Energy, Environment & Economy: Trade-Offs When Managing Wastes for Sustainability & Resiliency

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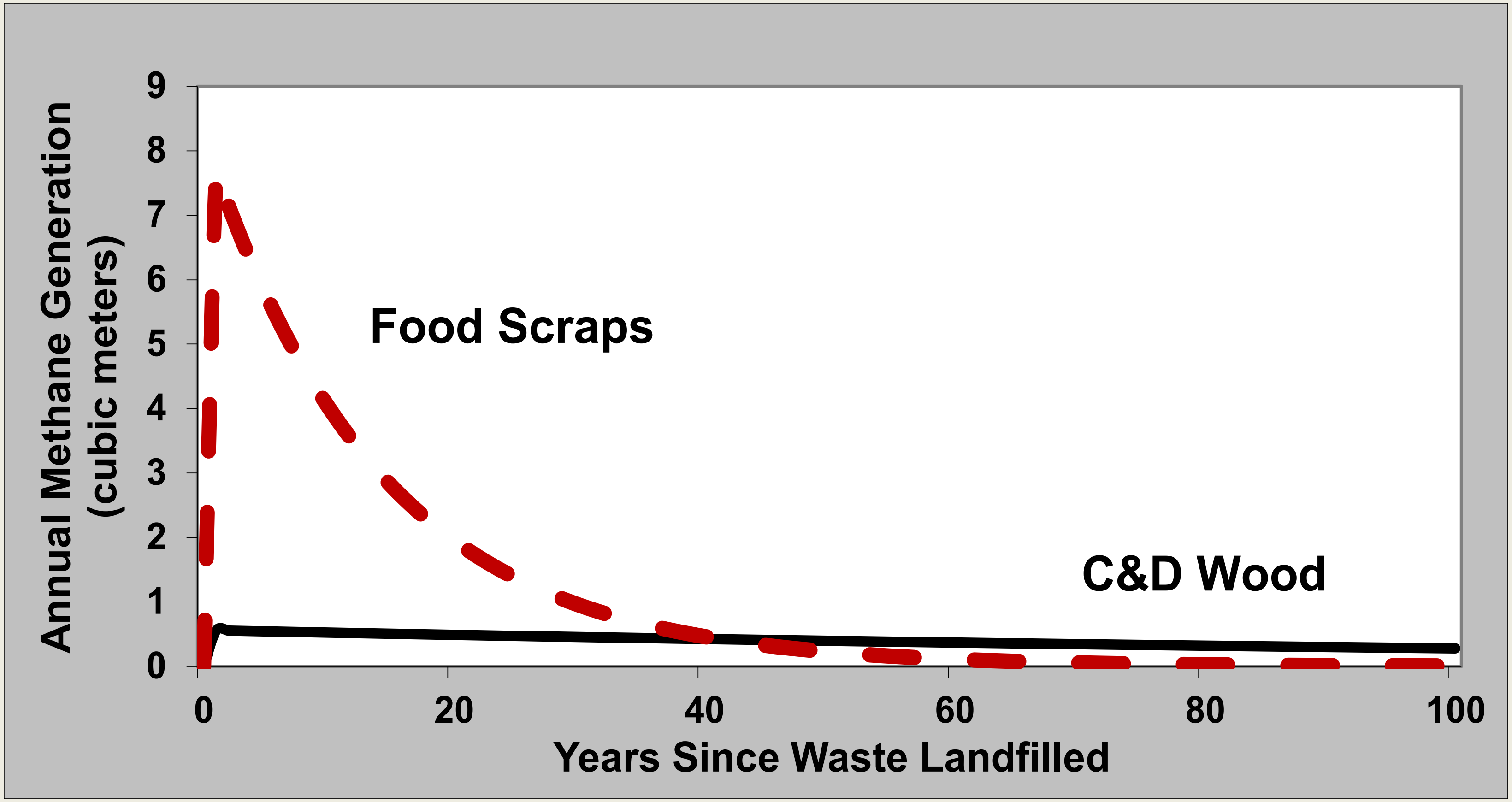
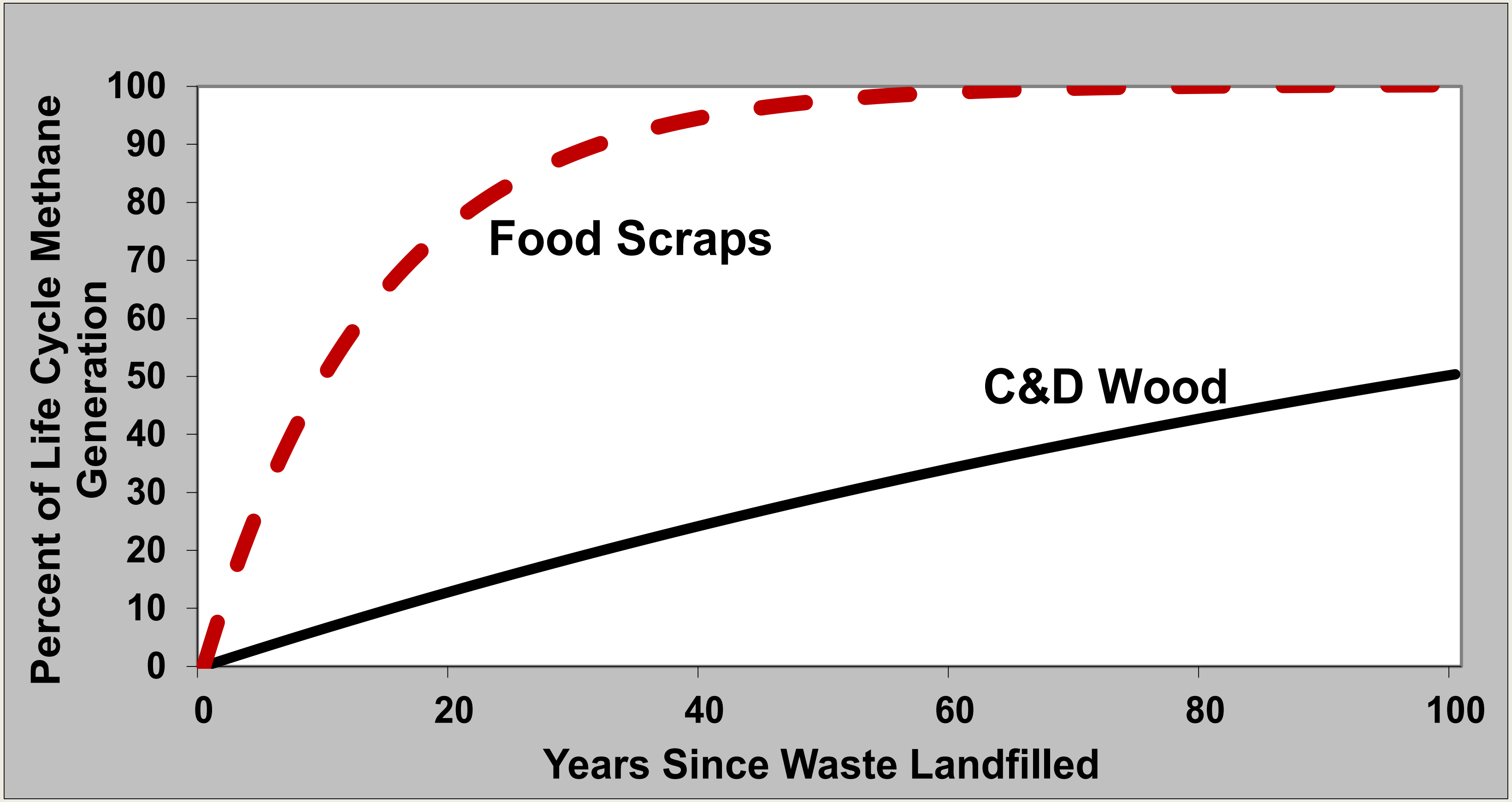
Cubic Meters (m^3) Methane (CH_4) Generated Each Year Since Waste Landfilled (m^3 CH_4/metric ton)



