of gas generation, as is explained at p. 18. In terms of what has been done in Canada to directly estimate collection efficiency, Ontario does indicate that it assumed, without providing any factual support, that landfills capture 75% of the gases generated, and also oxidize 10% of the gases that are not captured, as per the US EPA assumptions. (ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update* (2005), at p. 70.) Determining the basis for Ontario's 75% gas capture rate assumption is elusive. The Provincial plan does not provide details as to how its estimate was derived, but instead indicates it relied upon Environment Canada data from the National Inventory. (Ontario, *Ontario's Climate Action Plant: Annual Report 2007-2008* (2008), at p. 37.) The National Inventory, in turn, also does not provide any details, but rather refers to a background report prepared for Environment Canada by ICF Consulting for collection efficiency assumptions. (Environment Canada, *National Inventory Report:1990-2006* (2008), at p. 193.) That ICF report for Environment Canada, which restates almost verbatim the earlier work it did for US EPA, assumes the same 75% collection efficiency rate assumed by EPA. (ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update* (2005), at p. 70.) It refers for support to a US EPA life cycle study that, when examined, provides as its basis, "EPA assumed that these landfills have an average LFG recovery efficiency of 75 percent." (US EPA, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (2002), at p. 87.) The life-cycle report, though, does have a footnote on page 87 which references another EPA report as its citation, this one focusing on methane. (US EPA, *U.S. Methane Emissions 1990-2020: Inventories, Projections and Opportunities for Reductions* (1999).) A review of that methane report finds, at p. 2-7, "[g]as collection

efficiency is assumed to be 75 percent of emitted methane." At that point, there are no further references to a source for the 75% assumption.

16. The US EPA reports that cite the 75% value for collection efficiency largely cite each other for their basis, and ultimately fall back on a Memorandum to Brian Guzzone, US EPA, from Chad Leatherwood, Eastern Research Group, dated November 18, 2002, re: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency, which suffers from apparent selection bias. Mr. Leatherwood's putative literature review incorrectly stated that there are no collection efficiency estimates less than 60%, and he refused to acknowledge any of the numerous reports from outside the landfill industry, which he was provided, almost all of which suggest low collection efficiencies when the systems are operating, The literature from independent sources tends to assume instantaneous collection efficiency in the order of 40% capture rates, with a range of 34% to 50%. See, *e.g.*, Forbes McDougall, *et al.*, *Integrated Solid Waste Management: A Lifecycle Inventory* (Aspen Pub. 1999), at p. 275 [40%]; European Commission, *A Study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste* - FINAL APPENDIX REPORT (October 2000), at p. 144 [40%]; and Ofira Ayalon, *et al.*, "Solid Waste Treatment as a High-Priority and Low Cost Alternative for Greenhouse Gas Mitigation," 27 *Environmental Management* 5 (May 2001), at p. 699, TABLE 1 [50%]; Riitta Pipatti and Margareta Wihersaari, "Cost-Effectiveness of Alternative Strategies in Mitigating the Greenhouse Impact of Waste Management in Three Communities of Different Sizes,"*Mitigation and Adaptation Strategies for Global Change,* at p. 344 (1998) [40%]; Nickolas Themelis and Priscilla Ulloa, "Methane generation in landfills," *ScienceDirect-Renewable Energy* (April 2006), at p. 8 [34%]; Hans Williamson, "Production and Use of Landfill Gas: Energy Recovery," Paper for International Conference on Solid Waste Management & Technology (Lisbon, October 1997) [25% - 50%]; and US EPA Region 9, Ideas for Consideration to Strengthen WARM Model (2007) [30%].

At the same time, separate from the EC and MOE reports that are evaluated in the text, the published literature contains several other studies that claim to present objective data on collection efficiency. However, like the agencies' reports that are evaluated here, those other published papers are also attempts at mass balance analyses that suffer from two unknown variables. See, e.g., more recently, Kurt Spokas, et al., "Methane mass balance at three [French] landfill sites: What is the efficiency of capture by gas collection systems," *Waste Management* 26 (2006), at p. 516 ("French Study"); Shirley Thompson, et al., "Building a better methane generation model: Validating models with methane recovery rates from 35 Canadian landfills," *Waste Management* 29 (2009), at p. 2085 ("Canadian Study"), which are dealt with in this NOTE.

Essentially, the simplified form of their mass balance equation (ignoring for a moment variables for oxidation, sequestration and migration, which are not as central to the model's validity), is:

$$\text{Gas released} = \text{Gas generated} - \text{Gas captured}$$

To overcome the need to solve for two unknowns – Gas Released and Gas Generated – these papers, like Environment Canada, also use first order decay models to estimate the second of the two unknowns, Gas Generated, so they can solve the mass balance equation. But, the outputs from the different variants on the first order decay model in these recent studiesexhibit the same fatal deficiencies as EC's efforts. Most prominent is their failure to account for whether there exists minimum levels and distribution of moisture inside the waste mass for methanogenesis to occur, as discussed in more detail on page 17ff of the text.

The French study, which purported to find very high capture rates at three French landfills, uses a first order decay model to estimate gas generation in order to solve the mass balance equation. Even the US EPA rejected this use of the model to estimate gas generation at specific landfills because of the large variability of the first order's outputs depending its dependency of too many unknown inputs:

> "The results of this study on two landfills reported LFG collection efficiencies of 94 percent and 98 percent. However, at the French facility that reported 94 percent LFG collection efficiency, this efficiency was based on the lowest of three predicted LFG generation levels for that facility. When the highest estimate of LFG generation is used, then the LFG collection efficiency drops to 84 percent. This raises the issue again that a major difficulty in determining LFG collection efficiencies is accurately estimating LFG

generation levels."

Memorandum to Brian Guzzone, US EPA, from Chad Leatherwood, *supra,* at p. 2.

