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

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EXECUTIVE SUMMARY

This Report is an update of the 2011 Earth Engineering Center (EEC) Report to the American Chemistry Council (ACC) which was based on U.S. 2008 data and quantified the energy and economic value of municipal solid wastes (MSW) and non-recycled plastics (NRP). The study presented in this Report is based on 2011 data, compiled in the EEC 2013 *Survey of Waste Management in the U.S.* and on MSW characterization studies conducted by several states.

The 2013 EEC Survey reported that in 2011 the U.S. generated 389 million tons of MSW, of which 87.8 million tons were recycled, 24.6 million tons were composted, 29.5 million tons were used as fuel in WTE plants, and 247 million tons were landfilled.

Between 2008 and 2011, the recycling rate of plastics increased by 21% to 2.66 million tons, due to higher recovery of polyethylene terephthalate (PET) and high-density polyethylene (HDPE) bottles, other HDPE and polypropylene (PP) 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 non-recycled plastics (NRP), conversion to energy is preferred over landfilling, in accord with the U.S. Environmental Protection Agency's (EPA) waste management hierarchy.

The main objective of this study was to determine the quantities of non-recycled MSW and plastics that are available for converting to energy or fuel, nationally and state-by-state. In addition to MSW, the 2014 update study also included NRP contained in other waste streams that are disposed in MSW landfills.

Key findings:

- Between 2008 and 2011, recycling of all materials in the U.S. MSW stream increased by 18.5 million tons while landfilling decreased by about 23 million tons.

- Plastics represented nearly 11% (39.3 million tons) of the total MSW stream. Of this amount, 2.66 million tons (6.8%) were recycled, 3.9 million tons (9.9%) were converted to energy in waste-to-energy (WTE) plants, 0.27 million tons (0.7%) were used as alternative fuel in cement production, and 32.5 million tons (82.7%) were mixed in the MSW disposed in landfills. The rate of recycling plus energy recovery of plastics increased from 14.3% in 2008 to 17.3% in 2011. An additional source of about 1.9 million tons of NRP is in the form of automotive shredder residue (ASR).

- If all the MSW that was landfilled in 2011 were to be diverted to WTE power plants, it 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 could provide district heating for 9.8 million homes.

- Every ton of MSW combusted in recently built WTE power 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 (10% of U.S. 2012 coal production).

- 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 also result in reducing the greenhouse gas (GHG) emissions of managing the U.S. waste 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 green space 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 NRP contained in the MSW disposed to landfills in 2011 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

- Source-separation and conversion of the non-recycled plastics to synthetic oil, by means of pyrolysis, 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 power plants, these plants could generate 61.9 million MWh of electricity, enough to supply an estimated 5.7 million households.

- Connecticut, Maine, Massachusetts, Minnesota and New Hampshire, in that order, are closest to attaining sustainable waste management, by combining high rates of recycling with high WTE.

- There are economic and environmental advantages in increasing the current use (about 0.3 million tons) of NRP in the form of engineered fuel for cement production. Also, source-separated NRP and (ASR) can be used as fuel in dedicated power plants or transformed to synthetic fuel by means of pyrolysis.

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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
MJ/kg	Mega Joules per kilogram
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 Objectives of this study

This study is an update of the 2011 EEC Report to the ACC which was based on U.S. 2008 data and quantified the energy and economic value of MSW and NRP. This update is based on U.S. 2011 data compiled in the EEC *2013 Survey of MSW Management in the U.S.* (2), on MSW characterization studies conducted by fourteen states, and various other sources.

One objective of this study was to determine the quantities of (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 and NRP that are currently landfilled to 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 to MSW, this Report includes two other waste streams that contain NRP: Construction and demolition (C&D) debris and ASR.

1.2 The Earth Engineering Center and the Hierarchy of Waste Management

The 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 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.

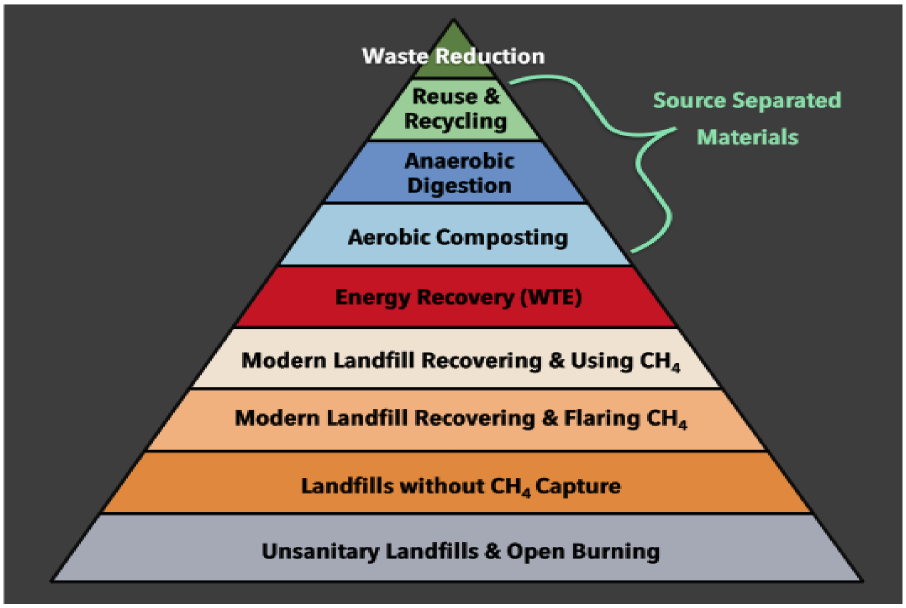


Figure 1: Hierarchy of Sustainable Waste Management developed by the EEC (4)

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

In the years 2004-2010, the EEC 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 ACC (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 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, based on 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 EEC 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	Total MSW generated	
388,959,390	250,420,000	138,539,390
Recycled materials	Recycled materials	
87,808,128	66,200,000	21,608,128
MSW composted	MSW composted	
24,646,893	20,700,000	3,952,774
MSW to WTE	MSW to WTE	
29,507,191	29,260,000	247,191
MSW landfilled	MSW landfilled	
246,977,177	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 packaging from imported goods, municipal wastewater sludge, construction and demolition debris, small-scale manufacture wastes that are not recycled, etc. The 2013 EEC 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 EEC 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 landfill space; 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 EEC 2013 Survey of 2011 data (2). Figure 2 is a graphical representation of some 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	0	2,729,305	2,866,104	5%
Missouri	967,814	0	3,965,327	4,933,141	20%
Montana	252,734	0	1,366,226	1,694,083	15%
Nebraska	333,207	0	2,219,461	2,552,668	13%
Nevada	1,150,601	0	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	0	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	0	7,702,232	9,137,435	9%
North Dakota	90,000	0	675,000	935,000	10%
Ohio	2,461,594	0	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	0	793,000	922,480	7%
South Carolina	954,748	0	3,295,771	4,425,431	22%
South Dakota	157,306	0	646,561	864,702	18%
Tennessee	1,531,310	0	6,036,132	7,642,442	20%
Texas	2,780,213	0	23,720,134	31,101,890	9%

