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Comparison of Coverage for Environmental Impacts in 3 Municipal Solid Waste (MSW) Life Cycle Assessment (LCA) Models
## LCA Characteristics of WARM, MSW DST and MEBCalc

<table>
<thead>
<tr>
<th>Features</th>
<th>WARM</th>
<th>MSW DST</th>
<th>MEBCalc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacts included in model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Climate change</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>- Human health (respiratory)</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Human health (toxic chemicals)</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Human health (carcinogens)</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Eutrophication</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Acidification</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Eco-toxicity</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Ozone depletion</td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>- Smog formation</td>
<td>limited</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Monetized Environmental Score</td>
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<td></td>
<td></td>
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<tr>
<td>Energy Impacts Included</td>
<td>✔</td>
<td>✔</td>
<td>limited</td>
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<tr>
<td># of MSW Materials Included</td>
<td>54</td>
<td>~30</td>
<td>27</td>
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</tbody>
</table>

Limited Inventory of Air Pollutants in DST

- Ammonia (NH₃)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO₂) – both biomass and fossil
- Hydrochloric Acid (HCL)
- Lead (Pb)
- Methane (CH₄)
- Nitrogen Oxides (NOₓ)
- Particulate Matter (PM)
- Sulfur Oxides (SOₓ)
- Volatile Organic Compounds (VOCs), excluding methane
# MEBCalc LF ICE & Flare Destruction Efficiencies for Some Landfill Gas (LFG) Constituents from Clean Wood Wastes

<table>
<thead>
<tr>
<th>Constituents of LFG</th>
<th>ICE</th>
<th>Flare</th>
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<tbody>
<tr>
<td>Benzene</td>
<td>86.1%</td>
<td>99.7%</td>
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<tr>
<td>Carbon tetrachloride</td>
<td>93.0%</td>
<td>98.0%</td>
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<tr>
<td>Chloroform</td>
<td>93.0%</td>
<td>98.0%</td>
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<tr>
<td>Dichloromethane (methylene chloride)</td>
<td>93.0%</td>
<td>98.0%</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>86.1%</td>
<td>99.7%</td>
</tr>
<tr>
<td>Ethylene dichloride</td>
<td>93.0%</td>
<td>98.0%</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Methane</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>Toluene</td>
<td>86.1%</td>
<td>99.7%</td>
</tr>
<tr>
<td>Tetrachloroethane</td>
<td>93.0%</td>
<td>98.0%</td>
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<tr>
<td>Trichloroethylene (trichloroethene)</td>
<td>93.0%</td>
<td>98.0%</td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>93.0%</td>
<td>98.0%</td>
</tr>
<tr>
<td>Xylenes</td>
<td>86.1%</td>
<td>99.7%</td>
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</tbody>
</table>

Examples of MEBCalc WTE Incineration Emissions from Clean Wood Wastes

<table>
<thead>
<tr>
<th>WTE Emissions Constituents</th>
<th>Input</th>
<th>Volatilization</th>
<th>Uncontrolled</th>
<th>Removal Efficiency*</th>
<th>Controlled*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg/Mg)</td>
<td>(%)</td>
<td>(kg/Mg)</td>
<td></td>
<td>(kg/Mg)</td>
</tr>
<tr>
<td>Antimony</td>
<td>5.00E-04</td>
<td>0.44%</td>
<td>2.21E-06</td>
<td>96.7%</td>
<td>7.28E-08</td>
</tr>
<tr>
<td>Arsenic</td>
<td>3.40E-02</td>
<td>0.18%</td>
<td>6.00E-05</td>
<td>99.9%</td>
<td>6.00E-08</td>
</tr>
<tr>
<td>Barium</td>
<td>2.79E-02</td>
<td>0.01%</td>
<td>3.24E-06</td>
<td>99.8%</td>
<td>6.48E-09</td>
</tr>
<tr>
<td>Cadmium</td>
<td>4.00E-05</td>
<td>12.20%</td>
<td>4.88E-06</td>
<td>99.7%</td>
<td>1.46E-08</td>
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<tr>
<td>Chromium</td>
<td>5.81E-02</td>
<td>0.54%</td>
<td>3.15E-04</td>
<td>99.3%</td>
<td>2.20E-06</td>
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<tr>
<td>Copper</td>
<td>4.60E-02</td>
<td>0.02%</td>
<td>9.85E-06</td>
<td>99.6%</td>
<td>3.94E-08</td>
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<tr>
<td>Lead</td>
<td>3.24E-01</td>
<td>5.26%</td>
<td>1.71E-02</td>
<td>99.8%</td>
<td>3.41E-05</td>
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<tr>
<td>Mercury</td>
<td>4.00E-04</td>
<td>49.25%</td>
<td>1.97E-04</td>
<td>92.7%</td>
<td>1.44E-05</td>
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<tr>
<td>Nickel</td>
<td>8.00E-04</td>
<td>1.69%</td>
<td>1.36E-05</td>
<td>96.6%</td>
<td>4.61E-07</td>
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<tr>
<td>Selenium</td>
<td>1.00E-05</td>
<td>0.19%</td>
<td>1.88E-08</td>
<td>92.9%</td>
<td>1.33E-09</td>
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<tr>
<td>Zinc</td>
<td>2.05E-01</td>
<td>2.32%</td>
<td>4.76E-03</td>
<td>99.7%</td>
<td>1.43E-05</td>
</tr>
</tbody>
</table>

