Transforming the Non-Recycled Plastics of New York City to Synthetic Oil

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EXECUTIVE SUMMARY

In 2010, New York City (NYC) generated approximately 750,500 short tons of municipal plastic waste (MPW). Currently, only 15% of NYC MPW is designated as recyclable plastic by the city's Department of Sanitation (DSNY). Under the DSNY recycling guidelines, only bottles and jugs of plastic resins #1-7 are source-separated and collected for recycling and of those collected, only #1-PET and #2-HDPE are actually recycled. Approximately, only 47% of the recyclable designated plastics (RDP) in NYC MPW are actually recycled. This relatively low recycling rate has been attributed to confusion about the DSNY guidelines and carelessness on the part of the waste generators. As a result, in 2010 NYC recycled only 7% (52,041 tons) of the total MPW it generated. Another 9% (68,311 tons), mixed with about 550,000 tons of trash, was sent to waste-to-energy facilities for energy recovery. The bulk of NYC's MPW - approximately 84% (630,187 tons per year) - was landfilled.

NYC currently uses landfill disposal as the primary waste management practice for its municipal solid waste (MSW). Although plastics are only the third largest material component of NYC MSW (after organics and paper), they are one of the most abundant material components of municipal landfilled waste. Most plastics are landfilled because the diverse chemical compositions and physical properties of the plastic material group make mechanical recycling of most plastics uneconomical. Approximately 60% of NYC's non-recycled plastics (NRP) consist of film plastics such as plastic bags.

NYC currently recycles approximately 1.45 million tons of MSW and combusts with energy recovery another 0.55 million tons. The bulk of the MSW - approximately 5.45 million tons - is transported via trucks, train, and barge to out-of-state landfills in Virginia, South Carolina, Pennsylvania, and Ohio. Although landfilling is comparatively cheaper than other waste management practices, it has become increasingly more expensive because local landfill space is sparse and NYC waste has to consequently travel farther distances to be landfilled. The NYC Office of Management and Budget projects that, in the next few years, the cost of landfilling for NYC for residential and institutional waste will increase by nearly 50% (from $305 million in 2013 to $450 million in 2016). Landfilling is not a sustainable long-term waste management solution because it has negative environmental impacts and the land available for landfill use is limited. Specifically, landfilling is estimated to generate 26 million tons of CO_2 emissions per year and to destroy 140 acres of green field space per year.

In this study, pyrolysis of MPW to synthetic oil was considered as an alternative to landfill disposal. Three types of pyrolysis technologies were examined and their potential application in processing NYC's NRP was evaluated. The technologies discussed were developed by JBI Inc, Agilyx, and Climax Global Energy Inc. All three technologies process NRP to yield synthetic fuels and other petrochemical products of market value.

Plastic residue from NYC's Sims Material Recovery Facility (MRF) in New Jersey was considered as the test-run feedstock for the pyrolysis technologies discussed. Sims generates approximately 60 tons of

plastic residue per day, which primarily consists of film plastics. In practice, if NYC were to construct a pyrolysis plant to process all of the city's municipal NRP (which includes landfill-bound plastic refuse in addition to plastic residue from Sims MRF), then the total required operating capacity of the plant would be approximately 1,700 tons per day.

JBI Inc's "Plastic2Oil" (P2O) process is a continuous thermal catalytic process that can handle all types of plastic waste and resins, except for #3-PVC and nylons. This highly automated process yields consumer-ready No. 6 and No. 2 oils, and naphtha, which requires further blending. The P2O process generates 4.4 barrels of oil per ton of plastic waste. A single P2O unit processes 48 tons of plastic waste per day at maximum capacity and operates at approximately 75% availability. The P2O process has low estimated overall CO_2 emissions (0.15 tons CO_2/ton of plastic waste), low waste generation, and low electricity consumption because it is powered by the off-gas generated during pyrolysis. The P2O process is estimated to generate a net income of approximately $280 per ton of plastic waste. JBI Inc. currently operates a demonstrational scale facility in Niagara Falls, NY and is constructing a 144-ton per day commercial facility in Jacksonville, FL.

Agilyx operates a batch thermal pyrolysis process that converts all plastic waste types and resins into low sulfur synthetic crude oil. The Agilyx process generates 4.1 barrels of crude oil per ton of plastic waste. A single Agilyx unit (referred to as a base system) processes 30 tons of plastic waste per day at maximum capacity. The Agilyx process has higher estimated overall CO_2 emissions (>0.57 tons CO_2/ton of plastic waste) than the P2O process and it also generates wastewater. Agilyx uses natural gas and electricity to power its process. Agilyx currently operates a demonstrational scale facility in Tigard, Portland, OR and a commercial facility near Portland, OR, which has been in operation for two years.