Similar, the Canadian study, which otherwise commends first order principles for landfills, notes, at p. 2086, that the particular analysis in the French study has compared methane recovery data from models "only for a few landfills. This limited approach is inadequate to validate the model for a wide, rather than site-specific application." The Canadian study, at p. 2086, also concurs with this NOTE that the first order decay "models continue to receive criticism due to their poor accuracy and insufficient validation." It then proceeds, at pp. 2088-2089, to evaluate six variants of the model at 35 non-randomly selected Canadian landfills with different assumptions about one of the inputs, namely the assimilated organic fraction in the landfill (a DOC_f value of 0.5 to 0.77), but does not state whether other variables were tested and discarded.

There are at least six flaws in this effort to correct the recognized shortcomings of first order modeling:

① ***Correlation fishing.*** The study does not present a rational conceptual solution to errors that it identified in past modeling practices. Instead, by trial and error, it calculates the modeled gas generation estimate for each non-randomized, self-selected landfill using six variations on the same core first order equation. It then uses several alternative values for coefficients, until this iterative process finds the highest r^2 value from the Pearson's correlation, which is a simple and unsophisticated measure of how closely two things are associated, among a historical set of landfill data.

However, this apparent arbitrary calibration technique does not show causality, but only an association that can be due to chance. That is, it produces a correlation that can be increased significantly – albeit for this particular self-selected sample only – as the number of different values for variables and model permutations multiply. But, this more closely resembles shooting correlates in a barrel than adducing anything reliable about causality. In addition, one of Pearson's many weaknesses is that it has no power to evaluate whether all critical explanatory variables, such as essential moisture levels, have been included in the model. As such, the study's protocols are not a valid statistically appropriate procedure to derive reasonable estimates for future predictions of gas behavior among the population of municipal solid waste landfills.

② ***Circularity.*** Apart from that limitation of the Pearson's correlation, the Canadian analysis also attempts to validate its conclusions by examining how good the association is between observed values and the parallel estimates of gas generation from the model it found to have the best correlations. However, there are no observed values of gas generation to search for associations with modeled generation outputs. In the three-term simplified mass balance equation above, only gas captured was known. In order to perform this Pearson's analysis, the *Canadian* study resorts, at p. 2088, to the following underlying equation in order to model further what is intended to be, but is not, *observed* gas generation:

$$Gas\ generated = \frac{Gas\ captured}{Gas\ capture\ rate}$$

But, again, this equation with three terms, which is used in an effort to provide a surrogate for an observed value for gas generation, also has two unknowns. To produce such a modeled surrogate, the study is forced to make another assumption, which is not based upon any observations, about the gas capture rate. In this study, collection efficiency is *assumed* to be an average 80%, derived from 75%, which is the oft-cited US EPA assumption based upon its questionable decision to focus on the best systems at the limited time of their peak performance, and 85%, the claimed, but disputed, French assumption.

Moreover, the problem is not just that the provenance of the 75% assumption is neither an observed value nor even a reasonable assumption. In addition, in order to perform the Pearson calculations, the analysis assumed that every single landfill in the study *(i)* exhibited identical performance, even though operating practices significantly affecting collection efficiency are known to vary widely among landfills, as well as *(ii)* achieved that same high capture rate during all phases of each sites' biologically active or latent life, including the challenging times when there is no installed or functioning gas collection system.

By way of comparison, the Intergovernmental Panel on Climate Change (IPCC) states that the average *lifetime* capture rate, even if one incorporates the EPA's or the landfill industry's best peak rate, is actually as low as 20%. IPCC, *Fourth Assessment Report:* Chapter 10:Waste Management (2007), at p. 600.

Thus, the Canadian study did not have an objective basis to reject several scenarios because they seemed to "consistently produce[] much higher estimates than the [observed] methane generation rates," at p. 2088-2089. For the calculated large standard errors it found were actually due to its arbitrary assumption about high capture rates – which was the only reason that the "observed" generation rates seemed too high – rather than a real statistical deviation.

The Canadian study is intended in part to provide observed values of gas generation to justify claims for high gas collection efficiency. However, it actually does that by *assuming* that gas collection is high. As such, the entire analysis is circular and, thus, of no value.

③ ***Second wave ignored.*** As discussed in the text at p. 15ff, there also will be a significant second wave of gas generation following closure of the landfill after post-closure maintenance ends, the cover deteriorates and rainfall re-enters the site, as a function of how much residual unsequestered carbon remains when the cover is installed. According to the best data available, possibly more than half of carbon remains upon closure at dry tomb landfills. The first order model ignores this.

④ ***Gas potential highly varied.*** One of the three explanatory variables in the first order decay equation is the assumed total methane gas potential, whose remaining value gradually declines over time as decomposition proceeds at a constant rate of decay. It is often denoted as "L_o". This value is assumed to be a function of the fraction of the waste mass that is decomposable. However, that fraction is also an unknown value, and guesstimates in the technical literature vary by a factor of three times, from 100 to 310 m^3/Mg. Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at p. 3-2.

The Canadian study attempts, at p. 2088, to circumvent this uncertainty by using reported organic fractions from waste *audits* reported by each Province in Canada. However, waste audits, which involve casual visual assessments, are, by definition, not statistical characterization studies, where sorters separate randomly selected samples by hand and the uncertainties around the reported mean values can be calculated. Being non-statistical, it is also impossible to know whether, or how much, they narrow the three-fold variation around the true value that Reinhart found in the literature. The absence of landfill-specific and statistical waste composition data is a problem also noted by the Canadian study, at p. 2090.

⑤ ***Decay rate misapplied.*** As noted, the first order model posits a constant decay rate applied to the total methane potential of the remaining carbon in the waste load after subtracting the amount decomposed in the prior years. It is referred to in the equations as "*k*". The *Canadian* study attempts to refine the *k* value for each of the 35 landfills sampled by varying the rate based upon US EPA's binary distinction for the *k* value to reflect two broad bands of precipitation in the area where the landfill is located. EPA recommends that 0.02/year be used for arid areas receiving less than 635 mm of precipitation per year, and the 0.04/year for non-arid areas with more than 635 mm of rain annually. US EPA, *AP-42 Compilation of Air Pollutant Emission Factors* (2008), at 2.4-6. But, the relevant criteria should be moisture *inside* the landfills at different points in a landfill's life, not rainfall *outside* the facility. Between the two after closure is a low permeable cover that prevents precipitation from infiltrating the waste mass for as long as the barrier retains its integrity.