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



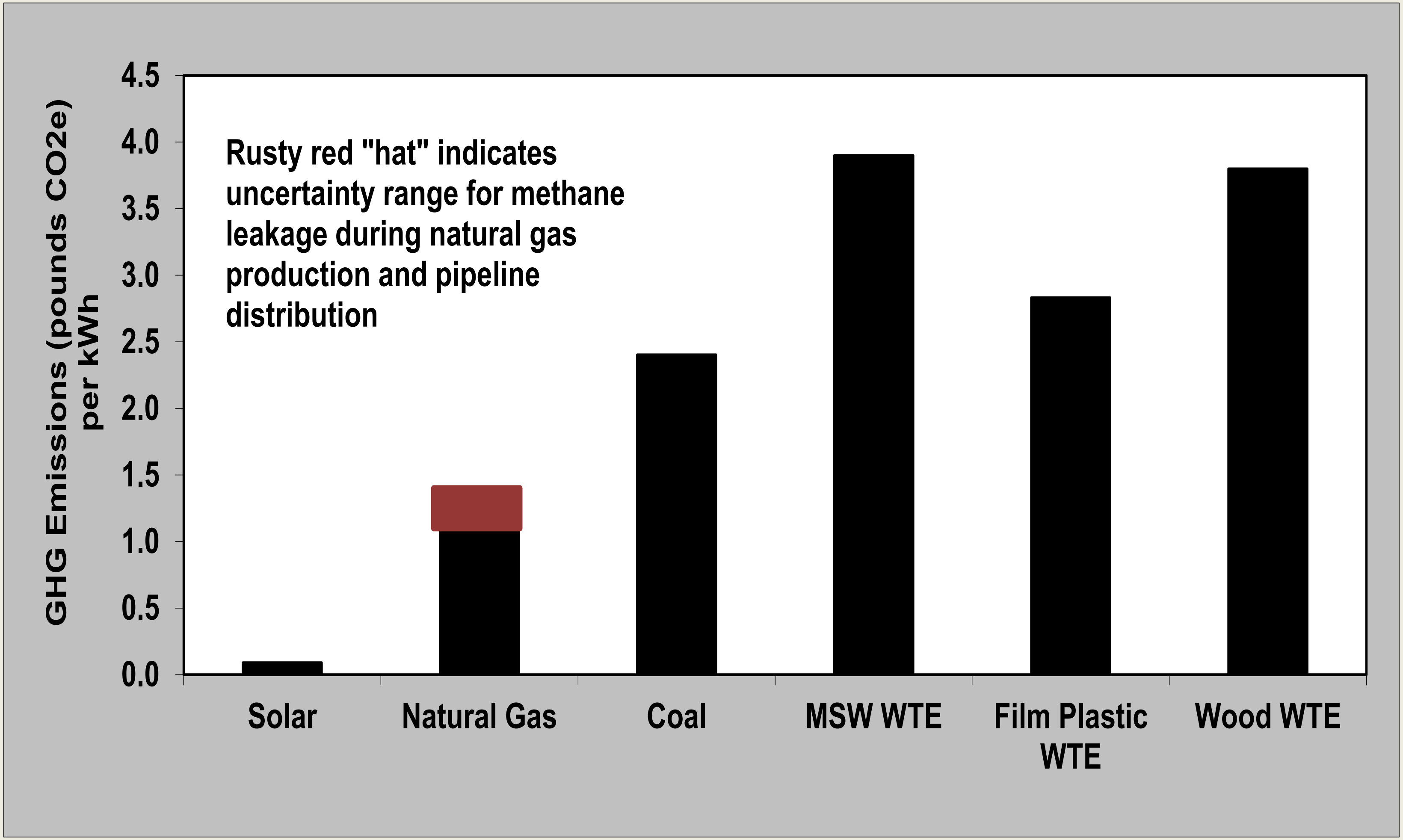
Sources: U. S. Environmental Protection Agency, 2005. *Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide.* EPA-600/R-05/047, EPA: Washington, DC; De La Cruz, F. B., Barlaz, M. A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *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.