Climax Global Energy Inc. (CGE) uses microwave energy for the pyrolysis of plastic waste to synthetic petroleum. Distillation of the synthetic petroleum product yields marketable diesel range fuel and wax. The CGE process generates 5 barrels of synthetic petroleum per ton of plastic waste. A single CGE unit processes 10 tons of plastic waste per day and operates at approximately 85% availability. CGE requires a high electricity demand to power its process. The CGE process has higher estimated overall CO_2 emissions than the P2O process (>0.33 tons CO_2/ton of plastic waste) but lower overall emissions than the Agilyx process. CGE uses a fraction of its process off-gas to heat its reactor. CGE is currently starting up a 10-ton per day commercial unit in Barnwell County, SC.

On the basis of a technical and environmental comparison of the three pyrolysis technologies examined in this study, it is concluded that JBI Inc.'s P2O process would be the most appropriate for potential application in processing NYC's municipal NRP. This process has the highest operating capacity at a low footprint and it has relatively low environmental impacts. Furthermore, the P2O process produces high quality, consumer-ready fuels and it has a low electricity demand because it utilizes energy from the combustion of the off-gas generated during pyrolysis. The P2O process also generates a significant net income per ton of plastic waste. It would take approximately 36 P2O units to process all of NYC's municipal NRP.

The recycling of plastic wastes in NYC seems to have reached a plateau. Since landfills are becoming more costly and progressively farther away from NYC, pyrolysis of NYC's municipal NRP would be advantageous because it has low environmental impacts and it recovers a valuable energy source that would otherwise be wasted.

Further research on the pyrolysis of NYC's municipal NRP should include a feasibility study for the source-separation and collection of this waste material and for the siting, building and operation of a pyrolysis plant of initial capacity of 60 tons per day (21,900 tons per year), which would process plastic residue from the Sims MRF.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Issues with Current Waste Management of Non-Recyclable Plastics in NYC MSW

In 2010, New York City (NYC) generated approximately 7.45 million short tons of municipal solid waste (MSW). Plastics are the third largest component of NYC MSW (after organics and paper). In 2010, NYC generated approximately 750,500 tons of municipal plastic waste (MPW). Of the total NYC MPW, only about 7% (52,041 tons) was recycled. Approximately 9% (68,311 tons) was sent to waste-to-energy facilities in New Jersey and Long Island for energy recovery and the remaining 84% (630,187 tons) was disposed of in landfills.

Some of NYC's landfill-bound MPW consists of recyclable designated plastics (RDP) that were not recycled by waste generators. The Department of New York Sanitation (DSNY) reports that recycling rates for the various neighborhoods in NYC range from 15% to 55%[1]. Although improved recycling performance of NYC's waste generators would help to reduce the tonnage of RDP that end up in landfills, it would not significantly reduce the total tonnage of landfill-bound plastics because most of NYC MPW is not designated for recycling under the DSNY's current recycling program. This is due to both a lack of reliable and stable secondary markets for most post-consumer plastics and a lack of technology to convert the post-consumer plastics into marketable materials.

NYC currently recycles approximately 1.45 million tons of municipal solid waste (MSW) and combusts with energy recovery another 0.55 million tons. The bulk of the MSW (5.45 million tons) is transported via trucks, train, and barge to out-of-state landfills in Virginia, South Carolina, Pennsylvania, and Ohio[2]. Landfill disposal is not sustainable and its continued use may result in major environmental and economic problems for NYC in the near future.

The land available for landfill use is a limited resource and the landfills in NY's neighboring states are reaching their full capacity. As a result, NYC has to transport its waste to landfills located as far as 700 miles away[3]. The farther NYC waste has to be transported in order to be disposed in a landfill, the more expensive it is. Furthermore, since the land available for landfill use is declining and the demand for landfilling is growing, due to increasing waste generation rates, landfill companies are charging higher fees to dispose in their landfills. 80% of the land commercially available for landfills east of the Mississippi is owned by only 2 companies[4]. The NYC Office of Budget and Management projects that, in the next few years,

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[1] New York City. Department of Sanitation. *Annual Report: New York City Curbside Municipal Refuse and Recycling Statistics.* 2011. Print.

[2] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

[3] Ibid.

[4] Ibid.

the cost of landfilling for NYC for residential and institutional waste will increase by nearly 50% (from $305 million in 2013 to $450 million in 2016)[5].

In addition to becoming a more costly waste management practice, landfilling has a negative impact on the environment. NYC deploys 900 23-ton trucks to travel to landfills every day. This massive fleet of trucks travels a total of 600 million miles per year and uses a total of 6,500 gallons of fuel per day[6]. The high fuel consumption required for long-haul trucking and the waste that is disposed of in landfills contribute to emissions of greenhouse gases such as methane and carbon dioxide. It estimated that landfilling generates approximately 26 million short tons of CO_2 per year. In addition to polluting the air, landfilling destroys approximately 140 acres of green field space per year[7].

