

**2014 ENERGY AND ECONOMIC VALUE OF MUNICIPAL SOLID
WASTE (MSW) AND NON-RECYCLED PLASTICS (NRP)
CURRENTLY LANDFILLED IN THE FIFTY STATES**

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EXECUTIVE SUMMARY

This report provides an update of the 2011 Earth Engineering Center (EEC) Report to the Plastics Division of the American Chemistry Council (ACC) quantifying the energy and economic value of municipal solid wastes (MSW) and non-recycled plastics (NRP). This update is based on the data obtained in Columbia University's 2013 *Survey of Waste Management in the U.S.* and from MSW characterization studies conducted by several states. The 2013 Survey uses waste numbers from 2011, while the 2011 study for ACC used waste numbers from 2008.

Recycling of plastics has continued to grow in the U.S. and increased to 2.66 million tons. This includes increased recovery of used plastics from polyethylene terephthalate (PET) and high density polyethylene (HDPE) bottles, HDPE and polypropylene (PP) non-bottle rigid plastics, and HDPE and low density polyethylene (LDPE) films, bags, and wraps. However, despite the growth in both access to and types of plastics collected for recycling, some plastics cannot be economically recycled. For these plastics, conversion to energy is preferred over landfilling, which is consistent with the U.S. Environmental Protection Agency's (EPA's) waste management hierarchy.

The main objective of this study was to determine the quantity of non-recycled plastics in the United States that is available to be converted into energy. To do this, EEC calculated – nationally and by state - the amount of non-recycled MSW generated in the U.S. and the amounts recycled, composted, converted to energy, and landfilled. A second objective was to explore the potential for converting the landfilled NRP to electricity, heat, or fuel. Therefore, the quantities of MSW plastics recycled, combusted with energy recovery, and landfilled across the nation were estimated along with their energy and economic values.

This study reported that the MSW generated in the U.S. in 2011 was 389 million tons in 2011. Plastics represented less than 11% (41.2 million tons) of the total MSW stream. Of this amount, 2.66 million tons were recycled, 3.9 million tons were converted to energy in waste-to-energy (WTE) plants, 0.27 million tons were used as alternative fuel in cement production, and 34.4 million tons were landfilled. In a key difference from the previous report to ACC, the scope of this report was expanded to include plastics not counted by the EPA as MSW but disposed at MSW landfills. This includes 0.5 million tons of plastics in construction and demolition debris (C&D) and an estimated 1.9 million tons of plastics contained in automotive shredder residue (ASR).

Key findings:

- Between 2008 and 2011, recycling of materials from the U.S. MSW increased by 18.5 million tons while tonnage to waste-to-energy plants increased by 3.8 million tons. For plastics, the total recovery rate (recycling + energy recovery) increased from 14.3% in 2008 to 16.7% in 2011.
- If all the MSW that was landfilled in 2011 were to be diverted to WTE power plants, they could generate enough electricity to supply 13.8 million households, i.e., 12% of the U.S. total. In addition, if the steam turbine exhaust of the WTE plants were to be used for district heating, as is done in Denmark and some other northern European countries, the “waste” steam would provide district heating for an additional 9.8 million homes.
- Every ton of MSW combusted in recently built WTE power plants replaces an estimated 0.4 ton of coal. Therefore, diversion of MSW from landfills to new WTE plants could reduce coal mining in the U.S. by about 100 million tons per year.
- If MSW were to be used as a fuel in WTE power plants, it could replace all the coal imported by states such as New York, California, Idaho, New Jersey and Maine. Use of MSW fuel in place of coal could reduce the U.S. state-to-state transportation of coal by 22%.
- Diversion of all MSW from landfills to WTE plants could result in reducing the greenhouse gas (GHG) emissions of waste management in the U.S. by at least 123 million tons of carbon dioxide equivalent (2.1% of U.S. total greenhouse gas emissions), comparable to the annual emissions of over 23 million cars.
- The current annual landfilling of MSW in the U.S. is estimated to require a land surface of about 6,100 acres, equivalent to nearly 4,600 U.S. football fields, or seven New York City Central Parks; diversion of MSW to new energy recovery facilities would reduce the amount of land converted from greenfields to landfills every year.
- The average lower heating value of non-recycled plastics (NRP) was estimated at 30.7 million Btu/ton (35.7 MJ/kg). The amount of NRP landfilled in 2011 (34.4 million tons) contained a chemical energy content equivalent to:
 - 48 million tons of coal, or
 - 180 million barrels of oil, or
 - 1 trillion standard cubic feet of natural gas
- If the NRP were to be source-separated and converted through pyrolysis into synthetic oil, this could produce 136 million barrels of oil per year, or 5.7

billion gallons of gasoline, enough to fuel an estimated 8.9 million cars.

- Alternatively, if the NRP were to be source-separated and used as fuel in dedicated WTE facilities, these plants could generate 61.9 million MWh of electricity, enough to supply an estimated 5.7 million households.

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LIST OF ACRONYMS

ABS	Acrylonitrile butadiene styrene
ACC	American Chemistry Council
AF	Alternative fuel
ASR	Automotive shredder residue
Btu	British thermal unit
CCNY	City College of New York
C&D	Construction and demolition
EEC	Earth Engineering Center
EF	Engineered fuel
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Green house gases
HDPE	High density polyethylene
IPTF	Integrated Processing and Transfer Facility
LHV	Lower heating value
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
MRF	Materials recovery facility
MSW	Municipal solid waste
MWh	Megawatt hours
NRP	Non recycled plastics
ORCR	Office of Resource Conservation and Recovery of EPA
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
SOG	State of Garbage
WTE	Waste to Energy
WTERT	Waste to Energy Research and Technology Council

1. INTRODUCTION

1.1 Objective of this study

This report is an update of the 2011 Earth Engineering Center Report (1) to the Plastics Division of the American Chemistry Council (ACC) quantifying the energy and economic value of municipal solid waste (MSW) and non-recycled plastics (NRP). This update is based on the data obtained in Columbia University's *2013 Survey of MSW Management in the U.S.* (2) and in MSW characterization studies conducted by several states. It also includes estimates of the amounts of other combustible streams of waste that are landfilled in U.S. MSW landfills.

One of the objectives of this study was to determine the quantities of non-recycled plastics (NRP) generated in the U.S. and how they are disposed nationally and by state. Another objective was to explore the potential for converting MSW, including non-recycled plastics (NRP) that are currently landfilled, into energy or fuel. The quantities of MSW and plastics recycled, combusted with energy recovery, and landfilled across the nation were estimated along with their energy value.

In addition, the current study included other waste streams that contain NRP, such as construction and demolition debris (C&D) and automotive shredder residue (ASR) that are currently landfilled, instead of being used as a source of energy.

1.2 The Earth Engineering Center and the Hierarchy of Waste Management

The Earth Engineering Center of Columbia University (EEC; ref. 3) is an academic research group recognized internationally for its extensive research and publications on materials and energy recovery from solid wastes. EEC has a wide global presence through its Waste-to-Energy Research and Technology Council (WTERT, www.wtert.org), an academia-industry consortium established in 2003. Since publication of the EEC 2011 report to ACC, the Global WTERT Council (global.wtert.org) has expanded to thirteen sister national organizations, including in Brazil (www.wtert.br), China (www.wtert.cn), and India (www.wtert.in).

The guiding principle of all EEC research is that responsible management of wastes must be based on science and the best available technology, and not on ideology and economics that exclude environmental costs. The Research Associates of EEC include Columbia University and City College of New York (CCNY) faculty, as well as specialists from other universities and organizations. The Hierarchy of Sustainable Waste Management (Figure 1, ref. 4) shows the generally preferred order of priority of various means for managing wastes; by now, it has been translated into ten languages.

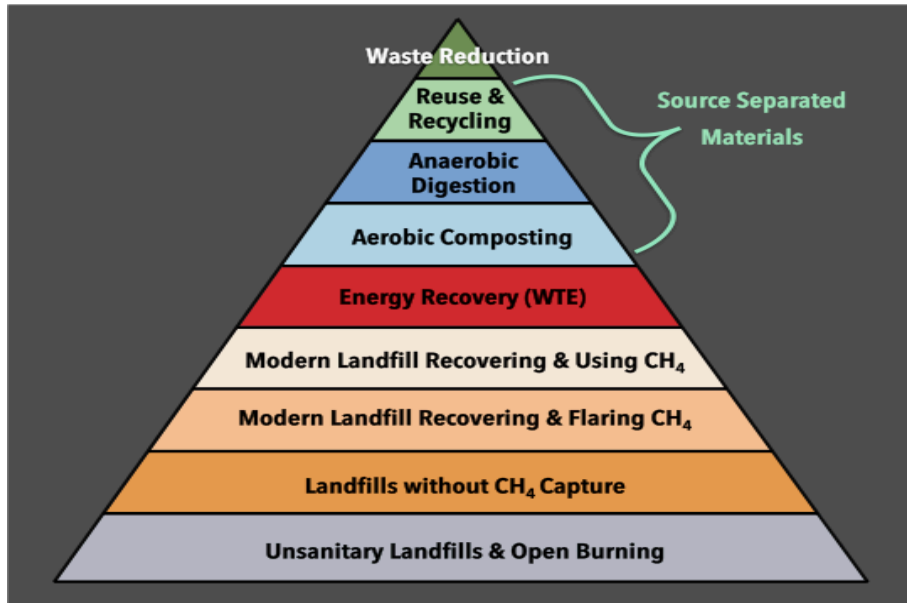


Figure 1: Hierarchy of Sustainable Waste Management developed by the EEC (4)

1.3 The Columbia/BioCycle Survey of MSWmanagement in the U.S.

In the years 2004-2010, the Earth Engineering Center collaborated with BioCycle journal on a bi-annual survey of MSW management in the U.S., called *State of Garbage in America* (SOG). The 2010 SOG Survey (5) was based on 2008 data and its results were used in the EEC 2011 study of non-recycled plastics (NRP), sponsored by the American Chemistry Council (1). Since 2009, the EPA has used the results of the Columbia/BioCycle Survey to calculate the greenhouse gas (GHG) effects of waste management.

The 2013 *Survey of Waste Management in the U.S.* was carried out solely by EEC and was sponsored by several organizations including the American Chemistry Council (ACC); it was based on 2011 data submitted by each state. At the request of EEC, the draft of the 2013 Survey Questionnaire was first reviewed by EPA's Office of Resource Conservation and Recovery (ORCR). Their comments were incorporated and the Questionnaire was then submitted in interactive form to the agencies responsible for waste management in the fifty states. Only eight states, representing 13% of the U.S. population, did not provide data. In these cases, data from the 2010 Columbia/BioCycle State of Garbage Survey was used, adjusted for population growth between 2008 and 2011.

2. MSW RECYCLED, COMBUSTED AND LANDFILLED IN EACH STATE

2.1 Comparison of EEC Survey of 2011 data and EPA 2011 Facts and Figures Report

The results of the Columbia 2013 Survey, using 2011 data, showed that the U.S. generated a total of 389 million tons of MSW, corresponding to a per capita generation of 1.3 short tons of MSW per year. Of the MSW generated, 22.6% was recycled, 6.3% composted, 7.6% was combusted with energy recovery at U.S. WTE plants, and 63.5% was landfilled. The 2013 Survey showed that, in comparison to the 2010 SOG Survey, landfilling decreased by about 20 million tons while recycling increased by nearly the same amount.

