Life Cycle Analysis for Disposal of MSW: Landfill with Energy Recovery vs. Incineration with Energy Recovery

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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

	LCA Model		
Features	**WARM**	**MSW DST**	**MEBCalc**
Impacts included in model			
-Climate change	✔	✔	✔
-Human health (respiratory)		limited	✔
-Human health (toxic chemicals)		limited	✔
-Human health (carcinogens)		limited	✔
-Eutrophication		limited	✔
-Acidification		limited	✔
-Eco-toxicity		limited	✔
-Ozone depletion			✔
-Smog formation		limited	✔
Monetized Environmental Score			✔
Energy Impacts Included	✔	✔	limited
# of MSW Materials Included	54	~30	27

Additional Comparison of WARM & MSW DST: H. Scott Matthews (Carnegie Mellon University), Cynthia J. Manson (Industrial Economics, Inc.), *Comparative Analysis of EPA Life Cycle Models: Differences between MSW-DST and WARM in Examining Waste Management Options*, prepared for EPA Office of Resource Conservation and Recovery, Internal Review Draft-Do Not Distribute, 11-12-2009.

Limited Inventory of Air Pollutants in DST

- Ammonia (NH_3)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2) – both biomass and fossil
- Hydrochloric Acid (HCL)
- Lead (Pb)
- Methane (CH_4)
- Nitrogen Oxides (NO_x)
- Particulate Matter (PM)
- Sulfur Oxides (SO_x)
- Volatile Organic Compounds (VOCs), excluding methane

MEBCalc LF ICE & Flare Destruction Efficiencies for Some Landfill Gas (LFG) Constituents from Clean Wood Wastes

Constituents of LFG	Removal Efficiency	
	ICE	Flare
Benzene	86.1%	99.7%
Carbon tetrachloride	93.0%	98.0%
Chloroform	93.0%	98.0%
Dichloromethane (methylene chloride)	93.0%	98.0%
Ethylbenzene	86.1%	99.7%
Ethylene dichloride	93.0%	98.0%
Mercury	0.0%	0.0%
Methane	99.0%	99.0%
Toluene	86.1%	99.7%
Tetrachloroethane	93.0%	98.0%
Trichloroethylene (trichloroethene)	93.0%	98.0%
Vinyl chloride	93.0%	98.0%
Xylenes	86.1%	99.7%

Sources: Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856; U.S. EPA, 2000. A Decision Support Tool for Assessing the Cost and Environmental Burdens of Integrated Municipal Solid Waste Management Strategies, Default Data and Data Input Requirements for the Municipal Solid Waste Management Decision Support Tool, prepared for EPA Office of Research and Development by North Carolina State University and Research Triangle Institute; U.S. EPA, 2005. LandGEM – Landfill Gas Emissions Model, Version 3.02.

Examples of MEBCalc WTE Incineration Emissions from Clean Wood Wastes

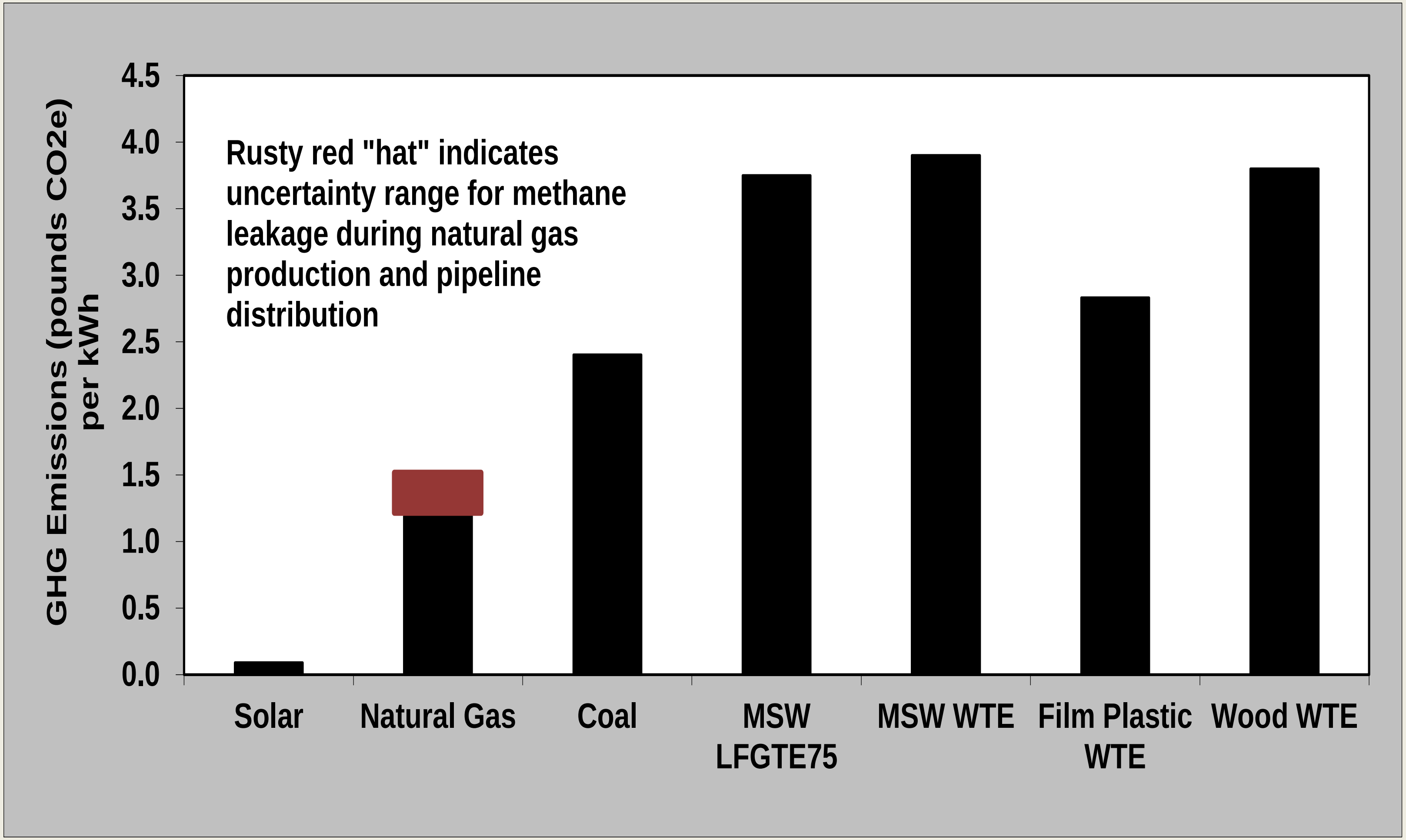
WTE Emissions Constituents	Input	Volatilization	Uncontrolled	Removal Efficiency*	Controlled*
	(kg/Mg)		(kg/Mg)		(kg/Mg)
Antimony	5.00E-04	0.44%	2.21E-06	96.7%	7.28E-08
Arsenic	3.40E-02	0.18%	6.00E-05	99.9%	6.00E-08
Barium	2.79E-02	0.01%	3.24E-06	99.8%	6.48E-09
Cadmium	4.00E-05	12.20%	4.88E-06	99.7%	1.46E-08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

Sources: Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856; U.S. EPA, 2000, *op. cit.,* Waste-to-Energy Process Model Appendices B: Nonmetal air emissions and C: Metals air emissions,

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

Carbon Footprints for Electricity Generation

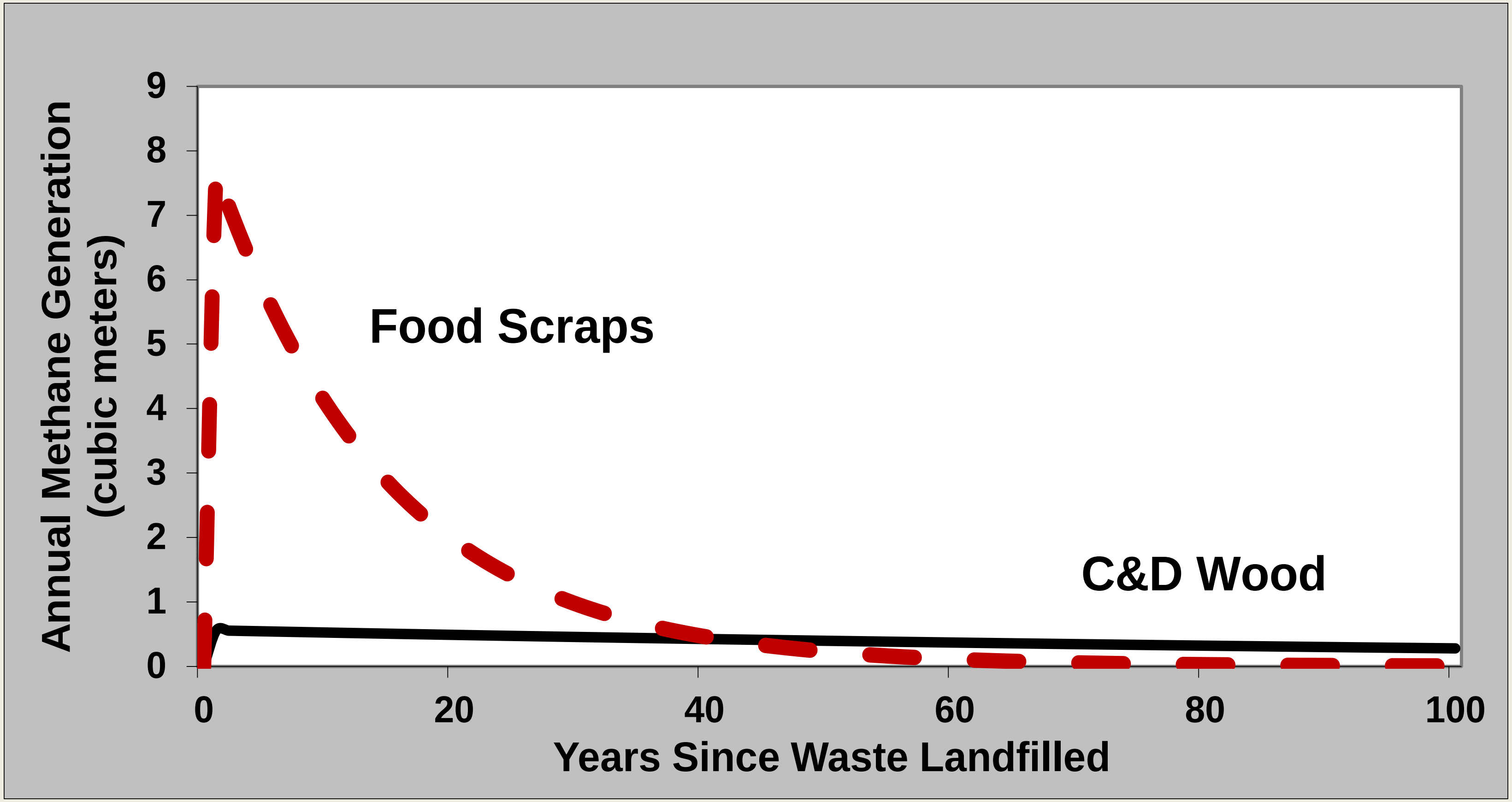


Sources: Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. *Journal of Industrial Ecology* 16 (S1): S110-S121; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856; and Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. *Environmental Science & Technology* 47 ( ): 5896-5903.