While organics and recyclable paper can be diverted from landfills via composting and more intensive recycling efforts, there is currently no established technology or process that can re-use NYC's non-recycled plastics (NRP) and consequently divert it from landfills. NYC's predominant use of landfill disposal in its waste management program will continue unless a cost-effective technology is developed that can convert NRP into products with a high market demand.

1.2 Objectives

The objective of this study was to characterize and quantify NYC's municipal plastic waste (MPW) and to assess the potential for recovering synthetic oil from NYC's non-recycled MPW via pyrolysis. Three pyrolysis technologies were compared and analyzed in terms of their technical and environmental aspects. These different technologies are thermal, thermal catalytic, and microwave pyrolysis and were developed by Agilyx, JBI Inc., and Climax Global Energy Inc. (CGE), respectively. All of these processes convert non-recycled plastics (NRP) into synthetic oils and other petrochemical products of market value.

Furthermore, this study compared the economic and environmental aspects of the pyrolysis technologies to those of landfill disposal. Based on the results of this comparison, a recommendation was made for improving waste management practices for non-recycled MPW in NYC.

[5] New York City, Department of Sanitation. *New and Emerging Conversion Technology.* 2013. Web

[6] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

[7] Ibid.

2. NEW YORK CITY'S MUNICIPAL SOLID WASTE

2.1 Definition of Municipal Solid Waste (MSW)

The Department of New York Sanitation (DSNY) defines municipal solid waste (MSW) as any waste that is set out at the curbside by residents and businesses for collection by the DSNY or private haulers[8]. It includes both trash and recycling. MSW generally consists of durable and non-durable goods, containers, packaging, food wastes, yard trimmings, and inorganic wastes. Although the Environmental Protection Agency (EPA) characterizes MSW as non-hazardous waste[9], the DSNY reports traces of household hazardous waste in New York City (NYC) MSW. Therefore, household hazardous waste is included in this study's reported tonnages of NYC MSW. Waste types that are excluded from this study's discussion of MSW are institutional waste (waste generated by schools, hospitals, etc) and construction and demolition (C&D) debris from large-scale commercial construction projects.

The primary generators of MSW are the residential and commercial sectors. The commercial sector refers to businesses which include offices, retail stores, restaurants, fast food chains, food stores, and hotels[10]. In NYC, residential MSW is collected curbside by the DSNY while commercial MSW is collected by private haulers. Prior to collection, MSW is separated into three waste streams: paper recycling, metals, glass, plastic (MGP) recycling, and refuse.

2.2 Recyclable and Non-Recyclable Designated MSW

NYC separates its MSW into three waste streams: paper recycling, metals, glass, plastic (MGP) recycling, and refuse. The DSNY defines recyclable waste as any material that is recovered after processing and returned to the stream of commerce for reuse[11]. The waste that is collected for recycling is either reused to make the same material or it is used to make a different type of product.

DSNY defines refuse as waste that is either discarded or disposed[12]. Refuse is either disposed of in a landfill or is sent to a waste to energy plant. At a waste to energy plant, the refuse undergoes complete combustion and its stored chemical energy is recovered for use as heat and electricity. The DSNY currently does not distinguish between landfill-bound and waste-to-energy bound refuse in its characterization studies of NYC MSW.

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[8] RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 1. Print.

[9] EPA. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010*. US EPA ,2011. Web. 2.

[10] New York City. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 2-9. Print.

[11] RW Beck. *Final Report: 2004-2005 NYC Residential and Street Basket Waste Characterization Study: Glossary*. 2007. GL-6. Print.

[12]Ibid.

Items that are designated for recycling under DSNY's current recycling program are listed in Table 1. Non-recyclable designated items are listed in Table 2.

Table 1: Items that are designated for recycling in NYC

Recyclable Designated Items				
Paper Recycling (Green Decal)	**Metals, Glass, Plastic Recycling (Blue Decal)**			
Newspapers	***Metal***	***Glass***	***Plastic***	***Beverage Carton***
Magazines	Cans (soup, food, paint)	Bottles	Bottles	Milk cartons
White and Colored Paper	Aluminum foil	Jars	Jugs	Juice Boxes
Mail and Envelopes	Aluminum Trays			
Paper Bags	Household metal (wire hangers, small appliances, tools)			
Wrapping Paper	Bulk Metal			
Soft Cover Books	Caps and lids			
Cardboard Egg Cartons and Trays				
Smooth Cardboard				

Source: NYC Dept. of Sanitation: Bureau of Waste Prevention, Reuse and Recycling

Table 2: Items that are not designated for recycling in NYC

Non-Recyclable Designated Items		
Paper and Cardboard	**Metals**	**Plastic**
Hardcover books	Batteries	Items other than plastic bottles and jugs (deli and yogurt containers, plastic toys, cups, wrap, etc)
Napkins, paper towels, tissues		Styrofoam (Cups, egg cartons, trays, etc)
Soiled paper cups and plates		Plastic bags
Paper with a lot of tape and glue		
Plastic or wax-coated paper (candy wrappers, take-out containers)		
Photographic paper		