Landfill (LF) Carbon Storage & Potential Life Cycle Carbon Emissions from Waste-to-Energy (WTE) & Landfill (LF) Disposal Facilities

MSW Material	Carbon Content (%)	Kilograms (kg) Carbon per Metric Ton	Landfill Carbon Storage (%)	Potential CO_2 & CH_4 Life Cycle Emissions (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

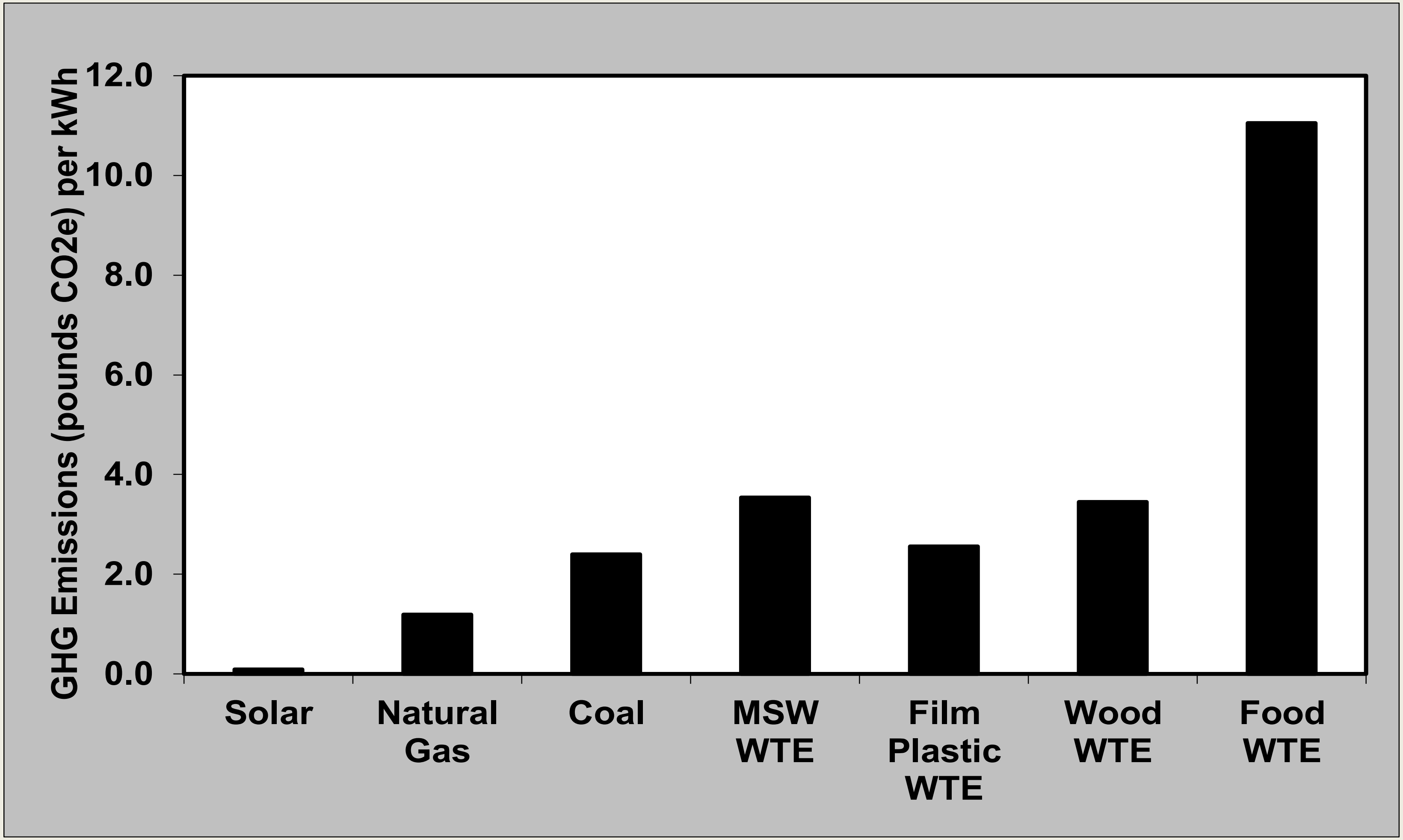
Sources: De La Cruz, F. B., Barlaz, M. A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology* 44 (12): 4722-4728; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & 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.