Similarly, in studies that are not massaged (i.e. when the landfills sampled are not self-selected without randomization, and the coefficients are not arbitrarily modified until the best fit to the equation is found), the results of the first order modeling are even more anomalous. A published paper that performed a random verification of related modeling of California landfills found a dispersion among 25 major landfills of predicted values for gas collection efficiency from 7% to

100%. Nickolas Themelis and Prisilla Ulloa, “Methane generation in landfills,” *Renewable Energy* 32 (2007), 1243, at 1250. A more recent unpublished survey of 46 California landfills by the California Air Resources Board found implied gas collection efficiency from gas generation estimated with LandGEM first order equations ranging from 6% to 225% gas captured, which is an exceedingly impressive engineering feat. California Air Resources Board, Staff Spreadsheet Titled Landfill Survey Data Public (2010), released in response to a Public Records request by Californians Against Waste.

⑥ ***Methane ratio varies.*** The first order decay model does not generate an estimate of methane, but actually of total landfill gas generation, of which the primary gases are carbon dioxide, as well as methane, along with various trace compounds. In order to estimate the fraction of total landfill gas that is methane, which is the critical anthropogenic greenhouse gas (due to the fact that CO_2 in this context is considered to be biogenic), the concentration of methane in landfill gas must be specified separate from the first order model. Following customary practice, the study assumes, at p. 2088, that methane is always 50% of the total gases generated. However, as discussed in the text at p. 29, the actual methane concentration ratio varies widely, depending primarily on operational practices and secondarily on precipitation. A study by the California Air Resources Board found that, among the 46 major landfills in the state, and averaged over a five year period, methane concentrations ranged from 29% to 59% among its sample of landfills. California Air Resources Board, Staff Spreadsheet Titled Landfill Survey Data Public (2010), released in response to a Public Records request by Californians Against Waste. These observations parallel earlier findings of methane concentration in landfill gas of 35%-60% by the Department of Energy. EIA, “Growth of the Landfill Gas Industry,” Chapter 10 of the Renewable Energy Annual Report 1996. Of import, the concentration of methane in landfill gas, as well as the rate of methane production, is a direct function of operational changes away from dry tomb precepts in order to increase moisture levels by such things as leachate recirculation. Debra Reinhart, *First Order Kinetic Gas Generation Model Parameters for Wet Landfills* (EPA-600/R-05/072, June 2005), at p. 2-2. This is another source of significant variation in actual values for the methane ratio, compared to the assumed constant model value of 50%, that the study fails to account for in its analysis of standard errors. In view of methane’s very large GWP, this wide variability also has an extremely significant, and unaccounted for, magnified impact on net GHG impacts.

In conclusion, until the first order decay model is substantially modified to account for changing internal moisture levels and the other timing considerations discussed above, all of these theoretical exercises will fail to provide any useful value for characterizing gas generation and gas emissions from landfills.

17. US EPA’s supporting documents show that the agency’s assumed 75% capture rates is actually what it considers that the best, not the average, systems “should or could achieve.” (US EPA, *Anthropogenic Methane Emissions in the United States* (EPA 430-R-93-003), at p. 4-11 Memorandum to Brian Guzzone, US EPA, from Chad Leatherwood, Eastern Research Group, Inc., dated November 18, 2002, re: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency.) This is a distinction of some significant import, because, in view of the fact that landfills are a non-point source, there are no enforceable emission rate restrictions to goad operators to do better. In practice, failures by landfill operators to control gas emissions are only practically constrained if there are odor complaints from neighbors, should any be nearby. However, as sophisticated misting equipment has become increasingly effective at masking odors, even that already weak proxy is attenuated. Also, many, especially privately operated, landfills are profit motivated to minimize compliance costs. Yet, optimization of gas capture requires expenditures and management time that is unrelated to selling waste generators a place to dump. Therefore, US EPA’s implied assumption that, for what would have to be altruistic reasons, all landfill owners nonetheless design, install, operate and maintain gas collection systems according to best practices seems to lack foundation.

18. EPA’s assumed capture rate is an instantaneous value, which is effectively focused in the limited time of a landfill’s life that is both *(i)* after a final cover is installed (and moisture is minimized); but *(ii)* before the cover later fails once post-closure maintenance ends (after which moisture reenters the site creating a second wave of gas generation). Part of the time before the cover is installed, there is no gas collection system, and the other part of that time the system is dysfunctional. This is because, without a cover, air will

be pulled from the surface along with landfill gas from the surrounding wastes. Mixing oxygen with methane is explosive, and the collection system's vacuum forces that pulls gas must be damped down to avoid causing fires. After post-closure ends, of course, there is no gas collection either. Yet most gas is generated when moisture is greatest, which is in the before and after time periods when there is little or no gas collection. (Intergovernmental Panel on Climate Change, *Expert Review of First Order Draft of Waste Chapter to IPCC's Fourth Assessment Report: Comments of Dr. Hans Oonk.*)

19. IPCC, *Fourth Assessment Report*, Chapter 10 on Waste (2008), at p. 600.

20. R.R.O. 1990 Reg. 247 §11. The well-intentioned purpose underlying these practices, which increase moisture while the site is operating, is to partially accelerate decomposition, which would otherwise not occur for decades hence, into the present. That is to leave less buried organics when the landfill is finally closed in order to reduce the threats to groundwater contamination decades hence. Fifty or sixty years from now, the original owner will either have gone out of business, or, even if not, will almost certainly have abandoned the long closed site from which he or she will not have received any revenues for a very long time. The likelihood of continuing maintenance by the original owner or its successors for many decades after closure is not excessively great. More organics remaining in the waste mass at that time means there will remain more leachate to then leak into the environment as the untended barriers deteriorate. It is not clear whether the adverse impacts on near term fugitive gas emissions were fully considered at that time.