Source: NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling

2.3 Characterization of NYC MSW

2.3.1 Material Composition of NYC MSW

In 2010, NYC generated 7.45 million short tons of MSW. Approximately 57% (4.23 million tons) of the total MSW was residential waste and the remaining 43% (3.21 million tons) was commercial waste. Calculations of the NYC MSW generation tonnages are provided in *Appendix I: MSW Generation in NYC.*

Figure 1 shows the material breakdown of NYC MSW. The composition of the MSW was determined based on DSNY reported tonnages for 2010 and the DSNY's *Annual Report for NYC Curbside Municipal Refuse and Recycling Statistics* and *2004 Commercial Waste Management Study.* Calculations for Figure 1 are provided in *Appendix I: Material Composition of NYC MSW*.

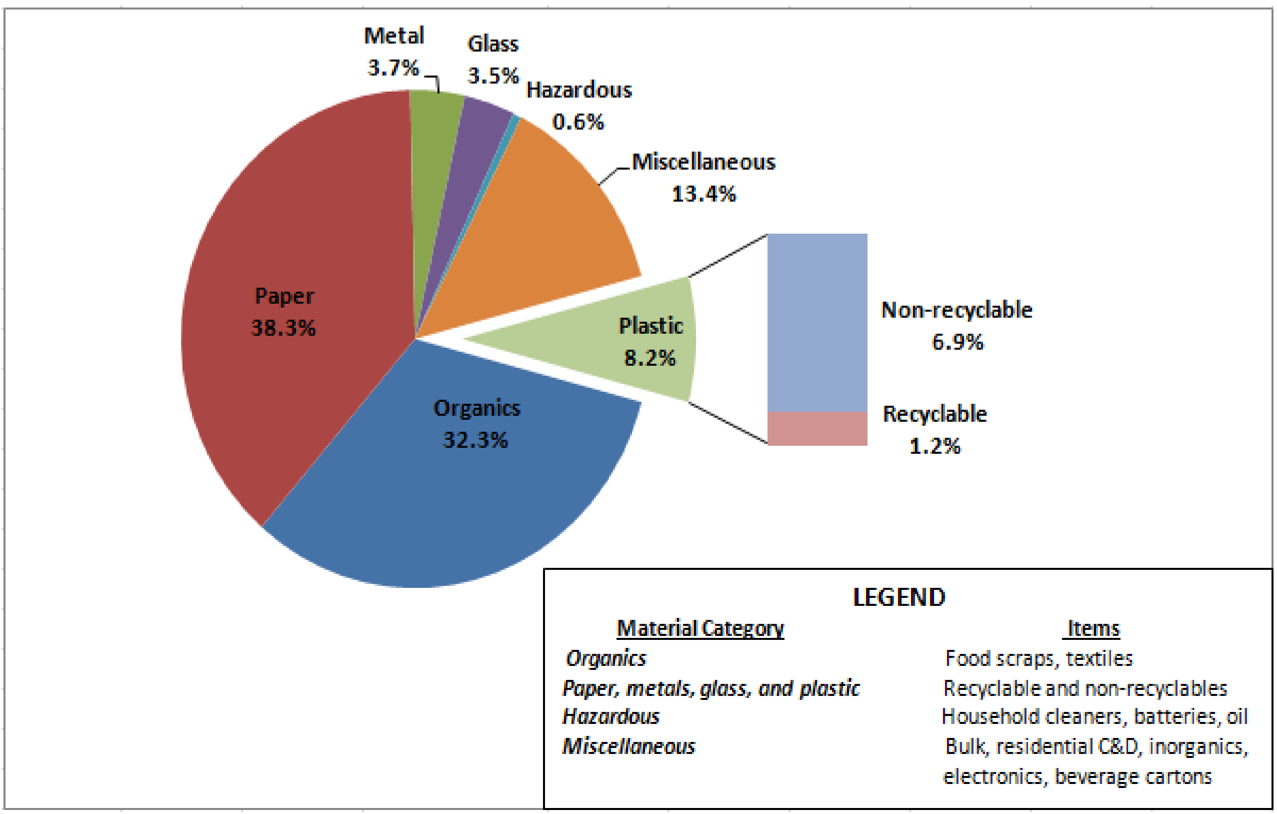

Figure 1: Material composition of NYC MSW, 2010

As is shown in Figure 1, paper makes up the largest portion of NYC MSW followed by organics and then plastics. While most of paper waste can be recycled and most of organic waste can be composted, most plastic waste is landfilled. This is because there are no commercial technologies currently implemented in NYC's waste management infrastructure that reuse the majority of the plastic waste generated. Plastics that are designated for recycling make up only about 1% of NYC MSW.