The Columbia 2013 Survey showed that in 2011 a total of 247 million tons of MSW was disposed in U.S. landfills, while the EPA Facts and Figures (7) reported that only 134.3 million tons were landfilled in that year. A comparison of these two estimates is shown in Table 1.

Table 1. Comparison of 2013 EEC Survey with EPA 2011 Facts and Figures Report

EEC 2011	EPA 2011	Difference (EEC minus EPA)
Total MSW generated 388,959,390	Total MSW generated 250,420,000	138,539,390
Recycled materials 87,808,128	Recycled materials 66,200,000	21,608,128
MSW Composted 24,646,893	MSW composted 20,700,000	3,952,774
MSW to WTE 29,746,223	MSW to WTE 29,260,000	486,223
MSW landfilled 246,977,177	MSW landfilled 134,260,000	112,717,177

The landfilling difference of 112.7 million tons, between the two studies, is due in part to the fact that the EPA definition of MSW does not include materials that do end up in MSW landfills, such as automobile shredder residue, commercial C&D debris, packaging from imported goods, municipal wastewater sludge, construction and demolition debris, small-scale manufacture wastes that are not recycled, etc. In contrast, the 2013 Columbia Survey is based on the sum of materials recycled, composted, combusted with energy recovery, and landfilled in MSW-designated-landfills, as reported by the waste management agencies of the fifty states. The Columbia Survey considers that all recyclable, compostable, or combustible materials that are discarded in MSW landfills represent a loss of materials or energy and an unnecessary use of land; therefore, they should be included in the national

account of waste management.

2.2 Results of Columbia’s Survey of 2011 national data

Table 2 shows the tonnages of MSW recycled, composted, combusted with energy recovery, and landfilled in the fifty states, according to the Columbia 2013 Survey of 2011 data (2). Figure 2 is a graphical representation of these data.

Table 2. U.S. recycling, WTE, and landfilling of MSW in 2011 (2)

State	Recycled	Combusted	Landfilled	Est. total	% Recycled
Alabama	486,260	178,690	4,730,330	5,435,579	9%
Alaska	30,166	0	647,227	677,393	4%
Arizona	382,645	0	6,609,376	7,057,796	5%
Arkansas	2,404,464	0	3,272,797	5,766,850	42%
California	27,746,174	856,121	30,047,841	66,299,346	42%
Colorado	1,745,860	0	6,138,752	8,062,492	22%
Connecticut	532,888	2,154,044	247,995	3,273,172	17%
Delaware	152,919	0	672,761	1,022,328	15%
District of Columbia	20,122	216,903	228,524	471,430	9%
Florida	7,364,857	5,798,975	13,877,987	26,824,098	29%
Georgia	691,386	0	9,869,000	10,600,921	7%
Hawaii	612,907	545,830	2,452,165	3,881,007	16%
Idaho	156,200	0	1,668,578	1,824,778	9%
Illinois	1,000,877	0	12,132,946	13,629,998	7%
Indiana	490,728	704,675	4,880,873	6,431,339	8%
Iowa	942,760	38,814	2,696,788	3,930,755	24%
Kansas	932,721	0	2,263,336	3,284,855	28%
Kentucky	1,660,239	0	4,195,361	6,222,727	27%
Louisiana	30,908 [1]	0	5,166,775	5,783,868	1%
Maine	674,258	472,478	212,836	1,632,151	48%
Maryland	1,572,200	1,389,632	2,352,939	6,096,061	26%
Massachusetts	2,152,212	3,174,603	1,533,068	7,526,336	29%
Michigan	833,589	993,990	11,952,636	13,783,782	6%
Minnesota	2,556,996	1,145,487	1,784,719	5,578,298	45%
Mississippi	131,602		2,729,305	2,866,104	5%
Missouri	967,814		3,965,327	4,933,141	20%
Montana	252,734		1,366,226	1,694,083	15%
Nebraska	333,207		2,219,461	2,552,668	13%
Nevada	1,150,601		2,809,979	4,046,301	28%
New Hampshire	466,707	251,539	402,497	1,158,418	41%
New Jersey	4,346,256	2,129,852	4,384,975	10,880,082	40%
New Mexico	339,590		1,981,884	2,389,434	14%
New York	2,246,064	3,686,097	10,263,710	17,525,006	13%
North Carolina	790,686		7,702,232	9,137,435	9%
North Dakota	90,000		675,000	935,000	10%
Ohio	2,461,594		9,126,809	12,729,405	19%
Oklahoma	176,961	204,633	4,397,372	4,776,799	4%
Oregon	1,438,560	181,316	1,918,649	3,953,185	36%
Pennsylvania	4,465,949	3,084,639	5,902,677	14,249,335	32%
Rhode Island	64,480		793,000	922,480	7%
South Carolina	954,748		3,295,771	4,425,431	22%
South Dakota	157,306		646,561	864,702	18%
Tennessee	1,531,310		6,036,132	7,642,442	20%
Texas	2,780,213		23,720,134	31,101,890	9%
Utah	56,474	126,522	2,059,152	2,533,390	2%
Vermont	120,009		379,005	535,425	22%
Virginia	2,830,702	2,037,401	10,095,859	15,345,008	18%

Washington	3,244,620	276,753	4,113,753	8,806,410	37%
West Virginia	345,271		1,812,675	2,157,946	16%
Wisconsin	843,934	76,000	4,181,867	5,661,515	15%
Wyoming	46,400		610,080	729,335	6%
Total	87,808,128	29,746,223	246,997,177	389,198,422	23%

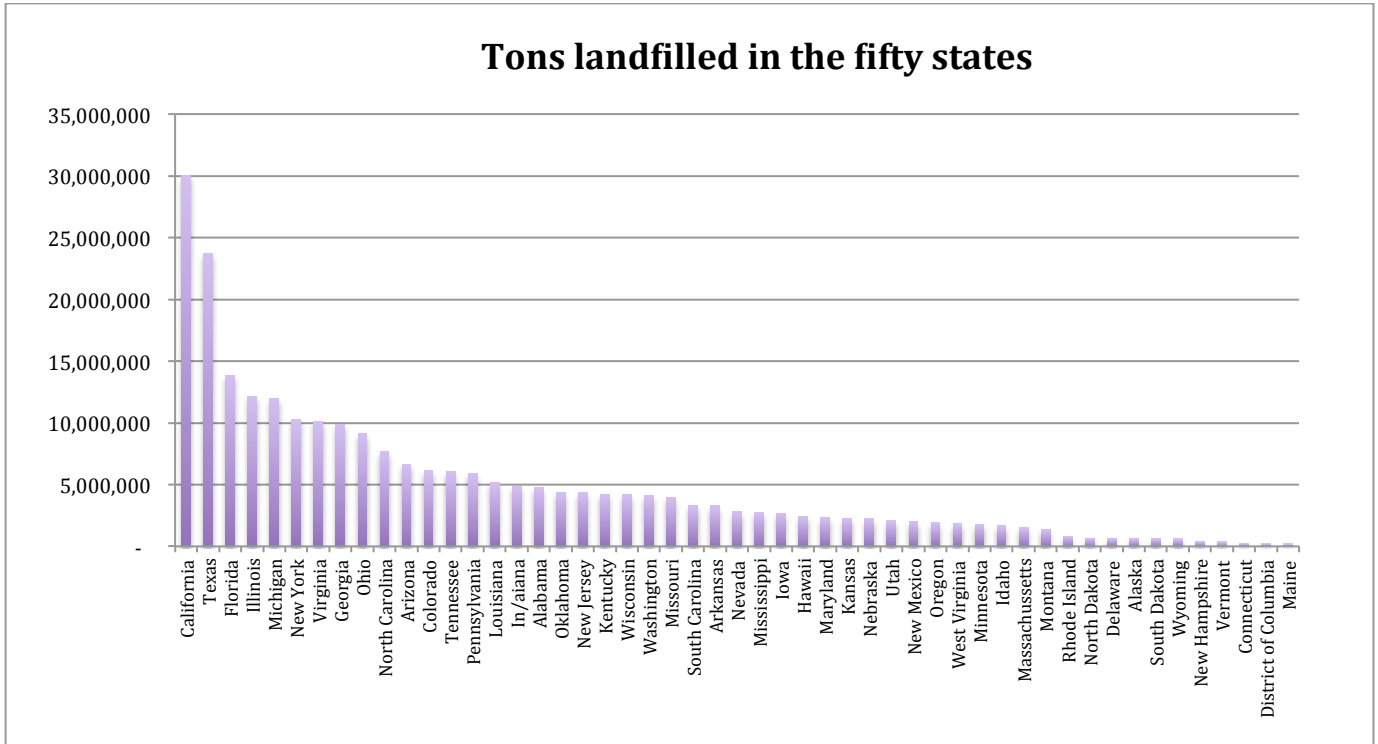


Figure 2: Tons of MSW landfilled per state

3. ESTIMATE OF U.S. GENERATION OF PLASTIC WASTES

3.1 Plastics in the MSW stream

The EPA Facts and Figures 2011 report (ref. 8, Table 1, p.9) estimated a total generation of post-consumer plastic wastes of 31.8 million tons. This was higher than the amount reported by EPA in 2008 (30 million tons). Also, EPA reported that 2.66 million tons of plastics were recycled in 2011 vs. 2.12 million tons in 2008. Table 3 compares the EPA numbers for generation, recycling and landfilling of U.S. NRP in 2008 and 2011 (8). It should be noted that both of the EPA reports combined the NRP that are combusted with energy recovery in WTE plants with those that were landfilled. This practice is not in accord with EPA's own waste management hierarchy which shows that energy recovery is preferable to landfilling. Table 10, presented later in this report, does differentiate between these two quite different methods of managing NRP.

Table 3. Comparison of the EPA 2008 and 2011 estimates of generation, recycling and disposal of plastics (in 1000 tons; ref 8)

(In 1000's of tons)	Generated, 2008	Recycled, 2008	Landfilled plus WTE 2008	Generated, 2011	Recycled, 2011	Landfilled plus WTE, 2011
Total durable goods	10,520	390	10,130	11,420	740	10,680
Non durable						
Cups/plates	780	Negligible	780	1,030	Negligible	1,030
Trash/bags	930	Negligible	930	1,010	Negligible	1,010
Other non durables	4810	Negligible	4,810	4,480	110	4,370
Total non durables	6,520	0	6,520	6,520	110	6,410
Bottles/jars, PET	2,680	730	1,950	2,740	803	1,937
Bottles/jars, HDPE	750	220	530	770	230	562
Other containers	1,900	280	1,620	1,870	290	1,767
Bags, sacks, wraps	3,960	390	3,570	3,880	430	3,683
Other packaging	3,720	110	3,610	4,640	60	3,460
Total Containers/packages	13,010	1,730	11,280	13,900	1,813	11,497
Total plastics	30,050	2,120	27,930	31,840	2,663	29,177
Total plastics (in %)	100%	7.1%	93%	100%	8.4%	91.6%

3.2 Concentration of plastics in MSW to WTE plants and landfills

The EPA 2011 Facts and Figures estimated that the concentration of plastics in their definition of MSW (250.4 million tons) was 12.7% (8). In the present study, the concentration of NRP in MSW to WTE plants or landfills was based on the detailed MSW characterization studies of 14 states (Table 4), during 2003-2011. For example, the Indiana study, by Purdue University (9), included rigorous MSW analysis tests at landfills in five counties in which nearly sixty different types of materials were sorted out. As shown in Table 4, these fourteen states in total represented a population of 139 million people. The composition of NRP ranged from a low of 9.6% to a high of 17%, and the average weighted composition was 13.16%. In the following calculations, it is assumed that the non-recycled MSW that was converted to energy at WTE plants, or landfilled, contained 13.2% NRP.