21. Environment Canada, *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada, 1990-2006* (2008), at Table S-2.

22. *Id.* This report was prepared prior to the time the IPCC corrected methane's GWP from 21 to 25 times CO_2. The reason turns on upgrading the calculation to consider the fact that methane is well mixed in the atmosphere, which will chemically form tropospheric ozone over time rather than decaying into gaseous byproducts that are warming neutral. At a GWP of 25x, landfills responsibility would increase to 3.4% of total anthropogenic GHG emissions.

23. Ontario, *Go Green: Ontario's Action Plan on Climate Change* (August 2007), at p. 16.

24. Ontario Regulation 232/98 Part III, ¶15.

25. Ontario, *Onatrio's Claimate Change ActionPlan: Creating Our Sustainable Future: Annual Report 2007-2008,* at p. 45.

26. IPCC, *Reporting guidelines on annual inventories* (Latest update, 2006).

27. There are a number of general methodological criticisms that have been raised about the IPCC's Guidelines for national inventories. In addition to the failure to properly account for GHG emissions associated with imports and exports, these concerns also focus on the manner in which GHG emission sources are grouped into categories based on industry sector. Instead, a cross-sector, systems-based approach has been suggested, which focuses on where GHG reductions can best be achieved by tracking material flows. US EPA, *Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices* (September 2009). In the case of the waste sector, for example, by focusing attention on the end-of-pipe approach, the outputs fail to delineate the significant impacts of upstream material policy on climate change. This report presumes the validity of those general concerns with the current sector-based inventory methodology, and focuses its analysis on specific concerns with how the inventory accounts for the waste sector.

28. Environment Canada, *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada, 1990-2006* (2008), at Table S-2.

29. There are improvements in development, such as optical scanning techniques, *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology*, Office of Research and Development, U. S. Environmental Protection Agency, Washington, DC, (EPA/600/R-07/032), February 2007. However, even these advances only address current emission patterns and fail to reach a dominant source of fugitive emissions, namely the release of landfill gases decades hence after the cover fails and precipitation re-enters the waste mass and a second wave of gas generation is re-ignited at a time when there are no controls. They also are not yet able to adequately scan steep side slopes where more of the current gas emissions may occur.

30. George Tchobanoglous, *Integrated Solid Waste Management* (McGraw Hill, 1993), at p. 394. U.S.E.P.A. Memorandum from Chad Leatherwood to Brian Guzzone, dated November 18, 2002, at p.1.

31. Solid Waste Management Agency of North America, *Comparison of Models for Predicting Landfill Methane Recovery* (1998), at pp. 2-5 to 2.26.

32. Allan Freeze and John Cherry, *Groundwater* (Prentice-Hall, 1979), at p. 437.

33. Ontario Regulation 232/98.

34. 53 US FEDERAL REGISTER 168, at pp. 33344-33345 (August 30, 1988). 46 US FEDERAL REGISTER 11128-11129 (February 5, 1981)

35. Staff *Post-Closure Maintenance Presentation* to CIWMB Permit and Enforcement Committee (November 3, 2003), Power Point Slide No. 18. Office of the U.S.E.P.A. Inspector General, *RCRA Financial Assurance for Closure and Post-Closure* (2001-P-007) (March 30, 2001), at pp.33-34.

36. Dr. Shirley Thompson, *Review of Existing Landfill Methane Generation Model: Interim Report* (November 2005)("Thompson Report").

37. Also referred to as reliability vs. validity. Susan Welch, *Quantitative Methods for Public Administration* (1988 2nd ed., Dorsey Press), at p. 43.

38. Thompson Report at p. 8.

39. George Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues* (McGraw-Hill, 1993), at pp. 72-73 and 393.

40. Debra Reinhart, *Prediction and Measurement of Leachate Head on Landfill Liners,* Florida Center for Solid and Hazardous Waste Management (Report #98-3) (1998), at p. viii.

41. M. El-Fadel et al., "Modeling Settlement in MSW Landfills: A Critical Review," *Critical Reviews in Environmental Science and Technology* (2000), at p. 327.

42. US EPA considers it necessary to add outside liquid additions in order to reach 45% moisture. 67 Federal Register 100 (May 23, 2002), at p. 36462.

43. Thompson Report, at p. 8.

44. Solid Waste Management Agency of North America, *Comparison of Models for Predicting Landfill Methane Recovery* (1998), at pp. 2-1.

45. IPCC, *2006 Guidelines for National Greenhouse Gas Inventories* (2006), at p. 3.6.

46. Report, at p. 2-6.

47. U.S. Department of Energy, *Renewable Energy Annual*, at Ch. 10 (Growth of the Landfill Industry) Table 28 (1996).

48. Thompson Report, at p. 16.

49. 40 C.F.R. §60.753(b).

50. IPCC, *Fourth Assessment Report*: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (2007), at p. 212.

51. Reinhart Report, at p. 2-3 to 2-8. This includes the First Order Model, the Modified First Order Model, the Multiphase Model, the Second Order Model, the Scholl Canyon Model, the Triangula Model, the Palos Verde Model, the Sheldon Artleta Model, GASFILL, EPA LandGEM and LFGGEN. Environment Canada considered eight of these.

52. US EPA, "Estimating Methane Generation from Regression Analyses" (1993),at p. 5.

53. See NOTE 19.

54. Thompson Report, at p. 8.

55. See discussion on p. 17.

56. Thompson Report, at p. 11.

57. Reinhart Report, at p. 2-3 to 2-8. Thompson Report, at p. 8 and 25 to 27.

58. Reinhart Report, p. 3-2.

59. Thompson Report, at p. 16.

60. Environment Canada, *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada, 1990-2006* (2008), at p. 404. Natural Resources Canada, *An Analysis of Resource Recovery Opportunities in Canada and the Projection of Greenhouse Gas Emission Implications* (March 2006), at pp. 90 to 94. See, also, Stewardship Canada, *Blue Box Program Composition* for limited residential data.