2.3.2 Recyclable and Non-recyclable Designated Items in NYC MSW

Figure 2 shows the breakdown of NYC MSW into designated recyclable and non-recyclable waste. This graph shows how much of NYC's MSW could be recycled, and consequently diverted from landfills, if there was 100% participation in the DSNY's recycling program and if all participants followed the DSNY's recycling guidelines correctly. Calculations for Figure 2 are shown in *Appendix I: Recyclable and Non-Recyclable Designated Items in NYC MSW*.

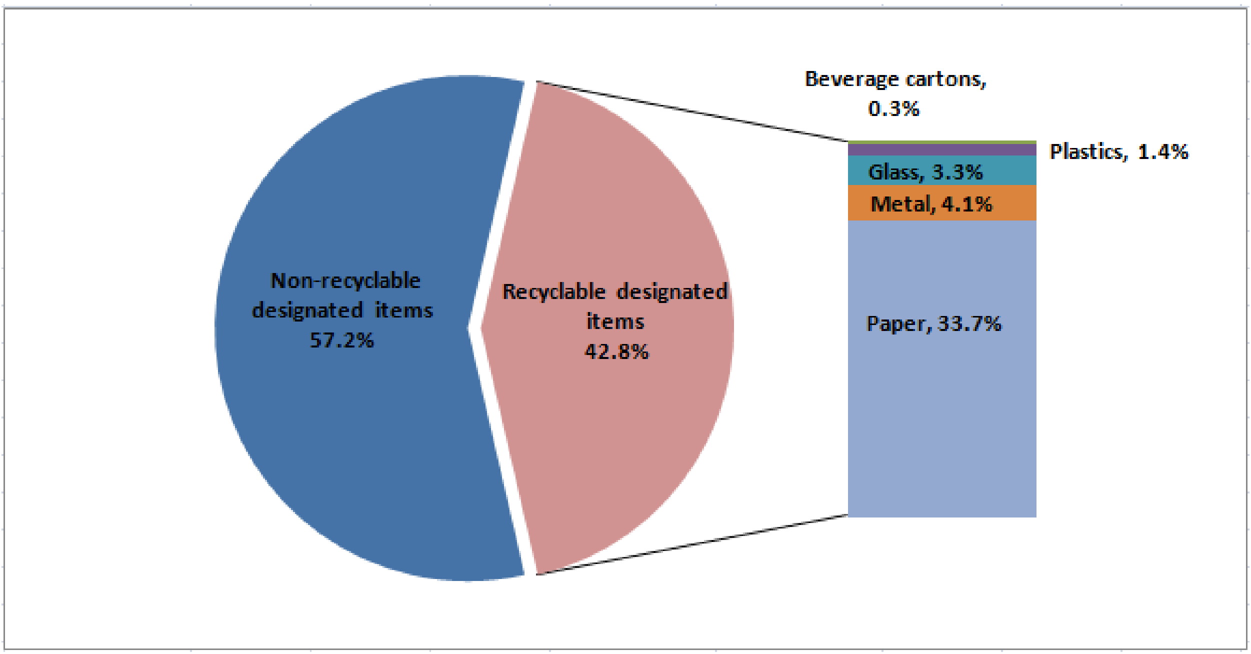

Figure 2: Recyclable and non-recyclable designated items in NYC MSW, 2010

Based on Figure 2, approximately 43% of the total waste generated in NYC can be diverted from landfills if all New Yorkers participate in DSNY's current recycling program. Unfortunately, not all New Yorkers recycle, and of those who do a significant percentage do not recycle correctly. This can be attributed to factors such as a general lack of education about the recycling program, confusing presentation of DSNY recycling guidelines, and carelessness on the part of the waste generator[13].

Since not all of the recyclable designated waste in NYC is actually recycled, the DSNY uses a performance metric, called the diversion rate, to evaluate the recycling performance of waste generators.
The diversion rate is defined as follows:

[13] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

Diversion rate = Tons of recycling collected/ Tons of recycling and refuse collected[14]

The diversion rate indicates how much of the waste generated in NYC is diverted from landfills. Figure 3 shows DSNY's 2010 and 2011 reported diversion rates for the residential sectors of NYC's five boroughs.