Utah	56,474	126,522	2,059,152	2,533,390	2%
Vermont	120,009	0	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**	**29,507,191**	**246,997,177**	**388,959,390**	**23%**

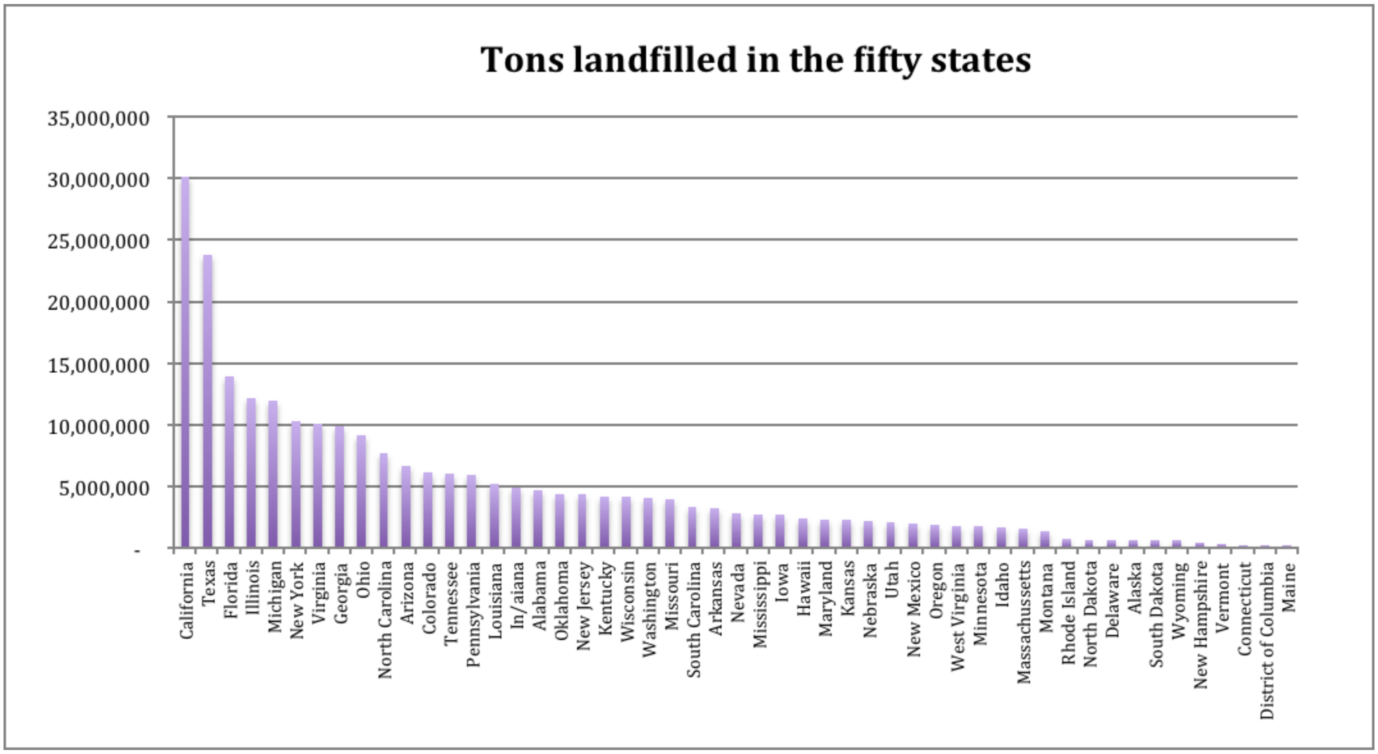


Figure 2: Tons of MSW landfilled per state

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 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,j570	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%**

The American Chemistry Council estimated (10, 11) 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 in agreement with the EPA estimate in Table 3.

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 Tons of NRP in MSW sent to WTE plants and landfills

Multiplying the 2013 national tonnage of post-recycling MSW to WTE plants (29.7 million tons; EEC 2013 Survey) by the average concentration of plastics from Table 4 (13.2%) yields the tonnage of NRP that were contained in the MSW to waste-to-energy plants, nationally (3.9 million tons).

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

3.4 Summing the amount of plastics in the MSW stream in 2011

From sections 3.2-3.3 above, the total amount of plastics in the U.S. MSW stream is calculated to be 39.3 million tons.

• Recycled plastics:	2.66 million tons	(6.8%)
• NRP to WTE power plants:	3.88	(9.9%)
• NRP to cement kilns:	0.27	(0.7%)
• NRP to landfills:	32.5	(82.5%)
• Total plastics in MSW stream:	39.3 million tons	(100.0%)

3.5 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 and the results are shown in Table 5 (16).

Table 5. 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 amount of non-recycled plastics in the U.S. C&D waste in 2011 is estimated at about 0.5 million tons.

Since several of the characterization studies by the states mentioned the presence of C&D debris in the truck loads they analyzed, it was decided to assume that the C&D debris was part of the MSW stream and therefore accounted for in the 13.2% plastics concentration in MSW (Table 4). Therefore, the C&D debris was not considered to be a separate source of NRP.

3.6 Plastics in automobile shredder residue (ASR)

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 6; ref. 18). The percentage of plastics and other combustible materials in the ASR is significant. 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 6. 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, the EPA 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 EEC 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 accounting of waste management.

Table 7 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 7 shows the plastic constituents of ASR, their concentration and heating value. The average lower heating value (LHV) of ASR is estimated at about 32 million Btu/ton (37 MJ/kg).

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

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

The ASR is an industrial waste and is used as daily cover or is disposed in special landfills. Therefore, in this study, it was considered as a separate source of NRP than the MSW stream.

3.7 NRP used as alternative fuel (AF) in cement kilns

A 2013 study by Jiao Zhang at Columbia University (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 3.3) is added to the energy recovery from NRP used in cement production (0.27 million short tons) in Table 9 (Section 4.4).