61. ASTM, Committee D-34, *Method for Determination of the Composition of Unprocessed Municipal Solid Waste* (1991). Albert Klee, "Sample Weights in Solid Waste Composition Studies," *Journal of the Sanitary Engineering Division* (August 1970), at pp. 945-954.

62. Thompson Report, at p. 9 and 11.

63. This note elaborates on the three reasons why this attempt to use rainfall as a proxy for the moisture levels in the waste mass fails.

First, precipitation is an invalid proxy for moisture levels in the waste mass, because the extent to which rainfall infiltrates and is distributed throughout the landfill depends upon, among other things:

① Whether there is a low permeable cover;
② Whether outside liquids are added;
③ Whether leachate is re-circulated;
④ The waste's composition, its overall and distributed heterogeneity, and how densely the wastes are compacted;
⑤ The effectiveness of the leachate collection system;

⑥ Ambient temperature and transpiration; and
⑦ The waste mass, site geometry and surface grading practices.

All of these significant intervening factors, which directly implicate the relationship, if any, between rainfall and internal moisture levels, are simply ignored. The result is to make the underlying analysis of rainfall differences meaningless as a predictor of moisture actually inside, and the extent it is distributed within, the landfill. Again, a data source has been selected, apparently for its measurement reliability between regions and over time, not to mention its inclusion in international guidelines, in an effort to approach precision. But, it also seems to have been done without regard for accuracy, which apparently has been largely ignored.

Second, apart from the disconnect between rainfall and moisture levels, the statistical basis for the specified relationships based upon precipitation patterns is uncertain. The EC report and supporting papers do not specify how the relationships were calculated. (Thompson Report, at p. 9.) But, if widely cited regression analyses by US EPA were used, they are not reliable. Their study by Peer et al. (R. L. Peer, et al., *A comparison of methods for estimating global methane emissions from landfills*, 26 CHEMOSPHERE 387 (1993) used a very small, and unrepresentative sample without any statistical validity.

The statistical reliability of regression or econometric studies are only as good as the suitability of the sample, the quality of the data, the theoretical foundation of the regression equations, and the appropriateness of error specifications and estimation methods. If there are significant deficiencies in any of the areas of sample suitability, data quality, regression structure, error specifications or estimation methods, a regression analysis' results should not be considered as statistically reliable. The Peer study is deficient in all of these areas.

The study is a single time period cross-sectional analyses utilizing data from a sample of individual landfill sites. Both studies use a derived measure of landfill production as the dependent variable. It regresses the derived measure of landfill methane production on various explanatory variables.

Sample Selection. The data set used by Peer was drawn from twenty-one non-randomly selected landfill sites, less than 1% of the total population. The size and selection procedures associated with the samples for each of the studies raise statistical reliability concerns. The representative quality of the sample is important for determining whether estimated regression results can be generalized to a broader population.

When samples are small and not representative, the estimation results can not reliability be applied to a broader population. Consider, for example, a statistical study of human height. If the study's sample is drawn from professional basketball players, the results will not be applicable to the population as a whole.

The sample selection methods used also tend towards the selection of unrepresentative samples. Individual landfills were selected on the basis that the sites were thought to be “optimized” or landfill operators “appeared to be trying to optimize methane recovery.” It appears that subjective qualitative assessments, rather than empirical standards, were used to select landfill sites for the Peer data set, and the criteria themselves does not reflect the diversity of the entire population.

Data Quality. Regression analysis is futile without well defined and accurately measured variables. Measurement errors in the dependent and independent variables create statistically reliability problems.

There are no actual measurements of the key variable, annual landfill methane production. The Peer study derives an annual methane production variable from the measured levels of methane recovery. Peer assumes a methane recovery rate 75%. Their derived methane production variable is calculated by dividing methane recovery by 0.75. Though they use a 75% recovery rate for all landfills, Peer states in its conclusion:

> “Gas recovery systems do not capture 100 percent of the gas; the recovery efficiency is generally estimated to range from 50 to 90 percent … but no field verification of this assumption has been found by the authors. Therefore, emission factors derived using gas recovery data may have to be adjusted upwards to account for the lost gas.”

Neither are there independent measures of actual methane production as a fraction of total gas generation, something for which there is actual data available. Rather, this estimation procedure is for total gas generation, not the methane fraction.

Equation Foundation. The Peer study does not advance a well formed theoretical model of landfill methane production which can serve as a basis for the estimated regression equations, apparently because earlier calculations suggested other important explanatory variables were statistically insignificant.

The problem of 'statistically insignificant' coefficient estimates arises for many reasons, some of which do not imply that the variable is not, in fact, important. One of the reasons for insignificant coefficients is a small sample size that leads to limited degrees of freedom, as is evident in the Peer study.

If the excluded data are truly relevant, their exclusion leads to estimation bias and unreliable results. Coefficient significance is not an appropriate means for deleting two or more variables from a regression model. Various appropriate tests exist for testing overall significance of a set of variables – in particular maximum likelihood ratio tests. It appears that these forms of significance testing were not performed, nor was the need to reopen the study parameters to widen the sample.

Error Specification and Estimation Procedures. Given the problems discussed above, one cannot assume that the equation error term has a standard normal distribution, which is an essential prerequisite for statistical analysis. For a standard normal error term specification to be appropriate, a number of conditions should to exist such as measurement errors for the independent variables are not symmetrically distributed around zero, there are no measurement errors for the explanatory variables, relevant variables are not excluded, and landfills are assumed without any supporting basis to operate at a similar level of efficiency. These conditions are not met for the two studies.

