CalRecycle Review of Waste-to-Energy and Avoided Landfill Methane Emissions

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Executive Summary

Diverting solid waste to a Waste-To-Energy (WtE) facility or a diversion facility such as a composting operation or anaerobic digester avoids the methane that would have been generated if the waste were sent to a landfill. Landfills are complex sources of methane emissions that occur over decades to centuries from the date of disposal in the landfill. Research and technology on landfill methane emissions and controls is rapidly advancing; however, given the heterogeneity in landfill siting, uncertainties regarding the scale and scope of their emissions and differences in professional judgment remain. In order to build upon CalRecycle's understanding of WtE, CalRecycle staff conducted a detailed analysis of WtE and avoided landfill methane greenhouse gas (GHG) emissions, employing recent, peer-reviewed models.

A detailed lifecycle analysis (LCA) study was beyond the scope of this analysis. Published LCA studies and best available published direct measurement data support CalRecycle staff's general conclusions. CalRecycle staff concludes that the three existing California WtE facilities provide net avoided methane emissions over waste otherwise disposed in a California landfill. The net avoided emissions exceed non-biogenic emissions from burning of the fossil fuel based components such as plastic in the WtE facility.

CalRecycle estimates the average net avoided landfill methane emissions are 0.18 $MTCO_2e$ per ton of waste (43,200 $MTCO_2e$ for Stanislaus WtE) with a range of 0.07-0.24 $MTCO_2e$/ton (15,800-52,252 $MTCO_2e$ for Stanislaus WtE). Additional avoided emissions from WtE potentially include electricity generation and ferrous metal recycling. Total avoided landfill methane emissions are estimated at 0.53 $MTCO_2e$/ton of waste (range 0.41-0.59). These totals could be adjusted based on anaerobically degradable organic carbon content of specific waste material fractions to apply to other waste management alternatives such as composting and anaerobic digestion.

CalRecycle staff concludes that the estimates of avoided emissions are representative where an average statewide ton of waste would be disposed. However, landfill emissions may be significantly different (lower or higher) depending on site-specific conditions. Additional research is necessary to improve our understanding of landfill emissions, improve modeling methods, and validate the models with best available measurement data. The estimates of avoided landfill emissions in this paper will warrant periodic reevaluation as new studies become available.

Results of this analysis differ from results received when using previous model versions, including results generated by the California Air Resources Board (ARB) to inform activities related to the California Global Warming Solutions Act of 2006 (AB 32). CalRecycle will continue to work with ARB, other agencies, and external stakeholders as new data and scientific methodologies become available, to ensure that California has the most up-to-date and scientifically accurate estimates of fugitive methane emissions.

Introduction

The AB 32 Scoping Plan identifies 9 MMTCO$_2$e in potential greenhouse gas (GHG) emissions reductions from measures to divert solid waste from landfill disposal (RW-3 High Recycling/Zero Waste Sector) (http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm). CalRecycle is working collaboratively with California Air Resources Board (ARB) staff as lead agency for implementing these measures.

When solid waste is delivered to a waste-to-energy or other waste diversion facility such as a composting operation or anaerobic digester, the methane that would have been generated if it were sent to a landfill is avoided. Emissions reductions for waste diversion measures compared with landfilling are in large part from these avoided landfill methane emissions that would occur over decades to centuries from when the waste disposed in the landfill. Research characterizing landfill emissions is rapidly advancing; however, landfills are a complicated emission source and there remains substantial uncertainty and differences in professional opinion.

There are three WtE (transformation) facilities in California accepting a total of approximately 800,000 tons per year. They include Covanta Stanislaus Inc. (Unincorporated Stanislaus County), Commerce Waste-To-Energy (Commerce), and Southeast Resource Recovery (Long Beach). These facilities were constructed prior to 1989 and are the only facilities where jurisdictions are allowed a transformation credit against annual disposal tonnage under the Public Resources Code (PRC) (http://www.calrecycle.ca.gov/LGCentral/Basics/Transform.htm). These facilities are required under the PRC to ensure to the greatest extent feasible that all recyclable materials are removed prior to burning. No new WtE facilities would be allowed a transformation credit under current law.

The purpose of this paper is to provide CalRecycle analysis and recommendations on landfill avoided emissions estimates for waste-to-energy (WtE), based onexisting analyses specific to California WtE facilities [1,2,3,4]. Additionally, recommendations are provided for estimating avoided emissions for other waste management options such as biomethane from anaerobic digestion. General conclusions and recommendations concerning related aspects of Lifecycle Analysis (LCA) and review of pertinent published LCA studies are provided. However, a detailed quantitative LCA comparing solid waste management alternatives is beyond the scope of this paper.