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

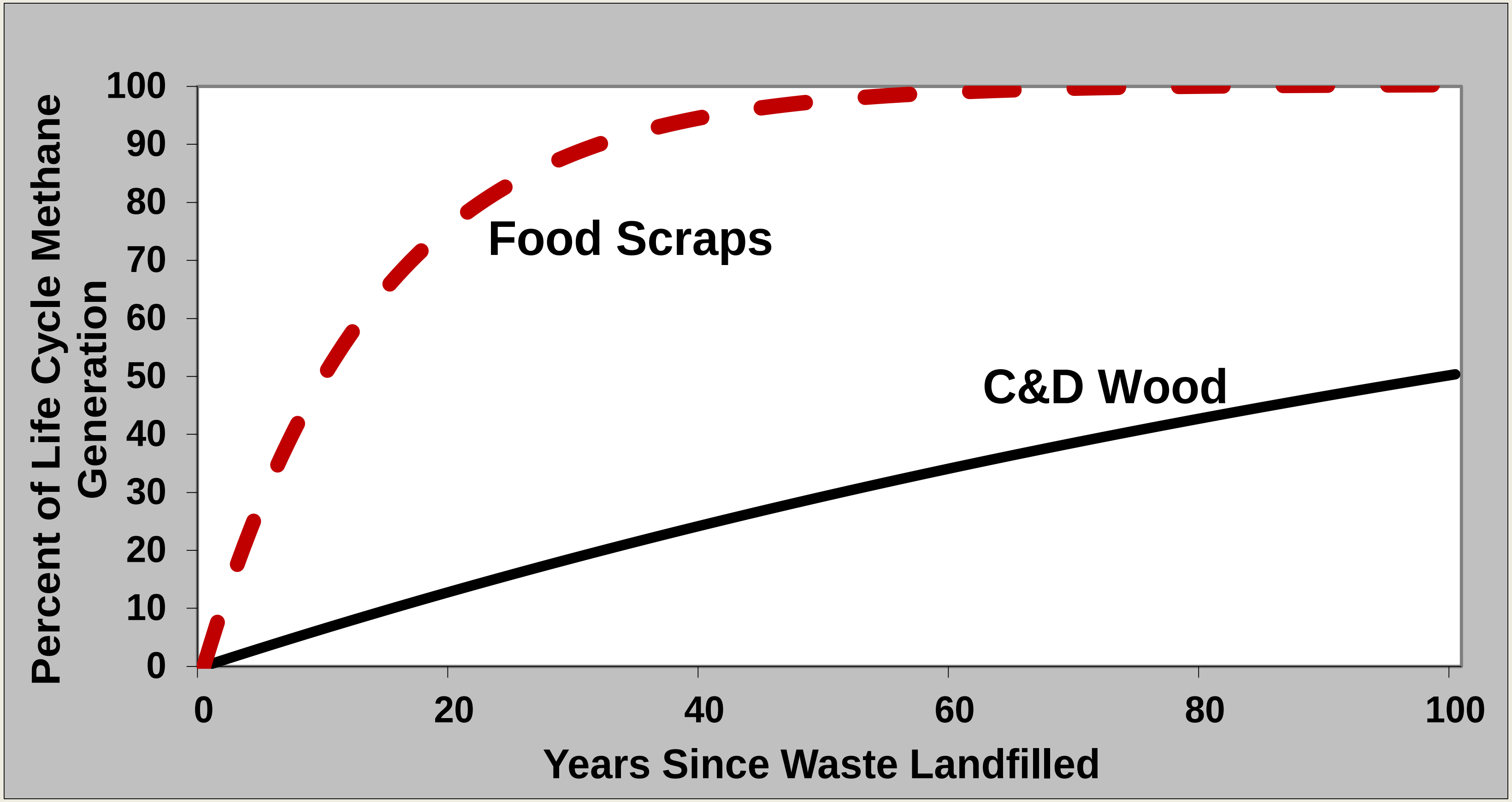
CO_2 and CH_4 Emissions Footprints for the Spectrum of Biogenic Wastes Buried in Landfills and Burned in Incinerators

Cubic Meters (m^3) Methane (CH_4) Generated Each Year Since Waste Landfilled (m^3 CH_4/metric ton)



Sources: U. S. Environmental Protection Agency, 2005. *Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide.* EPA-600/R-05/047, EPA: Washington, DC; De La Cruz, F. B., Barlaz, M. A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology* 44 (12): 4722-4728; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Wang, X., Padgett, J. M., De la Cruz, F. B., Barlaz, M. B., 2011. Wood biodegradation in laboratory-scale landfills. *Environmental Science & Technology* 45: 6864-6871, and Morris, J., 2017. Recycle, bury, or burn wood waste biomass? LCA answer depends on carbon accounting, emissions controls, displaced fuels, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856.

Cumulative Percentage of Life Cycle Methane Generated Since Waste Landfilled



Sources: U. S. Environmental Protection Agency, 2005. *Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide.* EPA-600/R-05/047, EPA: Washington, DC; De La Cruz, F. B., Barlaz, M. A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology* 44 (12): 4722-4728; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Wang, X., Padgett, J. M., De la Cruz, F. B., Barlaz, M. B., 2011. Wood biodegradation in laboratory-scale landfills. *Environmental Science & Technology* 45: 6864-6871, and Morris, J., 2017. Recycle, bury, or burn wood waste biomass? LCA answer depends on carbon accounting, emissions controls, displaced fuels, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856.

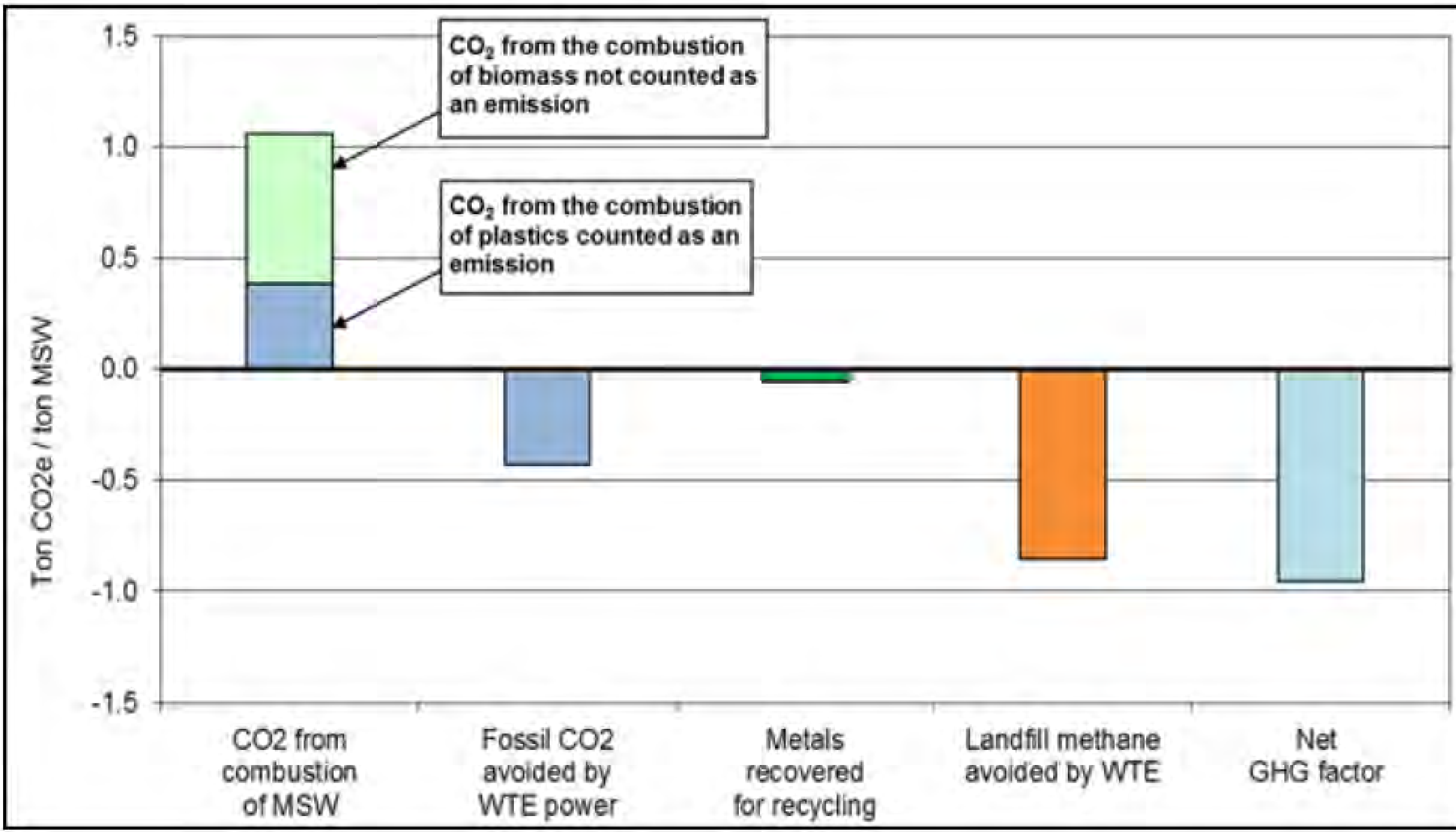
MSW Material Lifetime Carbon Generation in Landfill (LF) & Waste-to-Energy (WTE) Incineration Disposal Facilities

