Is It Better to Burn or Bury Waste For Clean Electricity Generation?

Supporting Information

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Table S1. Characteristics of Municipal Solid Waste

Category [a]	Discarded Waste, Thousands of Tons	Moisture Content, %[b]	Heating Value, BTU/lb[b]	L_o, L of CH_4 per kg of Waste Item [c]	Biogenic vs. Fossil	Additional Assumptions
Leaves	2,808	60%	2,600	30.6	Biogenic	23% of the total yard waste [d]
Grass	7,448	60%	2,600	136	Biogenic	61% of the total yard waste [d]
Branches	1,954	60%	6,600	62.6	Biogenic	16% of the total yard waste [d]
Old Newsprint	1,340	6%	7,500	74.3	Biogenic	
Old Corr. Cardboard	8,830	5%	6,900	152.3	Biogenic	
Office Paper	2,460	6%	6,300	217.3	Biogenic	
Phone Books	540	6%	6,300	74.3	Biogenic	
Books	860	6%	6,300	217.3	Biogenic	
Old Magazines	1,550	6%	5,400	84.4	Biogenic	
3rd Class Mail	3,740	6%	6,100	150.8	Biogenic	
Mixed Paper	22,650	6%	6,800	103.7	Biogenic	all other paper categories
HDPE	4,720	2%	19,000	0	Fossil	
PET	1,840	2%	19,000	0	Fossil	
Mixed Plastic	12,360	2%	14,000	0	Fossil	all other resins
Ferrous Cans	870	3%	300	0	Biogenic	steel packaging
Ferrous Metal	7,970	3%	0	0	Biogenic	
Aluminum Cans	1,210	2%	0	0	Biogenic	
Aluminum	1,310	2%	0	0	Biogenic	
Glass	8,160	2%	84	0	Biogenic	all glass except durable glass
Food Waste	28,540	70%	1,800	300.7	Biogenic	
CCN [e]	12,620	70%	6,600	0	Biogenic	100% Wood
Plastic – Non-Recyclable	10,000	2%	10,000 [g]		Fossil	100% Carpets
Misc. Organics	10,430	2%	7,700[h]	0	Biogenic	100% Clothing, 100% Textiles, 100% other non-durables

Table S1. Characteristics of Municipal Solid Waste (Continued)

Category [a]	Discarded Waste, Thousands of Tons	Moisture Content, %[b]	Heating Value, BTU/lb[b]	L_o, L of CH_4 per kg of Waste Item [c]	Biogenic vs. Fossil	Additional Assumptions
CNN [f]	1,800	2%	11,000	0	50% Biogenic / 50% Fossil	100% Rubber tires
Glass - Non-recyclable	1,830	2%	0	0	Biogenic	100% Durable Glass
Misc. Inorganics	15,910	2%	0	0	Fossil	other products, other inorganics, other nonferrous metals, durable plastics
Total MSW	**166,670**	**27%**			**77% Biogenic / 23% Fossil**	

a. Unless stated otherwise in the assumptions column, all the categories are consistent with (1).

b. Source: (2)

c. Source: (3)

d. The split of yard waste into leaves, grass and branches is based on (4).

e. CCN – combustible, compostable, and non-recyclable materials

f. CNN -- combustible, non-compostable, and non-recyclable material

g. Source: (5)