Table 4. Plastics composition in 14 state studies of non-recycled MSW

State	Year	Plastics in MSW	Population	Weighted % of Plastics	Tons of non-recycled MSW
California (a)	2008	9.60%	37,691,912	2.61%	30,047,841
Connecticut (b)	2010	14.70%	3,580,709	0.38%	247,995
Delaware (c)	2007	11.10%	907,135	0.07%	672,761
Georgia (d)	2005	15.80%	9,815,210	1.12%	9,869,000
Illinois (e)	2008	15.62%	12,869,257	1.45%	12,132,946
Indiana (f)	2011	16.10%	6,516,922	0.76%	4,880,873
Iowa (g)	2005	11.78%	3,062,309	0.26%	2,696,788
Minnesota (h)	2000	11.40%	5,344,861	0.44%	1,784,719
New York (i)	2010	17.00%	19,465,197	2.38%	10,263,710
Maryland (j)	2009	14.40%	4,574,836	0.47%	5,166,775
Ohio (k)	2004	15.62%	11,544,951	1.30%	9,126,809
Oregon (l)	2009	11.56%	3,871,859	0.32%	1,918,649
Pennsylvania (m)	2003	11.30%	12,742,886	1.04%	5,902,677
Washington (n)	2009	11.40%	6,830,038	0.56%	4,113,753
Total of 14 studies			138,818,082	13.16%	98,825,295

- a) Cascadia Consulting Group. *California 2008 Statewide Waste Characterization Study*; 2009.
- b) DSM Environmental Services I, Cascadia Consulting Group undefined Mid-Atlantic Solid Waste Consultants. *Connecticut Statewide Solid Waste Composition and Characterization Study, Final Report*; 2010.
- c) Cascadia Consulting Group. *Delaware Solid Waste Authority Statewide Waste Characterization Study, 2006-2007; 2007:2006-2007*.
- d) Beck RW. "Georgia Statewide Waste Characterization Study," 2005.
- e) Illinois Recycling Association "Illinois Commodity/Waste Generation and Characterization Study," 2009.
- f) Abramowitz H. and Sun Y. "Municipal Solid Waste Characterization Study for Indiana," Purdue University, 2011.
- g) Beck RW, "Iowa Statewide Waste Characterization Study," 2006.
- h) Beck RW, "Final Report Statewide MSW Composition Study," 2000.
- i) Department of Environmental Conservation, "Solid Waste Composition and Characterization-MSW Materials Composition in New York State." Available at: <http://www.dec.ny.gov/chemical/65541.html> [Accessed February 2011]
- j) SCS Engineers, "Waste Composition Sampling & Analysis Study," 2009.
- k) Engineering Solutions & Design, Inc., "State of Ohio Waste Characterization Study," 2004.
- l) Oregon Department of Environmental Quality, "Oregon Statewide Waste Composition 2009 Field Data," 2009.
- m) Beck RW, "Statewide Waste Composition Study," 2003.
- n) Cascadia Consulting Group, "Washington Statewide Waste Characterization report," 2009.

3.3 Tonnage of plastics to WTE plants and to landfills

Multiplying the 2013 national tonnage of post-recycling MSW to WTE plants (29.7 million tons – EEC estimate) by the average concentration of plastics from Table 4 (13.2%) yields the tonnage of NRP that were combusted with energy recovery nationally (3.9 million tons).

Similarly, multiplying the 2013 EEC estimate of tonnage of post-recycling MSW to landfills (247 million tons) by the average concentration of plastics (13.2%) yields the tons of plastics landfilled (i.e., 32.5 million tons).

3.4 Amount of plastics recycled nationally in 2011

The American Chemistry Council (10, 11) estimated that the recycling of non-durable plastics increased from 1.82 million tons in 2008 to 1.9 million tons in 2011. Adding to this number the 0.74 million tons of recycled durable plastics estimated by EPA (11) results in a total of 2.66 million tons of plastics recycled in 2011. This estimate is aligned with the EPA estimate of 2.65 million tons (Table 5).

Table 5. Components of plastics stream (10, 11, 12, 13)

Component of plastic stream	Tons '08	% '08	Tons '11	% '11
PET bottle	722,000	32.6%	802,820	30.3%
HDPE bottles	490,000	22.2%	229,961	8.7%
PP bottles	13,500	0.6%	19,841	0.7%
Bags/films	416,000	18.8%	430,000	16.3%
Non-bottle rigid plastics	180,000	8.1%	423,102	16.0%
ACC total of recycled non durable goods	1,821,500	82.4%	1,905,724	72.2%
EPA estimate of recycling of durable goods	390,000	17.6%	740,000	27.8%
Total tons of plastics recycled	2,211,500	100.0%	2,645,983	100.0%

3.6 Plastics in C&D waste

The 1996 EPA report on C&D waste (14), estimated the amount of C&D waste at 136 million tons. Extrapolating this number to 2011 by considering population growth increases this amount to 157 million tons. However, the construction industry is more likely to be aligned with economic rather than population growth (15).

Therefore, prorating the 136 million tons generated in 1996 to 2011, on the basis of economic growth, puts the amount of C&D waste in 2011 to 189 million tons. According to the EPA report referred to above (14), 20-30% of the C&D waste is recovered for re-use, 35-45% is landfilled in C&D landfills, and another 30-40% is disposed in MSW landfills (i.e. about 65 million tons).

The Cascadia Consulting Group analyzed the composition of C&D waste of California in 2006; the results are shown in Table 6 (16).

Table 6. Composition of C&D waste (16)

Composition of C&D waste	%
Paper	3.2%
Glass	1.1%
Metal	4.0%
Electronics	0.2%
Plastics	0.8%
Organic	3.0%
Household Hazardous Waste	0.4%
Special Waste	0.6%
Mixed Residue	0.1%
Concrete, stones, bricks, asphalt, and wood	86.7%

According to the Cascadia study, plastics comprised only 0.8% of the C&D waste; assuming that the 2011 composition of C&D waste has not changed since 2006, the 2011 contribution of U.S. C&D waste to non-recycled plastics is estimated at about 0.5 million tons.

3.7 Plastics in ASR waste

According to the U.S. Department of Transportation (17), 12.3 million vehicles were scrapped in 2011. An estimated 23 million tons of vehicles were shredded in industrial plants and the shredded materials were sorted mechanically to ferrous and non-ferrous metals that were sold to smelters. Of this amount, 4.5 million tons (19%) of “automobile shredder residue” (ASR) were landfilled (Table 7; ref. 18). The percentage of plastics and other combustible materials in the ASR is very high. Of the 4.5 million tons of ASR generated in 2011, an estimated 1.9 million tons (i.e., 42%) were plastics and 1.1 million tons (24%) rubber.

Table 7. Composition of materials in the automotive waste industry (18)

Shredded Automobile Material	Generation (1000's of tons)	Estimated % of shredder material	Estimated % of automotive shredder residue
Regular steel	9,484	40.3%	
Hi/Med Strength Steel	2,981	12.7%	
Stainless Steel	412	1.8%	
Other Steels	177	0.8%	
Iron castings	1,850	7.9%	

Copper and brass	295	1.3%	
Aluminum	1,802	7.7%	
Total Recycled	17,000	72.2%	
Plastics and Composites	1,897	8.1%	42%
Rubber	1,072	4.6%	24%
Coatings	153	0.7%	3%
Textiles	247	1.1%	5%
Glass	601	2.6%	13%
Other Materials	530	2.3%	12%
Total Landfilled	4,500	19.1%	100%
Magnesium Castings	58	0.2%	
Lead	295	1.3%	
Zinc Castings	236	1.0%	
Powder Metal Parts	51	0.2%	
Other Metals	247	1.1%	
Fluids and Lubricants	1,241	5.3%	
Total Partially Recycled	2,127	9.0%	
TOTAL	23,627	100%	

As noted earlier, EPA’s definition of MSW “does not include wastes of other types, including ASR, wastewater treatment sludge, ash, light industry residues, etc. that are also disposed in municipal waste landfills” (19). On the other hand, the Columbia Survey considers that all recyclable, compostable, or combustible materials that are discarded in MSW landfills represent a loss of materials or energy, as well as unnecessary use of land, and therefore should be included in the national survey of waste management.

Table 8 shows the types of plastics used by the automotive industry. Because plastics and composites are used more and more in automobiles, the amount of plastics ending in ASR will most likely increase (20). Analysis by EPA has shown (52) that the separation, recycling and use of plastics from shredder residue is consistent with existing authorizations that allow the use and distribution in commerce of products that contain low levels of PCBs, including provisions for “excluded PCB products” and “excluded PCB manufacturing processes” (as defined in 40 CFR 761.3).

Table 8 shows the plastic constituents of ASR, their concentration, heating value, and respective tonnages generated annually in the U.S. The average lower heating value (LHV) of ASR is estimated at about 32 million Btu/ton (37 MJ/kg).

Table 8. Plastics composition in vehicles (21) and energy content of each type of plastic (22, 23, 24 and 25)

Plastics composition in cars	%	MJ/kg	Million BTU/ton
PP	37.0%	44.3	38
Polyurethane	17.3%	27	23.2
ABS	12.3%	38.1	32.7
HDPE	10.8%	44.2	38

PC	6.8%	32.3	37.7
PMMA	4.4%	25.1	21.5
Composites	11.5%	30	25.7
Total	100%	37	32.0

3.8 NRP used as alternative fuels (AF) in cement kilns

A 2013 study by Jiao Zhang of the EEC (30) examined the use of alternative fuels (AF) in the U.S. cement industry, which produced 68 million metric tons of cement in 2011. The use of AF increased two-fold from 1993, up to 58 million GJ in 2011, corresponding to 20.9% of the total energy consumption in cement production. One of the two principal alternative fuels is used rubber tires and in 2011 amounted to 320,000 metric tons. The other type of AF, sometimes called “engineered fuel” (EF), involves processing to remove metals, glass, and other contaminants leaving a mixture of NRP and paper residues that are shredded and homogenized. The EF feedstock can come from post-industrial waste, materials recovery facilities (MRF), or even MSW. In 2011, the use of EF amounted to 699,000 metric tons, i.e., about 770,000 tons short tons.

Comparison of the LHV of EF (18 MJ/kg; ref. 40) to the LHV of plastic wastes (35.7 MJ/kg) and paper fiber (12 MJ/kg) leads to the conclusion that an approximate 35% of the EF (i.e., 270,000 short tons) is derived from NRP.