General Methodology

CalRecycle staff reviewed analyses prepared by ARB staff and the WtE industry and pertinent references to provide a detailed CalRecycle estimate of net landfill avoided emissions from the Stanislaus WtE facility. This analysis used Stanislaus WtE baseline 2008-2010 average annual waste throughput of 241,242 tons MSW and non-biogenic emissions of 83,598 MTCO$_2$e. The analysis for landfill avoided emissions over time is based on the scenario of one time annual disposal of 241,242 tons of Stanislaus WtE waste into the Fink Road Landfill located adjacent to

the facility. Based on this analysis, general conclusions are also provided regarding the other two WtE facilities and statewide landfill disposal. Detailed documentation of CalRecycle staff modeling runs and calculations are provided in attached spreadsheet electronic (Excel and word) files.

Landfill methane emissions modeling was conducted using 2006 Intergovernmental Panel on Climate Change (IPCC) based methodology [5,6,7,8] and California Landfill Methane Inventory Model (CALMIM) [9,10,11] methodology. CalRecycle staff uses a Global Warming Potential (GWP) of 25 for methane to be consistent with IPCC methodology. Additional data was incorporated to compare the modeling results with the most recent landfill emissions measurement data in the literature. Avoided emissions estimates are provided and compared with the WtE analyses. Qualitative analysis of sensitivity is provided for CALMIM results. A rigorous statistically based sensitivity analysis is beyond the scope of this paper. Only methane emissions are considered.

The above methodologies were supplemented using site-specific landfill information compiled by CalRecycle staff and presented September 2011 at the CalRecycle Monthly Public Meeting (http://www.calrecycle.ca.gov/Actions/PublicNoticeDetail.aspx?id=498&aiid=483) and augmented with subsequent CalRecycle compilations and field surveys of related landfill parameters (e.g. waste footprint, waste-in-place, gas control system coverage). These data are important in statewide estimates and validation using CALMIM and measurement data.

CalRecycle staff estimates include both the 100-year and 200-year lifecycle for avoided emissions. The 200-year lifecycle should be considered because a significant portion (about 15% in FOD models) of total methane generation potential remains at the 100-year mark after disposal.

IPCC First-Order-Decay (FOD) Methodology

IPCC-based methodology uses the Mathematically Exact First-Order Decay (FOD) model. This model assumes a fixed fraction of the waste available at any time will degrade (anaerobically degradable organic carbon (ANDOC)) at a rate factor (k) which is related to precipitation and moisture content. In contrast, USEPA AP-42 uses a single methane generation factor (Lo) with default values that do not vary with time [13,14,15]. The analysis for Stanislaus WtE in this paper is simplified because only one year of waste disposal (241,242 tons) was necessary to be modeled for degradation over time represented at the Fink Road Landfill site.

The Fink Road Landfill and vast majority of landfills in California have USEPA default k values of 0.02 (annual precipitation less than 25 inches). The initial ANDOC for the average landfill in California is 7.52% based on the CalRecycle waste characterization survey of 2008. Stanislaus WtE excludes construction/demolition debris, medical waste, and sludge/manure and is recalculated by CalRecycle staff at 8.9% ANDOC.

To estimate the quantity of methane emitted and collected, the FOD models apply default collection efficiencies of 75% with landfill gas collection and control systems and methane oxidation of 10% in cover soils. This analysis incorporates a 99.5% destruction efficiency where 0.5% of the methane collected is not destroyed and is emitted from the control device. Statewide approximately 95% of the total statewide waste-in-place and annual disposal is in landfills with active landfill gas collection and control systems with combustion in flares or energy recovery systems. Approximately 1% of active landfills have active venting or carbon adsorption systems which pass methane directly through to the atmosphere without benefit of methane combustion or oxidation in cover soils.

Default landfill methane collection efficiencies and oxidation rates in FOD models are uncertain[5] and controversial. On one side are those who consider collection efficiencies and oxidation rates significantly higher than the default values. On the other side are those that consider collection efficiencies much lower, especially within the first few years after disposal when collection systems are not fully collecting gas from those areas, and generation of landfill gas per the FOD models is high. Collection and control systems are expanded as new areas of waste are filled and covered. Landfill operators are required to balance the timing of installation and optimization of the expanded systems with landfill gas generation, but no later than 5 years from waste placement under USEPA requirements. Researchers conclude that higher emissions are likely during the delay period [16,23,24].

Application of the IPCC-based and USEPA FOD methodologies do not normally apply varying collection efficiencies over time. However, in addition to the unvarying default efficiencies of 75% collection (with control) and 10% oxidation (without control), CalRecycle staff applied another approach of variable rate of collection efficiency based on Kaplan et al (2009)[16]. Under this approach, the collection efficiency is 0% Years 1 and 2, 50% Year 3, 70% Year 4, and 80% Year 5 until shutdown of the control system, and default oxidation is 15% of the remaining uncollected landfill gas.