h. Average of heating value of textiles and leather

Table S2 Components of MSW DST and References

Component	**References**
Collection *	○ Dumas, R. D. and E. M. Curtis, **1998**, "A Spreadsheet Framework for Analysis of Costs and Life-Cycle Inventory Parameters Associated with Collection of Municipal Solid Waste," Internal Project Report, North Carolina State University, Raleigh, NC. (https://webdstmsw.rti.org/docs/Collection_Model_OCR.pdf)
Transfer stations *	○ https://webdstmsw.rti.org/docs/Transfer_Station_Model_OCR.pdf
Separation of refuse and recyclables *	○ Nishtala, S. and E. Solano-Mora, **1997**, "Description of the Materials Recovery Facilities Process Model: Design, Cost and Life-Cycle Inventory," Project Report, North Carolina State University, Raleigh, NC. (https://webdstmsw.rti.org/docs/MRF_Model_OCR.pdf)
Treatment including refuse derived fuel *, waste-to-energy, yard- and mixed-waste composting *	○ Nishtala, S., **1997**, "Description of the Refuse Derived Fuel Process Model: Design, Cost and Life-Cycle Inventory," Project Report, Research Triangle Institute, RTP, NC. ○ Composting process model: https://webdstmsw.rti.org/docs/Compost_Model_OCR.pdf ○ Harrison, K. W.; Dumas, R. D.; Barlaz, M. A.; Nishtala, S. R., A life-cycle inventory model of municipal solid waste combustion. J. Air Waste Manage. Assoc. **2000**, 50, 993-1003.
Disposal including traditional and wet landfills, and ash landfill	○ Camobreco, V.; Ham, R; Barlaz, M; Repa, E.; Felker, M.; Rousseau, C. and Rathle, J. Life-cycle inventory of a modern municipal solid waste landfill. Waste Manage. Res. **1999**. 394-408. ○ Sich, B.A. and M. A. Barlaz, **2000**, "Calculation of the Cost and Life Cycle Inventory for Waste Disposal in Traditional, Bioreactor and Ash Landfills," Project Report, North Carolina State University, Raleigh, NC. (https://webdstmsw.rti.org/docs/Landfill_Model_OCR.pdf)
Background LCI models	○ Energy process model: https://webdstmsw.rti.org/docs/Energy_Model_OCR.pdf ○ Remanufacturing process model: https://webdstmsw.rti.org/docs/Remfg_OCR.pdf

Table S2 Components of MSW DST and References (Continued)

Decision Support Tool, Optimization and Alternative Strategy Generation *	○ Harrison, K.W.; Dumas, R.D.; Solano, E.; Barlaz, M.A.; Brill, E.D.; Ranjithan, S.R. A Decision Support System for Development of Alternative Solid Waste Management Strategies with Life-Cycle Considerations. ASCE J. of Comput. Civ. Eng. **2001**, 15, 44-58. ○ Solano, E.; Ranjithan, S.; Barlaz, M. A.; Brill, E. D. Life Cycle-Based Solid Waste Management - 1. Model Development. *J. Environ. Engr*. **2002**, 128, 981-992. ○ Manual: https://webdstmsw.rti.org/docs/DST_Manual_OCR.pdf ○ Tool Website: https://webdstmsw.rti.org/resources.htm
Uncertainty Propagation and Sensitivity Tools *	○ Kaplan, P. O.; Barlaz, M. A.; Ranjithan, S. R. Life-Cycle-Based Solid Waste Management under Uncertainty. J. Ind. Ecol. **2004**, 8, 155-172.
* These process models were not utilized in this study.	

Table S3. Emission Factors for Pollutants Exiting from Landfill Gas Control Devices [a]

Pollutant	Units	Flare	Internal Combustion Engine	Turbine
CO	kg/hr/dry standard cubic meter of CH_4/minute	0.72	0.45	0.22
NO_x	kg/hr/dry standard cubic meter of CH4/minute	0.039	0.24	0.083
PM	kg/hr/dry standard cubic meter of CH4/minute	0.016	0.046	0.021
SO_2	kg/hr/dry standard cubic meter of biogas/minute	0.01	0.01	0.01
HCl	kg/hr/dry standard cubic meter of biogas/minute	0.0096	0.0091	0.0098

a. Source: (6)

Table S4. Regulated and Average Emissions Concentrations in the Stack Gas of Waste-to-Energy Facilities

Pollutants	Units	Regulatory Emission Limits [a]	Average at New Facilities [b]
SO_2	(ppmv @ 7% oxygen, dry)	30	10
HCl	(ppmv @ 7% oxygen, dry)	25	11
NO_x	(ppmv @ 7% oxygen, dry)	150	170
CO	(ppmv @ 7% oxygen, dry)	100	100
PM	(mg/dscm @ 7% oxygen, dry)	24	4.7
Dioxins / Furans	(ng/dscm @ 7% oxygen, dry)	13	4.5

a. Source: (7)

b. Source: (8)

Table S5. Life-cycle Emission Factors for Landfill Gas to Energy and Waste-to-Energy