The use of EF in the cement industry effectively increases the total waste-to-energy (WTE) transformation in the U.S. by 0.77 million tons, or about 2.7%. Energy recovery from NRP in WTE plants (3.9 million short tons; Section 4.5) is added to the energy recovery from NRP used in cement production (0.27 million short tons) in Table 11 (Section 4.7).

3.9 Non-hazardous, small-company industrial wastes

Small industrial companies cannot recycle their residues easily and it is likely that many of these residues end up in MSW landfills or at WTE plants. As noted earlier, these unaccounted wastes add to the discrepancy between the EEC and EPA estimates of landfilled tons.

4. STATE BY STATE ESTIMATE OF PLASTICS RECYCLED, COMBUSTED WITH ENERGY RECOVERY, AND LANDFILLED

4.1 Summing up of plastic waste generation and disposition in 2011

As discussed in earlier sections, the total amount of plastic wastes in the MSW stream consisted of 2.66 million tons recycled, 3.9 million tons combusted in WTE plants, 0.27 million tons used as fuel in cement kilns, and 32.5 million tons landfilled. To the landfilled amount, EEC has added 1.9 million tons of plastics in the

ASR landfilled, since this material is not included in the MSW characterization studies carried out by the states. Therefore, the total amount of non-recycled plastics disposed in landfills in 2011 was estimated at 34.4 (32.5 +1.9) million tons. The methodology used in developing the state-by-state data was as follows:

- a) As noted earlier, the total amount of plastics recycled in 2011 has been estimated by EPA, and confirmed by the American Chemistry Council, at 2.66 million tons. This amount was apportioned to each state in accordance to the fraction of national recycling (87.8 million tons of all materials in MSW stream), as reported by each state to the Columbia University 2013 *Survey of Waste Management in the U.S.*
- b) The percentage of plastics present in post-recycling MSW was based on the very detailed characterization studies carried out by fourteen states, during the period of 2003-2011. In total, these states represented a population of 140 million people. The composition of post-recycling MSW ranged from a low of 9.6% to a high of 17%, and the average weighted composition was 13.2%.
- c) The tonnages of MSW combusted with energy recovery in each state, as reported by the states to the Columbia 2013 Survey, were multiplied by the average plastics composition of 13.2% to yield the amounts of NRP processed in WTE plants and converted to energy in each state.
- d) The tonnages landfilled in each state, reported by the states to the Columbia 2013 Survey, were multiplied by the average plastics composition of 13.2% to yield the amount of NRP disposed at landfills, in each state.

The results are discussed in the following sections.

4.2 Tons of plastic recycled in each state

In the 2011 EEC report to the American Chemistry Council (1), the estimate of tons of plastics recycled in a state (based on the percentage of national recycling reported by the state) was compared to the percentage of the national capacity of materials recovery facilities existing in the state. The results of this comparison were in good agreement, i.e., states that had more MRF capacity recycled more. In this study, the total amount of plastics recycled nationally (2.66 million tons) was distributed across the states on the basis of the ratio of reported tons of all materials recycled, divided by the national recycled tonnage (87.8 million tons). For example, the state of California reported recycling of 27.7 million tons; therefore, the plastics recycled in California were estimated to be 841,000 ($2.66 \times 27.7/87.8$) tons.

4.3 Tons of plastic combusted with energy recovery in each state

The amount of NRP sent to WTE plants in a state was estimated by multiplying the tons of MSW to state WTE plants by the 13.2% concentration of plastics in the MSW to WTE plants and landfills (Table 4). For example, Connecticut reported 2.15

million tons combusted in the state's WTE facilities; therefore, the amount of NRP used for electricity production was 2.28 million x 13.2% = 292,000 tons.

4.4 Estimate of plastic wastes landfilled

The amount of plastics landfilled in each state was obtained by multiplying the tons of MSW landfilled, as per the Columbia 2013 Survey, by the 13.2% average concentration of plastics in the MSW to landfills (Table 4). For example, Florida landfilled 13.9 million tons of MSW, which contained an estimated 1.83 million tons of NRP.

4.5 Recycling, energy recovery, landfilling, and generation of plastics in each state

The results of the above calculations are shown in Table 9.

Table 9. Tons of plastics recycled, combusted for energy, landfilled and generated in each state

	Population 2011	Plastics recycled	Plastics to energy recovery plants	Plastics to landfills	Total plastic wastes generated
Alabama	4,802,740	14,746	28,810	622,328	665,884
Alaska	722,718	915	0	85,150	86,065
Arizona	6,482,505	11,604	0	869,538	881,141
Arkansas	2,937,979	72,915	0	430,573	503,489
California	37,691,912	841,403	112,632	3,953,131	4,907,166
Colorado	5,116,796	52,943	0	807,622	860,565
Connecticut	3,580,709	16,160	291,862	32,627	340,648
Delaware	907,135	4,637	0	88,509	93,147
District of Columbia	617,996	610	28,536	30,065	59,211
Florida	19,057,542	223,339	734,277	1,825,805	2,783,421
Georgia	9,815,210	20,966	0	1,298,378	1,319,344
Hawaii	1,374,810	18,586	71,395	322,610	412,591
Idaho	1,584,985	4,737	-	219,520	224,257
Illinois	12,869,257	30,352	-	1,596,225	1,626,577
Indiana	6,516,922	14,881	91,471	642,134	748,486
Iowa	3,062,309	28,589	5,092	354,793	388,474
Kansas	2,871,238	28,285	-	297,767	326,052
Kentucky	4,369,356	50,347	-	551,947	602,294
Louisiana	4,574,836	937	-	679,747	680,685
Maine	1,328,188	20,447	91,114	28,001	139,562
Maryland	5,828,289	47,677	174,915	309,556	532,147
Massachusetts	6,587,536	65,266	418,387	201,692	685,345
Michigan	9,876,187	25,279	131,240	1,572,504	1,729,022
Minnesota	5,344,861	77,541	133,335	234,800	445,676
Mississippi	2,978,512	3,991	-	359,071	363,062
Missouri	6,010,688	29,349	-	521,683	551,032
Montana	998,199	7,664	-	179,742	187,407
Nebraska	1,842,641	10,105	-	291,995	302,100
Nevada	2,723,322	34,892	-	369,684	404,576
New Hampshire	1,318,194	14,153	34,915	52,953	102,021

New Jersey	8,821,155	131,800	282,705	576,893	991,398
New Mexico	2,082,224	10,298	-	260,739	271,037
New York	19,465,197	68,112	507,991	1,350,306	1,926,409
North Carolina	9,656,401	23,978	-	1,013,315	1,037,293
North Dakota	683,932	2,729	-	88,804	91,533
Ohio	11,544,951	74,648	-	1,200,734	1,275,382
Oklahoma	3,791,508	5,366	26,637	578,524	610,527
Oregon	3,871,859	43,624	24,919	252,420	320,963
Pennsylvania	12,742,886	135,430	420,769	776,563	1,332,762
Rhode Island	1,051,302	1,955	-	104,328	106,283
South Carolina	4,679,230	28,953	-	433,596	462,548
South Dakota	824,082	4,770	-	85,062	89,833
Tennessee	6,403,353	46,437	-	794,121	840,558
Texas	25,674,681	84,310	-	3,120,650	3,204,960
Utah	2,817,222	1,713	16,361	270,905	288,978
Vermont	626,431	3,639	-	49,862	53,502
Virginia	8,096,604	85,841	266,094	1,328,224	1,680,159
Washington	6,830,038	98,393	37,076	541,210	676,679
West Virginia	1,855,364	10,470	-	238,478	248,948
Wisconsin	5,711,767	25,592	11,454	550,172	587,218
Wyoming	568,158	1,407	-	80,263	81,670
Total	311,591,917	2,662,781	3,941,987	32,525,319	39,130,087
% of plastic wastes generated		6.8%	10.1%	83.1%	100.0%

4.6 Discussion of results

The present study showed that 6.5% of the plastics present in the MSW stream (2.66 million tons) were recycled, 9.7% (3.9 million tons) was combusted with energy recovery, and 0.7% (0.27 million tons) was used as alternative fuel in cement kilns. This represents an increase in the total recovery rate (recycling + energy recovery) of plastics from 14.3% in 2008 to 16.6% in 2011; most of the NRP (83.3% or 32.5 million tons) was landfilled. The percent distribution of recycling, energy recovery, and landfilling of plastics in the waste stream across the fifty states is shown in graphical form in Figure 3. The states near the top of this graph, i.e., higher up on the “ladder” of sustainable waste management, are Connecticut, Maine, Massachusetts, Minnesota and New Hampshire. These states combine a high rate of recycling with a high waste-to-energy capacity.

4.7 Generation and disposition of plastic wastes in 2011

Table 10 shows the generation and disposition of plastic in the waste stream in 2011. The amount of plastics in the MSW stream in 2011, as estimated by the EEC, is 39 million tons. The plastics in C&D debris (0.5 million tons) are considered to be accounted for in the MSW stream whereas the automotive shredder residue (1.9 million tons) that is landfilled in MSW landfills should be added, as is done in Table 10. Therefore, the total amount of plastic wastes generated in 2011 was estimated at 41.2 million tons. Of this amount, 2.66 million tons were recycled, in comparison to 2.2 million tons in 2008. The quantity of plastics combusted with energy recovery in WTE facilities was 3.9 million tons while cement kilns used 270,000 tons of NRP

as an alternative to conventional fuels such as coal and petroleum coke. Finally, 34.4 million tons of plastics were landfilled. Table 10 summarizes the generation and disposition of plastic wastes in 2011.