Carbon Monoxide: 8.35E-02
Formaldehyde: 6.58E-05
Hydrochloric Acid: 3.75E-02
Nitrogen Oxides: 4.68E-01
PM_{10}: 1.05E-02
Sulfur Dioxide: 5.85E-02

*Newer WTE facilities using spray dryer for acid gas control, fabric filter for PM control, selective non-catalytic reduction (ammonia or urea injection) for nitrogen oxides control, and carbon injection for mercury control.

Carbon Footprints for Solar, Natural Gas, Coal, LFGTE and WTE Incineration Power Generation
**Carbon Footprints for Electricity Generation**

Gross CO2 emissions (pounds CO2e) per kWh

- Solar
- Natural Gas
- Coal
- MSW LFGTE75
- MSW WTE
- Film Plastic WTE
- Wood WTE

Rusty red "hat" indicates uncertainty range for methane leakage during natural gas production and pipeline distribution.

Landfill-Gas-to-Energy (LFGTE) & Incineration Waste-to-Energy (WTE) Climate Changing Emissions

$\text{CO}_2$ and $\text{CH}_4$ Emissions Footprints for the Spectrum of Biogenic Wastes Buried in Landfills and Burned in Incinerators
Cubic Meters (m³) Methane (CH₄) Generated Each Year Since Waste Landfilled (m³ CH₄/metric ton)

Cumulative Percentage of Life Cycle Methane Generated Since Waste Landfilled

## MSW Material Lifetime Carbon Generation in Landfill (LF) & Waste-to-Energy (WTE) Incineration Disposal Facilities

<table>
<thead>
<tr>
<th>MSW Material</th>
<th>Carbon Content (%)</th>
<th>Kilograms (kg) Carbon per Metric Ton</th>
<th>Landfill Carbon Storage (%)</th>
<th>Lifetime CO₂ &amp; CH₄ Generation (kg CO₂e per Metric Ton)</th>
<th>LF Methane (CH₄) Capture for Breakeven Emissions vs. WTE (%)</th>
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</thead>
<tbody>
<tr>
<td>Film Plastic</td>
<td>66%</td>
<td>660</td>
<td>100%</td>
<td>2,420</td>
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<tr>
<td>Newspaper</td>
<td>46</td>
<td>460</td>
<td>81</td>
<td>1,687</td>
<td>1,793</td>
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<tr>
<td>C&amp;D Wood</td>
<td>42</td>
<td>420</td>
<td>&gt;80</td>
<td>1,540</td>
<td>1,637</td>
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<tr>
<td>Leaves</td>
<td>34</td>
<td>340</td>
<td>77</td>
<td>1,247</td>
<td>1,604</td>
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<tr>
<td>Evergreen Trimmings</td>
<td>55</td>
<td>550</td>
<td>72</td>
<td>2,017</td>
<td>3,159</td>
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<tr>
<td>Yard Debris</td>
<td>19</td>
<td>190</td>
<td>60</td>
<td>697</td>
<td>1,559</td>
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<tr>
<td>Cardboard</td>
<td>45</td>
<td>450</td>
<td>55</td>
<td>1,650</td>
<td>4,154</td>
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<tr>
<td>Grass</td>
<td>12</td>
<td>120</td>
<td>25</td>
<td>440</td>
<td>1,846</td>
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<tr>
<td>Food Scraps</td>
<td>15</td>
<td>150</td>
<td>15</td>
<td>550</td>
<td>2,615</td>
</tr>
</tbody>
</table>