MSW Material	Carbon Content (%)	Kilograms (kg) Carbon per Metric Ton	Landfill Carbon Storage (%)	Lifetime CO_2 & CH_4 Generation (kg CO_2e per Metric Ton)		LF Methane (CH_4) Capture for Breakeven Emissions vs. WTE (%)
				WTE	LF	
Film Plastic	66%	660	100%	2,420	0	0%
Newspaper	46	460	81	1,687	1,793	<10
C&D Wood	42	420	>80	1,540	1,637	<10
Leaves	34	340	77	1,247	1,604	20
Evergreen Trimmings	55	550	72	2,017	3,159	35
Yard Debris	19	190	60	697	1,559	55
Cardboard	45	450	55	1,650	4,154	60
Grass	12	120	25	440	1,846	75
Food Scraps	15	150	15	550	2,615	80

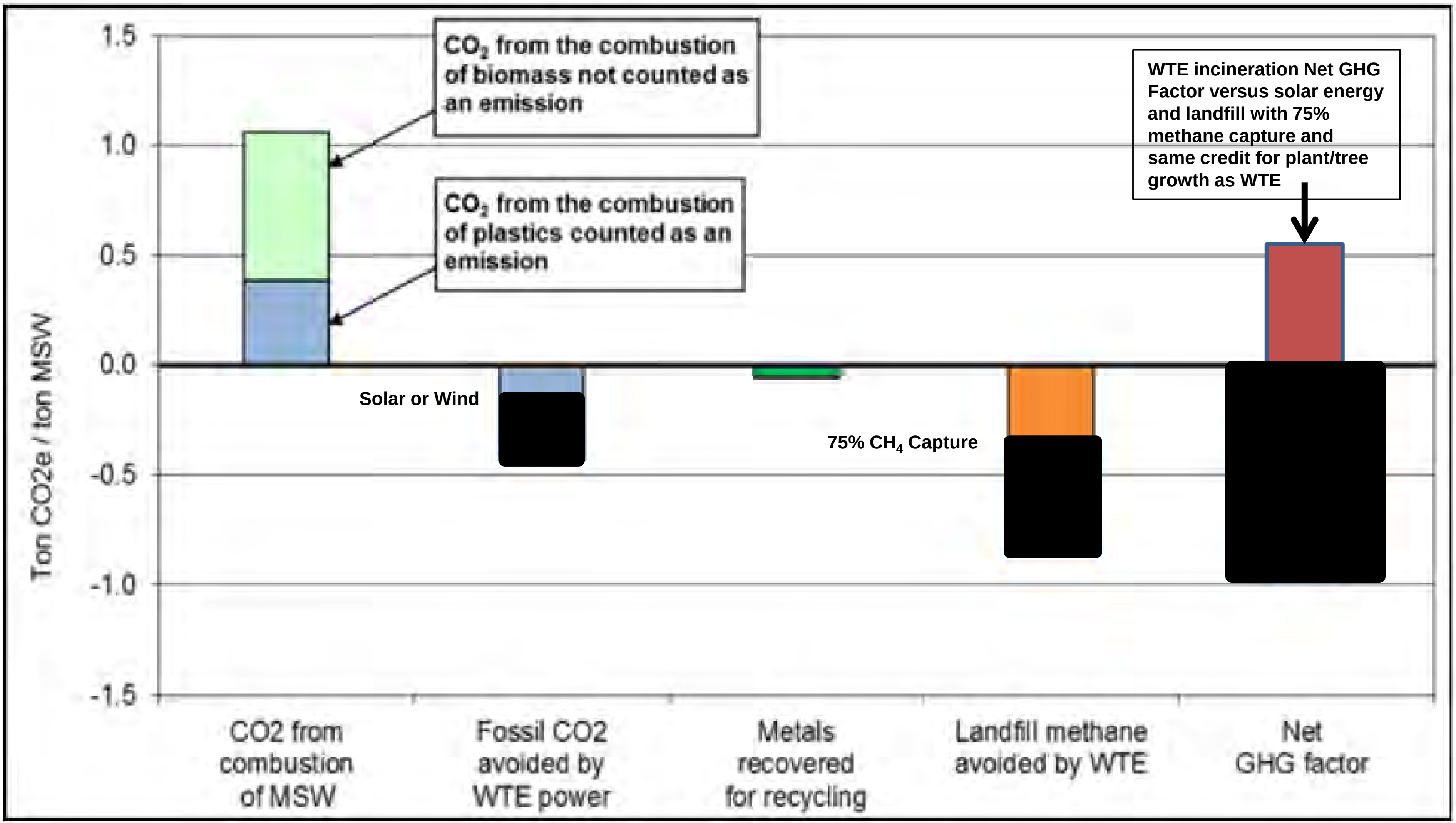
Sources: De La Cruz, F. B., Barlaz, M. A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology* 44 (12): 4722-4728; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Wang, X., Padgett, J. M., De la Cruz, F. B., Barlaz, M. B., 2011. Wood biodegradation in laboratory-scale landfills. *Environmental Science & Technology* 45: 6864-6871, and Morris, J., 2017. Recycle, bury, or burn wood waste biomass? LCA answer depends on carbon accounting, emissions controls, displaced fuels, and impact costs. *Journal of Industrial Ecology*, 21 (4) 844-856.

Global Warming Pollution

[Energy Recovery Council Public Relations on MSW Incineration]