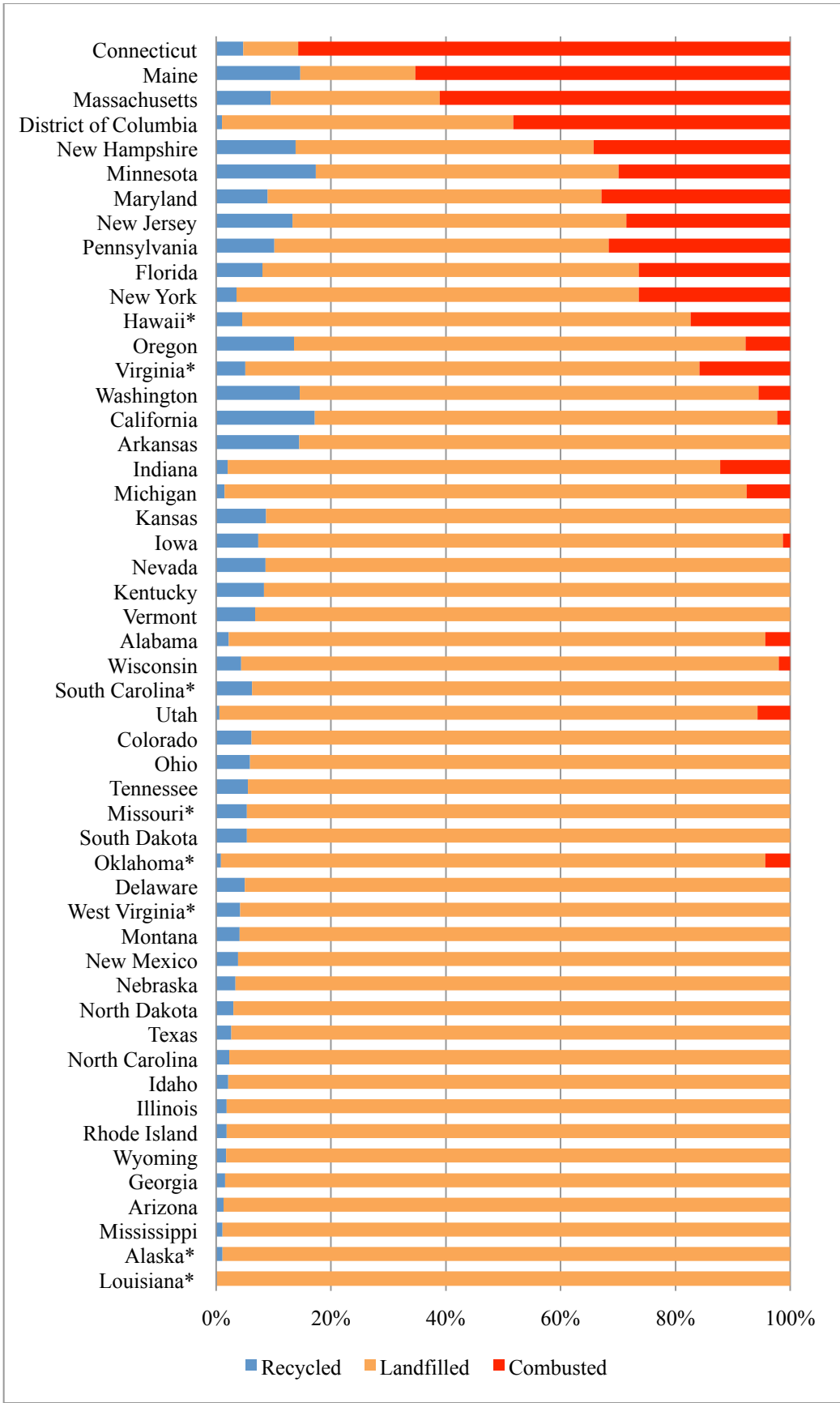
Table 10. Generation and disposition of plastic wastes in 2011 (in short tons)*

<i>Generation</i>	Tons	Percent of all plastic waste
Plastics in MSW	39,341,484	95.4%**
Plastics landfilled as ASR	1,896,743	4.6%
Total plastics generated	41,238,227	100.0%
<i>Disposition</i>	Tons	Percent of all plastic waste
Plastics recycled	2,662,781	6.5%
Plastics as alternative fuel for cement kilns	270,000	0.7%
NRP to WTE	3,941,987	9.5%
NRP to landfills includes landfilled ASR)	34,363,459	83.4%
Total plastics disposed	41,238,227	100.0%

* The generation of plastics looks at the quantities of plastics generated but not at the end destination while the disposition of plastic wastes is repartitioned according to its destination (where does it go to?), i.e. amount of plastics recycled, plastics used in cement kilns and plastics that were not recycled (NRP).

** This percentage does not indicate a presence of 95.4% of plastics in the MSW stream but applies to the ratio of 39,341,484 tons of plastics in MSW to the total amount of 41,238,227 tons of plastics generated, i.e. of all plastics that are present in the various waste streams, 95.4 % finds its origins in municipal solid waste.

Figure 3 (on next page): State-by-state comparison of the fraction of plastics recovered as materials (i.e. recycling; blue bars), as electricity or heat (red bars), and landfilled (brown bars), in 2011. States with higher sum of materials and energy recovery from plastic wastes are placed higher up on the “ladder” of waste management.



5. POTENTIAL FOR ENERGY RECOVERY FROM NRP

Energy is recovered from NRP at WTE facilities by combustion to generate steam and electricity; by partial combustion, to produce syngas; or by pyrolysis, to produce synthetic oil. In 2011, most of the energy recovery from non-recycled plastics was by combustion in the 84 waste-to-energy plants of the U.S. An estimated 3.9 million tons of plastics, mixed in the municipal solid waste stream to WTE plants, were processed in this way.

As noted earlier, a certain amount of plastic and paper residues is used as an alternative to fossil fuels by the U.S. cement industry. This “engineered fuel” (EF) is co-combusted with petroleum coke, coal, or other fossil fuels to produce clinker in rotary kilns which is then ground to cement. The American Chemistry Council, in collaboration with the University of Texas, has reported that the use of EF for cement production has several environmental benefits (e.g., lower CO₂, SO₂ emissions, etc.) (49). The environmental benefits of using EF from non-recycled waste have also been studied by EEC (30) under the sponsorship of CEMEX cement company.

Pyrolysis is a process that transforms the NRP to oil and some syngas by thermal or thermal/catalytic de-polymerization at moderate temperatures and in the absence of oxygen. An external heat source is needed and is usually provided by combustion of the syngas by-product in a separate combustion chamber and then by transferring the heat of combustion to the pyrolysis reactor across a metal interface. There are several pyrolysis processes under development, including Agilyx (43), Climax Global Energy (44), RES Polyflow (45), CYNAR (46), Vadxx (47), JBI (48) and others. Some of these processes are discussed in the EEC thesis of Demetra Tsiamis (33) and others will be discussed in the forthcoming EEC-Columbia thesis of Diane Ye. Since the chemical energy stored in one ton of NRP is equivalent to about 5 barrels of oil, these processes, operating at 80% thermal efficiency, are expected to produce, on average, four barrels of oil per ton of plastic wastes processed.

Another way to increase diversion of NRP from landfills is by converting them to thermal energy in new WTE plants. In this way, energy would be recovered from plastics and also other combustible components in the MSW stream.

5.1 Energy value of plastic wastes

In the 2011 Report of EEC to ACC, the LHV of plastic wastes was estimated at 28 million Btu (32 MJ/kg) per short ton. However, in the meantime, it came to the attention of EEC that the LHV of LDPE, provided in the 2007 report of the EIA (24.1 MJ/kg; ref. 32) and used in the 2011 EEC Report to ACC, was too low. Several sources were consulted (ref. 22, 23, 24, 32, 33, 42) and there is agreement as to the proper values of the principal resins in NRP, as shown in Table 11.

Table 11. Comparison of lower heating values (LHV) reported in literature for principal components of plastics in the waste stream (ref. 22, 23, 24, 32, 33, 42)

LHV, Plastic material	EIA, 2008, Mbtu/ton	Stanford, MJ/kg	Polymer Handbook, MJ/kg	Franklin Associates, MJ/kg	Phyllis database, MJ/kg	Used in this study MJ/kg
PET	20.5	23.2	-	24.7	21.9	23.9
HDPE	38	44.6	43.6	46.5	43.6	44.3
Polyvinyl chloride (PVC)	16.5	-	16.4	18.3	16.8	19.2
LDPE/LLDPE	24.1	42.2	-	46.2	43.5	44.3
PP	38	42.7	43.4	46.4	44.2	44.3
Polystyrene (PS)	35.6	42.0	39.2	-	44.2	41.5

Table 12 shows the recalculation of the average LHV of plastics in the waste stream to MRFs and WTE plants. It is estimated at 30.6 million Btu/ton (35.7 MJ/kg).

Table 12. Plastics composition and lower heating value (LHV) of principal plastics in the U.S. generated plastic waste stream (ASR excluded)

LHV, Materials	NRP in thousands of tons	% in NRP	MJ/kg	Million Btu/ton	MJ/kg NRP	Million Btu/ton
PET	4,878	12.40%	24	21	3.0	2.5
HDPE	7,003	17.80%	44	38	7.8	6.7
PVC	2,164	5.50%	19	16.5	1.0	0.9
LDPE/LLDPE	7,711	19.60%	44	38	8.6	7.4
PP	5,468	13.90%	44	38	6.1	5.2
PS	3,423	8.70%	41	35.6	3.6	3.1
Other	8,655	22.00%	25	22	5.5	4.8
Total plastic wastes NRP	39,341	100%			35.7	30.6

An estimated 22% of the generated plastic wastes are categorized by EIA as “Other” and have a calorific value (LHV) of 22 million Btu/ton (25 MJ/kg). This is most likely due to the inclusion, in the “Other” category, of non-combustible and low calorific materials, such as inks, metals, paper, etc. It should be noted that the percent composition of plastics in the waste stream is the same as was presented in the 2011 EEC Report to ACC; the only difference is the corrected LHV of LDPE, i.e., 38 million Btu/ton (44 MJ/kg).

As mentioned earlier, in contrast to WTE plants, the NRP landfilled also includes ASR and C&D debris deposited in MSW landfills. Table 13 uses the LHV of Tables 8 (ASR) and 12 (NRP), and their respective tonnages (Table 10), to calculate the energy content in all plastic-containing streams discarded in landfills. Very little is known about the composition and calorific value of plastics contained in C&D debris; therefore it was assumed that its LHV is the same as the NRP in the MSW

stream (i.e., 30.6 million Btu/ton). The composite heating value of the plastic wastes ending up in U.S. landfills was estimated at 30.7 Btu/ton.

Table 13. Amount of plastics that are landfilled, present in MSW and ASR

	Tons	Million BTU/ton	Energy content (MBtu)
Plastics in MSW landfilled	32,495,253	30.6	994,351,130
Plastics in ASR landfilled	1,896,743	32.0	60,666,146
Total tons of plastics landfilled	34,391,996	30.7	1,055,017,276

5.2 Energy equivalence of NRP to coal, oil, and natural gas

The value of 30.6 million Btu/ton (35.7 MJ/kg; Table 13) was used in the following calculations. In comparison, the fossil fuels used in the U.S. have the heating values shown in Table 14 and Figure 4.

Table 14. Energy content of different types of fuels in Btu per pound

Fuel type	Btu/lb	MJ/Kg
Natural gas	20,300	47.3
Crude Oil	18,400	42.9
Non-recycled plastics	15,338	35.7
Petroleum coke	12,700	29.6
U.S. coal 1	11,200	26.1
U.S. coal 2	9,800	22.8
Wood	6,000	14.0

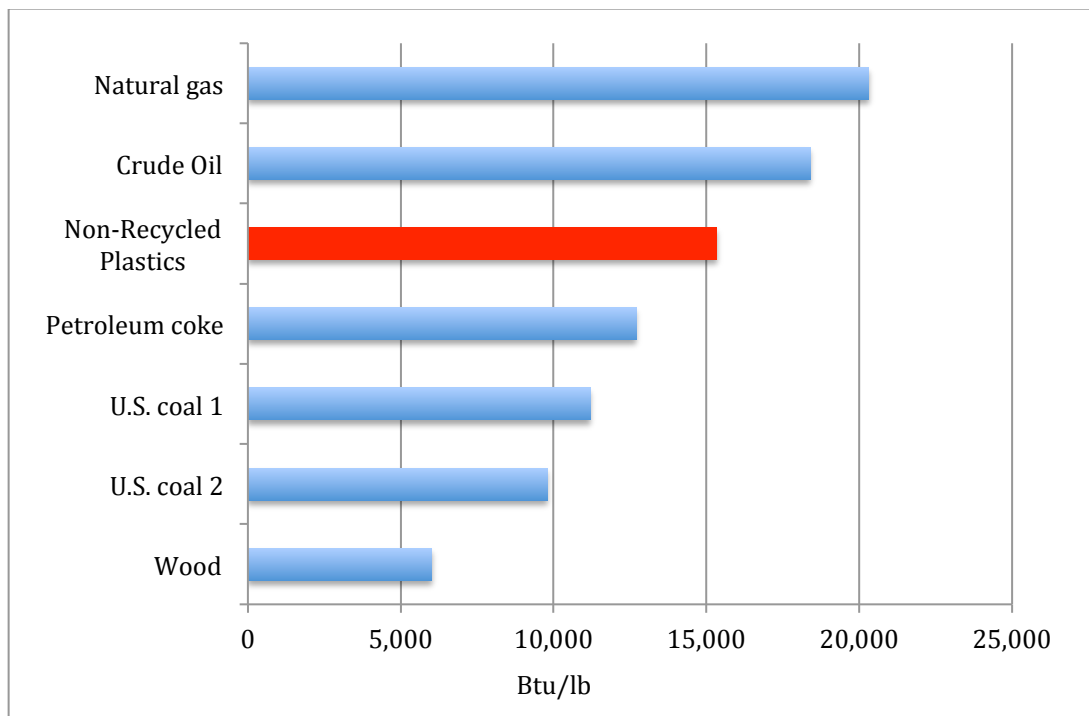


Figure 4: Graphical representation of the energy content of the different fuel types mentioned in Table 15 (lower heating value, Btu/lb)

The above chart contains two entries for the LHV of coal because different grades of coal contain different amounts of fixed carbon, volatiles, moisture and other non-combustible minerals. Thus, U.S. Coal 1 is an average of high grade coals, such as the Appalachian bituminous coal while U.S. Coal 2 is an average of low grade coals, such as coal from the Powder River Basin in Wyoming.