There are the significant limitations of FOD models for landfill gas which are not good predictors of site-specific emissions. Waste decomposition and emissions from landfills are complex systems not easily represented by a mathematical model. Input parameters may vary significantly with time based on field conditions and are difficult to measure and validate. Default collection efficiencies and oxidation rates are empirical and not verified with measurement. The FOD models also do not represent secondary permeability or point sources of landfill gas emissions that can occur through cracks, pipe penetrations, or other localized defects in cover systems. Furthermore, landfill gas generation at arid landfill sites may have unexpected site-specific k and low (effective Lo) methane generation conditions (e.g., Kern County landfills[17]) and waste material-specific k and Lo. IPCC methodology includes site specific options to input a fraction of methane generated in landfill gas less than the 50% default and a correction factor for aerobic decomposition (MCF). However, these site-specific factors are difficult to characterize.

California Landfill Methane Inventory Model (CALMIM) Methodology

The California Landfill Methane Inventory Model (CALMIM) is an improved field and laboratory validated inventory methodology for landfill methane emissions in California[9,10,11]. CALMIM provides a higher order model based on emissions and measurements rather than FOD-based models based indirectly on theoretical methane generation and empirical control efficiency.

CALMIM incorporates the most important factors on emissions including landfill gas recovery impact on diffusive flux at the base of cover materials, the physical properties of cover materials, and seasonal rates of methanotrophic oxidation in cover materials. CALMIM incorporates site-specific distribution of daily, intermediate, and final cover soils for any combination of layered cover. Site-specific climatic modeling uses USDA globally-validated methods based on regional climatic databases and soil microclimate (temperature and moisture) variability over an annual cycle. Results of emissions flux are inclusive of engineered gas collection systems and seasonal methane oxidation and do not depend on the mass of waste and generation rate because of the principals of diffusional flux. Therefore, total emissions flux (or emissions factor) are controlled by the surface footprint size and cover properties and percent coverage of the

gas collection system. CALMIM allows input of custom input data such as unsaturated (free drainage) transport and site-specific methane concentrations.

CALMIM also has limitations. It is based primarily on flux chamber field measurements and should be further validated with advanced field measurement methods such as Optical Plume Mapping (EPA OTM-10 method) and tracer methods. CALMIM also does not represent secondary permeability or point sources of landfill gas emissions that can occur through cracks, pipe penetrations, or other localized defects in cover systems.

CalRecycle applied CALMIM methodology to the entire lifecycle Stanislaus WtE and Fink Road Landfill scenario. Three phases were modeled- active landfill operations, closure at year 20 to shutdown at Year 60, and post-shutdown Years 60 to100 and 100to 200. Closure to shutdown was modeled with site specific input of final cover base methane content at default 55% linearly declining to 5% (methane lower explosive limit) at shutdown and free draining unsaturated conditions. This approach is supported by the actual methane content data (12% average 2010 for Palos Verdes Landfill which closed in 1980.The permitted footprint at closure is 146 acres (LF-2) and average operational footprint estimated at 90 acres over an active life of 40 years (20 years prior to WtE one-year disposal and 20 years after WtE). The final cover system was assumed to be a 4' thick monolithic water balance cover system using on-site silty clay loam, gas collection coverage 100%. The water balance final cover system is the most common system used in California and appropriate for the Fink Road Landfill location.

The application of CALMIM to the Stanislaus WtE scenario requires consideration of the relative contribution to surface emissions of the one-year WtE disposal to the remaining waste. The proportion of Stanislaus WtE (241,242 tons) to total LF-2 capacity (5.8 million tons) is 4%. Statewide landfill footprint is correlated with waste-in-place by site and the equation is used to calculate the equivalent footprints for the Stanislaus WtE (4 acres) and total capacity (134 acres) and proportion 3%. Including the relative contribution of Stanislaus WtE with higher ANDOC (8.9/7.52=1.18x) the correction factor by these methods averages 4% (range 2.8% to 5.0%). The correction factor based on statewide disposal/footprint data is similar, 3.7% including Puente Hills Landfill and 4.4% without Puente Hills Landfill (PHL). PHL is not recommended for representative modeling because it closes in 2013 and is uniquely large (120 million tons).

CalRecycle used 15% as the proportion of daily cover surface area (6 inches minimum or ADC, up to 180 days since waste disposal) to total daily and intermediate cover (12 inches minimum, >180 days to final cover), 0% collection system coverage for daily cover, and 75% collection system coverage for intermediate cover (range 50-90%). These factors are based on ongoing CalRecycle survey of landfill operations and equations for landfill cover operations (Neal Bolton personal communication). Intermediate cover thickness was estimated at 15 inches (range analyzed 12 to 18 inches). CalRecycle staff's CALMIM results are most sensitive to intermediate cover thickness (see attached files: Final 052012 CalRecycle CALMIM WtE.xlsx and CalRecycle CALMIMReports WtE 052012.docx)

ARB Staff and WtE Industry Modeling Results

ARB staff and the WtE Industry Representative (Covanta) applied a conservative FOD approach for the Stanislaus WtE scenario assuming 83% landfill gas collection efficiency and 10% soil oxidation factor. Lower collection efficiencies initially after disposal were not applied. ARB staff and Covanta also used a Global Warming Potential (GWP) for methane of 21 rather than the current adopted IPCC GWP for methane of 25[12].