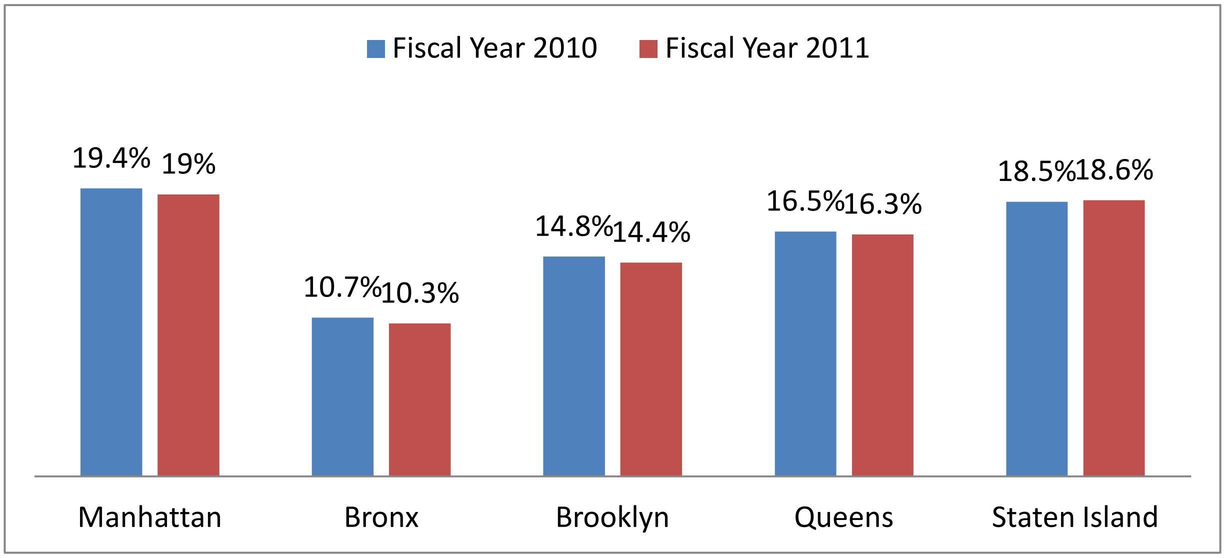

Figure 3: Residential MSW diversion rates of NYC boroughs
Source: DSNY Annual Report Fiscal Year 2010, NYC Curbside Municipal Refuse and Recycling Statistics

The varying diversion rates between boroughs reveal that the success of DSNY's recycling program depends largely on the waste generator. The average diversion rate for the residential sector of NYC is 15.8%. Based on the average diversion rate and the fact that recyclable designated items make up approximately 36% of residential waste[15], it can be concluded that NYC residents currently recycle only about 40% of the recyclable designated waste that they generate. Therefore, the majority of NYC's recyclable designated waste is landfilled. Furthermore, Figure 3 shows that the diversion rates of most of NYC's boroughs decreased from 2010 to 2011. This trend indicates that increasingly more recyclable designated waste is being sent to landfills.

Although measures should be taken to improve the recycling performance of NYC waste generators, it is a challenging task. US cities with successful recycling programs, like San Francisco and Seattle, charge a monetary penalty to waste generators if they do not recycle[16]. Unfortunately, such a policy cannot be easily

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[14] RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 4. Print.

[15] Ibid, 2.

[16] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

implemented in NYC because the city contains a high number of multi-tenant residential buildings. Since the waste generated by individual tenants is mixed together before collection, it is difficult to identify which tenants recycle and which do not[17].

Figure 4 shows the percentage of recyclable designated items in NYC MSW that are actually recycled and the percentage that are not.