The following heating values were used in these calculations:

- 1 ton NRP: 30.7 million Btu
- 1 ton coal: 22 million Btu
- 1 barrel oil: 5.8 million Btu
- 1000 standard cubic feet of natural gas: 1.03 million Btu

The above numbers correspond to 5.3 barrels of oil per ton of NRP and 1.4 tons of coal per ton of NRP. Hypothetically, if all the landfilled NRP in 2011 were to be used for energy recovery, the U.S. would avoid the extraction and use of:

- 48 million tons of coal, or
- 180 million barrels of oil, or
- 1 trillion standard cubic feet of natural gas.

Table 15 shows the amounts of NRP landfilled in each state and their energy equivalent lost to landfills. Subsequently, this energy loss is calculated to show equivalent tons of coal, barrels of oil, and cubic feet of natural gas.

Table 15. Comparison of the heating value of landfilled NRP to other fuels

State	NRP not converted to energy (tons)	Million Btu of NRP lost (at 30.7 MBtu/ton)	Tons of coal equivalent to NRP heating value	Barrels of oil equivalent to NRP heating value	Natural gas eq. to NRP Heating value (in 1000 standard cubic ft.)
Alabama	622,328	19,082,798	867,400	3,290,138	18,526,989
Alaska	85,150	2,611,002	118,682	450,173	2,534,954
Arizona	869,538	26,663,127	1,211,960	4,597,091	25,886,531
Arkansas	430,573	13,202,911	600,132	2,276,364	12,818,360
California	3,953,131	121,217,102	5,509,868	20,899,500	117,686,507
Colorado	807,622	24,764,565	1,125,662	4,269,753	24,043,267
Connecticut	32,627	1,000,446	45,475	172,491	971,307
Delaware	88,509	2,714,010	123,364	467,933	2,634,961
Washington DC	30,065	921,897	41,904	158,948	895,046
Florida	1,825,805	55,985,698	2,544,804	9,652,707	54,355,047
Georgia	1,298,378	39,812,896	1,809,677	6,864,292	38,653,297
Hawaii	322,610	9,892,369	449,653	1,705,581	9,604,242
Idaho	219,520	6,731,272	305,967	1,160,564	6,535,215
Illinois	1,596,225	48,945,964	2,224,817	8,438,959	47,520,354
Indiana	642,134	19,690,109	895,005	3,394,846	19,116,611

Iowa	354,793	10,879,211	494,510	1,875,726	10,562,341
Kansas	297,767	9,130,607	415,028	1,574,243	8,864,667
Kentucky	551,947	16,924,660	769,303	2,918,045	16,431,709
Louisiana	679,747	20,843,477	947,431	3,593,703	20,236,386
Maine	28,001	858,610	39,028	148,036	833,601
Maryland	309,556	9,492,078	431,458	1,636,565	9,215,610
Massachusetts	201,692	6,184,606	281,118	1,066,311	6,004,472
Michigan	1,572,504	48,218,569	2,191,753	8,313,546	46,814,145
Minnesota	234,800	7,199,801	327,264	1,241,345	6,990,098
Mississippi	359,071	11,010,390	500,472	1,898,343	10,689,699
Missouri	521,683	15,996,672	727,121	2,758,047	15,530,749
Montana	179,742	5,511,543	250,525	950,266	5,351,012
Nebraska	291,995	8,953,609	406,982	1,543,726	8,692,825
Nevada	369,684	11,335,840	515,265	1,954,455	11,005,670
New Hampshire	52,953	1,623,728	73,806	279,953	1,576,435
New Jersey	576,893	17,689,589	804,072	3,049,929	17,174,358
New Mexico	260,739	7,995,191	363,418	1,378,481	7,762,322
New York	1,350,306	41,405,210	1,882,055	7,138,829	40,199,233
North Carolina	1,013,315	31,071,858	1,412,357	5,357,217	30,166,852
North Dakota	88,804	2,723,042	123,775	469,490	2,643,730
Ohio	1,200,734	36,818,796	1,673,582	6,348,068	35,746,404
Oklahoma	578,524	17,739,600	806,345	3,058,552	17,222,913
Oregon	252,420	7,740,093	351,822	1,334,499	7,514,653
Pennsylvania	776,563	23,812,205	1,082,373	4,105,553	23,118,646
Rhode Island	104,328	3,199,070	145,412	551,564	3,105,894
South Carolina	433,596	13,295,591	604,345	2,292,343	12,908,341
South Dakota	85,062	2,608,316	118,560	449,710	2,532,345
Tennessee	794,121	24,350,582	1,106,845	4,198,376	23,641,342
Texas	3,120,650	95,690,265.93	4,349,558	16,498,322	92,903,171
Utah	270,905	8,306,901	377,586	1,432,224	8,064,952
Vermont	49,862	1,528,958	69,498	263,613	1,484,425
Virginia	1,328,224	40,728,077	1,851,276	7,022,082	39,541,822
Washington	541,210	16,595,442	754,338	2,861,283	16,112,080
West Virginia	238,478	7,312,579	332,390	1,260,789	7,099,591
Wisconsin	550,172	16,870,224	766,828	2,908,659	16,378,858
Wyoming	80,263	2,461,146	111,870	424,336	2,389,462
ASR*	1,896,743	58,160,905	2,643,677	10,027,742	56,466,898
Total	34,391,996	1,055,017,276	47,955,331	181,899,530	1,024,288,618

* The quantity of ASR has been estimated, however, its disposition has not been determined. As a result, this ASR quantity has not been appointed to any state in specific, but has been accounted for separately as it does contribute to the NRP tonnage not converted to energy.

5.3 Transforming NRP to oil by means of pyrolysis

At present, many U.S. communities source separate the types of plastics that can be sold as feedstock for plastic recycling. As illustrated in the EEC Hierarchy of Sustainable Waste Management (Figure 1), reuse and recycling are the preferred waste management, but it is not practical to collect and recycle all plastic wastes. However, NRP can also be source-separated and converted into oil by means of a thermal treatment called pyrolysis. As noted earlier, the heating value of one ton of NRP corresponds to the heating value of 5.3 barrels of oil. In the 2011 EEC Report to ACC, the efficiency of conversion had been estimated very conservatively at 3

barrels per ton of NRP. Over the last three years, EEC analysis and research on pyrolysis processes tested on a large pilot scale (34), along with other information, have shown that a more realistic estimate is 4 barrels per ton of oil, i.e., at a thermal efficiency of $4/5.3 = 75\%$. Therefore, a conversion factor of 4 barrels per ton of NRP has been used in this study, as it is more in-line with processes under development.

If, hypothetically, the NRP that are currently landfilled were to be converted into oil, a total of 136 million barrels of oil would be produced, corresponding to about 5.7 billion gallons of transportation fuel. Light vehicles and trucks have an average mileage of 21.5 miles per gallon at an average yearly driving distance of 12,000 miles, thus yielding an average consumption of 535 gallons of diesel per year (36). However, it has been shown (35) that oil derived from plastics contains about 20% less energy than diesel oil; therefore, consumption of plastics oil will be 20% higher than diesel oil, i.e., 641 gallons per year. On the basis of these estimates, about 8.9 million cars could be driven on NRP-derived fuel. The economic value of this amount of NRP converted into gasoline, assuming an average price of \$3.5 per gallon in 2011 (37) would be about \$20 billion dollars.

It should be noted that the above numbers are based on the current amount of MSW landfilled. Based on recent trends, EEC expects that some of the current landfilling will likely be replaced by increased recycling and composting. For example, the American Chemistry Council has reported a trend towards increased recycling of non-container rigid plastics and plastic bags, wraps, and film (50).

5.4 Transforming of NRP to methanol, ethanol or other chemicals

Plastics can be partially oxidized to synthetic gas ($\text{CO} + \text{H}_2$), which can then be synthesized chemically to methanol (CH_3OH) (38). However, as discussed in detail in Appendix 1 to this report, the thermal efficiency of this combination of processes is relatively low and is not justified by the price of methanol at this time (about \$50 per barrel) and the fact that the LHV of methanol (20 MJ/kg) is about one half that of synthetic oil.

Converting the green and food wastes contained in MSW into ethanol has been reported to have a conversion efficiency of about 70 gallons of ethanol per ton of MSW (38; 1 barrel = 42 U.S. gallons). Mixed MSW is a very heterogeneous material and so far there has not been an industrial application of such a process. However, Enerkem has built the first commercial scale facility for converting MSW to fuels and chemicals in Edmonton, Alberta. This plant is expected to produce 10 million gallons of ethanol per year from pre-processed and sorted MSW, at Edmonton's Integrated Processing and Transfer Facility (IPTF).

5.5 Potential of using source-separated NRP in dedicated power plants

A hypothetical alternative to pyrolysis of NRP to fuel oil is the combustion of source-separated NRP in dedicated WTE plants. On average, the electricity generated in a

U.S. WTE plants fueled with MSW is 0.6 MWh/ton of MSW. However, the LHV of non-recycled plastics is about three times higher than that of MSW. Therefore, combustion of NRP in a dedicated WTE power plant could be expected to generate 1.8 MWh/ton of energy. If all NRP that are currently landfilled were to be source-separated and combusted in NRP-fueled WTE facilities, the amount of energy produced could amount to 61.9 million MWh. The average amount of electricity a U.S. household uses on a yearly basis is 10.8 MWh (36). Therefore, the use of all landfilled NRPs in dedicated WTE facilities could create sufficient amounts of energy for 5.7 million such households (a typical house hold consists of four persons).