		LF-VENT2[a]	LF-VENT2-ICE 15	LF-VENT2-ICE 30	LF-VENT2-ICE 45	LF-VENT2-ICE 60	LF-VENT4[b]	LF-VENT4-ICE 15	LF-VENT4-ICE 30	LF-VENT4-ICE 45	LF-VENT4-ICE 60	LF-VENT 100[c]	WTE-Reg	WTE-Avg
Criteria Pollutants														
CO	g/MWh	5000	6200	3800	3100	2800	5100	6500	4000	3200	2900	330	790	790
NO_x	g/MWh	1200	2800	2200	2100	2000	1300	3000	2400	2200	2100	1000	1300	1500
SO_x	g/MWh	530	800	550	470	430	590	900	610	520	480	530	580	220
PM	g/MWh	240	500	390	360	340	260	530	410	370	360	140	180	60
PM-10	g/MWh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	0.0
Other Pollutants														
HCL	g/MWh	35	51	34	29	27	36	53	36	30	28	3	260	110
Dioxins/Furans	g/MWh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	0.0
Ammonia	g/MWh	0.41	0.61	0.42	0.36	0.33	0.45	0.69	0.47	0.40	0.37	0.43	0.0	0.0
Hg	g/MWh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.05	0.05
Greenhouse gases														
CO_2-biomass	Mg/MWh	2.3	3.5	2.4	2.0	1.9	2.5	3.8	2.61	2.2	2.1	1.8	0.91	0.91
CO_2-fossil	Mg/MWh	0.10	0.15	0.10	0.09	0.08	0.11	0.17	0.12	0.10	0.09	0.11	0.56	0.56
CH_4	Mg/MWh	0.13	0.19	0.13	0.11	0.10	0.16	0.25	0.17	0.14	0.13	0.38	0.00	0.00
CO_2e	$MTCO_2E$/MWh	2.8	4.2	2.9	2.5	2.3	3.6	5.4	3.7	3.1	2.9	8.2	0.56	0.56

Table S5. Life-cycle Emission Factors for Landfill Gas to Energy and Waste-to-Energy (Continued)

		LF-VENT2[a]	LF-VENT2-ICE 15	LF-VENT2-ICE 30	LF-VENT2-ICE 45	LF-VENT2-ICE 60	LF-VENT4[b]	LF-VENT4-ICE 15	LF-VENT4-ICE 30	LF-VENT4-ICE 45	LF-VENT4-ICE 60	LF-VENT 100[c]	WTE-Reg	WTE-Avg
	TWh	11	7.6	11	13	14	10	6.8	9.9	12	13	11	98	98.
	kWh/ton	-	46	67	78	84	-	41	60	70	75	-	590	590

a. LF-VENT 2 alternative, potential electricity generated is estimated from the average of LF-VENT 2-ICE 15, -ICE 30, -ICE 45 and –ICE6 that is (7.6+ 11.1+ 12.9+ 14)/4 = 11.4 Twh.

b. LF-VENT 4 alternative, potential electricity generated is estimated from the average of LF-VENT 4-ICE 15, -ICE 30, -ICE 45 and –ICE6 that is (6.8+ 9.9+ 11.7+ 12.6)/4 = 10.2 Twh.

c. LF-VENT 100 alternative, potential electricity generated is estimated from the average of all alternatives, that is 10.8 Twh.

d. CO_2e is represented in metric tons of CO_2 equivalents (MTCO2E) per MWh of electricity generated = $CO_2 + 21 \times CH_4$

Table S6. Life-cycle Emission Factors for Conventional Power Plants [a]

		Coal	Natural Gas	Oil	Nuclear
System Parameters					
Efficiency	%	33	50	33	33
Criteria Pollutants					
CO	g/MWh	220	800	340	27
NO_x	g/MWh	3700	1500	1400	280
SO_x	g/MWh	6900	3400	6100	830
PM	g/MWh	1300	14	120	210
PM-10	g/MWh				
Other Pollutants					
HCl	g/MWh	82	0	22	2
Dioxins/Furans	g/MWh				
Ammonia	g/MWh	0.05	9.1	56	0.15
Hg	g/MWh				
Greenhouse gases					
CO_2-biomass	Mg/MWh	0.00	0.00	0.00	0.00
CO_2-fossil	Mg/MWh	0.97	0.41	0.88	0.03
CH_4	Mg/MWh	0.00	0.00	0.00	0.00
CO_2e	MTCO2E/MWh	1	0.44	0.89	0.03

a. Source: (9); The raw data on pre-combustion emission factors are collected on a unit mass of fuel; when converted on a per unit electricity generated, the magnitude of resultant emissions depends on the efficiency of the power plant. To provide transparency, the assumed efficiencies are provided along with the factors.