The primary difference between ARB and Covanta approaches is at control system shutdown (two scenarios: at years 30 and 45). Covanta maintained FOD calculated methane generation rates beyond shutdown with total control efficiency ((collection + oxidation) /generation) at the default oxidation factor of 10%. This approach resulted in significant portion of the total 100-year timeline emissions occurring after control system shutdown (36-48%). ARB staff applied a combined methodology with FOD approach up to control system shutdown and CALMIM for the site after control system shutdown. This approach resulted in ARB's total 100-/45-year control avoided landfill emissions estimates (23,275 MTCO$_2$e) significantly lower than Covanta's (112,396 MTCO$_2$e). Compared with 83,598 MTCO$_2$e in non-biogenic emissions, Covanta's estimates resulted in net avoided emissions of 30,465 MTCO$_2$e. However, ARB staff's estimates resulted in higher emissions from non-biogenic WtE of -58,656 MTCO$_2$e as compared with the avoided landfill emissions.

For the Fink Road Landfill modeling scenario, CalRecycle staff estimates that there would be approximately 20 years from WtE disposal to closure of the landfill, and an additional 25-40 years until control system shutdown (total 45-60 years). CalRecycle staff used the more conservative 60-year system operation period for its analysis.

There is very limited information available concerning when and at what conditions landfill gas system shutdown will occur. Engineered landfills and landfill gas collection and control systems have only been in place less than approximately 30 years and no systems have gone through the process of complete shutdown. Furthermore, FOD methodologies do not provide a basis at this time to input other than the collection efficiency plus oxidation during system operation and just oxidation with system shutdown. Additional research will be necessary to establish more confidence in estimating system shutdown conditions and timing.

Comparison of Results

CalRecycle detailed calculations are in attached Excel Spreadsheets to this paper with results summarized in Table 1 and Figure 2.

Table 1. CalRecycle Results for Landfill Avoided Emissions from Stanislaus WtE (For supporting calculations see attached file: CalRecycleFOD WtE 07032012.xlsx.)

Stanislaus WtE	Total Landfill Emissions (MTCO$_2$e)	Total Landfill Emissions (MTCO$_2$e/ton)	Net Avoided Landfill Emissions (MTCO$_2$e)	Net Avoided (MTCO$_2$e/ ton)	Control Efficiency (Lo 327,000 MTCO$_2$e)
CalRecycle CALMIM 200-yr	141,850	0.59	58,252	0.24	57%
CalRecycle CALMIM 100-yr	133,710	0.56	50,112	0.21	59%
CalRecycle FOD 200-yr	132,232	0.55	48,634	0.20	61%
CalRecycle FOD 100-yr	99,398	0.41	15,800	0.07	70%
Average	**126,798**	**0.53**	**43,200**	**0.18**	**62%**
Range	**99,398-141,850**	**0.41-0.59**	**15,800-58,252**	**0.07-0.24**	**57-70%**

Figure 1. Estimated Net Landfill Methane Avoided Emissions Stanislaus WtE
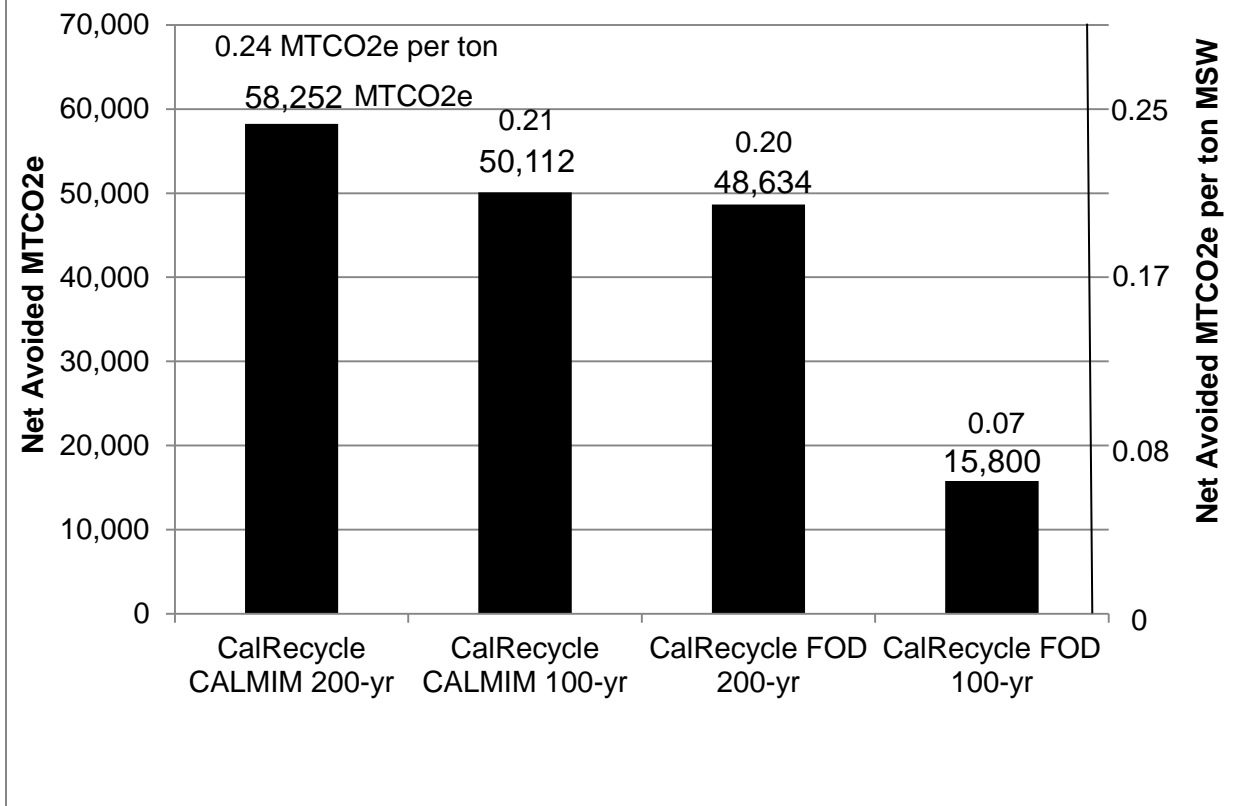
Direct Field Measurement