There are alternative estimation procedures that can adequately deal with the problems (other than a lack of sufficient degrees of freedom) discussed above. Such estimation formulations would involve more complex non-linear regression equations and non-standard normal error distributions. Though more complex, the coefficients of such equations could be estimated by procedures such as maximum likelihood estimation.

For the reason of all of the deficiencies discussed above, the results of the regression analyses should not be relied upon to provide credible annual methane production quantities and generation rates. Even if all of the problems discussed above did not exist, just the low levels of R^2s (one measure of the explanatory power of estimated regression equations) do not support a conclusion that the regression analyses provide reliable results.

By their stated limitations, the analyses also shed no light on pre-coverage methane production and do not address the problem of rehydration and associated methane production after a landfill had been abandoned.

Third, the "*k*" factor, or the methane generation rate, is a constant value that is applied each year over many decades against the assumed total gas potential in the remaining carbon in order to estimate annual gas generation. However, after the first or second decades, a final cover will be installed over the landfill. Capping will severely restrict rainfall from infiltrating the waste mass (until sometime in the distant future when maintenance ends and the cover fails). After that transition point when the cover is installed, the amount of rainfall becomes far less important if not meaningless, and, therefore, distorts the annual estimates. Essentially, then, over the entire relevant time period, modifications to increase or decrease "*k*" cannot cure the fact that the model fails to include a coefficient to control for discontinuous data for moisture inside the landfill.

64. US EPA, *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (EPA530-R-98–13)(1998), at p. 102 (under contract with ICF).

65. Among the study's flaws is the fact that the Barlaz study incorrectly included fossil carbon in the form of plastic along with carbon in organic matter, even though the proper interpretation of the carbon in polymer chains made from petroleum is that the carbon has shifted from one form of storage medium to another, not that a new storage vector has been created.

Another error is that Dr. Barlaz failed to measure the percent of organic carbon in the original sample, and based his outputs on assumptions. He then converted laboratory data from a wet to dry basis as part of the calculations assuming 16% moisture content, which, as noted earlier, is approximately a third too low. Also, attempts to correct other methodological errors were made with uncertain adjustments. (Brian Bahor, et al., "Updated Analysis of Greenhouse Gas Emissions and Mitigation from Municipal Solid Waste Management Options Using a Carbon Balance," *Global Symposium* (2008), at p. 17.)

In the end, Dr. Barlaz was required to withdraw the results of his earlier analysis and concede that the best that can be deduced from his flawed study is that the value lies between 6.9% and 9.4% storage. Other researchers such as Bahor who have redone his work to correct those errors estimate the study should show 6%, although using their preferred mass balance approach have found the range of possible storage values between 0.8% to 7.8%.

66. Also, apart from the difficulty in reliably calculating the theoretical capacity of lignin to sequester carbon in the anaerobic conditions of a landfill, there are two other more systemic problems with claiming carbon sequestration benefits from the landfilling of woody discards: [1] organic discards are biogenic, and [2] sequestration may be double counted.

① ***Biogenic.*** The definition of what carbon source is properly categorized as sequestered is usually determined by whether it is biogenic (naturally occurring) or anthropogenic (manmade) (*see* discussion on page 4). Thus, on the one hand, all organic discards, including the paper and wood that contain most of the lignin, are presently designated as biogenic because they are a part of a closed carbon cycle. Therefore, they would normally not be included in national GHG inventories, and sequestration claims would be irrelevant:

"Sustainable biogenic sources include paper and wood products from sustainably managed forests. When these materials are burned and aerobically decomposed to CO_2, the CO_2 emissions are not counted." US EPA, *Solid Waste Management and Greenhouse Gases* (2^d Ed. 2002), at p. ES-17.

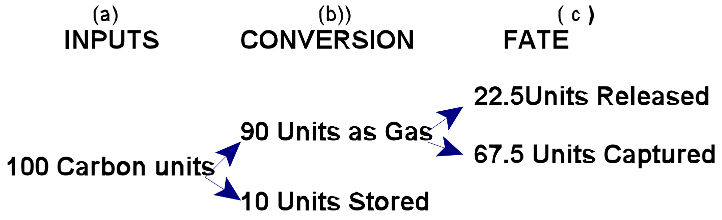
If these sources are not to be counted when they are aerobically decomposed into CO_2, there would be a significant logical incompatibility in counting them when they are argued to be sequestered.

On the other hand, an argument has been made for claiming an exception to that general rule for excluding biogenic carbon from national inventories. It is the claim that, were the lignin not disposed of in the anaerobic conditions of a lined landfill, the carbon would be released into the atmosphere. *See*, e.g., US EPA, *Greenhouse Gas Emissions from Management of Selected Materials in MSW* (September 1998), at p. 6. Essentially, the contention compares landfilling woody discards against incineration, which is posited to be the only other alternative pathway, where the entrained carbon is released as a byproduct of combustion.

Beyond the question of whether any exception can appropriately be made once a carbon-containing discard has been categorized as biogenic, the problem with this view is two-fold. For one thing, there is a logical inconsistency in denying that carbon's relevance to the inventory when paper is burned, but claiming a benefit when that same paper's lignin fraction is sequestered. For another, there is not just one alternative pathway that discarded paper may take if not landfilled. Although incineration would release the carbon from burning paper, another path is recycling. Not only would recycling continue the discards' life as new product where the carbon would continue to be stored, but also recycling would reduce the amount of land needed to be tilled for silvaculture, which would produce another source of further carbon savings. See, e..g., US EPA, *AP-42 Compilation of Air Pollutant Emission Factors* (2008), at 14.1. Similarly, if the wood were chipped and composted, the humus would create significant gains in soil carbon storage. US EPA, *Solid Waste Management and Greenhouse Gases* (2^{d} Ed. 2002), at p. 6. Yet, a deduction is proffered for landfill sequestration without the required parallel accounting for reduced GHG emissions from soils were the discards recycled or composted.