Table S7. Sensitivity of Emission Factors for Conventional Power Plants to System Efficiency

		Coal		Natural Gas		Oil		Nuclear	
System Efficiency	%	25	40	30	60	20	35	30	40
Criteria Pollutants									
CO	g/MWh	290	180	1300	670	560	320	30	22
NOx	g/MWh	4800	3020	2600	1300	2300	1300	300	230
SOx	g/MWh	9100	5700	5700	2800	10000	5700	910	680
PM	g/MWh	1700	1100	23	11	200	110	230	170
PM-10	g/MWh								
Other Pollutants									
HCL	g/MWh	108	68	0.49	0.25	37	21	2.3	1.8
Dioxins/Furans	g/MWh								
Ammonia	g/MWh	0.07	0.04	15	7.6	92	52	0.16	0.12
Hg	g/MWh								
Greenhouse gases									
CO2-biomass	MT/MWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2-fossil	MT/MWh	1.28	0.80	0.69	0.34	1.5	0.83	0.04	0.03
CH4	MT/MWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHE	MTCO2E/MWh	1.3	0.84	0.73	0.36	1.5	0.84	0.04	0.03

Table S8. Sensitivity of Emission Factors for WTE to System Efficiency, Waste Composition and Remanufacturing Benefits of Steel Recovery

				Sensitivity on:				
		Baseline Factors		**System Efficiency**	**Waste Composition**		**Steel Recovery**	
Input Parameters Varied								
Heat Rate	BTU/kWh	18,000		**[11000, 23000]**	18,000	18,000	18,000	18,000
Efficiency	%	19		**[15, 30]**	19	19	19	19
Composition		Default		Default	**All Biogenic**	**All Fossil**	Default	Default
Stack Gas Limits		Reg	Avg	**Reg. / Avg.**	Reg.	Reg.	**Reg**	**Avg**
Steel Recovery		Excludes		Excludes	Excludes	Excludes	**Includes**	**Includes**
Results: Criteria Pollutants								
HCl	g/MWh	260	110	[71, 320]	240	280	260	110
Dioxins/Furans	g/MWh	8.1E-05	2.8E-05	[1.8E-05, 1.0E-04]	7.6E-05	9.1E-05	8.1E-05	2.8E-05
Ammonia	g/MWh	3.8E-03	3.8E-03	[2.4E-03, 4.8E-03]	4.4E-03	2.7E-03	3.8E-03	3.8E-03
Hg	g/MWh	5.0E-02	5.0E-02	[3.2E-02, 6.4E-02]	6.5E-02	2.7E-02	5.0E-02	5.0E-02

Table S9. Emission Factors for Long Haul of MSW by Heavy Duty Trucks and Rail

		Heavy Duty Trucks	**Rail**
Criteria Pollutants			
CO	g/ton-mile	8.9E-01	1.9E-01
NO_x	g/ton-mile	9.0E-01	3.9E-01
SO_x	g/ton-mile	2.6E-01	8.7E-02
PM	g/ton-mile	1.3E-01	1.1E-01
PM-10	g/ton-mile	NA	NA
Other Pollutants			
HCl	g/ton-mile	NA	NA
Dioxins/Furans	g/ton-mile	NA	NA
Ammonia	g/ton-mile	1.7E-04	5.6E-05
Hg	g/ton-mile	5.8E-07	2.0E-07
Greenhouse gases			
CO_2-biomass	g/ton-mile	2.5E-02	8.6E-03
CO_2-fossil	g/ton-mile	1.0E+02	3.6E+01
CH_4	g/ton-mile	1.7E-02	5.7E-03
CO_2e	MTCO2E/ton-mile	1.0E-04	3.6E-05

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