The IPCC methodology considers direct measurement of landfill methane emissions as a good practice to validate models, but with caveat of significant limitations of measurement methods.[5]

Landfills are considered an "area" source where emissions vary spatially and over time and are far more complex a "point" source such as a stack or pipe vent. Area sources include oil and gas pipelines, animal waste lagoons, and landfills. Landfills are considered the most challenging because of their size, and highly variable nature due to changes in waste composition, design and operation, and natural site conditions.

Flux chamber (or flux box) tests have been the most common method to measure landfill emissions but they have significant limitations. It is a point sampling method and unless there is a very high density of flux box tests, statistically there will always be a relatively significant degree of uncertainty as to the actual emission flux. Furthermore, flux boxes cannot account for emissions from cracks, pipe penetrations, or other localized defects in cover systems. Direct measurement methods addressing these limitations are being developed. Significant advances are being made in developing optical remote sensing (USEPA OTM-10 Method[19, 20,21,22]) and tracer gas methods[18] Huitric and Dong (2006)[30] estimated collection efficiencies using

integrated surface monitoring concentrations and the USEPA Industrial Source Complex (ISC) atmospheric dispersion model, a potential cost effective approach that would benefit if correlated with flux and direct flux measurements.

The USEPA recently released a detailed study and report of three landfills to quantify fugitive emissions using Open-Path Tunable Diode Laser (TDL) instruments and further develop the OTM-10 method.[23] The study combined measurement of surface emissions flux with collected gas to determine abatement efficiency (Methane Collected / (Methane Collected + Methane Emissions).

The landfills are fully compliant facilities with landfill gas collection and control systems. Two are active facilities with interim covers and one closed with final cover in-place. The facilities and locations are not identified but appear to be in the eastern US and representative of a much higher humidity and precipitation as a typical landfill site in California. Results indicated average methane emission factors ranging from 9.2 to 150 gm/day/m^2 and abatement efficiencies from 38% to 88%. With inclusion of methane oxidation the efficiencies are higher, for 10% default oxidation, the range is 44% to89%.

The study combined integrated surface monitoring measurements in accordance with California methods. These results were all below (in compliance with) the California Landfill Methane Capture rule standard of 25 part per million by volume (ppmv). For one of the three landfills, a forward-looking infrared (FLIR) camera was used to identify potential point source leaks from the landfill surface and wellheads. Pictures of leaks are provided from the use of the FLIR. The study found at one site methane emissions from areas that had waste placed within 6 months, contrary to most models with assume no generation within 6 months. The site with low abatement efficiency was measured a few months before upgrade of the landfill gas collection system. The report concludes that the data provided is considered the best available data to date to evaluate methane abatement efficiency by measuring emissions across the surface and side slopes using TDL instruments.[23]

Additional OTM-10 TDL method measurements were conducted by Green et al (2009)[28] at three California Landfills in 2007-2008 and compared with flux chamber measurements[28]. The measurements included methane oxidation and control efficiency (Methane Collected + Methane Oxidation/ (Methane Collected + Methane Oxidation + Methane Emissions). Results indicated methane emission factors ranging from 1.1 to 41.5 gm/day/m^2 and abatement efficiencies from 81% to 92%. TDL study of 20 landfills across the United States was recently published[29], and flux results (control efficiency was not measured) differentiated by climate type, including five California Landfills (Mediterranean climate type). The California flux results were reported[29] overall at 11 gm/m^2/day (intermediate cover) and 6 gm/m^2/day (final cover). One semi-arid landfill (Colorado) flux was reported in gm/m^2/day at 85 (working face), 11 (daily cover), 3.7 (intermediate cover), and 2.7 (final cover). Humid climate landfills reported fluxes much higher at 26-207 gm/m^2/day.