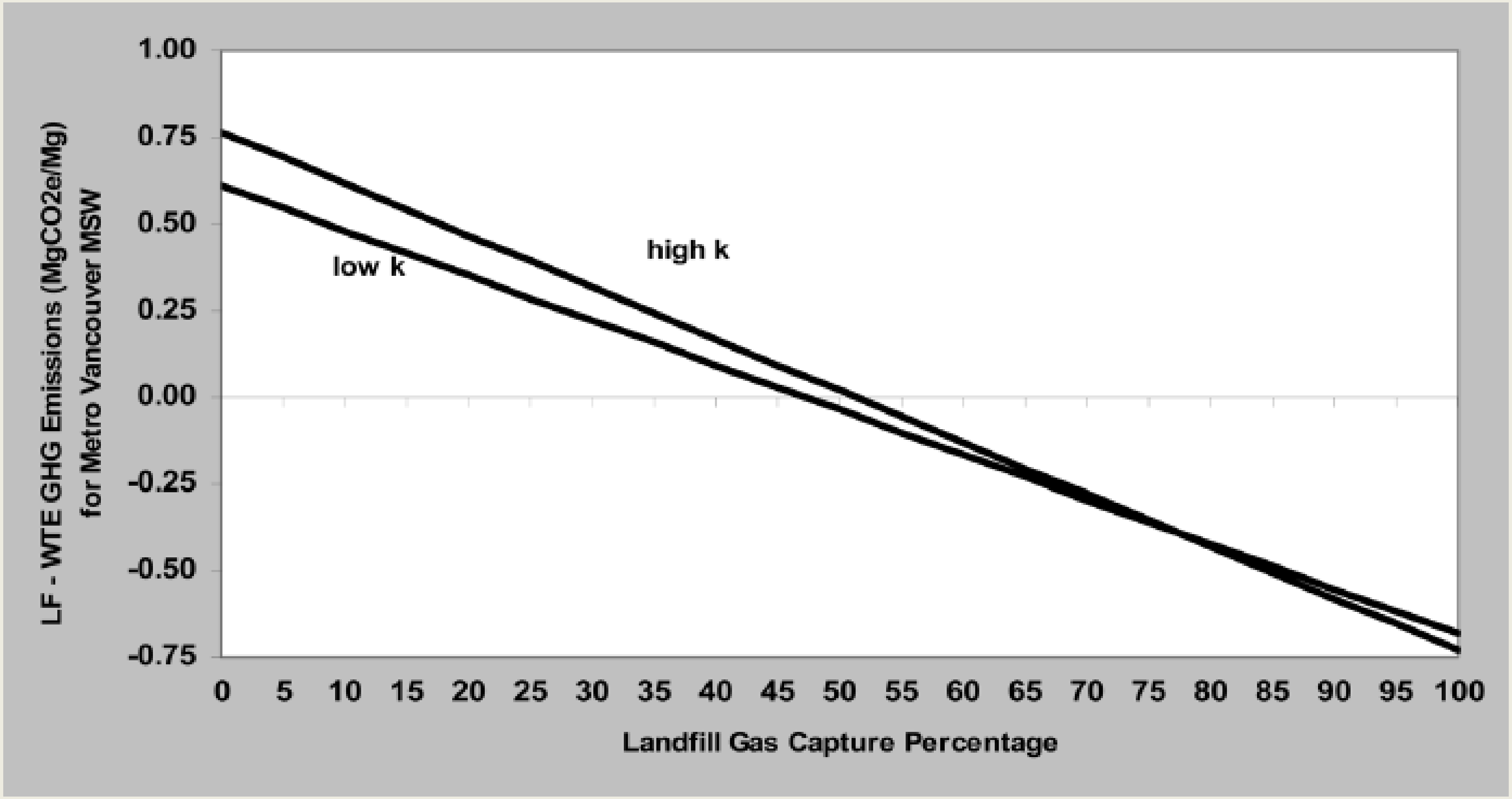


Global Warming Pollution
Better Estimates for WTE vs. LF



Some Results

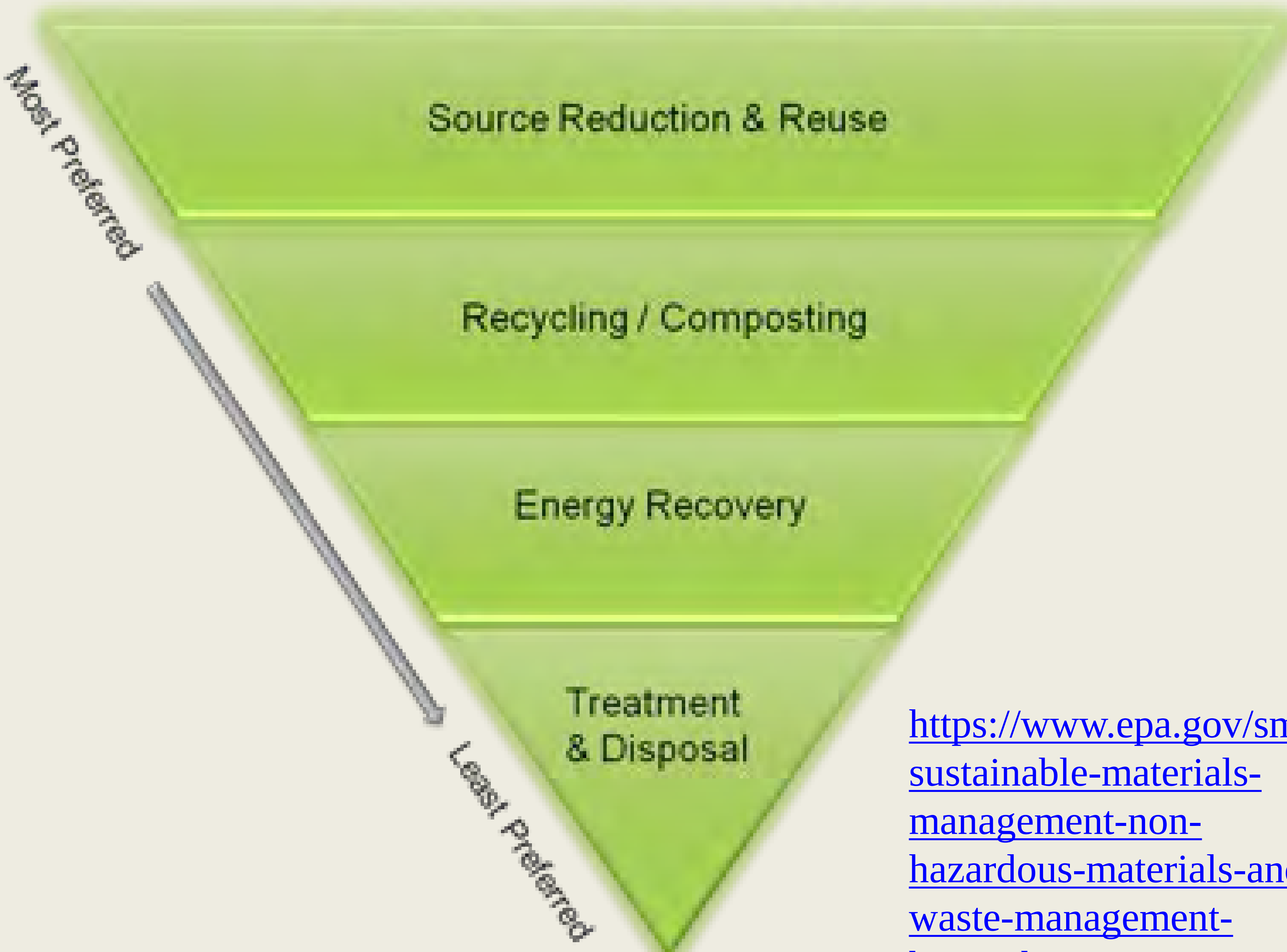
Landfill Gas Capture Rates for Which LF Has Lower Greenhouse Gas (GHG) Emissions Than WTE



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

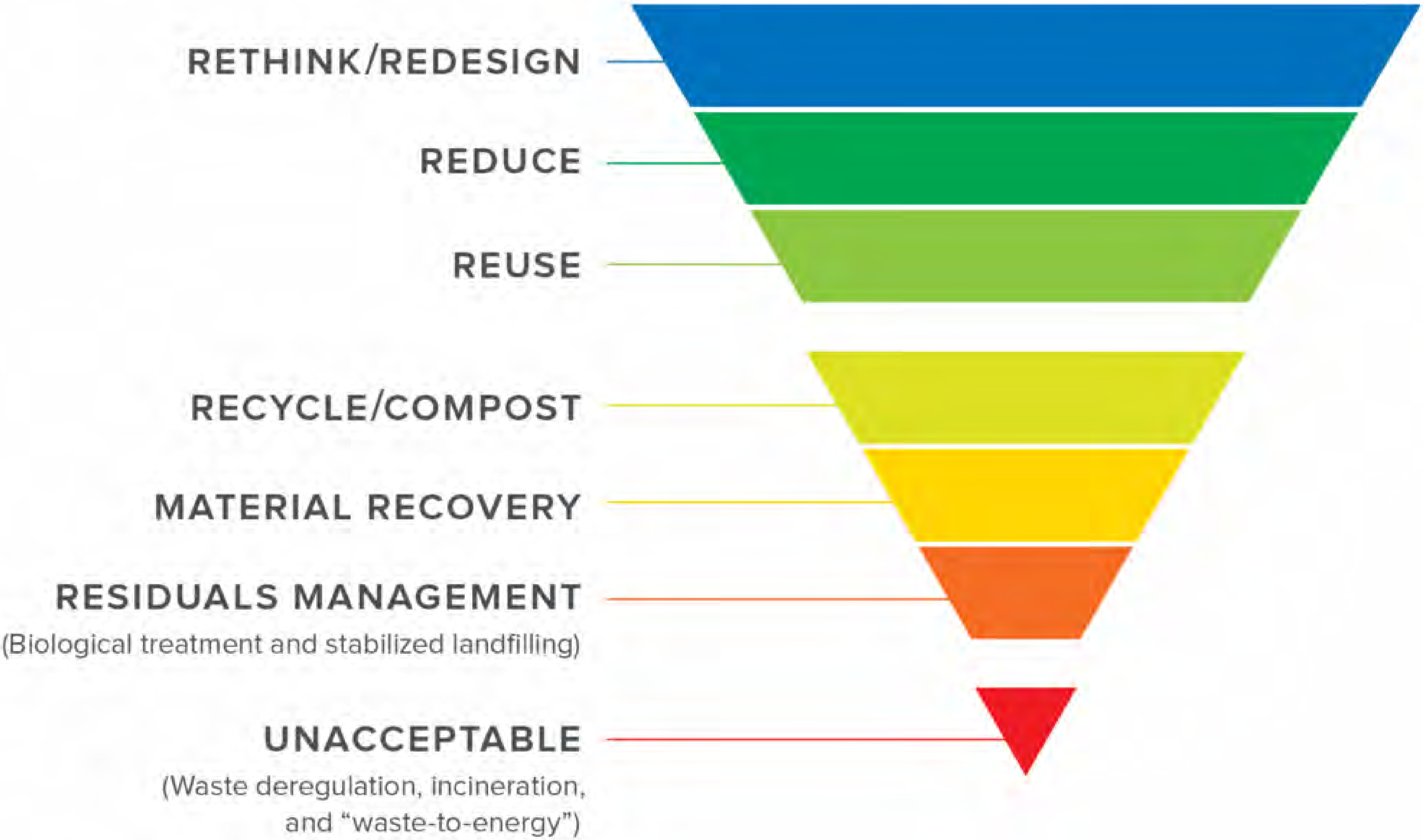
Source: Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949.