② ***Double-counting.*** The inclusion of any value for sequestration also may constitute double-counting. Proponents of landfill sequestration claim that the estimated methane emissions from landfills into the atmosphere should be reduced equal to the amount of carbon that theoretically may be sequestered. However, when one common methodology for estimating those fugitive methane emissions is examined, it seems likely that the estimate has been calculated after already subtracting the claimed sequestered amounts. This is because these models calculate an estimate of the amount of methane gas released – the value of which is not directly known – based upon the amount of gas that is captured – which is known ---and that is done by dividing the known volume of captured gas by a second unknown, a guesstimate of the gas collection efficiency rate. But, the amount that is captured is a value that occurs after any sequestration has happened. This point is illustrated by the following chart:

FATE OF ORGANIC CARBON IN LANDFILL



In this simplified depiction, 100 units of organic carbon are disposed of in the landfill (see col. (a)). Using the values suggested by EC, 90% would be converted to gas over the time that gas is generated, and 10% would be sequestered (see col. (b)). Of the 90% converted to gas, 25%, or 22.5 units, would be released into the atmosphere, and 75%, or 67.5, units would be captured (see col. (c)), all assuming for simplicity that there were fully functioning gas for the entire time that gas is generated.

Using the illustrative numbers in this example with that common equation for estimating fugitive methane, the calculation of gas captured from col. (c), is: 67.5 ÷ 75%, the usual guesstimate of collection efficiency, or 90 units. Calculated in this way, the value for the methane that escapes is 90 units, not the original 100 units in col. (a) disposed of in the landfill, because the value used for gas captured in col. (c) is *after* subtracting the amount sequestered in col. (b). This results in double counting the claimed sequestration.

For examples of sources that use this methodology, see, e.g., US EPA, *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills* (September 2008), at pp. 8-9; R.L. Peer, *A Comparison of Methods for Estimating Global Methane Emissions from Landfills*, 26 CHEMOSPHERE 387, 395 (1993); US EPA, *Estimating Methane Generation from Regression Analyses* (1993), at p. 5. See also discussion on p. 18. Of course, the fundamental problem with this equation is that, of the three factors, two are unknown, and there are no other interrelated equations from which one of the two unknowns can be deduced. With official assumptions of the unknown gas capture ranging from 20% to 75% -- a factor of nearly four – the result is meaningless.

Although the model used by EC for calculating total gas potential , IPCC, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (2000), at p. 5.6, is not linked directly to the circularity of AP-42, its suggested values for key input factors, such as dissimilated degradable organic carbon, are only unsupported assumptions. The question remains whether the assumed values in *Good Practices* assumed values were derived in whole or in part indirectly from methodologies, such as AP-42, whose logic also double counts whatever effect is appropriate for sequestration.

In short, sequestration seems to be inappropriate for inclusion in national inventories at this time, although further investigation is in order.

67. *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (EPA 530-R-98-013)(September 1998) at p. 106.

68. P. M. Czepiel, *et al.*, “Quantifying the effect of oxidation on landfill methane emissions,” *Journal of Geophysical Research* (July, 20, 1996), at p. 16,720.

69. 40 C.F.R. §258.60(a)(1)..

70. ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update* (2005), at p. 70.

71. P. M. Czepiel, *et al.*, “Quantifying the effect of oxidation on landfill methane emissions,” *Journal of Geophysical Research* (July, 20, 1996), at pp.16,727 16,721 16727 and 16729. Also, AEA Technology, *Methane emissions from UK landfills* (UK Dept.of the Environment)(1999), at p. 2-9.

72. Thompson Report, at p. 15. However, note that this estimate is derived from a landfill without a low permeable cover that prevents rain infiltration until decades hence when the cover fails. That fact of modern engineered landfills effectively interrupts the referenced decay function. The result will be the that the final act of gas generation can extend beyond those 80 years, depending how long the cover keeps biological activity in temporary abeyance.

73. Hans Oonk, “Landfill gas formation, recovery and emissions” (TNO Report 95-130)

74. IPCC, *Fourth Assessment Report*: Chapter 10 Waste (2007), at p. 600.

75. IPCC, *Second Assessment - Climate Change 1995* (1995).

76. US EPA., *Solid Waste Managment and Greenhouse Gases: A Life-cycle Assessment of Emissions and Sinks* (2nd Ed. 2002), at p. 12.

77. Environment Canada, *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada, 1990-2006* (2008), at p. 23. In calculating GHGs, the different types of warming gases are converted into a CO_2E basis for ease of comparison. To do this, the fact that methane breaks down in the atmosphere over a shorter interval than CO_2 must be accounted for. Most nations’ inventories uses a 100 year time to account for CO_2's longer residence time than CH_4's If instead, they consistently used a single year as the time period for equivalence, the multiplier to convert CH_4 to CO_2 would be more than *20 times* the 25× GWP currently used to estimate landfills’ GHG responsibility. The use of opposite time periods for comparison, applied improbably in a way that consistently minimizes landfills’ responsibility for GHGs, is not easily explained.

78. EPA, *Greenhouse Gases and Global Warming Potential Warming Values* (April 2002), at p. 9.

79. Ontario, *Ontario’s Climate Action Plant: Creating Our Sustainable Future: Annual Report 2007-2008* (2008), at p. 43.

80. Ontario Power Authority, “Ontario Unveils North America’s First Feed-in Tariff,” (March 12, 2009).

81. ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update* (2005), at p. 71.

82. Anaerobic digesters, which are sometimes used to process source-separated organics, also produce methane. However, they do so in enclosed vessels that prevent any methane from escaping.

83. As one example, Toronto uses bi-weekly collection of the residual refuse, which incentivizes problem non-coooperators to cooperate otherwise their putrescibles will remain in their abode for two weeks. The power of this incentive is shown by the fact that Toronto captures more than 70% of its targeted organic discards, while San Francisco, which continues collecting refuse weekly, less than 30%. Center for a Competitive Waste Industry, *Beyond Recycling: Composting Food Scraps and Soiled Paper* (2010), at p. 42.