Figure 2 provides a graph of TDL measurement data with methane emission factor and control efficiency. Included are equivalent factors and control efficiencies estimated from theoretical maximum methane generation and the CalRecycle staff model runs And avoided landfill methane equal to WtE non-biogenic emissions. The best available measurement data show large range but indicate higher emissions than other methods.

The results support the general conclusion that based on the best information and range of methods available, avoided methane emissions from landfills are higher than non-biogenic WtE emissions. Measured and modeled flux results vary and should be refined and reconciled with additional research. Control efficiency based on theoretical methane generation varies considerably with flux based estimates and measurements.

Figure 2. Landfill Methane Flux and Control Efficiency
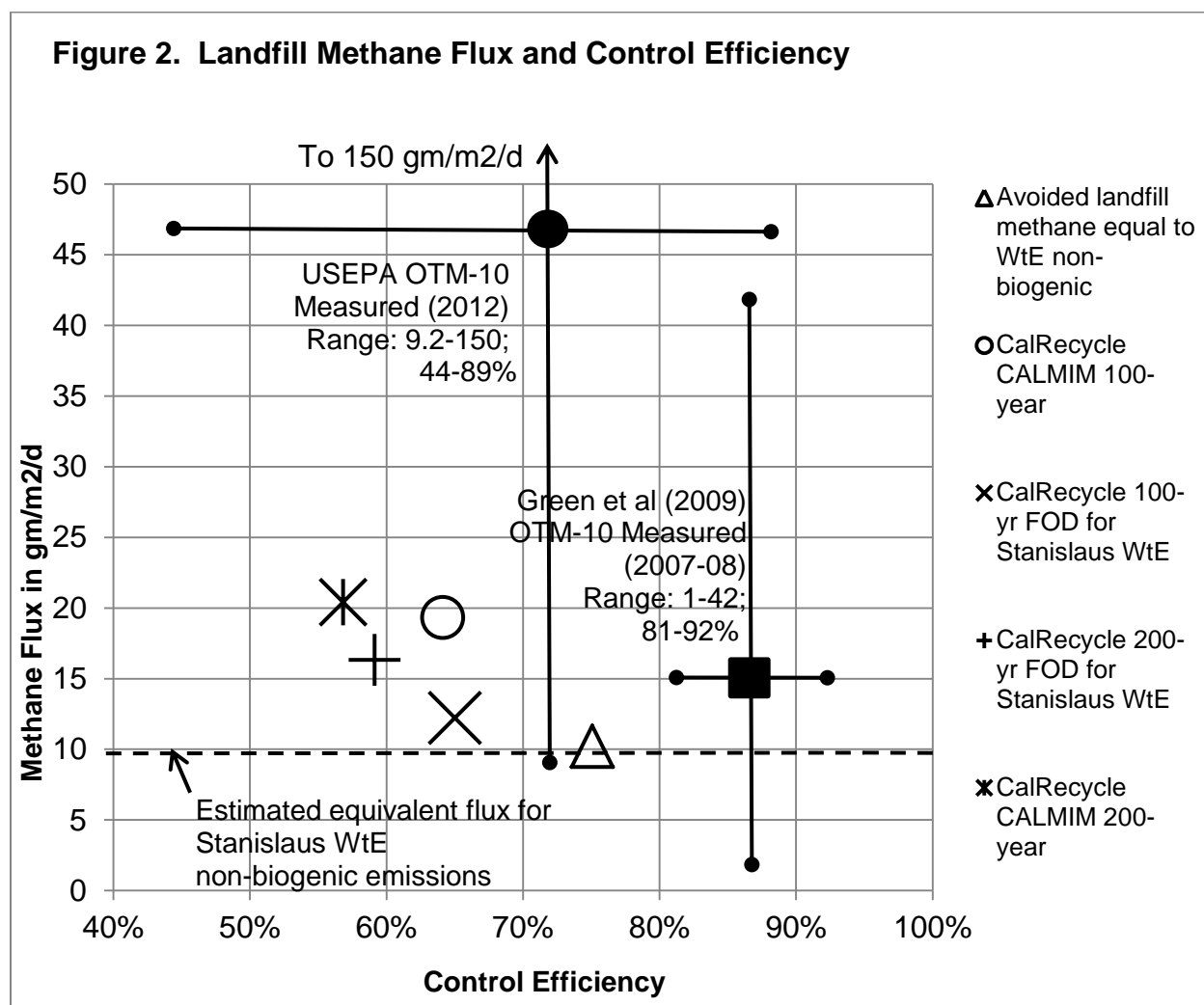
Consideration of Landfill Long-Term Postclosure and Corrective Action Issue