5.6 Increased utilization of NRP by means of increased U.S. waste-to-energy capacity

Waste-to-energy facilities built in recent years generate about 0.6 MWh/ton, up from 0.5 MWh/ton for older WTE plants. This higher efficiency corresponds to the use of 0.4 ton of coal in utility power plants. If it were possible to divert all tonnage landfilled in the US in 2011 (247 million tons) to new WTE facilities, the electricity generated could be about 150 million MWh, enough to power 13.8 million homes, about 12% of the U.S. total, at an assumed average household consumption of 10.8 MWh per year. Using MSW as a fuel instead of importing coal from other states is particularly interesting for states that import large quantities of coal and export large amounts of MSW to other states for landfilling. Figure 5 gives an overview of the amount of coal imported and the MSW coal equivalent produced per state. If the MSW were used as a fuel instead of coal, it is possible that states such as New York, California, Indiana, New Jersey and Michigan would not need to import coal anymore and the transportation of coal from state to state would be reduced by 22%. It is also interesting to point out that the state of California could even stop importing coal if only the NRP coal equivalents were used. California imports on a yearly basis 1.9 million tons of coal. If California were to divert about 15% of its MSW (or 4.7M tons to WTE plants), the state would no longer need to import coal. Diverting all MSW to WTE plants would result in an energy production that equals about 6.5 times the coal energy equivalent of what the state currently imports.

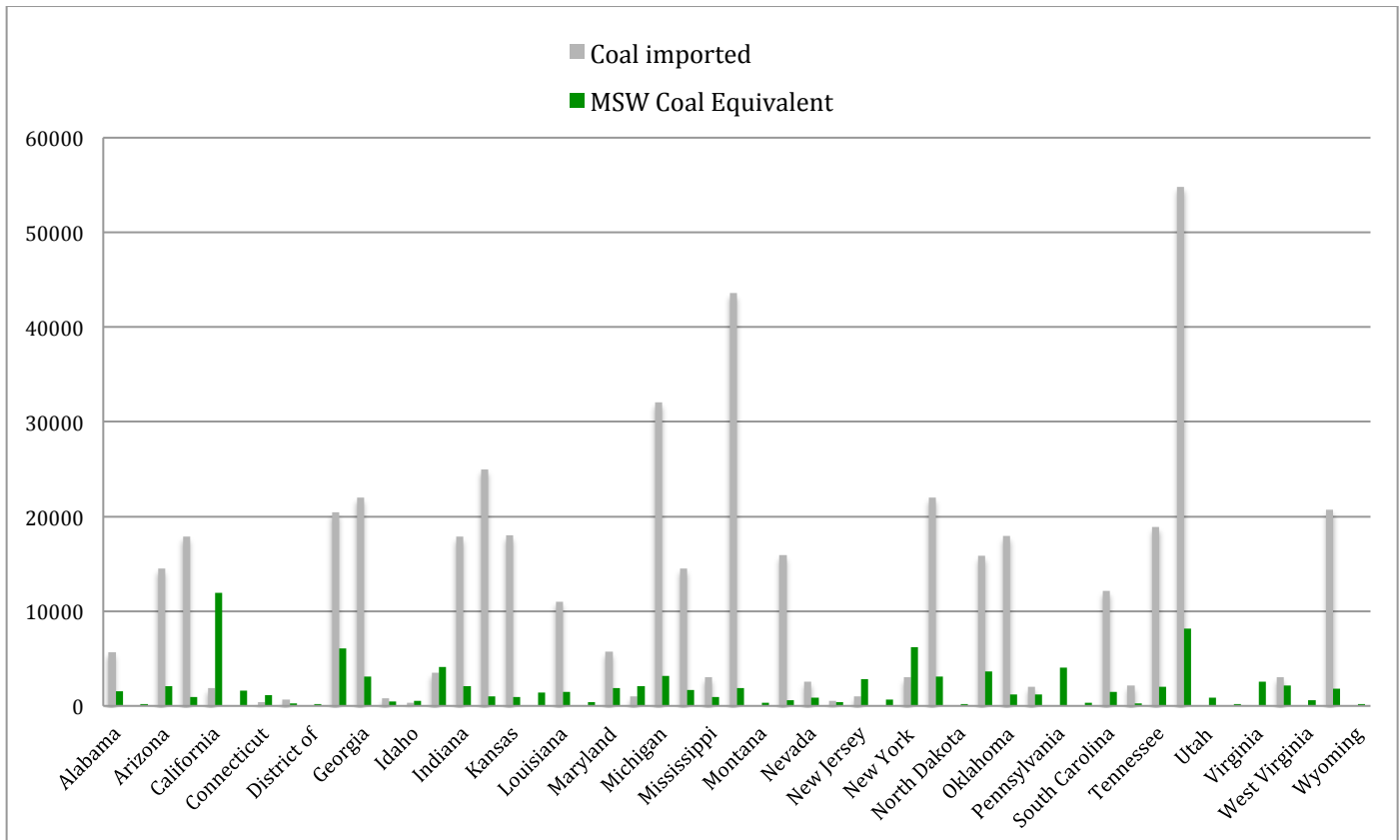


Figure 5: Coal imported per state (grey) and the MSW coal equivalent produced per state (green) in thousands of short tons (39).

Further, in some European nations, the low pressure steam produced by turbines at the WTE facilities heats water that is used for district heating or industrial purposes. For example, 30% of the district heating of Denmark is provided by 28 waste-to-energy plants (41). If the same practice were to be followed in the U.S., the energy recovered from WTE plants could increase by an estimated 1 MWh of thermal energy per ton of MSW combusted. A household typically uses about 70% of its total energy for heating and cooling purposes and the average amount of energy needed per U.S. household is 25 MWh per year. On the basis of these numbers, the thermal energy from WTE low-pressure steam could be 247 million MWh, enough to supply heating and cooling to an additional 9.8 million homes.

5.7 Greenhouse gas (GHG) benefit of increasing WTE capacity

Increasing the WTE capacity of the U.S. would also result in a significant reduction of the emission of greenhouse gases (GHG). It has been estimated that diverting one ton of MSW from landfilling to WTE reduces GHG emissions by 0.5 to 1 ton of carbon dioxide equivalent, depending on the degree of landfill gas capture (51). Therefore, diverting the 247 million tons of MSW that are landfilled could reduce the U.S. GHG emissions by 123-247 million tons of CO₂ equivalent, depending on the average methane collection efficiency of U.S. landfills.

5.8 Landfill avoidance by dedicated usage of MSW and NRP plastics

Landfills stock on average about 10 tons of garbage per square meter. Knowing that the amount of MSW landfilled in 2011 was 247 million tons, 24.7 km² of land is being lost each year, or an equivalent of about 4,600 American football fields.. Comparing this with the size of Central Park in Manhattan, about 7.3 Central Parks are needed for the U.S. MSW landfilled each year. Another useful comparison is that about 28% of the surface area of the island of Manhattan is used for landfilling the entire U.S. MSW.

CONCLUSIONS

While the U.S. continues to make improvements in reducing waste generation per capita and increasing recycling rates, there remains a large fraction of municipal solid waste (MSW) that cannot be recycled economically. Some of this waste is converted to energy at WTE plants, but the U.S. remains behind much of Europe and Japan in using this technology. The main objective of this study was to determine the quantity of non-recycled plastics in the United States that are now landfilled but could be converted into energy. The study included municipal solid waste (MSW) and, also, other waste streams that contain plastics, such as construction and demolition (C&D) debris, and automotive shredder residue (ASR), which are now disposed in MSW landfills.

The MSW generated in the U.S. in 2011 was 389 million tons, with plastics representing about 11% (41.2 million tons) of the total. Of this amount, 2.66 million tons were recycled, 3.9 million tons were converted to energy in waste-to-energy plants, 0.27 million tons were used as alternative fuel in cement production, and 34.4 million tons were landfilled. This study also included other waste streams that are disposed in MSW landfills. These included 0.5 million tons of plastics in construction and demolition debris (C&D) and an estimated 1.9 million tons of plastics contained in automotive shredder residue (ASR).

Key findings of this study were:

- Between 2008 and 2011, recycling of materials from the U.S. MSW increased by 18.5 million tons while tonnage to waste-to-energy plants increased by 3.8 million tons. For plastics, the total recovery rate (recycling + energy recovery) increased from 14.3% in 2008 to 16.7% in 2011.
- If all the MSW that was landfilled in 2011 were to be diverted to WTE power plants, they could generate enough electricity to supply 13.8 million households, i.e., 12% of the U.S. total. In addition, if the steam turbine exhaust of the WTE plants were to be used for district heating, as is done in Denmark

and some other northern European countries, the “waste” steam would provide district heating for an additional 9.8 million homes.

- Every ton of MSW combusted for electricity generation in recently built WTE plants replaces an estimated 0.4 tons of coal. Therefore, diversion of MSW from landfills to new WTE plants could reduce coal mining in the U.S. by about 100 million tons per year.
- If MSW were to be used as a fuel in WTE power plants, it could replace all the coal imported by states such as New York, California, Idaho, New Jersey and Maine. Use of MSW fuel in place of coal could reduce the U.S. state-to-state transportation of coal by 22%.
- Diversion of all MSW from landfills to WTE plants could result in reducing the greenhouse gas (GHG) emissions of waste management in the U.S. by at least 123 million tons of carbon dioxide equivalent (2.1% of U.S. total greenhouse gas emissions), comparable to the annual emissions of over 23 million cars.
- The current annual landfilling of MSW in the U.S. was estimated to require a land surface of about 6,100 acres, equivalent to nearly 4,600 U.S. football fields, or seven New York City Central Parks.
- The average lower heating value of non-recycled plastics (NRP) was estimated at 30.7 million Btu/ton (35.7 MJ/kg). The amount of NRP landfilled in 2011 (34.4 million tons) contained a chemical energy content equivalent to:
 - 48 million tons of coal, or
 - 180 million barrels of oil, or
 - 1 trillion standard cubic feet of natural gas
- If the landfilled NRP were to be source-separated and converted through pyrolysis into synthetic oil, this could produce 136 million barrels of oil per year, or 5.7 billion gallons of gasoline, enough to fuel an estimated 8.9 million cars.
- Alternatively, if the NRP were to be source-separated and used as fuel in dedicated WTE facilities, these plants would generate 61.9 million MWh of electricity, enough to supply an estimated 5.7 million households.

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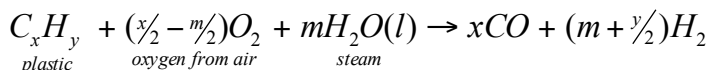
APPENDIX 1. Potential for processing non-recycled plastics (NRP) to methanol

by Prof. Marco J. Castaldi, Earth Engineering Center, City College of New York (CUNY)

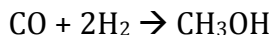
Gasification of relatively high heating value solid wastes is becoming more prevalent as it can produce carbon monoxide (CO) and hydrogen (H₂), commonly referred to as a synthesis gas. This gas can be used as a building block for other chemicals and this provides options downstream of the gasifier. Those options range from combustion of the syngas in a boiler to synthesis of chemicals, such as alcohols and fuels. A considerable amount of work has been completed regarding gasification options using various plastic types as starting materials. The more fundamental studies have been conducted on high-density polyethylene (HDPE) to determine the parameters that affect product distribution from gasification and pyrolysis systems.