3.8 Summing plastic wastes in MSW, ASR and C&D debris streams

All of the waste streams discussed in Section 3 can be now summarized as follows:

Total plastics in MSW (Section 3.4)	39.3 million tons
NRP in ASR	1.9 million tons
Total plastic wastes	41.2 million tons

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

4.1 Methodology used in the state-by-state calculations

The methodology used in developing the state-by-state data was as follows:

a) The percentage of plastics present in post-recycling MSW was based on the very detailed characterization studies carried out by fourteen states, in the period of 2003-2011 (Table 4). 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%.

b) The total amount of plastics recycled in 2011 was estimated by EPA (Section 2) to be 2.66 million tons. This tonnage was apportioned to each state according to the ratio of in-state-tons recycled divided by the tons recycled in the U.S. (87.8 million tons; Columbia University 2013 *Survey of Waste Management in the U.S.).* For example, the state of California reported recycling of 27.7 million tons; therefore, the plastics recycled in California were estimated to be 0.84 million tons (2.66 x 27.7/87.8).

c) The tonnage of MSW to WTE power plants in a state, as reported by the state to the EEC 2013 Survey, was multiplied by the plastics composition in MSW (13.2%) to yield the amount of NRP converted to energy in the state. 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 2.15 million x 13.2% = 0.28 million tons.

d) The tonnage of MSWs landfilled in each state, as reported by the states to the Columbia 2013 Survey, was multiplied by the plastics composition in MSW (13.2%) to yield the amount of NRP landfilled in the state. For example, Florida landfilled 13.9 million tons of MSW, which when multiplied by 13.2% yields the estimate of 1.83 million tons of NRP.

4.2 State-by-state recycling, energy recovery, and landfilling of plastics

The results obtained using the methodology described in Section 4.1 are shown in Table 8.

Table 8. Plastics recycled, NRP mixed in MSW to WTE power plants, and NRP mixed in MSW to landfills (ASR excluded)

	Population 2011	Plastics recycled	NRP to energy recovery plants	NRP to landfills	Total plastic wastes generated
Alabama	4,802,740	14,746	23,509	622,328	660,583
Alaska	722,718	915	-	85,150	86,065
Arizona	6,482,505	11,604	-	869,538	881,141
Arkansas	2,937,979	72,915	-	430,573	503,489
California	37,691,912	841,403	112,632	3,953,131	4,907,166
Colorado	5,116,796	52,943	-	807,622	860,565
Connecticut	3,580,709	16,160	283,389	32,627	332,175
Delaware	907,135	4,637	-	88,509	93,147
District of Columbia	617,996	610	28,536	30,065	59,211
Florida	19,057,542	223,339	762,920	1,825,805	2,812,065
Georgia	9,815,210	20,966	-	1,298,378	1,319,344
Hawaii	1,374,810	18,586	71,810	322,610	413,006
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	92,708	642,134	749,723
Iowa	3,062,309	28,589	5,106	354,793	388,488
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	62,160	28,001	110,608
Maryland	5,828,289	47,677	182,795	309,556	540,028
Massachusetts	6,587,536	65,266	417,655	201,692	684,613
Michigan	9,876,187	25,279	130,771	1,572,504	1,728,553
Minnesota	5,344,861	77,541	150,702	234,800	463,042
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	33,093	52,953	100,199
New Jersey	8,821,155	131,800	280,180	576,893	988,873
New Mexico	2,082,224	10,298	-	260,739	271,037
New York	19,465,197	68,112	484,947	1,350,306	1,903,366
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	26,922	578,524	610,812
Oregon	3,871,859	43,624	23,854	252,420	319,898
Pennsylvania	12,742,886	135,430	405,819	776,563	1,317,812
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	16,645	270,905	289,263
Vermont	626,431	3,639	-	49,862	53,502
Virginia	8,096,604	85,841	268,043	1,328,224	1,682,108
Washington	6,830,038	98,393	36,344	541,210	675,948
West Virginia	1,855,364	10,470	-	238,478	248,948
Wisconsin	5,711,767	25,592	9,999	550,172	585,763
Wyoming	568,158	1,407	-	80,263	81,670
Total	**311,591,917**	**2,662,781**	**3,882,002**	**32,495,253**	**39,310,037**

4.3 Position of states on the sustainable waste management "ladder"

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 have combined a high rate of recycling with a high waste-to-energy capacity to reduce landfilling.

4.4 National sources and sinks of plastic wastes in 2011

This study showed that 6.8% of the plastics present in the MSW stream (2.66 million tons) were recycled. Another 9.9% (3.9 million tons) was combusted with energy recovery in WTE power plants; an additional 0.6% (0.27 million tons) was used as alternative fuel in cement kilns, for a total 10.5% use of NRP for energy recovery. Therefore, the total recovery rate of used plastics, as material and as energy, in 2011 was 17.3%, in comparison to the 14.3% total recovery reported by EEC in 2008 However, most of the NRP (83.3% or 32.5 million tons) was landfilled in mixed MSW.

Table 9 lists the sources and sinks of plastic wastes in the U.S. in 2011. The plastics in the C&D debris (0.5 million tons) are considered to be part of the MSW stream, while the automotive shredder residue (1.9 million tons) is a separate stream and should be added to the national account of plastic wastes, as is done in Table 9.

Table 9. Sources and sinks of plastic wastes in 2011 (in short tons)

Sources	Tons	Percent of total
Plastics in MSW	39,310,037	95.4%
NRP in automobile shredder residue (ASR)	1,896,743	4.6%
Total	**41,206,780**	**100.0%**

Sinks	Tons	Percent of total
Plastics recycled	2,662,781	6.5%
NRP to WTE power plants	3,882,002	9.4%
NRP to cement kilns as alternative fuel	270,000	0.7%
NRP mixed in MSW to landfills	34,391,996	83.5%
Total	**41,206,780**	**100.0%**