EPA's Waste Management Hierarchy

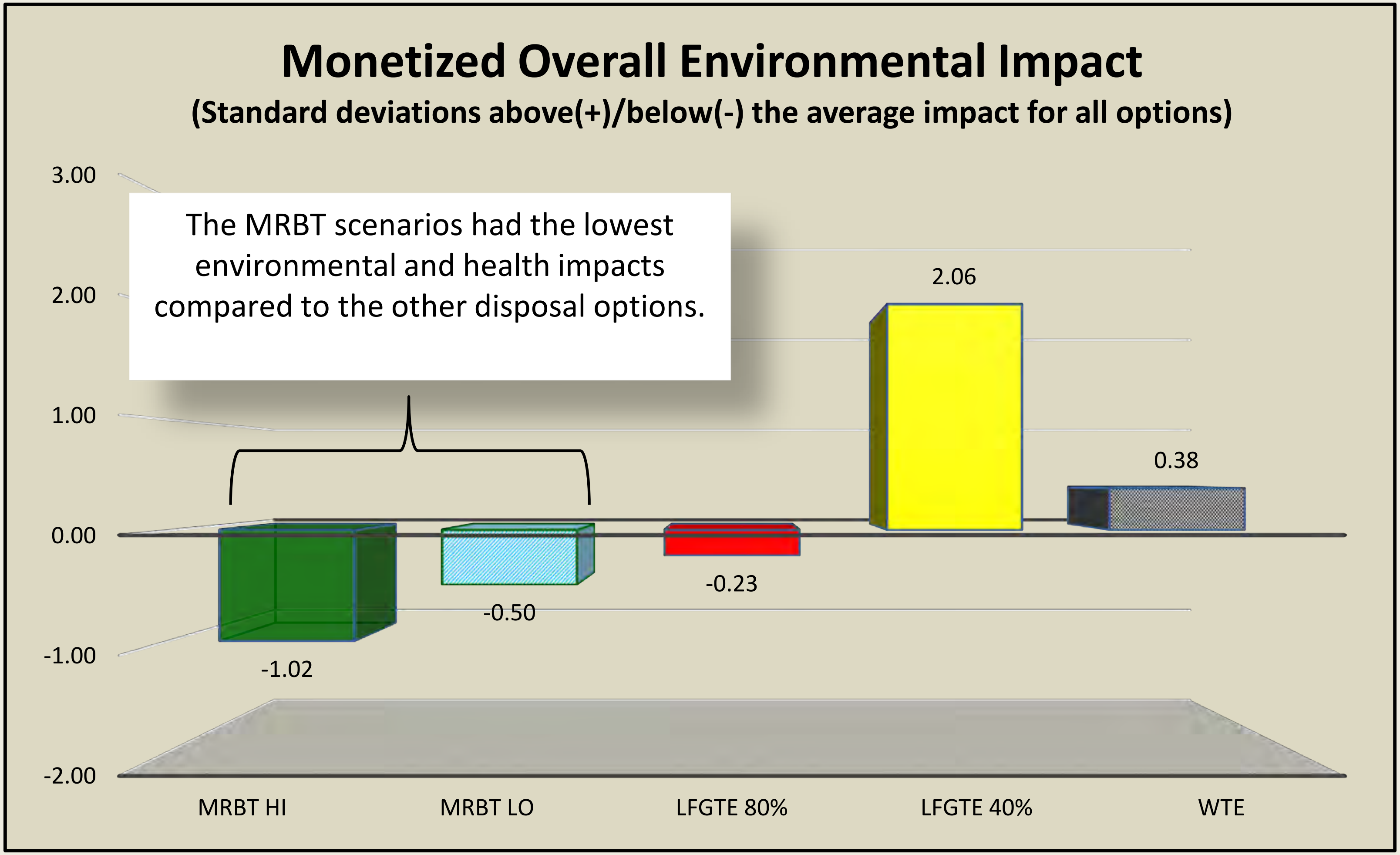


https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

THE ZERO WASTE HIERARCHY



Comparison of Five Options for MSW Disposal



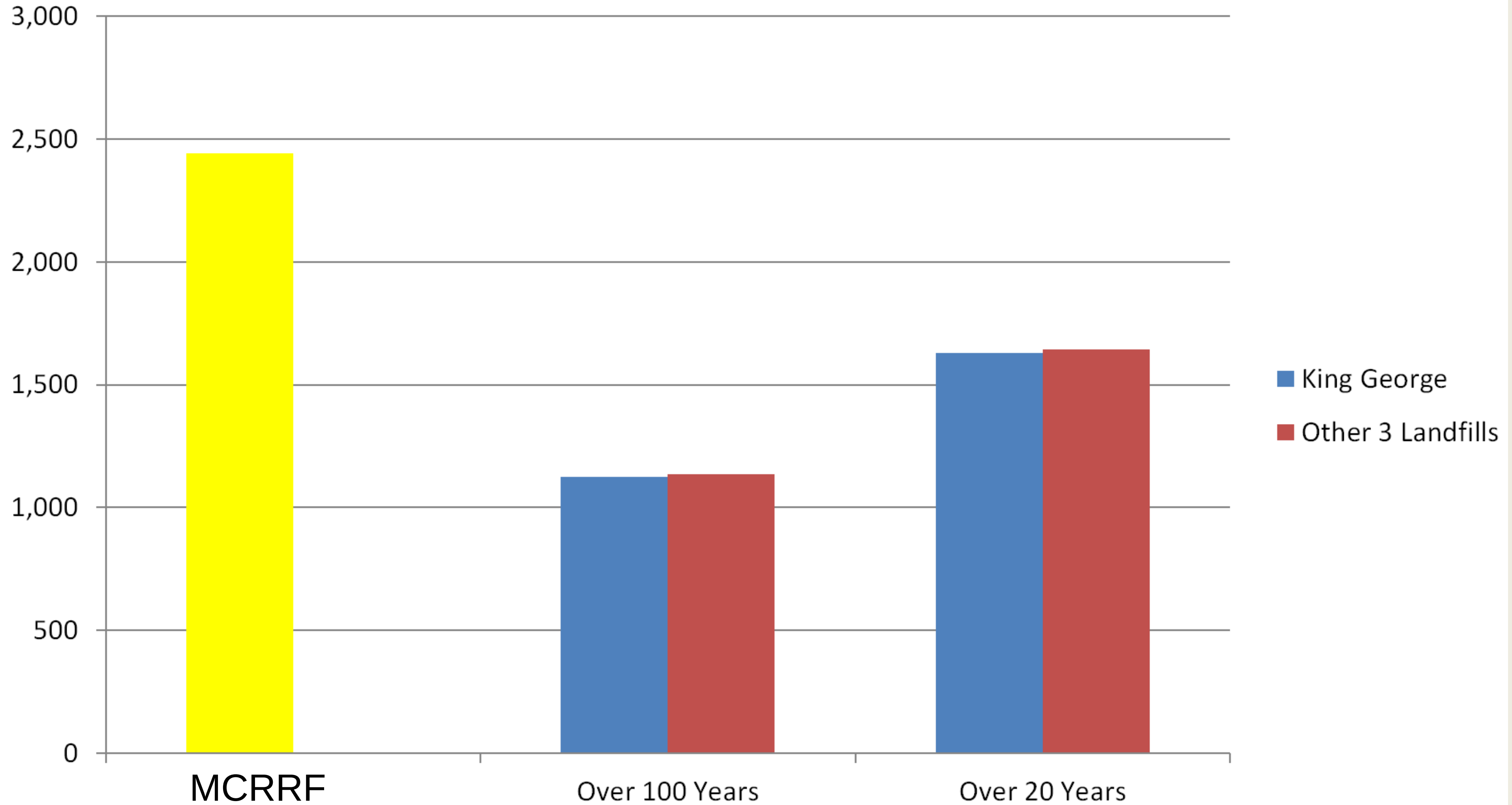
Source: Morris, J., Favoino, E., Lombardi, E., Bailey, K., *What is the best disposal option for the "Leftovers" on the way to Zero Waste?,* prepared for Eco-Cycle, Boulder, CO, 2013.

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

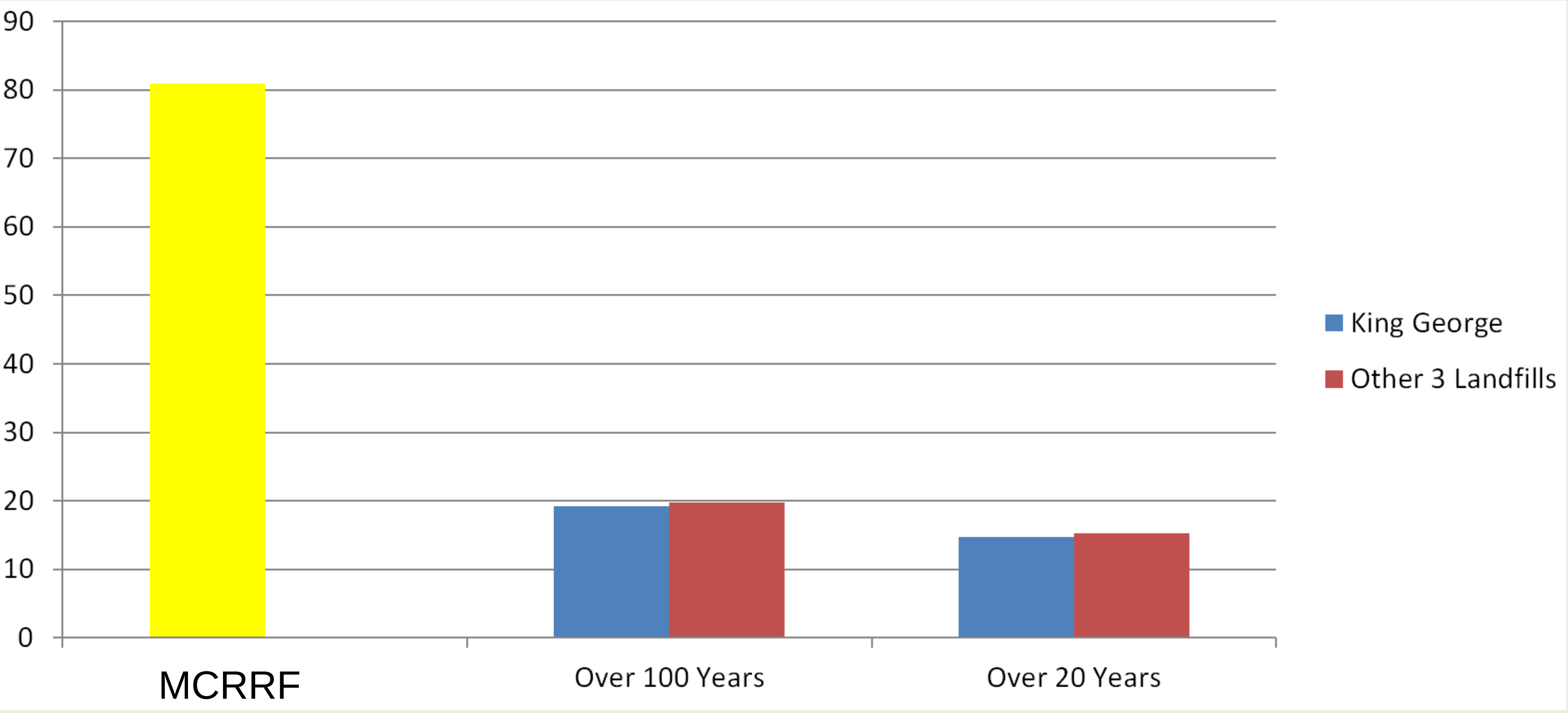
Global Warming Pollution

[Pounds of CO_2 equivalent per ton of waste disposed.]