Global Warming Pollution
[Energy Recovery Council Public Relations on MSW Incineration]
Global Warming Pollution
Better Estimates for WTE vs. LF

- CO₂ from the combustion of biomass not counted as an emission
- CO₂ from the combustion of plastics counted as an emission

WTE incineration Net GHG Factor versus solar energy and landfill with 75% methane capture and same credit for plant/tree growth as WTE
Some Results
Landfill Gas Capture Rates for Which LF Has Lower Greenhouse Gas (GHG) Emissions Than WTE

Notes: LF and WTE GHG emissions both include deductions for their power generation offsets. Metro Vancouver (BC) MSW composition.

EPA’s Waste Management Hierarchy

- Source Reduction & Reuse
- Recycling / Composting
- Energy Recovery
- Treatment & Disposal

THE ZERO WASTE HIERARCHY

RETHINK/REDESIGN

REDUCE

REUSE

RECYCLE/COMPOST

MATERIAL RECOVERY

RESIDUALS MANAGEMENT
(Biological treatment and stabilized landfilling)

UNACCEPTABLE
(Waste deregulation, incineration, and “waste-to-energy”)
Comparison of Five Options for MSW Disposal

Monetized Overall Environmental Impact
(Standard deviations above(+) / below(-) the average impact for all options)

The MRBT scenarios had the lowest environmental and health impacts compared to the other disposal options.

Life Cycle Analysis on MCRRF vs. Landfill

• All comparison data includes pollution from trucking based on DC’s waste options. Rail haul from Montgomery County wouldn’t be much different, as transportation is a small fraction of impact.
  – Note the tiny difference that doubling hauling distance makes.
• A 75% landfill gas capture rate is assumed, based on what was reported to us in calls to the four landfills. All three we reached independently reported the same percentage.
• Actual emissions data for MCRRF is used, as reported to EPA.
• Local precipitation data used from the areas where the landfills are located, which is wetter than average.
• “Other 3 Landfills” = King & Queen LF, Middle Peninsula LF, and Charles City LF
Global Warming Pollution

[Pounds of CO₂ equivalent per ton of waste disposed.]

- MCRRF

![Bar Chart]

- King George
- Other 3 Landfills

- Over 100 Years
- Over 20 Years
Smog Formation
[Asthma / respiratory impacts]
[Pounds of ozone (O₃) equivalent (from NOx and VOC emissions) per ton of waste disposed.]

- MCRRF
- Over 100 Years
- Over 20 Years

- King George
- Other 3 Landfills
Particulate Matter Pollution

[Pounds of PM2.5 equivalent per ton of waste disposed.]
Toxic Pollution

[Pounds of toluene equivalent per ton of waste disposed.]

Does not include dioxin/furan emissions or ash leaching.
Carcinogenic Pollution

[Pounds of benzene equivalent per ton of waste disposed.]

Does not include dioxin/furan emissions or ash leaching. Landfill impacts very localized compared to incineration.
Eutrophication

[Pounds of nitrogen equivalent per ton of waste disposed.]

NOx and ammonia air emissions plus BOD, COD, phosphate, and ammonia water releases from landfills.
Incinerator emissions are largely from nitrogen oxides, but also include other acid gases ($SO_2$, $HCl$, $HF$). For the landfills, it’s hydrogen sulfide ($H_2S$) from the landfill, plus ammonia, NOx and SOx from the landfill gas burners.
Ecosystems Toxicity

[Pounds of 2,4-D herbicide equivalent per ton of waste disposed.]

For the incinerator, this is mainly based on mercury emissions. For the landfill, mainly formaldehyde.
Ozone Depletion

[Pounds of CFC-11 equivalent per ton of waste disposed.]
Monetized Health & Environmental Cost

[All impacts combined and monetized.]