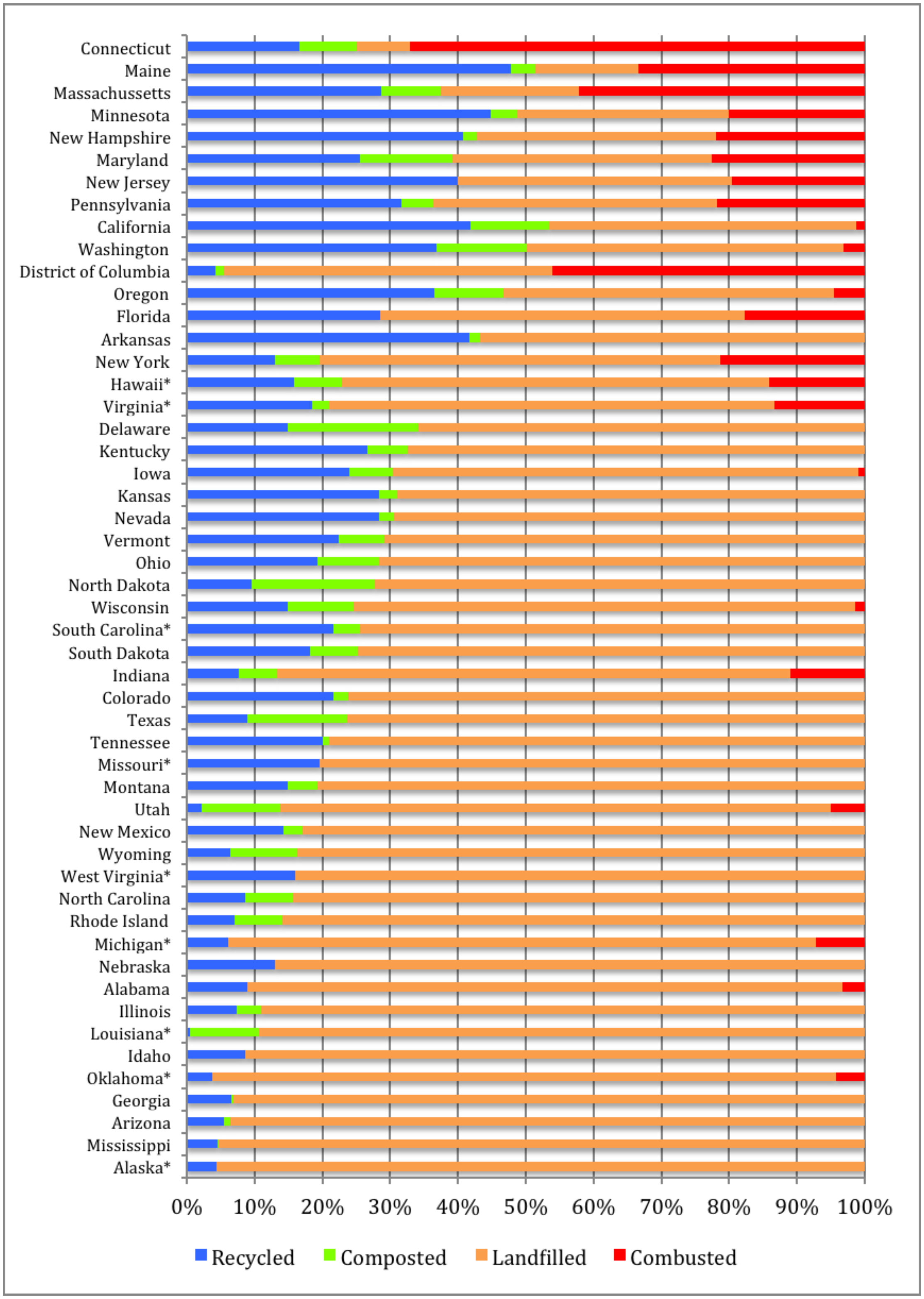


Figure 3: State-by-state comparison of the fraction of plastics recovered as materials (i.e. recycling, blue) or energy (red). ****Indicates states where 2008 population adjusted data was used, as these states did not provide data to the Columbia 2013 Survey***

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.

5.1 Use of NRP as alternative fuel in the U.S. cement industry

As noted earlier in this report, EEC has estimated that about 0.3 million tons of NRP were used in 2011 as part of a mixture of plastic and paper residues 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 ACC, in collaboration with the University of Texas, has reported that the use of EF for cement production has several environmental benefits (e.g., lower CO_2, SO_2 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.

5.2 Potential for transforming sorted-out NRP to synthetic oil

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.

5.3 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 10.

Table 10. Comparison of lower heating values (LHV) reported in literature for principal components of plastics in the waste stream (ref. 22-24, 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 11 shows the composition of principal plastics existing in the MSW stream and their calculated average LHV (35.7 MJ/kg, or 30.6 million Btu/ton).

Table 11. Composition of plastics in the MSW stream and their average lower heating value (LHV)

LHV, Materials	NRP in thousands of tons	% in NRP	MJ/kg	Million Btu/ton	MJ/kg NRP	Million Btu/ton
PET	4.874	12.40%	24	21	3.0	2.5
HDPE	6.997	17.80%	44	38	7.8	6.7
PVC	2.162	5.50%	19	16.5	1.0	0.9
LDPE/LLDPE	7.705	19.60%	44	38	8.6	7.4
PP	5.464	13.90%	44	38	6.1	5.2
PS	3.420	8.70%	41	35.6	3.6	3.1
Other	8.648	22.00%	25	22	5.5	4.8
Total plastic wastes NRP	**39.310**	**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 discarded NRP also includes ASR and C&D debris. 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). To determine the combined LHV of NRP from MSW (30.6 MJ/kg), C&D (30.6 MJ/kg) and ASR (32 MJ/kg), NRP fractions of each stream were multiplied with its proper heating value and summed up. The composite heating value of the plastic wastes was estimated at 30.7 Btu/ton.

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

The value of 30.7 million Btu/ton was used in the following calculations. In comparison, the fossil fuels used in the U.S. have the heating values shown in Table 12 and Figure 4.

Table 12. 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

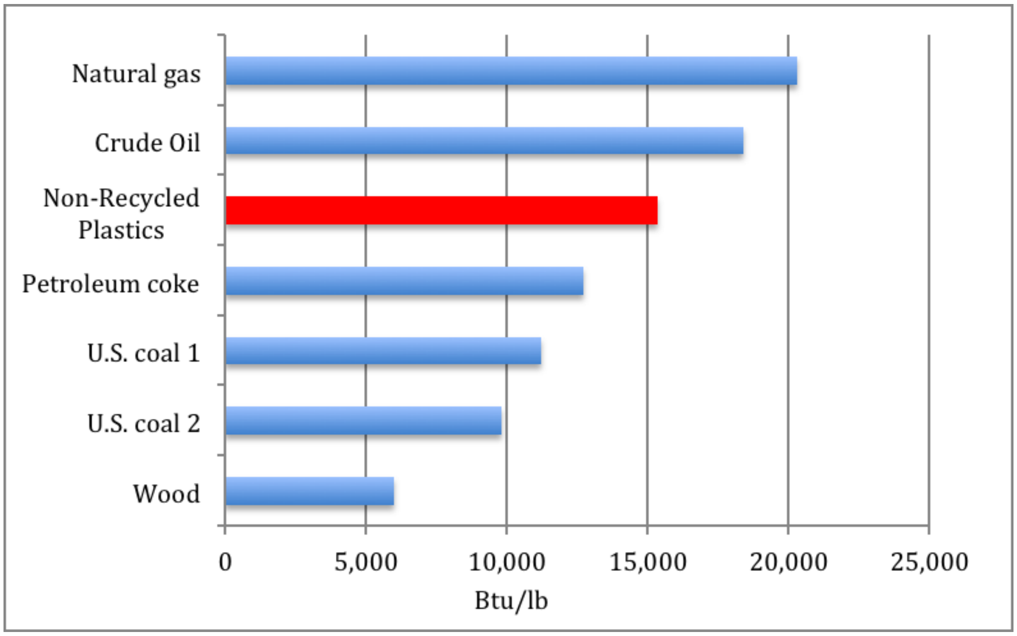


Figure 4: Graphical representation of the energy content of the different fuel types mentioned in Table 15 (lower heating value, Btu/lb)