Carbon Footprints for Electricity Generation



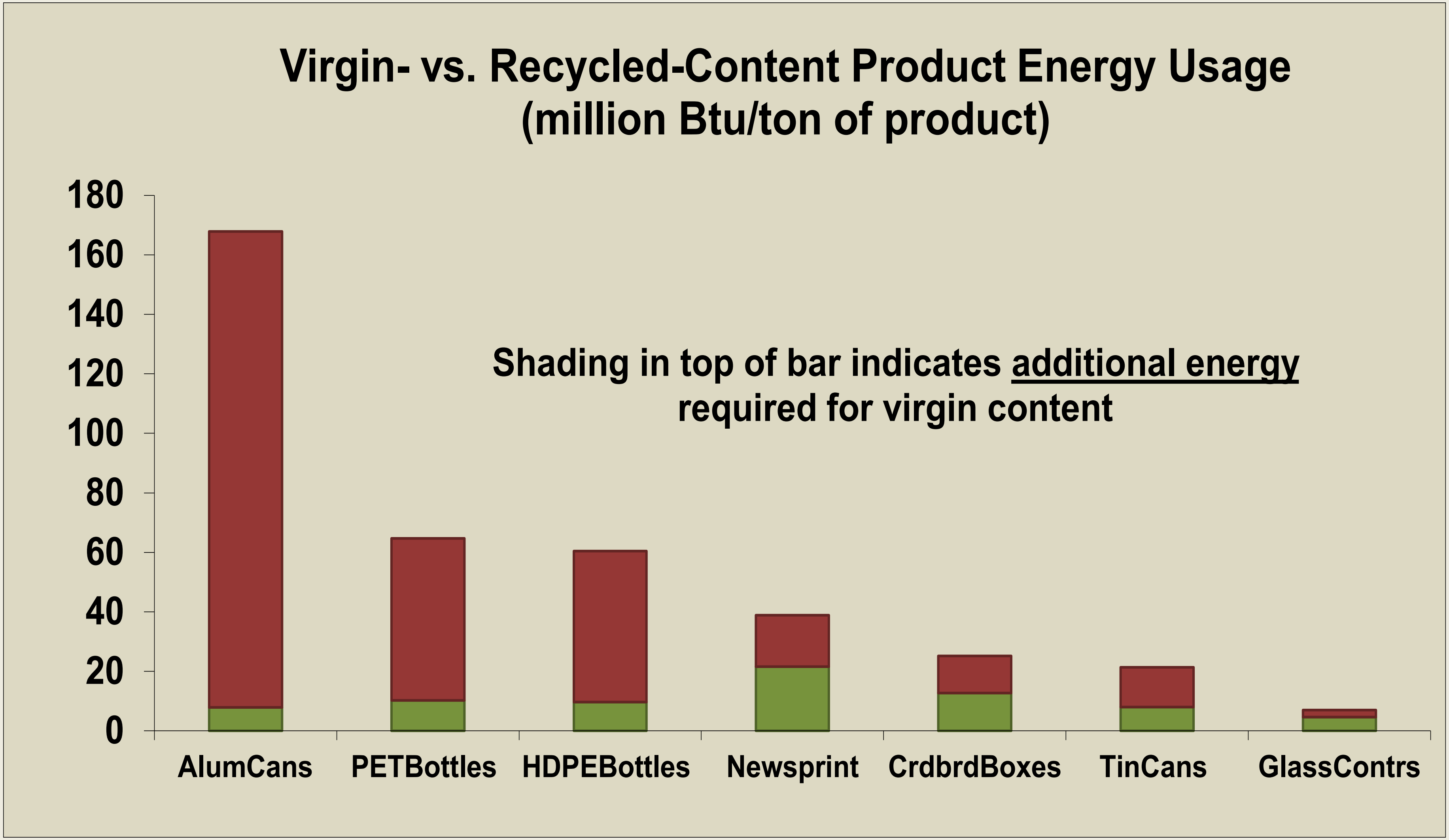
Sources: Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. *Journal of Industrial Ecology* 16 (S1): S110-S121; Morris, J., 2010. Bury or burn North American MSW? LCAs provide 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.

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.