84. European Community, COUNCIL DIRECTIVE 1993/31EC (April 26, 1999), at Art. 5, ¶1 and ¶2.

85. ICF Consulting, *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update* (2005), at p. 69.

86. George Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues* (McGraw-Hill, 1993), at pp. 72-73. Rapid dehydration can be seen by the fact that, at 100% saturation and 40° C (104°F) temperature, the condensate is 51% by weight of the weight of the gas, according to standard Humidity Tables, and landfill gas weighs 0.0834 lbs./cf., according to standard conversions.

87. George Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues* (McGraw-Hill, 1993), at p. 393. Others suggest that optimal range lies between 40% - 70%. Debra Reinhart, *Landfill Bioreactor Design & Operation* (Lewis Publishers, 1998), at p. 140. Others have done research suggesting full methane conversion does not proceed until moisture reaches 60%-70%. G. J. Farquhar, "Gas Production During Refuse Decomposition." 2 *Water, Air and Soil Pollution* 9, at pp. 483-495 (1973). *See, also*, 67 FED. REG. 346462 (May 23, 2002).

88. 40 C.F.R. §60.753(b)(1).

89. Don Augenstein et. al., Improving Landfill Methane Recovery – Recent Evaluations and Large Scale Tests, Presentation to Methane to Markets Partnership Expos (2007), at p. 3.

90. SCS Engineers (SCS), *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills* (July 2007), at p. 10, posits three ranges of gas collection for different conditions:

> "•50-85% (mid-range default = 68%) for a landfill or portions of a landfill that are under daily cover with an active LFG collection system installed ...; 85-99% (mid-range default = 92%) for a landfill or portions of a landfill that contain intermediate or an engineered final soil cover with an active LFG collection system ...and; 95-99% (mid-range default = 97%) for landfills that have a RCRA Subtitle D equivalent liner with an active LFG collection system....
>
> "The high ends of the range of these values (i.e., 85%, 99%, and 99%) are proposed for sites with NSPS or similar quality LFG collection systems which are designed for and achieve compliance with air quality regulations. *The low end would be for full LFG systems that are installed and operated for other purposes, such as energy recovery*, migration control, or odor management, or those landfills with surface emission monitoring levels at times greater than 500 parts per million by volume (ppm) per the NSPS; or systems that were retroactively installed well after the landfills operating life had begun. A mid-range default value is provided for those landfills for which detailed information about the construction of the unit is not known." (Emphasis added.)

The instantaneous average of the three ranges, or 18%, is their implied conclusion of the magnitude of the capture rate reduction due to "LFG systems that are operated for other purposes, such as energy recovery."

91. Contrast: Pat Sullivan and Alexander Stege, "An Evaluation of Air and Greenhouse Gas Emissions and Methane-Recovery Potential from Bioreactor Landfills," *MSW Management* (Sept./Oct. 2000), at p. 78, states that bioreactor landfills increase near term gas capture per ton of waste-in-place by 76%; with 67 FEDERAL REGISTER 36463 and 36465 (May 22, 2002), which states that bioreactors increase gas generation

in the near term by 2 to 10 times. Therefore, when gas generation is doubled, while capture increases only 76%, the degradation in collection efficiency would be 50%, and when increased by one magnitude, by 90%.

92. Solid Waste Industry for Climate Solutions, *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation and Carbon Sequestration in Landfills*(2007), at 10.

93. US EPA, AP-42 (5th Ed.), Table 2.4-3. The reported control efficiencies for flares and ICEs are for only NMOCs, halogenated species and non-halogenated species, not for CH4 or CO2 specifically. In the absence of data on point, the typical control values for all three were averaged as an initial estimate, pending the availability of better data.

94. The inputs used in preparing the graph are as follows: LFG Generation-0.1,cf/lb/yr; Weight of Methane-0.04228,pounds/cf; Metric Conversion for Tons-0.9072,Metric Ton; CH4 GWP-25 CH4 Multiplier; Btu Content- 1000,Btu/cf; Base Capture Rate- 75%; Reduction in Capture Rate w/ LFGTE-82%; ICE Heat Rate-9492; Btu/kWh; Gas-0.79 Lbs.CO2/KWH; Coal-1.93 Lbs.CO2/KWH; Flare CH4 Destruction-99.4%; ICE CH4 Destruction,-94.0%.

95. Ontario, Ontario’s Climate Change Action Plan: Creating Our Sustainable Future: Annual Report 2007-2008, at p. 45.

96. Ontario Regulation 232/98 Part III, ¶15.

97. Ontario Regulation 232/98 Part III, ¶15.

98. Ontario Ministry of the Environment, Waste Management Policy Branch landfill data.

99. European Commission, COUNCIL DIRECTIVE 1999/31/EC of 26 April 1999 on the landfill of waste. A copy of the text of the Directive is on line at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1999:182:0001:0019:EN:PDF.

100. SCS Engineers, *Technologies and Management Options for Reducing Greenhouse Gas Emissions From Landfills* (2008), at pp. 20 - 73, on-line at: http://www.ciwmb.ca.gov/Publications/Facilities/20008001.pdf. SCS also includes some recommendations aimed at accelerating decomposition in the section following page 73. While these appear counter productive for concerns over climate change, the great bulk of the report’s recommendation preceding page 74 are widely adaptable. Whatever gains that leachate recirculation offers in slightly improved site stabilization in the distant future are negated by the unacceptable losses in higher methane emissions in the critical short-term that we confront the tipping point.

101. Don Augenstein, et. al., *Improving Landfill Methane Recovery -- Recent Evaluations and Large Scale Tests* (2007); Hans Oonk, *Expert Review of First Order Draft of Waste Chapter to IPCC’s Fourth Assessment Report* (2008); SCS Engineers, *Technologies and Management Options for Reducing Greenhouse Gas Emissions From Landfills* (2008); and US EPA, 40 CFR Part 60 WWW (proposed and final rule), *AP-42 Draft Revisions*, and *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology* (EPA/600/R-07/032), February 2007.