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 lower 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 13 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 13. 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	19,082,829	867,401	3,290,143	18,527,018
Alaska	85,150	2,611,006	118,682	450,174	2,534,958
Arizona	869,538	26,663,169	1,211,962	4,597,098	25,886,572
Arkansas	430,573	13,202,932	600,133	2,276,368	12,818,380
California	3,953,131	121,217,294	5,509,877	20,899,533	117,686,693
Colorado	807,622	24,764,605	1,125,664	4,269,759	24,043,306
Connecticut	32,627	1,000,447	45,475	172,491	971,308
Delaware	88,509	2,714,014	123,364	467,933	2,634,965
Washington DC	30,065	921,899	41,904	158,948	895,047
Florida	1,825,805	55,985,787	2,544,809	9,652,722	54,355,133
Georgia	1,298,378	39,812,959	1,809,680	6,864,303	38,653,359
Hawaii	322,610	9,892,385	449,654	1,705,584	9,604,257
Idaho	219,520	6,731,283	305,967	1,160,566	6,535,226
Illinois	1,596,225	48,946,042	2,224,820	8,438,973	47,520,429
Indiana	642,134	19,690,141	895,006	3,394,852	19,116,641
Iowa	354,793	10,879,228	494,510	1,875,729	10,562,357
Kansas	297,767	9,130,622	415,028	1,574,245	8,864,681
Kentucky	551,947	16,924,687	769,304	2,918,050	16,431,735
Louisiana	679,747	20,843,510	947,432	3,593,709	20,236,418
Maine	28,001	858,611	39,028	148,036	833,603
Maryland	309,556	9,492,093	431,459	1,636,568	9,215,624
Massachusetts	201,692	6,184,616	281,119	1,066,313	6,004,481
Michigan	1,572,504	48,218,645	2,191,757	8,313,560	46,814,219
Minnesota	234,800	7,199,812	327,264	1,241,347	6,990,109
Mississippi	359,071	11,010,407	500,473	1,898,346	10,689,716
Missouri	521,683	15,996,697	727,123	2,758,051	15,530,774
Montana	179,742	5,511,551	250,525	950,267	5,351,021
Nebraska	291,995	8,953,624	406,983	1,543,728	8,692,838
Nevada	369,684	11,335,858	515,266	1,954,458	11,005,687
New Hampshire	52,953	1,623,731	73,806	279,954	1,576,437

New Jersey	576,893	17,689,617	804,074	3,049,934	17,174,386
New Mexico	260,739	7,995,204	363,418	1,378,483	7,762,334
New York	1,350,306	41,405,276	1,882,058	7,138,841	40,199,297
North Carolina	1,013,315	31,071,907	1,412,359	5,357,225	30,166,900
North Dakota	88,804	2,723,047	123,775	469,491	2,643,735
Ohio	1,200,734	36,818,855	1,673,584	6,348,078	35,746,461
Oklahoma	578,524	17,739,628	806,347	3,058,557	17,222,940
Oregon	252,420	7,740,105	351,823	1,334,501	7,514,665
Pennsylvania	776,563	23,812,243	1,082,375	4,105,559	23,118,683
Rhode Island	104,328	3,199,076	145,413	551,565	3,105,899
South Carolina	433,596	13,295,612	604,346	2,292,347	12,908,361
South Dakota	85,062	2,608,320	118,560	449,710	2,532,349
Tennessee	794,121	24,350,621	1,106,846	4,198,383	23,641,380
Texas	3,120,650	95,690,417	4,349,564	16,498,348	92,903,318
Utah	270,905	8,306,914	377,587	1,432,227	8,064,965
Vermont	49,862	1,528,960	69,498	263,614	1,484,428
Virginia	1,328,224	40,728,141	1,851,279	7,022,093	39,541,885
Washington	541,210	16,595,469	754,339	2,861,288	16,112,106
West Virginia	238,478	7,312,591	332,390	1,260,791	7,099,602
Wisconsin	550,172	16,870,250	766,830	2,908,664	16,378,884
Wyoming	80,263	2,461,150	111,870	424,336	2,389,466
US total	**32,495,253**	**996,832,328**	**45,310,560**	**171,867,643**	**967,798,377**
NRP in 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 generated nationally has been estimated, but not its state-by-state disposition.

5.5 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 ACC has reported a trend towards increased recycling of non-container rigid plastics and plastic bags, wraps, and film (50).

5.6 Transforming of NRP to methanol, ethanol or other chemicals

Plastics can be partially oxidized to synthetic gas ($CO+H_2$), which can then be synthesized chemically to methanol (CH_4OH) (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).

5.7 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 new 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 and combustion of NRP in a dedicated power plant could generate 1.8 MWh/ton of electricity. Therefore, if all NRP that are currently landfilled were to be source-separated and combusted in NRP-fueled WTE facilities, they could produce 61.9 million MWh. Since the average amount of electricity used by U.S. households in 2011 was 10.8 MWh (36), the use of all landfilled NRP in dedicated power plants could provide electricity for 5.7 million households.

According to the EIA definition (53), a household is a family or group of one to nine persons occupying the same housing unit. Under the U.S. Census Bureau definition, family households consist of two or more individuals who are related by birth, marriage, or adoption but may include other unrelated people; in 2011, the average household consisted of 2.6 people.

5.8 Increased utilization of NRP by means of new 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 households, 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 shows graphically the amount of coal imported and the MSW coal-equivalent in each state. If MSW were to be used as a fuel instead of coal, it could be possible for states such as New York, California, Indiana, New Jersey and Michigan to stop importing coal. Nationally, the use of MSW fuel in place of coal could reduce the U.S. state-to-state transportation of coal by 22%. It is also interesting to point out that the state of California could even stop importing coal if only the NRP were used to replace coal (California imports 1.9 million tons of coal annually); furthermore, if California were to divert only 15% of its MSW (i.e., 4.7 million tons) to WTE plants, the state would no longer need to import coal.