Modern landfills are primarily designed, operated, and regulated as "dry tombs" where waste is kept as dry as possible. Dry tomb landfills provide substantial protection of public health and safety and the environment. However, dry tomb landfills will require postclosure care well

beyond the 30 year period, possibly in perpetuity. If dry tomb landfill containment is breached with failure to implement postclosure maintenance and long term corrective action (e.g., flood event or earthquake), gas generation and emissions may increase when there are no finanical assurances or viable responsible parties. Financial assurances are limited and do not cover the statewide estimates of long-term liability from landfill operators that will default. The long-term performance and financial assurances of dry tomb landfills is a significant CalRecycle policy issue.

The potential increase in emissions from risk of default for long-term postclosure maintenance and corrective action from dry tomb landfills is a significant policy consideration for greenhouse gas emissions. Models may predict very low emissions during postclosure; however, expecting such high level of postclosure performance for perhaps centuries from all landfills is not realistic.

Other Factors for Lifecycle (LCA) Analysis

In addition to landfill avoided methane emissions, other factors should be considered for Lifecycle analysis (LCA) of GHG emissions and WtE. Consideration of these factors will increase the carbon benefits of WtE as compared with the landfill alternative. Note that a detailed quantitative LCA comparing solid waste management alternatives including landfills is beyond the scope of this paper. However, published LCA studies are available and have been reviewed for this paper[16,24,25,26]. These studies support CalRecycle staff's general conclusions. Kaplan (2009)[16] applies the municipal solid waste decision support tool (MSW-DST) developed by USEPA's Office of Research and Development and RTI International (http://www.epa.gov/wastes/nonhaz/municipal/pubs/ghg/f02024.pdf). The application of MSW-DST concludes significant overall carbon benefits for WtE ascompared to landfills recovering energy or just flaring (emissions avg. 3.34 MTCO2/MWh landfills to 0.56 MTCO2/MWh WtE)[16].

Energy Recovery
When a megawatt of electricity is generated by a waste-to-energy or landfill gas-to-energy (LFGTE) facility, carbon dioxide emissions that would have been generated by fossil-fuel fired power plants are avoided. The amount of the avoided emission depends on the difference in the electricity emission factors of WtE and marginal electricity. WtE recovers 470 to 930 kWh electricity per ton of municipal solid waste, an order of magnitude more than aggressive landfill-gas-to-energy (LFGTE) recovery (41-84 kWh/ton)[16]. From 2008 to 2010, the three WtE California facilities averaged 505 kWh/ton. Net electrical production from LFGTE in CA is approximately 261 MW (2010) or 30 kWh/ton. Landfills in California also recover about 9 million standard cubic feet per day (mmscfd) of landfill gas for medium BtU boiler fuel or direct thermal and 3.5 mmscfd for LNG fuel. The ARB Inventory accounts for these avoided emissions in the energy sector.

Recovery of Ferrous Metals
WtE facilities recover ferrous metals for recycling prior to burning. This recovery does not occur for the landfill alternative. Recycling metals saves energy and avoids CO2 emissions that would have been emitted if virgin materials were mined and new metals were manufactured, such as steel. USEPA estimates the carbon benefits of ferrous metals (category steel cans) recycling is 0.49 $MTCO_2e$/ton (http://www.epa.gov/climatechange/wycd/waste/downloads/chapter8.pdf).

carbon benefit for Stanislaus WtE is 0.01 MTCO$_2$e/ton based on 2009 ferrous metals recovery of 40 lb/ton. Additional avoided emissions from ferrous metals recovery for Stanislaus WtE is 2,400 MTCO$_2$e.

Landfill Process Emissions

Landfill process emissions include emissions associated with landfill construction, operations, cover placement, gas and leachate management, and long-term maintenance and monitoring. These emission are small (<5%) relative to fugitive landfill methane emissions and typically ignored in LCA calculations. Levis and Barlaz (2011)[24] estimate total landfill process emissions of 0.007 MtCO2/ton. Stanislaus WtE will have landfill process emissions associated with disposal of residual ash, although less than a landfill because the ash is inert and less than10% the volume of equivalent landfilled waste. Commerce and Long Beach WtE have no landfill process emissions because they recover residual ash for reuse as aggregate or alternative daily cover (note this reuse will result in a small carbon benefit from displaced mined aggregate or soil).

Collection, Transportation, and Separation of Waste

Solid waste collection, transportation, and separation (processing) from point of collection to the facility is considered equivalent for the WtE and landfill alternatives.

Manufacturing Equipment

Emissions associated with manufacture of WtE equipment such as turbines and boilers are considered by Kaplan et al (2009)[16] insignificant and ignored in its LCA.