Because HDPE is well characterized, it is possible to develop a complete understanding of the reaction sequences and how operating conditions influence these sequences. For example, gasification experiments have shown that reactor temperatures near 730°C increase the yield of ethylene (1). In addition, the total yield of gaseous products increases as the temperature is increased. This is similar for pyrolysis processes that operate without any oxygen reactant. At the same time, a decrease in the amount of heavy hydrocarbons, such as oil and wax, is observed. The ethylene/ethane (C₂H₄/C₂H₆) ratio increases with temperature and is generally higher for gasification as compared to pyrolysis. The presence of oxygen appears to result in a more effective cracking of the HDPE with C₃ and C₄ compounds exhibiting a maximum concentration near 730°C.

In terms of utilization of the syngas resulting from the gasification of solid material, methanol (CH₃OH) production is considered one of the more promising chemicals. This is due to the large market and the development of specialty catalysts that provide very high selectivity toward methanol production compared to other processes such as the Fischer-Tropsch (F-T) method for more complex chemicals and fuels. The primary theoretical pathway to synthesize methanol is shown below in the following two equations. First the plastic must be gasified in the presence of an oxygen co-reactant to form the necessary CO.



The syngas is then routed to a high pressure catalytic reactor to make methanol.



It should be recognized that these are ideal stoichiometric reactions that are rarely achieved in practice. In practice, the conversion of plastic waste to synthesis gas usually results in formation of the by-products CO₂, H₂O and carbonaceous particulate matter (soot). These by-products lower the overall efficiency and may cause operating problems in the downstream methanol reactor. Therefore, there must be gas cleaning equipment installed to remove water and soot as well as other hydrocarbons and impurities that can foul or damage the methanol synthesis catalyst. This gas cleaning equipment is similar to air pollution control systems installed for combustion processes (see Figure 1 below). In addition the syngas leaves the gasifier at elevated temperature (700°C or greater) and must be cooled, typically to about 250°C or less, before entering the gas cleaning train. If the enthalpy from that temperature change is not utilized, it will significantly reduce the process efficiency.

The production of methanol is one of the simplest chemicals to make from syngas yet it is a reaction that is constrained by thermodynamic equilibrium, which limits the process to low conversion through the reactor and therefore requires recycling of unconverted syngas. To minimize energy usage and capital equipment costs, any by-products and inert gases that are in the syngas stream - such as CO₂, N₂ - need to be minimized. The reaction is also strongly exothermic requiring significant cooling during the process, otherwise the methanol can further react to produce different alcohols (such as ethanol and propanol) and methane. These recycle and cooling systems are largely responsible for the investment costs associated with the syngas conversion to methanol. Importantly, the relevant stoichiometry is not the molar ratio of H₂ to CO₂, which should in principle equal 2 as shown by the reaction above. Instead a molar ratio of (H₂-CO₂)/(CO+CO₂) = 2 is more applicable. CO₂ appears in the stoichiometric number because it is present when synthesis gas is produced and consumes hydrogen during the methanol synthesis.

There have been many attempts to make syngas from waste plastics, but only a couple of processes have been demonstrated to actually make methanol. A patent that describes a process via gasification for converting solid waste with the chemical composition to methanol is shown in Table 1². This system produced 2809 kg/hr of methanol from a 5 ton/hr solid feed rate, i.e., about 0.6 tons methanol per ton of plastic waste. Because the density of methanol is 0.79 kg/liter and there are 119 liters in a fluid barrel, the methanol yield, according to this patent, was 6.4 barrels of methanol per ton of plastic wastes (e.g., 0.6 ton MeOH per ton plastic × 1000 kg/ton

÷ (0.79 kg/l × 119 l/barrel) instead of the estimated 4 barrels of oil obtained by pyrolysis of the plastic wastes.

The heating value from NRP is 35.7 MJ/kg, therefore it is theoretically possible to produce approximately 12.9 barrels of methanol per ton of NRP. The patented process yields approximately 6.4 barrels of methanol per ton, resulting in an overall process efficiency of 49.6%. However this could have a significant impact on the methanol industry. Currently, there is approximately 2.6 billion gallons of methanol produced each year in the U.S, mostly from natural gas. Taking the 6.4 barrels and multiplying by the 34.1 million tons of NRP sent to landfills yields 218 million barrels of methanol or 7 billion gallons of methanol, about 2.5 times the total U.S. methanol production per year.

The example provided in this patent shows that 68% by volume of the syngas consists of H₂ and CO. The syngas mixture was brought to a temperature and pressure of about 300°C and 1400 psi, as required to synthesize the methanol. The reactor is fed with a high purity O₂ gas stream as the oxidizing environment to form the syngas components with some CH₄, CO₂ and some higher hydrocarbons. The gasifier produced the products shown in Table 2.

Table 1. Ultimate Analysis of Waste²

Component	Wt. %
Carbon	47.1
Hydrogen	6.4
Oxygen	45.8
Nitrogen	0.6
Sulfur	0.1
	100.0

Table 2. Gasifier Exit Stream

Component	Vol. %	Wt. %
Hydrogen	31.1	2.8
Carbon monoxide	37.1	46.8
Carbon dioxide	17.3	34.1
Methane	6.8	4.9
Ethane	1.18	1.6
Ethylene	3.42	4.3
Propane	0.24	0.5
Propylene	1.75	3.3
Butane	0.19	0.5
Oxygen	0.07	0.1
Nitrogen	0.85	1.1

This gas stream was separated using a cryogenic system to separate the CH₄ and CO₂ from the higher hydrocarbons. The higher hydrocarbons were further reacted to produce more H₂ for the methanol synthesis process. The reactions yielded an approximate 60% conversion rate per run through the reactor, yielding methanol and by-products such as higher alcohols. These by-products and unreacted CO, CO₂ and H₂ need to be separated to enable the CO, CO₂ and H₂ to be recycled back to the methanol synthesis reactor.

A 5 ton/day demonstration was conducted by Nippon Steel in 2002 using primarily polyethylene (PE) obtained from electrical wire insulation and about 10% PVC.⁴ The figure below, taken from the technical report, shows an overall process flow diagram from waste feeding to final methanol separation and output.

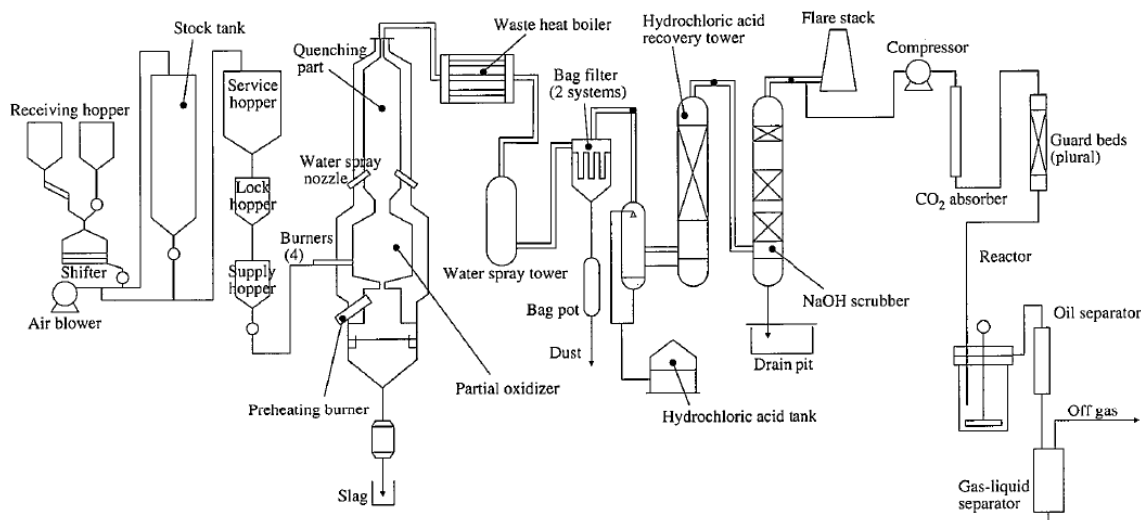


Figure 1. Demonstration test equipment for conversion of waste plastic to methanol (from 4)

Figure 1 demonstrates that the process to convert the syngas to methanol is almost two-thirds of the entire system. The gasification system has a feed rate of 250 kg/hr operating at approximately 1350°C. The carbon conversion rate (i.e., carbon from plastic to carbon in the syngas) was 92%, with an overall thermal efficiency of 51%. The optimum configuration would produce a 96% carbon conversion and 63% efficiency.

This low thermal efficiency was due to the fact that there was about 8% of carbon remaining in a solid phase exiting the gasifier, which had to be removed, and about 49% of the energy that was in the plastic feed was not captured. The resulting syngas composition is shown in the table below and is similar to the composition from the patented process described above.

Table 3. Syngas Composition for Nippon Steel Demonstration⁴

Gas composition (N ₂ , H ₂ O-free, vol%)	PE electric wire covering + PVC 10%
H ₂	34.3
CO	38
CH ₄	0.0068
CO ₂	24.5
H ₂ /CO	0.9

It can be seen from Table 3 that the H₂/CO = 0.9 and the (H₂-CO₂)/(CO+CO₂) = 0.16, which is significantly below the optimal value of 2.0. This is because of the high amount of CO₂ that is produced due to the partial oxidation process (i.e., the use of oxygen).

These two examples show that it is technically possible to convert waste plastics to syngas followed by methanol synthesis. However, they are complicated processes that require significant engineering and operating expertise. To efficiently gasify

the plastic is a complex process that requires a significant input of heat energy. If the goal of the gasification of plastic is to produce syngas, then an oxygen source must be provided. The obvious source is air, which can be metered in properly to partially oxidize the solid plastic producing heat for the reaction and the syngas mixture. But air brings 3.76 times more nitrogen than oxygen, and nitrogen is an inert that must be removed prior to entering any downstream synthesis reactor system. The nitrogen can be removed prior to the gasification system, but that requires cryogenic separation technologies and is expensive. Another method of getting oxygen as a co-reactant is from steam. The advantages of using steam over oxygen include no dilution due to nitrogen, additional hydrogen and production of very little CO₂. However, a heat source must be added because the steam gasification reaction is endothermic. Some processes mix oxygen and steam, such as that applied in the Nippon steel demonstration, to achieve autothermal operation. The oxygen initiates the exothermic partial oxidation process which then activates the endothermic steam gasification. The oxygen/steam mixture is typically considered the best mode of operation because it balances the thermal requirements while minimizing the amount of steam that must be generated and the amount of CO₂ that will be produced.

Based on the above information the concept of converting waste plastics to chemicals, such as methanol, is technically viable. Yet there are two complex systems, gasification to form syngas and chemical production from syngas, that need to interface efficiently. Usually it is easier to optimize a process that yields a single output, such as gasification which produces a large amount of CO and H₂ at the proper ratio with small amounts of inert and other by-products. The high quality syngas stream can then be transported (or sold) to a process that is optimized to convert syngas to a chosen chemical. This model is currently used by Aglylix to produce a crude oil from waste plastics that it sells to a local refiner to further process into fuel. Aglylix concentrates on producing consistent oil with high efficiency and low cost and the refiner buys the oil incorporating it into existing streams.

REFERENCES TO APPENDIX 1:

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