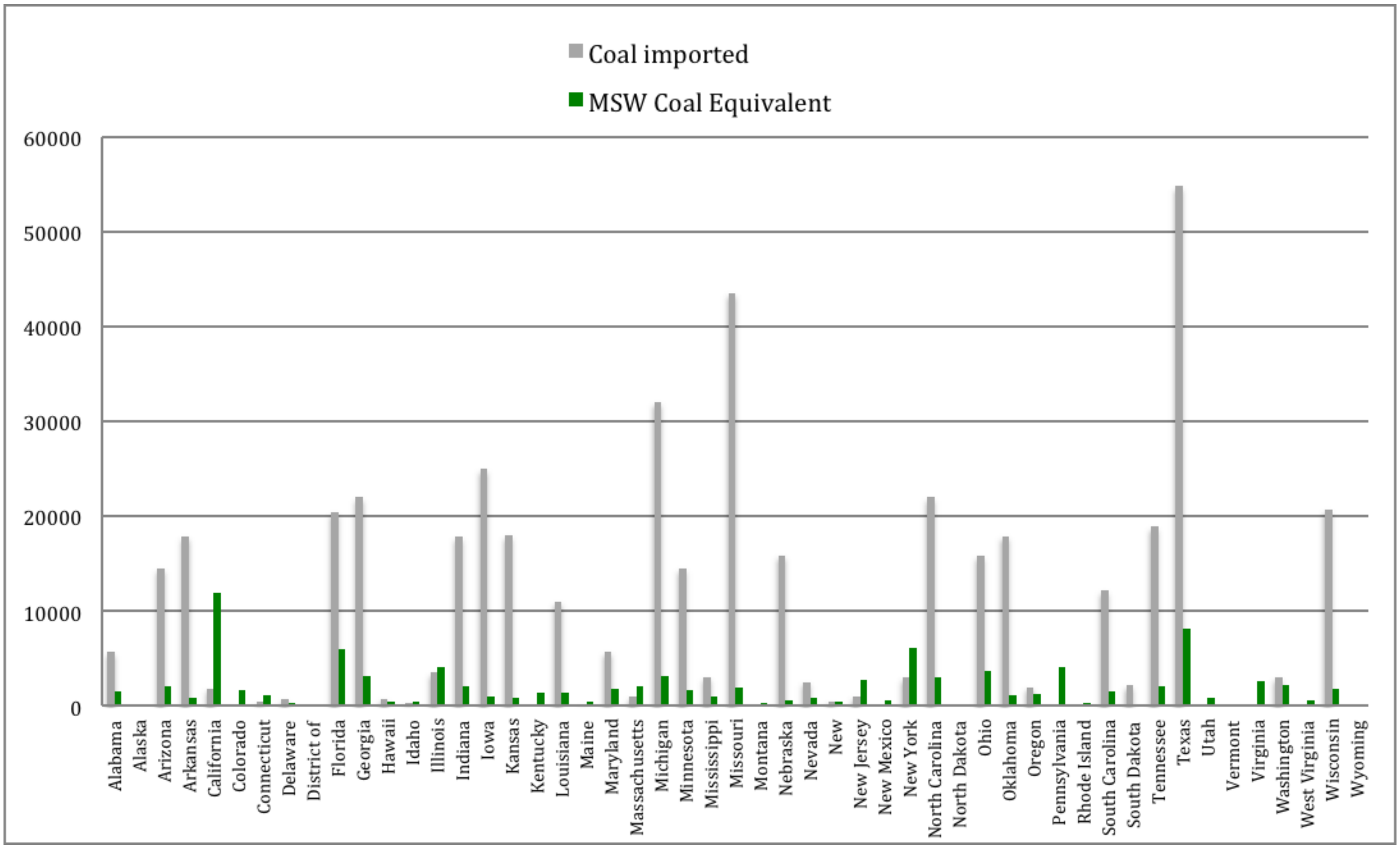


Figure 5: Coal imported per state (grey) and the MSW coal equivalent produced per state (green) in thousands of short tons (39).

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 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.

5.9 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 CO_2 equivalents, depending on the average methane collection efficiency of U.S. landfills.

5.10 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 km^2 of land is being lost each year, or an equivalent of 6,100 acres or 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. Currently, the U.S. converts less than 10% of the chemical energy stored in MSW to energy at WTE plants and lags behind other developed nations in using this technology. The main objective of this study was to determine the quantity of non-recycled MSW and 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 3.9 million tons. For plastics, the total recovery rate (recycling + energy recovery) increased from 14.3% in 2008 to 17.3% 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 European countries, the “waste” steam could 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 reduce 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 equal to:

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

- Source-separation and conversion of landfilled NRP to synthetic oil by means of pyrolysis 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.

- Connecticut, Maine, Massachusetts, Minnesota and New Hampshire, in that order, are closest to attaining sustainable waste management, by combining a high rate of recycling with a high WTE capacity to reduce landfilling.

- There are economic and environmental advantages in increasing the current use (about 0.3 million tons) of NRP in the form of engineered fuel for cement production. Also, source-separated NRP and also automotive shredder residue (ASR) can be used as fuel in dedicated power plants or transformed to synthetic fuel by means of pyrolysis.

REFERENCES

1. Themelis N. J., Castaldi M. and Arsova L. "Energetic and Economic value of Non-Recycled Plastics (NRP) and Municipal Solid Waste (MSW) that are currently landfilled in the 50 States," 2011
2. Shin D. and Themelis N.J. "Generation and Disposition of Municipal Solid Waste in the United States – A National Survey," 2013.
3. Earth Engineering Center of Columbia University (accessed 12/2013). Available from: http://www.seas.columbia.edu/earth/
4. Kaufman S.M., and N. J. Themelis, "Using a Direct Method to Characterize and Measure Flows of Municipal Solid Waste in the United States," J. Air and Waste Management Association, Volume 59, p.1386-1390, December 2009.
5. Van Haaren R., Themelis N.J., Goldstein, "State of Garbage in America," 2010.
6. Detailed Characterization of Construction and Demolition Waste, Cascadia Consulting Group, 2006.
7. EPA, Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2011 Facts and Figures, 2011 (accessed 12/2013). Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/MSWcharacterization_508_053113_fs.pdf
8. EPA, Facts and Figures, Plastics 2011 (accessed 12/2013). Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/MSWcharacterization_508_053113_fs.pdf
9. Abramowitz and Sun, Indiana Waste Characterization Report, 2012.
10. Municipal Solid Waste in the United States, 2011 Fact and Figures, United States Environmental Protection Agency (accessed 12/2013). Available from: http://www.epa.gov/epawaste/nonhaz/municipal/pubs/MSWcharacterization_fnl_060713_2_rpt.pdf
11. American Chemistry Council: 2011 United States National Post-Consumer Plastics Bottle Recycling Report, 2011 (accessed 12/2013). Available from: http://www.plasticsrecycling.org/images/pdf/resources/reports/Rate-Reports/National-Postconsumer-Plastics-Bottle-Recycling-Rate-
12. EPA, Municipal Solid Waste in the United States: 2009 Facts and Figures, 2009 (accessed 12/2013). Available from: http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2009rpt.pdf
13. 2011 National Postconsumer Non-Bottle Rigid Plastic Recycling Report, Moore Recycling Associates Inc., 2011 (accessed 12/2013). Available from: http://www.moorerecycling.com/2011Non-Bottle%20Rigid%20Rpt_FINAL.pdf
14. EPA, Characterization of Building-related Construction & Demolition Debris in the United States, Franklin Associates, 1998.
15. European Environment Agency, Eurostat: "Waste Generated in Europe" Luxembourg 2000 and ETC/W enquiry on specific waste streams.
16. Detailed Characterization of Construction and Demolition Waste, Cascadia Consulting Group, 2006.
17. United Stated Department of Transportation, Bureau of Transportation