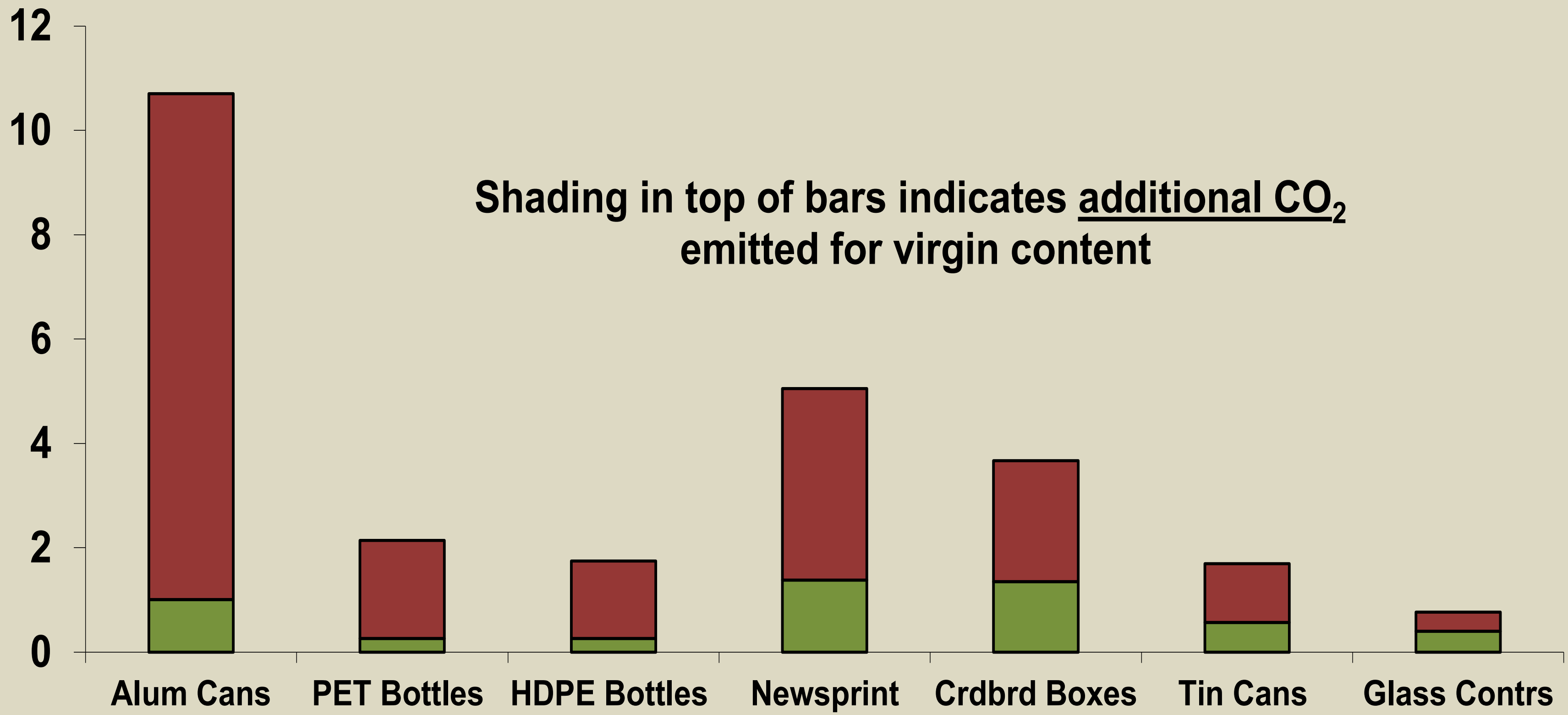
Energy Conservation from Recycled-Content Manufacturing



Sources: Morris, J., (1996). Recycling versus incineration: an energy conservation analysis. *Journal of Hazardous Materials* 47(1-3) 277-293; U.S. EPA (2016). Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM); WARM model and supporting documentation available at: https://www.epa.gov/warm/versions-waste-reduction-model-warm#WARM Tool V14 .