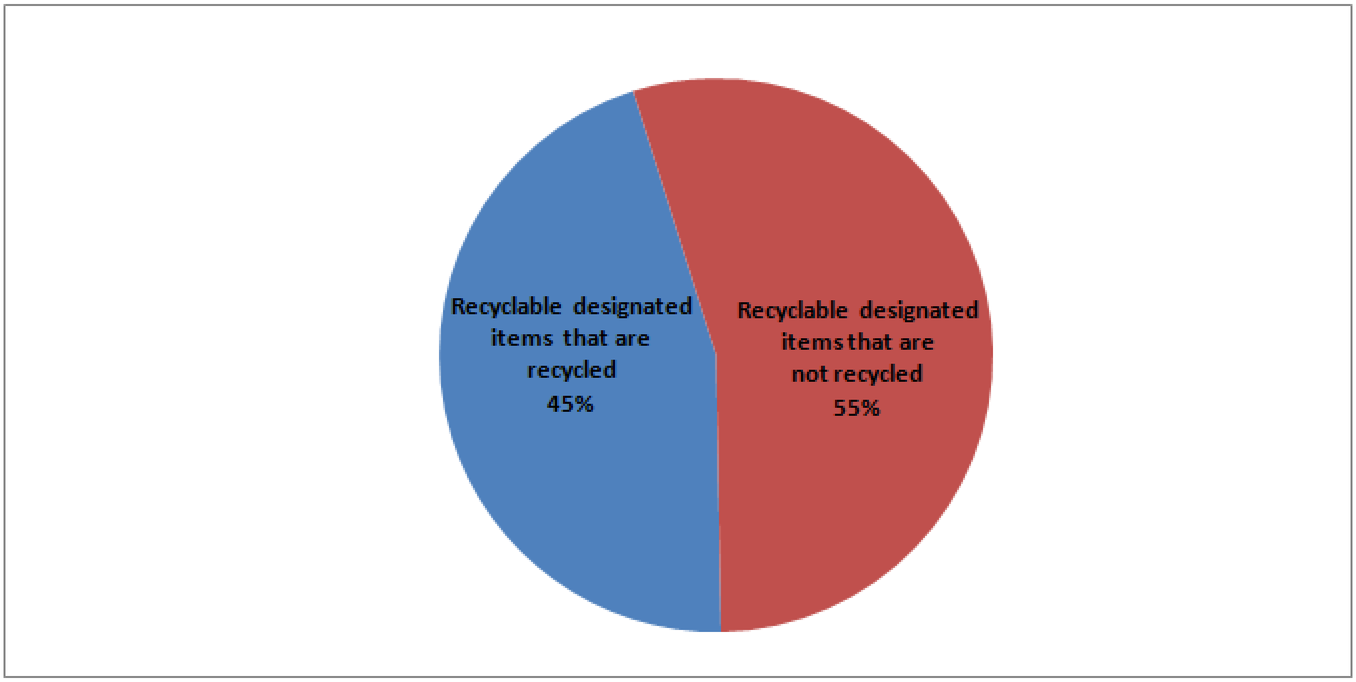

Figure 4: Fate of recyclable designated items in NYC MSW, 2010

NYC recycles approximately half of the waste that it could potentially recycle under DSNY's current recycling program. It should be noted that the total recycling rate for NYC is slightly higher than that for the NYC residential sector because the diversion rate of the commercial sector is higher than the residential sector (diversion rate for commercial sector is estimated to be approximately 26%).

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[17] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

2.3.3 Fate of NYC MSW: Tonnages Landfilled, Recycled, and Sent to Waste-to-Energy

In 2010, NYC generated 7.45 million short tons of MSW. Of the total MSW generated, 73.2% (5.45 million tons) was landfilled, 19.4% (1.45 million tons) was recycled, and 7.4% (0.55 million tons) was sent to waste-to-energy plants.

Table 3 shows the tonnages of NYC MSW from each sector that was landfilled, recycled, and sent to waste-to-energy plants. Figure 5 graphically shows the fate of NYC's total MSW based on the results in Table 3. Calculations for Table 3 and Figure 5 are provided in *Appendix I: Fate of NYC MSW*.

It should be noted that in Table 3, the category "Total MSW recycled" excludes the tonnage of non-recyclable designated items present in the collected recycling streams. This residue is accounted for in the "Total MSW landfilled" tonnage.

Table 3: Estimated tonnages of NYC MSW landfilled, recycled, and sent to waste-to-energy, 2010

		Recycling collected				
	Estimated generation of MSW (10^6 tons/year)	**Metals, glass, & plastic recycling (10^6 tons/year)**	**Paper recycling (10^6 tons/year)**	**Total MSW recycled (10^6 tons/year)**	**Total MSW sent to waste-to-energy (10^6 tons/year)**	**Total MSW landfilled (10^6 tons/year)**
Residential Sector	4.23	0.27	0.39	0.59	0.38	3.26
Commercial Sector	3.21	0.14	0.72	0.86	0.17	2.19
TOTAL	**7.45**	0.41	1.11	**1.45**	**0.55**	**5.45**