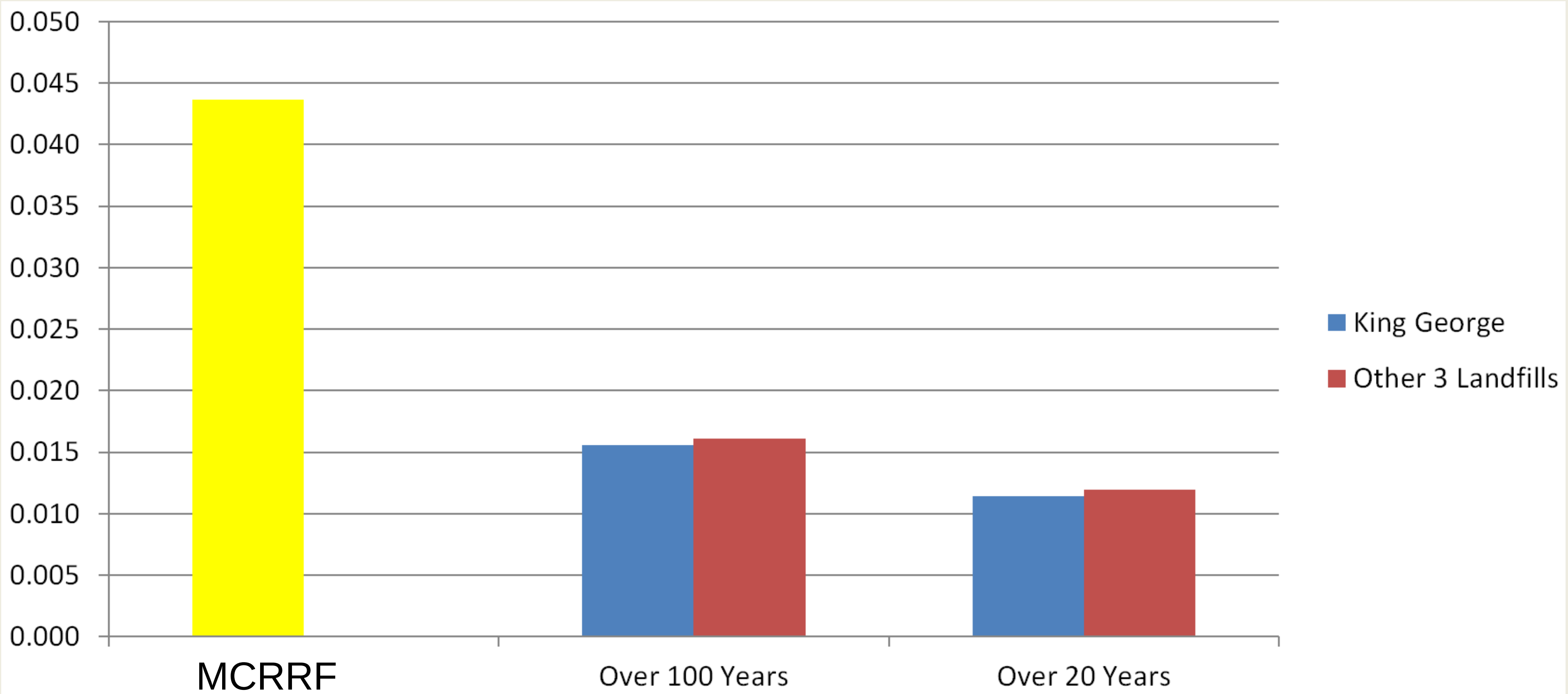
Smog Formation
[Asthma / respiratory impacts]

[Pounds of ozone (O_3) equivalent (from NOx and VOC emissions) per ton of waste disposed.]



Particulate Matter Pollution

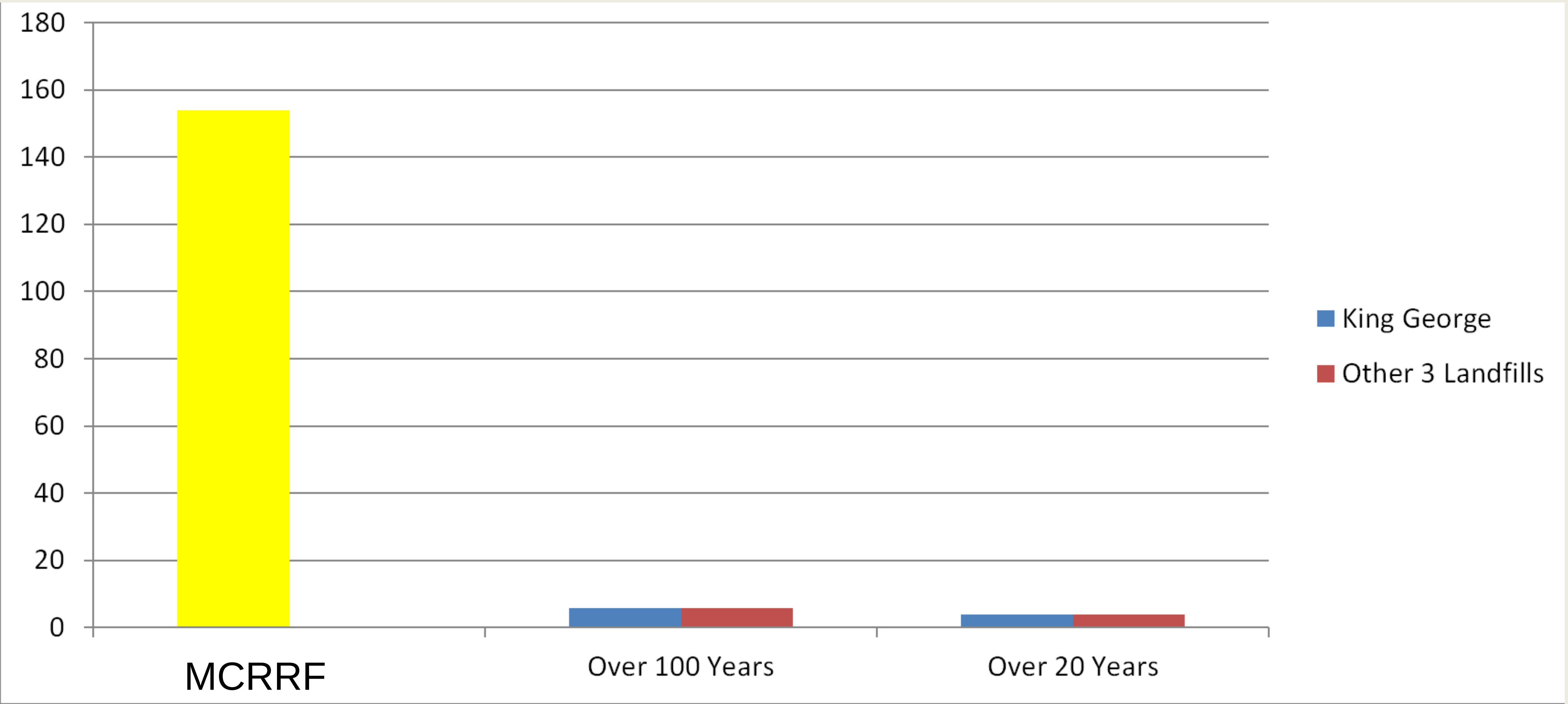
[Pounds of PM2.5 equivalent per ton of waste disposed.]



Toxic Pollution

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

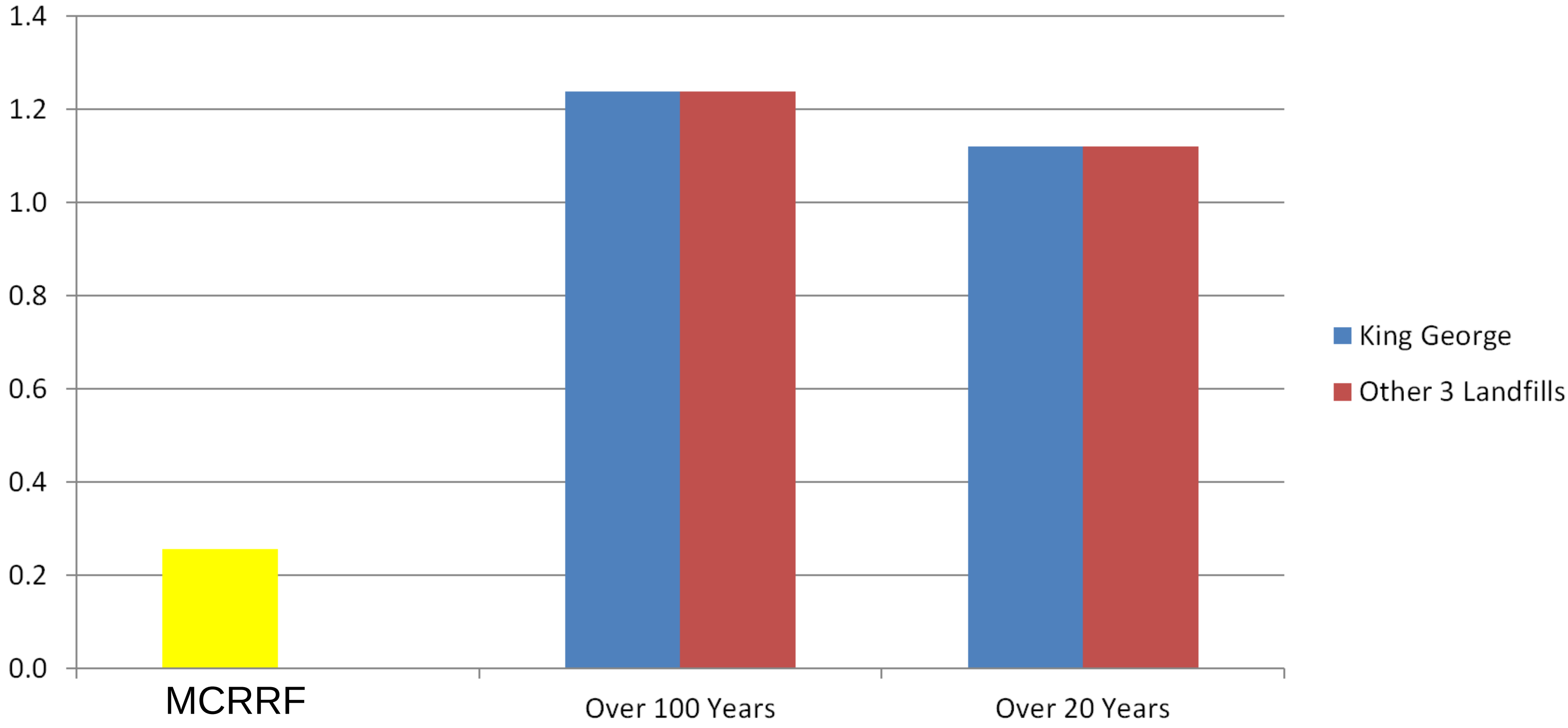
Does not include dioxin/furan emissions or ash leaching.