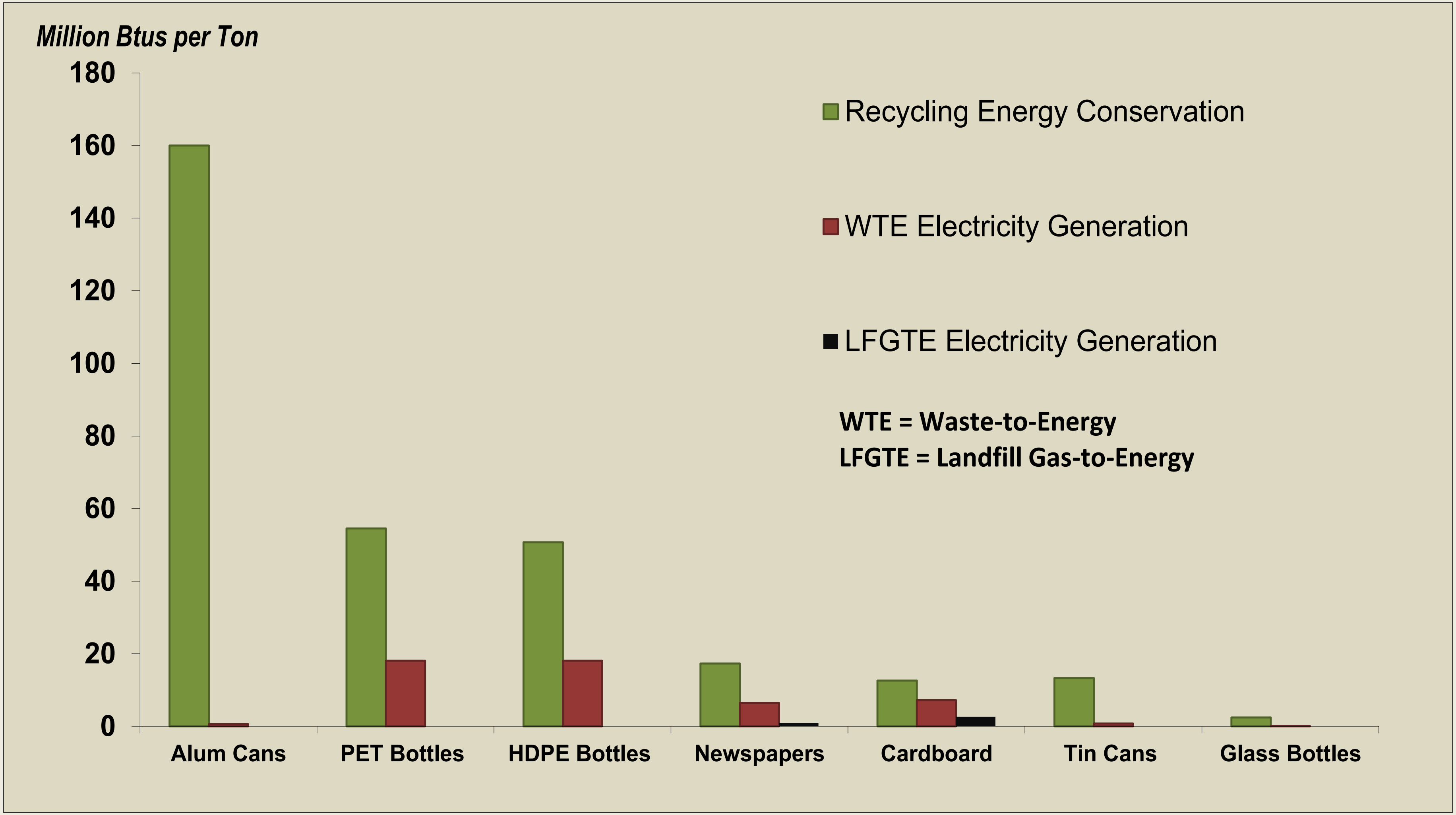
Carbon Emissions Reduction from Recycled-Content Manufacturing

Virgin- vs. Recycled-Content Product Carbon Emissions (metric tons CO_2 equivalents/ton of product)



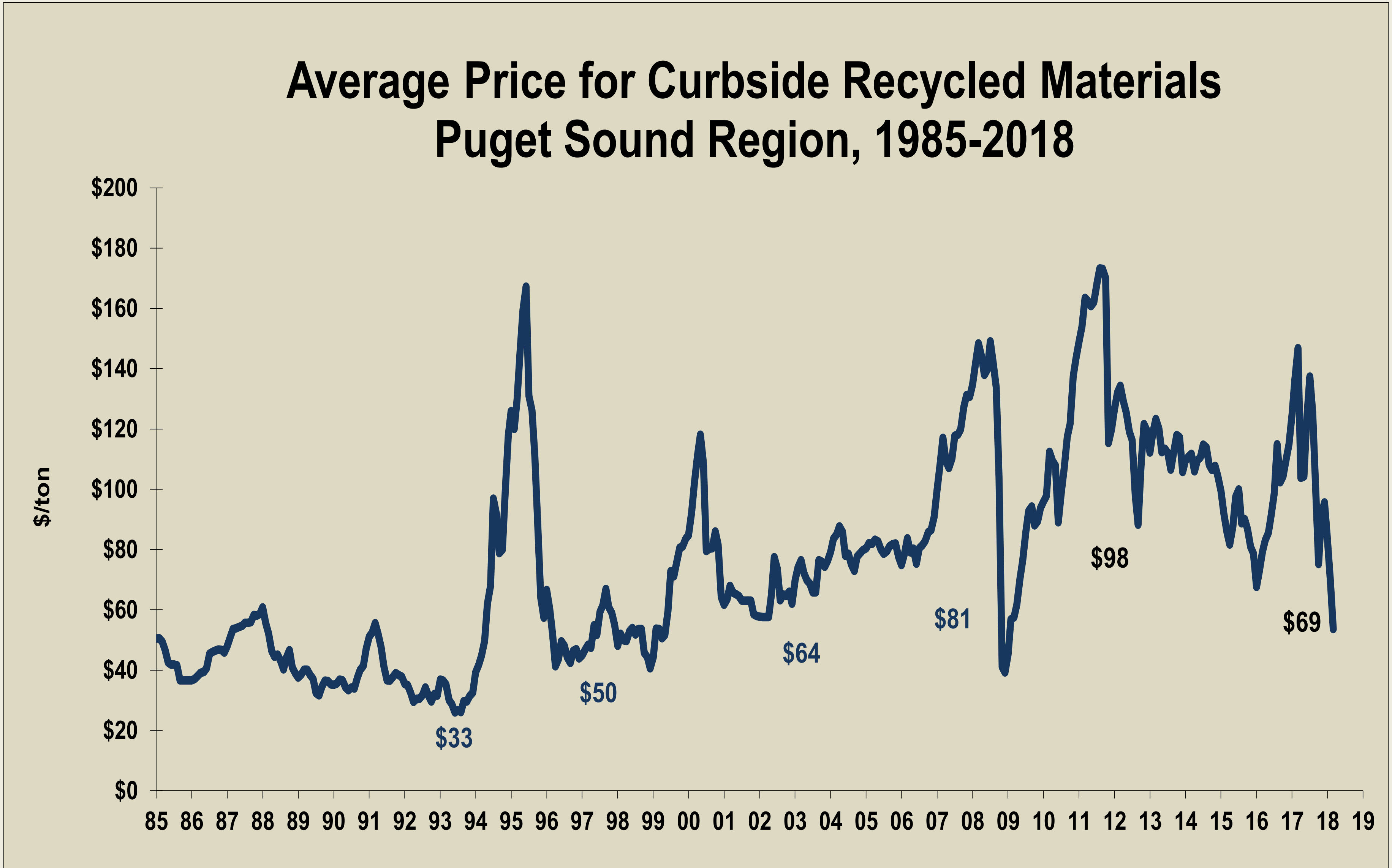
Sources: Morris, J., (2005). Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery. *International Journal of Life Cycle Assessment* 10(4) 273-284; U.S. EPA (2016). Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM); WARM model and supporting documentation available at: https://www.epa.gov/warm/versions-waste-reduction-model-warm#WARM Tool V14 .