Statistics (accessed 12/2013). Available from: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_58.html

18. Jody, B.J. et al. “End of Life Vehicle Recycling: State of the Art Resource Recovery from Shredder Residue,” Energy Systems Division, Argonne National Laboratory, 2011.
19. EPA, “Municipal Solid Waste in The United States: 2011 Facts and Figures,” p. 20.
20. “Plastics: A material of choice for the automotive industry. Insight into consumption and recovery in Western Europe,” 1999.
21. From report buyer (chemicals, plastics): Automotive Plastics Market for Passenger Cars, By Type (Polypropylene, Polyurethane, HDPE, ABS, Polycarbonate & Composites), Application (Interior, Exterior & Under Bonnet) & Geography.
22. Franklin Associates: Fire, Frank L. Combustibility of Plastics. Van Nostrand. 1991 Thermodynamic Data for Biomass Materials and Waste Components. The American Society of Mechanical Engineers. 1987.
23. Polymer Handbook (CRC Press): Tewarson A. and Babrauskas, V., in SFPE Handbook of Fire Protection Engineering, 2nd ed., National Fire Protection Association, Quincy, MA, 1995.
24. Heats of combustion of high temperature polymers. Richard N. Walters, Stacey M. Hackett and Richard E. Lyon. Federal Aviation Administration, William J. Hughes Technical Center, Fire Safety Section AAR-422 (accessed 12/2013). Available from: http://large.stanford.edu/publications/coal/references/docs/hoc.pdf
25. Wittbecker, Daems and Werther, “Performance of Polyurethane (PUR) in building products in fires,” 2001.
26. Lee B. et al. “Alternatives for treatment and disposal cost reduction of regulated medical waste,” 2003.
27. Medical Waste Committee (MWC), “Medical waste disposal.” J. Air & Waste Manage. Assoc. 44, 1176–1179, 1994.
28. Pruess A. et al. “Safe management of wastes from health-care activities,” World Health Organization, 1999.
29. American Hospital Association Annual Survey of Hospitals, Hospital Statistics, 1976, 1981, 1991-2011.
30. Zhang J. and Themelis N.J., “Energy, Environmental and greenhouse gas effects of using alternative fuels in cement production,” 2013.
31. N.J. Themelis and L. Arsova “Identification and assessment of available technologies for materials and energy recovery from flexible packaging waste (FWP),” 2010 (accessed 12/2013). Available from: http://www.seas.columbia.edu/earth/wtert/sofos/FPW_Recycling_May2011.pdf
32. Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy (2007) (accessed 12/2013). Available from: http://www.eia.gov/totalenergy/data/monthly/pdf/historical/msw.pdf
33. Phyllis database for biomass and waste (accessed 12/2013). Available from:

https://www.ecn.nl/phyllis2/

34. Tsiamis D. and Themelis N.J., "Transforming the Non-Recycled Plastics of New York City to Synthetic Oil," 2013.
35. C. Cleetus, S. Thomas and S. Varghese, "Synthesis of Petroleum-Based Fuel from Waste Plastics and Performance Analysis in a CI Engine," Journal of Energy, Volume 2013, 2013.
36. EIA and EPA, calculations and references (accessed 12/2013). Available from: http://www.epa.gov/cleanenergy/energy-resources/refs.html and http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3
37. Gasoline and Diesel Fuel Update (accessed 12/2013). Available from: http://www.eia.gov/petroleum/gasdiesel/
38. "Gasification of Non-Recycled Plastics from MSW in the United States," Gershman, Brickner and Batton Inc., 2013 (accessed 12/2013). Available from: http://plastics.americanchemistry.com/Sustainability-Recycling/Energy-Recovery/Gasification-of-Non-Recycled-Plastics-from-Municipal-Solid-Waste-in-the-United-States.pdf
39. Production of bio-methanol – Technology Brief. International Renewable Energy Agency, International Energy Agency, 2013 (accessed 12/2013). Available from: http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I08%20Production_of_Bio-methanol.pdf
40. Data from National Mining Association (accessed 12/2013). Available from: http://www.nma.org/pdf/c_use_state.pdfg
41. Ulloa P. and Themelis N.J., "Potential for Combined Heat and Power and District Heating and Cooling from Waste-to-Energy Facilities in the U.S. – Learning from the Danish Experience," 2007.
42. Phyllis international database, (accessed 1/2014) www.ecn.nl/phyllis2/Browse/Standard/ECN-Phyllis.
43. www.agilyx.com
44. www.climaxglobalenergy.com/
45. www.respolyflow.com
46. http://Cynarplc.com
47. http://www.vadxx.com/
48. www.plastics2oil.com
49. Fyffe, J. et al., "Residue-Derived Solid Recovery Fuel for Use in Cement Kilns," 2012 (accessed 1/2014). Available from: http://plastics.americanchemistry.com/Sustainability-Recycling/Energy-Recovery/Residue-Derived-Solid-Recovered-Fuel-for-Use-in-Cement-Kilns.pdf
50. 2011 National Postconsumer Non-Bottle Rigid Plastic Recycling Report, Moore Recycling Associates Inc., 2011 (accessed 12/2013). Available from: http://plastics.americanchemistry.com/Education-Resources/Publications/2012-National-Report-on-Post-Consumer-Non-Bottle-Rigid-Plastic-Recycling.pdf
51. Matthews E. and N.J. Themelis, "Potential for Reducing Global Methane Emissions From Landfills, " 2007 (accessed 1/2014). Available from:

http://www.seas.columbia.edu/earth/wtert/sofos/Matthews_Themelis_Sardinia2007.pdf

52. EPA, Polychlorinated Biphenyls: Recycling Plastics from Shredder Residue, 2012 (accessed 3/2014). Available from: http://www.epa.gov/wastes/hazard/tsd/pcbs/pdf/prepubl_notice_isri_frn_signed_032913.pdf

53. EIA Glossary, http://www.eia.gov/tools/glossary/index.cfm?id=H

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 (H_2), 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 (C_2H_4/C_2H_6) 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 C_3 and C_4 compounds exhibiting a maximum concentration near 730°C.