Carcinogenic Pollution

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

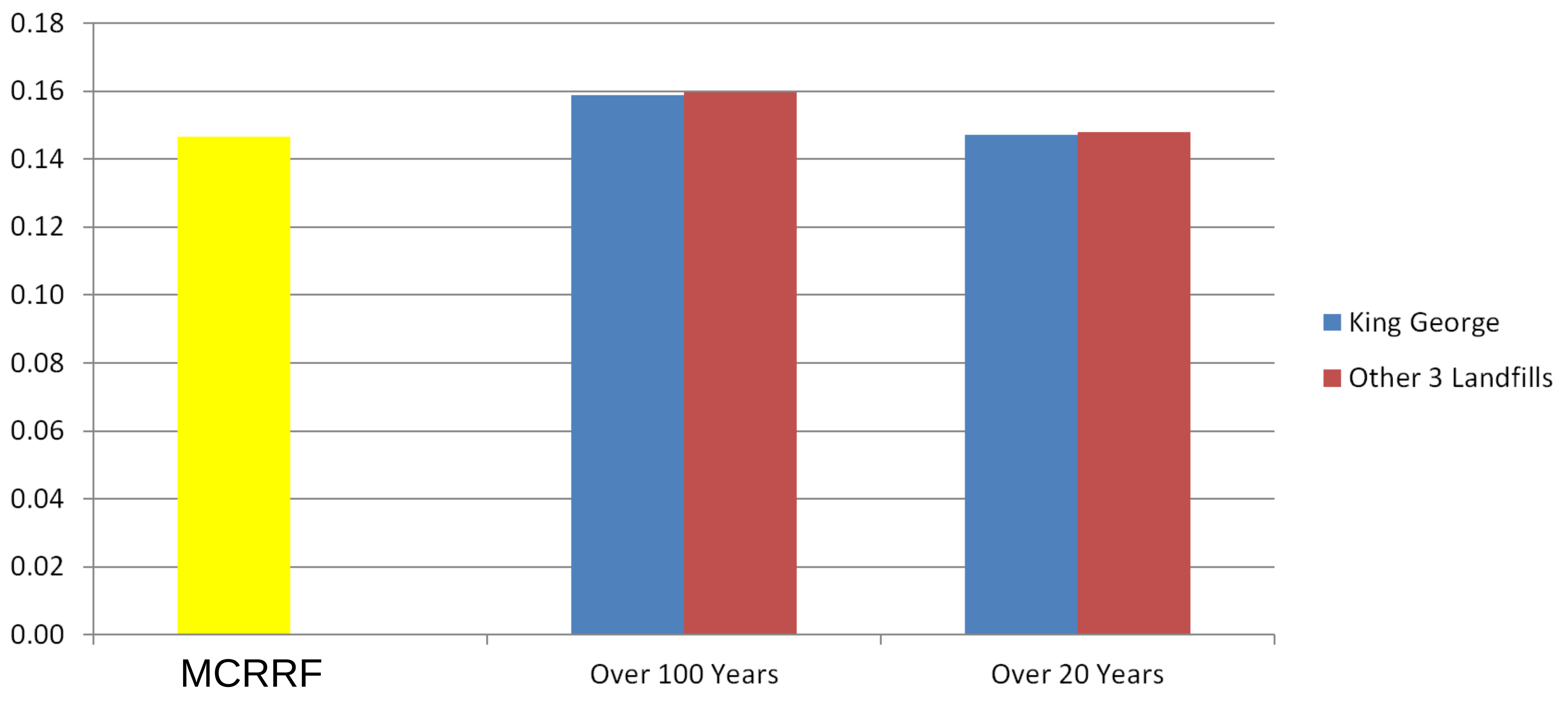
Does not include dioxin/furan emissions or ash leaching. Landfill impacts very localized compared to incineration.



Eutrophication

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

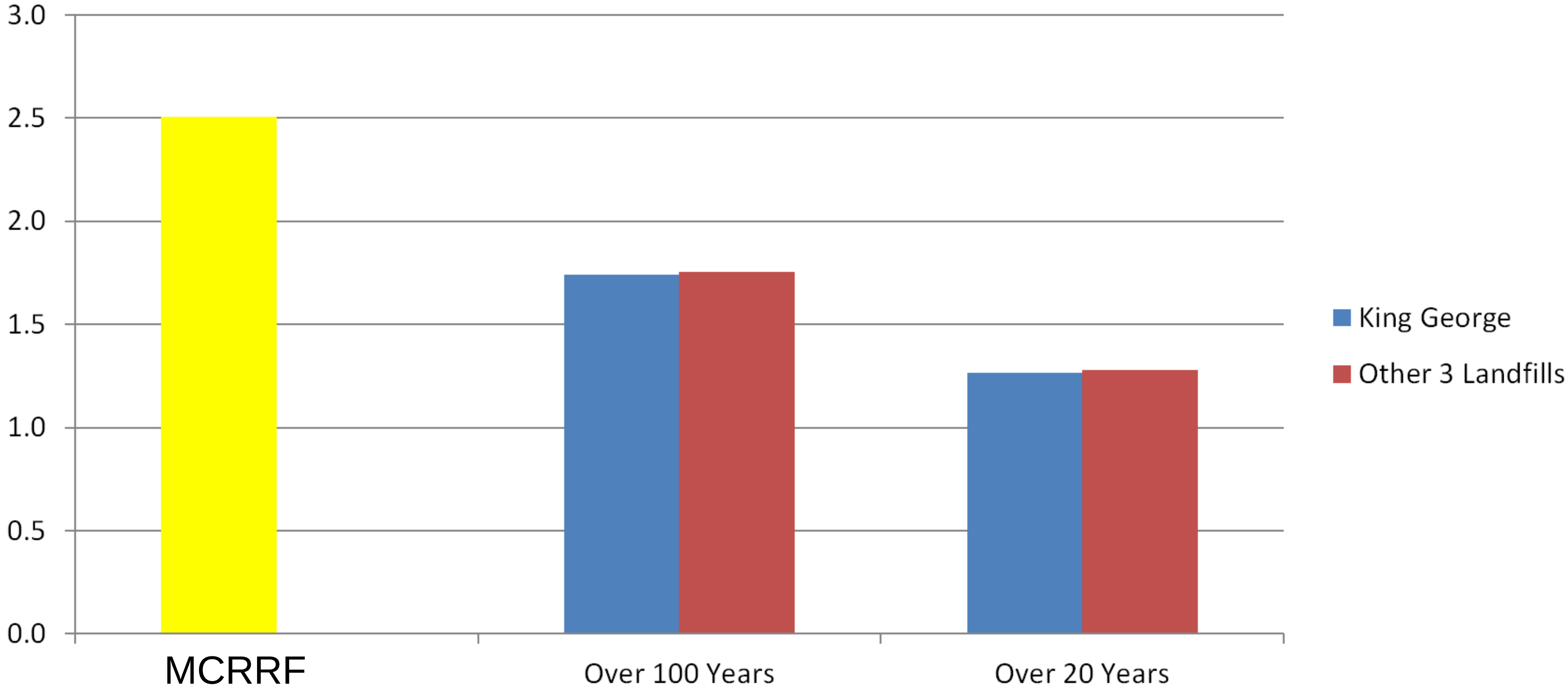
NOx and ammonia air emissions plus BOD, COD, phosphate, and ammonia water releases from landfills.



Acidification

[Pounds of SO_2 equivalent per ton of waste disposed.]