$288/ton for incineration vs. $103-155/ton for landfilling.
Additional References
Suggestions for Additional Reading

Glossary

- DST Decision Support Tool
- EPA Environmental Protection Agency
- GHG Greenhouse Gas
- GWP Global Warming Potential
- ICE Internal Combustion Engine
- IPCC Intergovernmental Panel on Climate Change
- IWGSCC Interagency Working Group on the Social Cost of Carbon
- LandGEM Landfill Gas Emissions Model
- LCA Life Cycle Analysis or Life Cycle Assessment
- LFG Landfill Gas
- LFGTE Landfill Gas-to-Energy
- MEBCalc Measuring Environmental Benefits Calculator
- MSW Municipal Solid Waste
- RTI Research Triangle Institute
- SRMG Sound Resource Management Group
- TRACI Tool for Reduction and Assessment of Chemicals and other environmental Impacts
- WARM WAste Reduction Model
- WTE Waste-to-Energy
Methane Emissions Factors for Life Cycle Assessments (LCAs)

1. Proportion of biogenic vs. fossil materials in MSW.

2. Carbon amounts in those biogenic materials.

3. Proportion of each landfilled material’s biogenic carbon that biodegrades to CH$_4$ and CO$_2$, i.e., is not stored in the landfill.

4. Proportion of landfill generated CH$_4$ that is oxidized to CO$_2$ before it reaches the landfill’s surface and is released to the atmosphere.

5. Proportion of CH$_4$ that is captured by LFG collection system.

6. Timing of LF & WTE CO$_2$ and CH$_4$ releases over the LCA’s time frame (typically 100 years, sometimes 20 years).
Carbon Accounting Issues for LF and WTE

1. Emissions of fossil and biogenic carbon dioxide (CO₂) have identical atmospheric climate impacts.

2. Additionality is necessary for offsets and credits. If burying or burning MSW does not affect where, when or now much CO₂ is sequestered from the atmosphere by new plant/tree growth, then WTE should not get an offset or credit for its biogenic carbon emissions unless LF also gets the exact same offset or credit.

3. Continued carbon storage in products or compost or landfills is not the same as new sequestration of carbon in plants & trees through photosynthesis of CO₂ from the atmosphere.

4. Timing of CO₂ and methane (CH₄) releases is important.

5. Scale of releases over time is important.
Conservative Assumptions on Toxicity

• This study did not factor in two main things that would also trend toward incinerators being worse than landfills:

  – It did not include data on leaching of toxic chemicals from incinerator ash, but DID include leaching from trash. In fact, leaching of toxic chemicals from incinerator ash is expected to be worse, especially where the ash is used as landfill cover or is mixed with municipal solid waste, as it is in Old Dominion Landfill.

  – Dioxin/furan emissions were not included. This was due to a lack of good data on dioxin emissions from landfills. Dioxins and furans are the most toxic man-made chemicals known to science, and are largely associated with incineration sources, so ignoring them biases the study in a conservative way, making incinerators out to be less toxic than they truly are.
Conservative Assumptions on Global Warming

• This study looks at the 20-year impact (most relevant for methane’s impacts on global warming) as well as the 100-year impact. The 20-year impact, based on methane being worse in the short-term, makes landfills out to be worse than they are when evaluated over 100 years.

• This study uses the latest science for methane's global warming potential (86 times worse than CO2 over 20 years based on the latest International Panel on Climate Change report).

See [www.energyjustice.net/naturalgas/#GWP](http://www.energyjustice.net/naturalgas/#GWP) for a link to the various data sources in the evolving science on global warming potentials.
Food Scraps
### Rankings from Meta-Analysis/Harmonization & Qualitative Assessment of Food Waste Management Methods

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Climate</th>
<th>Energy</th>
<th>Soil Carbon</th>
<th>Fertilizer Replacement</th>
<th>Water Conservation</th>
<th>Plant Yield Increase</th>
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</thead>
<tbody>
<tr>
<td>Aerobic Composting</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Anaerobic Digestion</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
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<tr>
<td>In-Sink Grinding</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>Landfill</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Thank you.

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