Production and Use of Limestone in Control Technologies (Scrubbers)

WtE uses limestone for emissions control systems. The production and use of this limestone results in carbon emissions for WtE is not present for the landfill alternative. The average CO2 emissions from the production of lime is approximately 1 ton of CO2/ton of lime produced [27]. At an addition rate of 25 lb CaO per ton of MSW, this is then equivalent to roughly 25 lb CO2/ton of MSW processed. CO2e emissions per ton of waste (CO2-fossil + N2O + CH4) as reported to ARB by Stanislaus WtE, are approximately 630 lb CO2/ton MSW (Michael Van Brunt, personal communication). Therefore, GHG emissions associated with the upstream production of lime are about 4.0% of total CO2e emissions reported for Stanislaus WtE (0.01 MTCO$_2$e/ton total for 241,242 tons is 2,400 MTCO$_2$e).

Biogenic Carbon and Landfill Carbon Storage

Some portion of biogenic carbon in landfills does not biodegrade. ~~This carbon is stored or "sequestered" in landfills and would result in a carbon benefit for landfills.~~ There is debate on how to account for relative emissions of biogenic carbon who should be entitled potential sequestration credits or "sinks". Kaplan (2009)[16] ignores ~~landfill carbon sequestration and~~ biogenic carbon in its analysis.

Conclusions

CalRecycle staff concludes the following with respect to avoided greenhouse gas (GHG) emissions from Waste-to-Energy (WtE) facilities when compared to landfill disposal in California:

1. Based on best available information, California WtE facilities provide net avoided GHG emissions from methane that would have been generated if the waste was disposed in a California landfill. The net avoided emissions exceed non-biogenic WtE emissions from burning of the fossil fuel based materials.

2. Published studies including lifecycle analyses support WtE GHG benefits from avoided landfill methane, and indicate additional lifecycle GHG benefits from renewable that would not occur if the waste was disposed in a landfill.

3. CalRecycle estimates the average net avoided landfill methane emissions are 0.18 $MTCO_2e$ per ton of waste (43,200 $MTCO_2e$ for Stanislaus WtE) with a range of 0.07-0.24 $MTCO_2e$/ton (15,800-52,252 $MTCO_2e$ for Stanislaus WtE).

4. Total avoided landfill methane emissions are estimated at 0.53 $MTCO_2e$ per ton of waste (range 0.41-0.59). These totals could be adjusted based on material specific anaerobically degradable organic carbon content (ANDOC%) to apply to other waste management alternatives such as composting and anaerobic digestion in California. The ANDOC% used in this analysis is 8.9%.

5. The corresponding average control efficiency based on theoretical maximum methane generation is 62% (range 57%-70%). Control efficiency based on theoretical methane generation has significant uncertainty and varies considerably with flux based estimates and measurements. Therefore, CalRecycle staff recommends emphasis on flux based estimates rather than traditional control efficiency for estimating methane emissions.

6. The three WtE facilities in California provide infrastructure for managing approximately 800,000 tons of solid waste per year and generate 505 kWh/ton in renewable electricity. These facilities are required under current state law to recycle waste received prior to burning to the extent feasible. The residual solid waste burned by only these facilities is granted transformation credits in accordance with California solid waste policy goals.

7. Although the analysis in this paper was focused on Stanislaus WtE, the conclusions would be similar for a more detailed analysis of the Commerce and Long Beach (SERRF) WtE facilities.

8. CalRecycle staff concludes the avoided landfill methane emissions estimates based on the Fink Road Landfill and adjusted in the analysis are reasonably representative of landfill sites where an average statewide ton of waste would be disposed. However,

landfill avoided methane emissions may be significantly higher or lower depending on site-specific conditions and controls where the waste is disposed.

9. The potential increase in emissions from risk of default for long-term postclosure maintenance and corrective action from dry tomb landfills is a significant policy consideration for greenhouse gas emissions. Models may predict very low emissions during postclosure; however, expecting such high level of postclosure performance for perhaps centuries from all landfills is not realistic.

10. Landfills are complex area sources of methane emissions and the subject of rapid advances in research and technology. However, there is substantial uncertainty and differences in professional judgment regarding landfill methane emissions. Additional research is recommended to improve our understanding of landfill methane emissions. Modeling methods should be further developed and verified with best available direct measurement data reflecting representative stages in landfill development, secondary permeability or point sources of landfill gas emissions, and better relative waste degradation process data. The estimates of avoided landfill methane emissions in this paper will warrant periodic reevaluation as new studies become available.

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ATTACHMENTS

1. CalRecycle FOD and CALMIM Model Summary and Calculations (Excel format)
    (CalRecycle FOD WtE 07032012.xlsx and CalRecycle CALMIM WtE 07032012.xlsx)

2. CalRecycle CALMIM Model Output Documentation (Word Format)
    (CalRecycle CALMIMReports WtE 052012.docx)