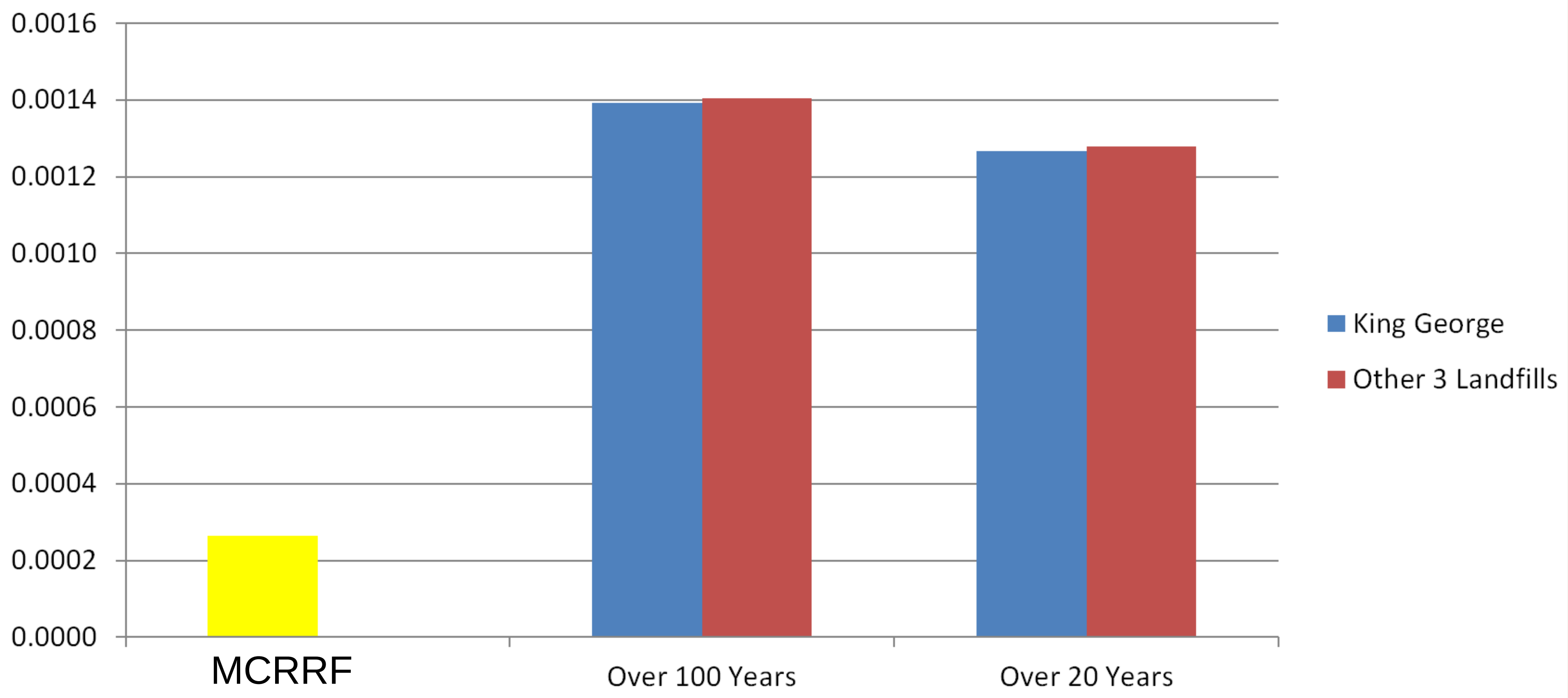
Incinerator emissions are largely from nitrogen oxides, but also include other acid gases (SO_2, HCl, HF). For the landfills, it's hydrogen sulfide (H_2S) from the landfill, plus ammonia, NOx and SOx from the landfill gas burners.



Ecosystems Toxicity

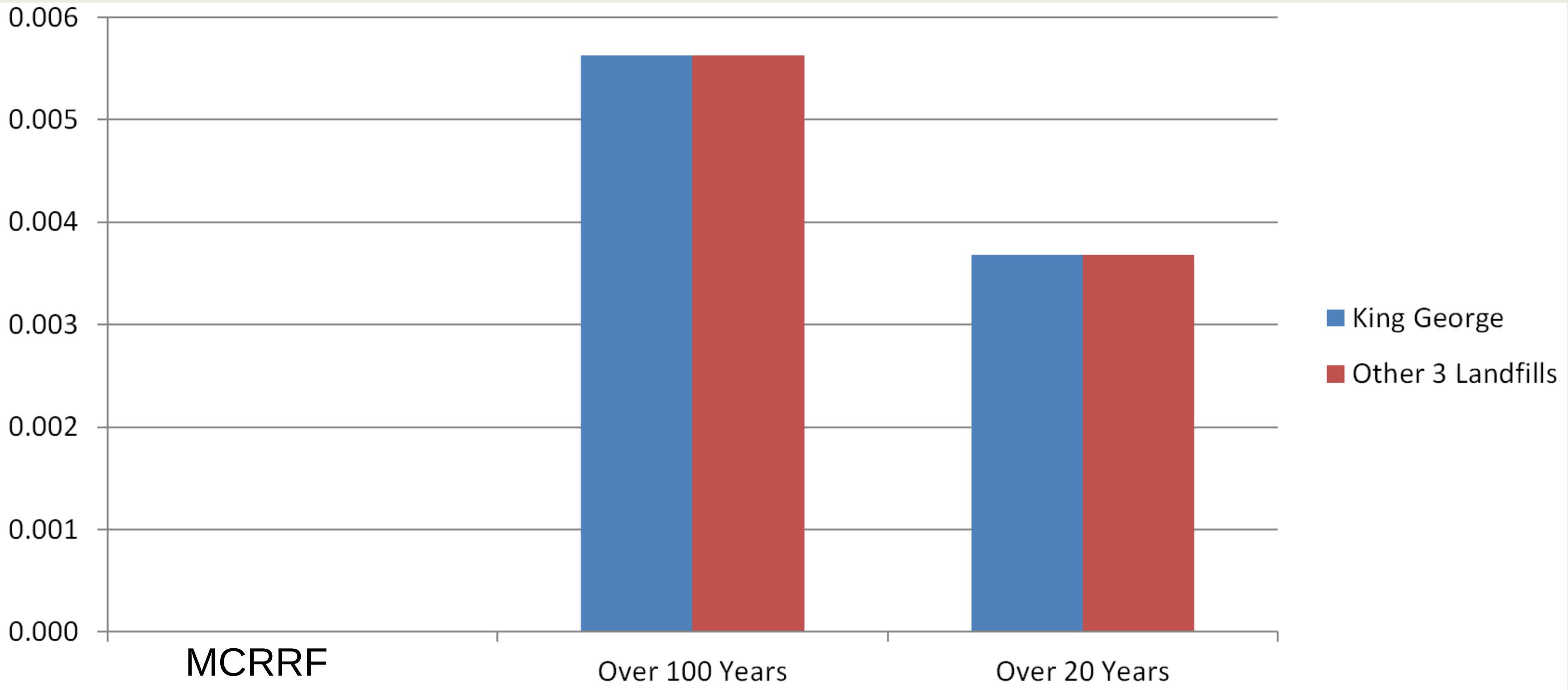
[Pounds of 2,4-D herbicide equivalent per ton of waste disposed.]

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



Ozone Depletion

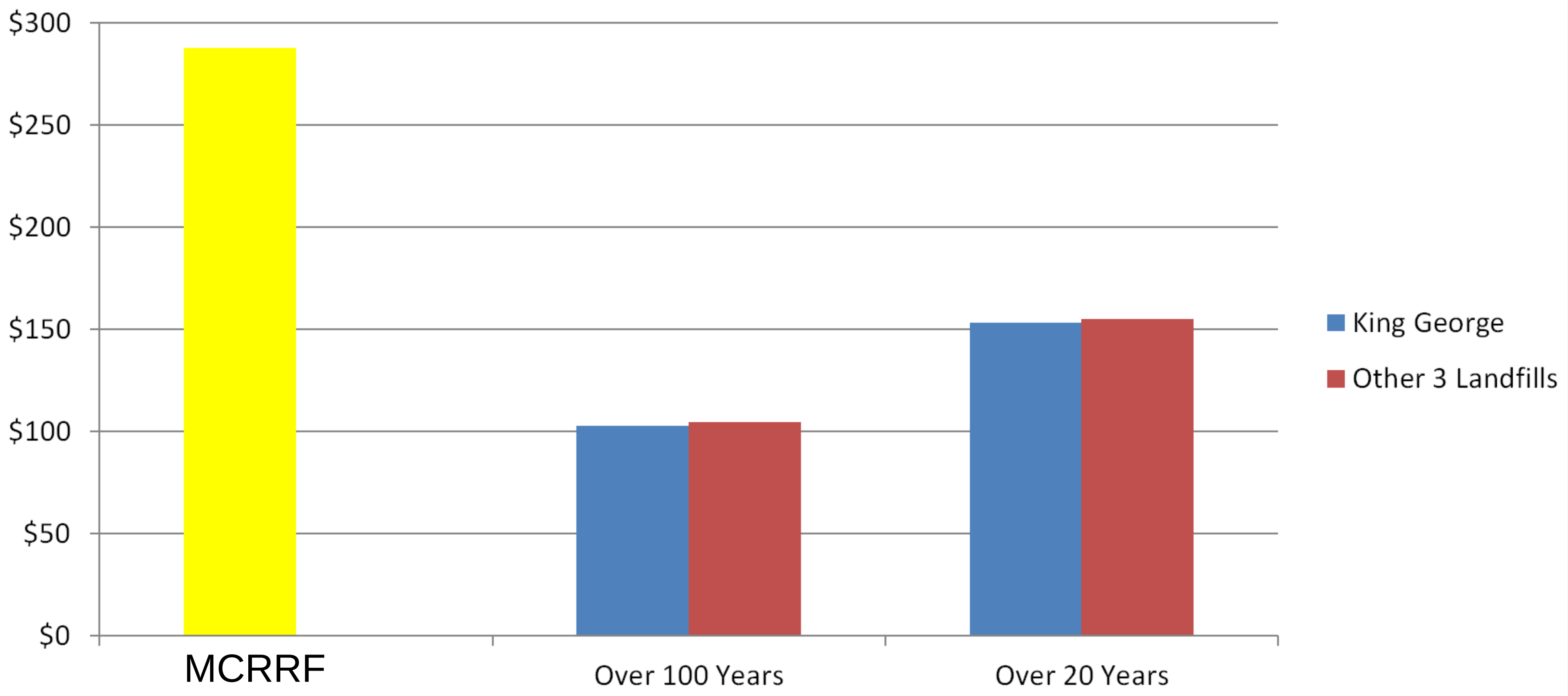
[Pounds of CFC-11 equivalent per ton of waste disposed.]



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

- Alvarez, R.A., *et* al, 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science, 361*: 186-188.
- De la Cruz, F.B., *et* al, 2016. Comparison of Field Measurements to Methane Emissions Models at a New Landfill. *Environmental Science & Technology, 50* (17): 9432-9441.
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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 (CO_2) 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 CO_2 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 CO_2 from the atmosphere.

4. Timing of CO_2 and methane (CH_4) 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 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

Treatment	Climate	Energy	Soil Carbon	Fertilizer Replacement	Water Conservation	Plant Yield Increase
Aerobic Composting	2	4	1	2	1	1
Anaerobic Digestion	1	2	2	1	2	1
In-Sink Grinding	3	1	3	3	3	3
Landfill	4	3	4	4	4	4

Source: Morris, J., Brown, S., Cotton, M., Matthews, H.S., 2017. Life-cycle assessment harmonization and soil science ranking results on food-waste management methods. *Environmental Science & Technology,* 51 (10): 5360-5367, Table 5.

Thank you.

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