Energy Conservation from Recycling vs. Energy Generation from Disposal



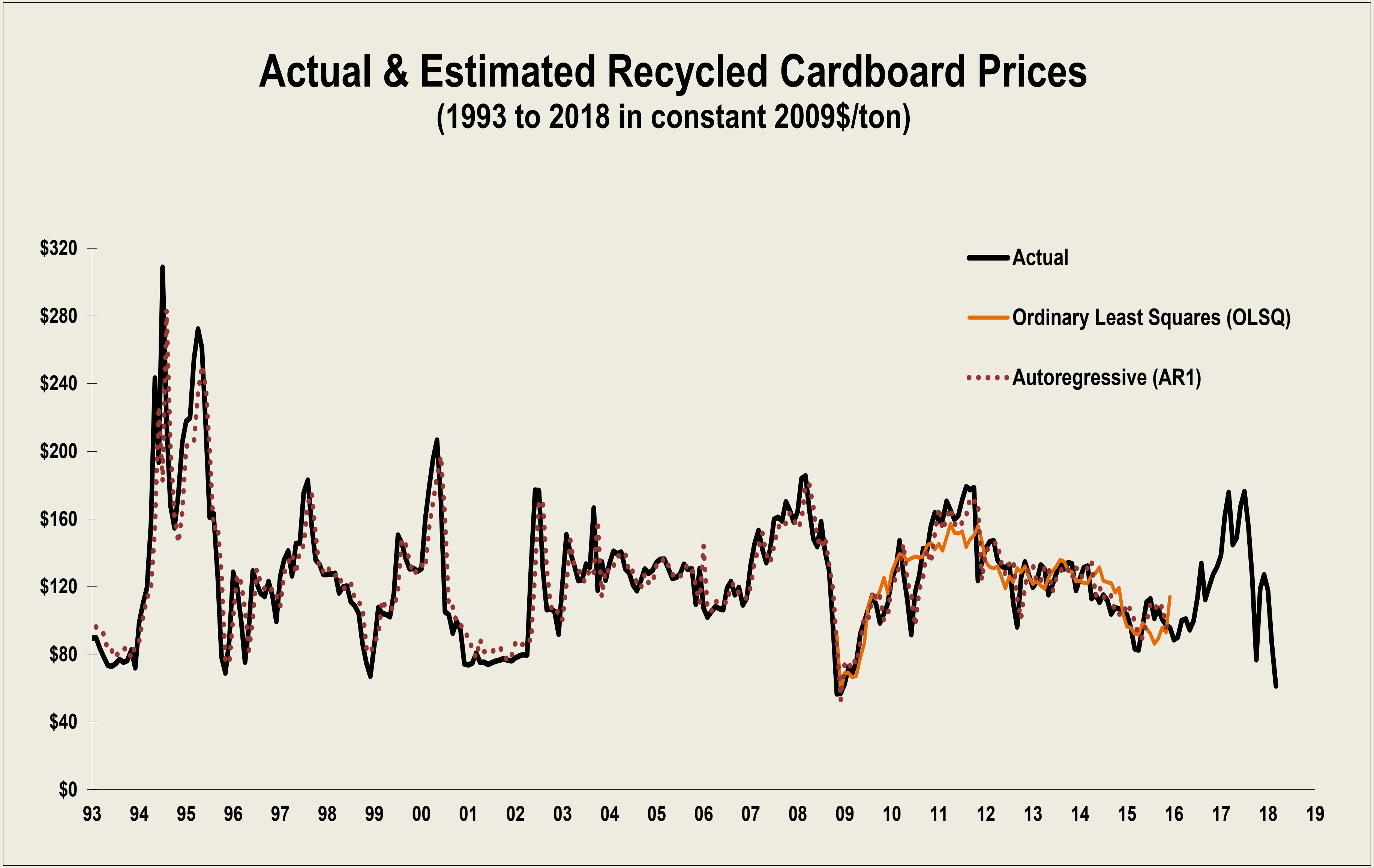
Sources: Morris, J., (1996). Recycling versus incineration: an energy conservation analysis. *Journal of Hazardous Materials* 47(1-3) 277-293; U.S. EPA (2016). Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM); WARM model and supporting documentation available at: https://www.epa.gov/warm/versions-waste-reduction-model-warm#WARM Tool V14 ; 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.