In terms of utilization of the syngas resulting from the gasification of solid material, methanol (CH_3OH) 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-Tropsh (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.

$$\underset{plastic}{C_xH_y} + \underset{oxygen\,from\,air}{(x/2 - m/2)O_2} + \underset{steam}{mH_2O(l)} \rightarrow xCO + (m + y/2)H_2$$

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

$$CO + 2H_2 \rightarrow CH_3OH$$

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 CO_2, H_2O 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 CO_2, N_2 - 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 H_2 to CO_2, which should in principle equal 2 as shown by the reaction above. Instead a molar ratio of $(H_2\text{-}CO_2)/(CO+CO_2) = 2$ is more applicable. CO_2 appears in the stoichiometric number because it is present when synthesis gas is produced and consumes hydrogen during the methanol synthesis.

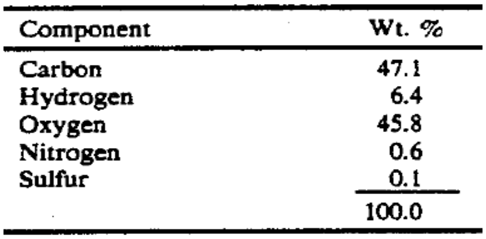
There have been many attempts to make syngas from waste plastics, but only a couple of processes have been demonstrated to actually make methanol. A patent that describes a process via gasification for converting solid waste with the chemical composition to methanol is shown in Table 1[2]. This system 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.

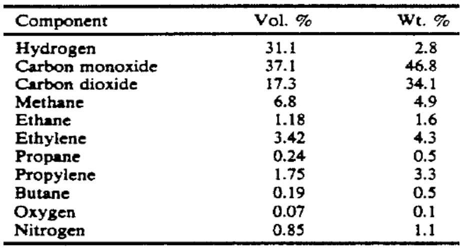
The example provided in this patent shows that 68% by volume of the syngas consists of H_2 and CO. The syngas mixture was brought to a temperature and pressure of about 300°C and 1400 psi, as required to synthesize the methanol. The reactor is fed with a high purity O_2 gas stream as the oxidizing environment to form the syngas components with some CH_4, CO_2 and some higher hydrocarbons. The gasifier produced the products shown in Table 2.

Table 1. Ultimate Analysis of Waste[2]



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 CH_4 and CO_2 from the higher hydrocarbons. The higher hydrocarbons were further reacted to produce more H_2 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, CO_2 and H_2 need to be separated to enable the CO, CO_2 and H_2 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.

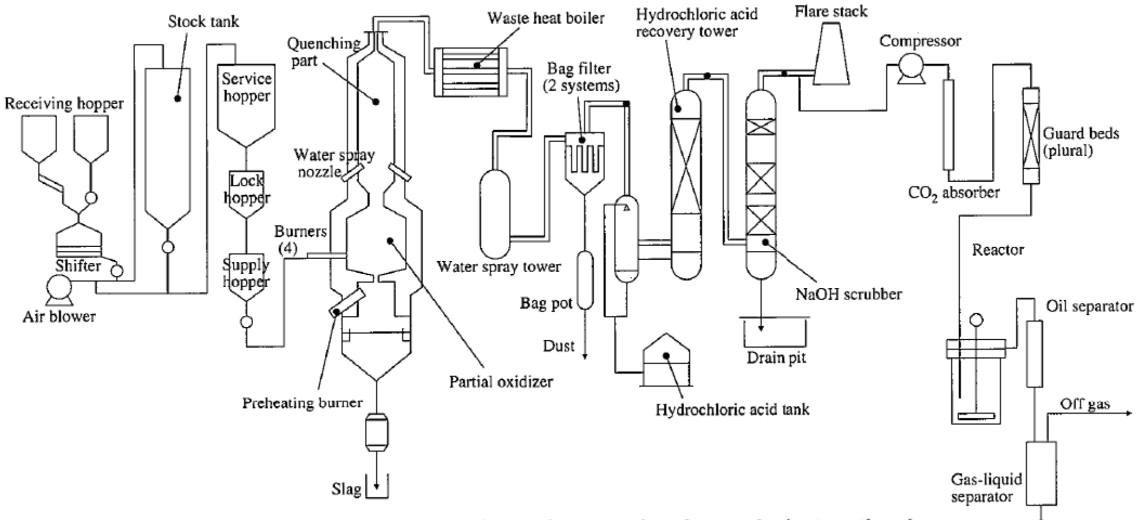
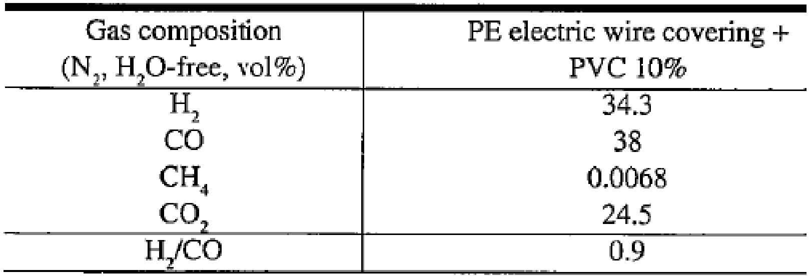


Figure 1. Demonstration test equipment for conversion of waste plastic to methanol (from 4)

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 Demonstration[4]



Gas composition (N_2, H_2O-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 $H_2/CO = 0.9$ and the $(H_2-CO_2)/(CO+CO_2) = 0.16$, which is significantly below the optimal value of 2.0. This is because of the high amount of CO_2 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 CO_2. 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 CO_2 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 H_2 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 Agylix to produce a crude oil from waste plastics that it sells to a local refiner to further process into fuel. Agylix 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:

1. Mastral, F.; Esperanza, E.; Berrueco, C.; Juste, M.; Ceamanos, J., Fluidized bed thermal degradation products of HDPE in an inert atmosphere and in air–nitrogen mixtures. *Journal of Analytical and Applied Pyrolysis* 2003, *70* (1), 1-17.
2. Funk, H. F. Solid waste refining and conversion to methanol. 1992.
3. Boundy, R. G.; Diegel, S. W.; Wright, L. L.; Davis, S. C., *Biomass energy data book*. 2011.
4. IKEDA, Y.; UENOYAMA, K.; SAMPE, H.; KOSUGE, K., Development of chemical recycle technology to methanol by partial oxidation of waste plastics. *Nippon Steel Technical Report*2002, *86* (0).