Recycling Market Price Fluctuations



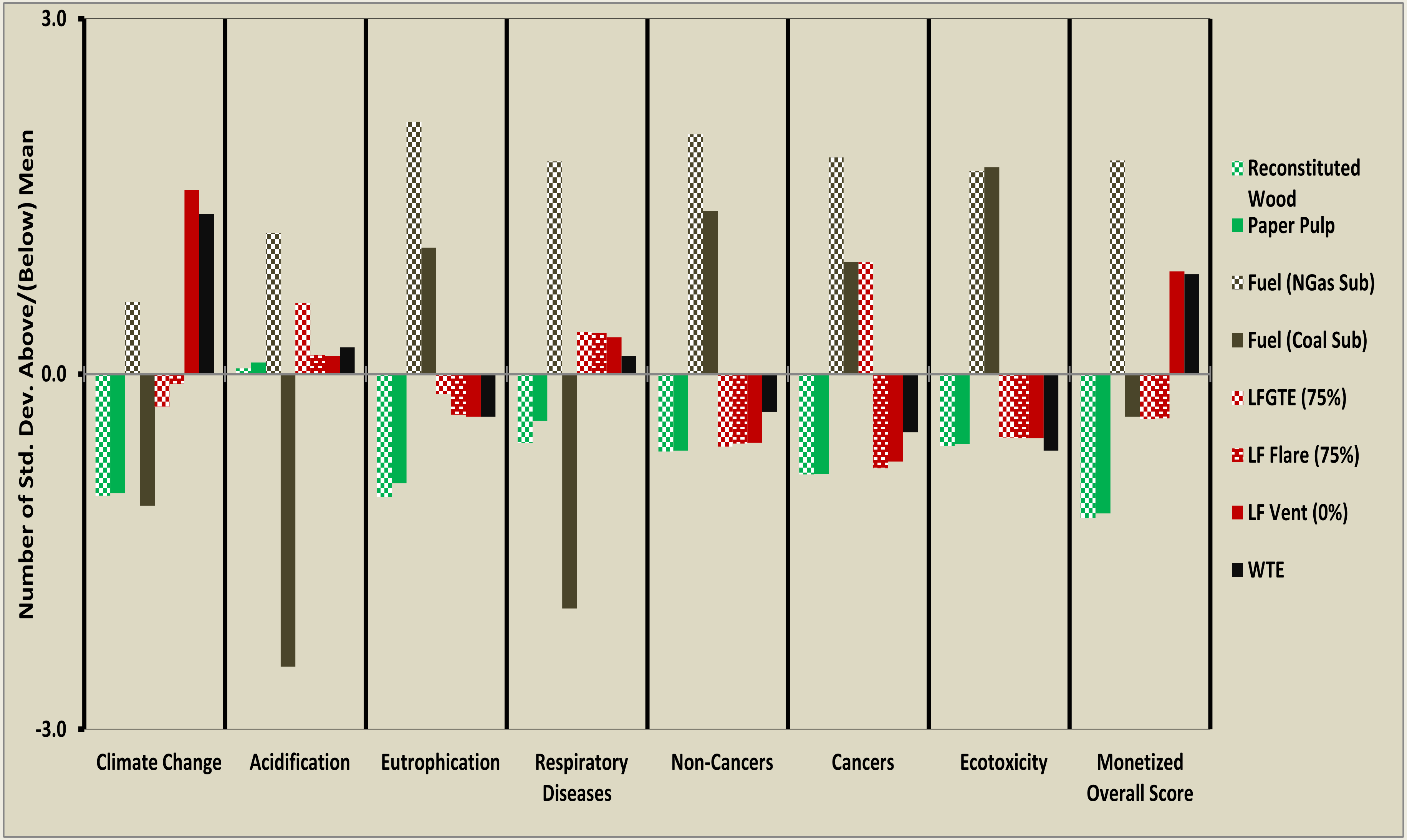
Source: Sound Resource Management Group, Inc. database on Northwest recycling market prices. This graph and graphs for individual materials available for download at: www.zerowaste.com .

Recycling Market Price Fluctuations for Cardboard



Source: Morris, J., Oregon Recycling Markets Price Cycles and Trends: A Statistical Search for Significant Economic Causes, prepared for the State of Oregon Department of Environmental Quality, October 2016. Available at http://zerowaste.com/images/Recycling-Prices-Analysis.pdf or at http://www.oregon.gov/deq/FilterDocs/RecyclingPriceAnalysis.pdf.

Life Cycle Environmental Impacts for Clean C&D Wood Waste



Source: 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, Figure 2.

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.

Suggestions for Additional Reading

- 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.
- Farquharson, D., *et al*, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. *Journal of Industrial Ecology,* 21 (4): 857-873.
- ICF International, 2016. *Finding the Facts on Methane Emissions: A Guide to the Literature*, prepared for The Natural Gas Council by ICF International, Fairfax, VA.
- National Academy of Sciences, 2018. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press.
- Raimi, D., 2017. *The Fracking debate: The Risks, Benefits, and Uncertainties of the Shale Revolution*. Columbia University Press, New York, NY.
- Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, RRF, Washington, DC.
- Venkatesh, A., *et al*, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy. *Environmental Science & Technology, 45* (19): 8182-8189.

Thank you.

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