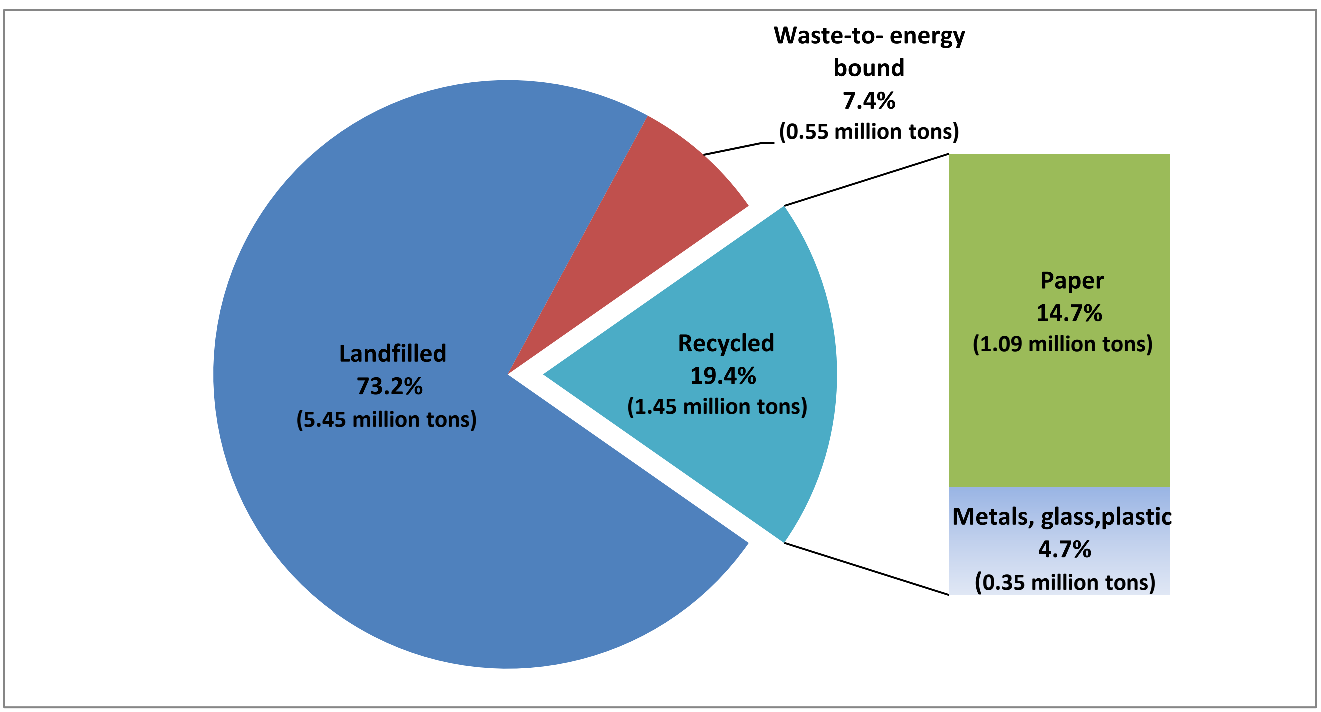

Figure 5: Fate of NYC MSW, 2010

As can be seen from Figure 5, most of NYC MSW is currently landfilled. The calculated tonnage of landfilled waste listed in Table 3 includes recyclable designated waste that was either not recycled or was recycled incorrectly. Recyclable designated items that aren't recycled properly end up as part of the residue stream of material recovery facilities (MRFs). MRFs are facilities that sort and separate recycling streams and prepare the recyclable items for manufacturers. Residue from MRFs is discarded in landfills.

Only about 20% of total NYC MSW is recycled. NYC's overall diversion rate is slightly higher than the reported 15.8% diversion rate for the residential sector. This difference is attributed to the commercial sector, which has a calculated diversion rate of about 26%. Of the recycled waste, paper is recycled 3 times more than metals, glass, and plastic (MGP).

Less than 10% of the total MSW generated in NYC is sent to waste-to-energy plants for energy recovery.

3. NEW YORK CITY'S MUNICIPAL PLASTIC WASTE

3.1 Definition of Municipal Plastic Waste (MPW)

Plastic is a synthetic material made of repeating organic monomer units that form a chain called a polymer. When polymers are dried and shaped into pellets, they are called plastic resins. Resin refers to the basic chemical composition of a plastic. Each resin has unique chemical and physical properties. Plastic resins serve as the building blocks of all manufactured plastic products[18]. The six most common plastic resins are polyethylene terephthalate (PET), high density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). Table 4 lists the chemical and physical properties of these six plastic resins and their typical applications in consumer products.

Table 4: Properties and applications of common plastic resins

Plastic Resin	Chemical and Physical Properties	Typical Applications
PET	Tough and strong; Gas and moisture resistant	• Carbonated beverage containers • Food containers
HDPE	Chemically resistant; Moisture resistant	• Non-carbonated beverage bottles • Snack food packaging • Packaging for detergents & bleach • Film for grocery sacks
PVC	Transparent; Chemically resistant; Stable; Resistant to weathering; Stable electrical properties; Can be rigid or flexible	• Rigid: pipes and fittings • Flexible: insulation • Flexible: synthetic leather products
LDPE	Tough; Flexible; Transparent; Stable electrical properties	• Shopping and grocery bags • Flexible bottles and lids • Wires and cables
PP	Heat and moisture resistant; Chemically resistant; Can be rigid or flexible	• Flexible or rigid packaging • Yogurt containers
PS	Clear; Hard and brittle; Excellent thermal insulator; Can be rigid or expanded; Lightweight (when expanded);	• Expanded: foam cups and trays • Expanded: take-out containers • Expanded: egg cartons • Medical and food packaging • Labware

Source: American Chemistry Council

There are two main types of plastics: thermosets and thermoplasts. Thermosets are plastics that are set into a mold once and cannot be re-softened or molded again. Thermoplasts, on the other hand, can be re-molded repeatedly when heated. Most of everyday consumer plastics are thermoplasts[19].

Plastics are most commonly used for packaging and food containers but they are also found in durable (appliances, furniture, etc.) and non-durable goods (trash bags, cups and utensils, etc). Plastics are a popular material because they are chemically resistant, they're lightweight with varying degrees of strength,

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[18] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "Plastics Science: Polymers". 2012. Web.

[19] American Chemistry Council. "The Basics: Polymer Definition and Properties". 2012. Web.

they can be both thermal and electric insulators, they can be molded in various ways, and they offer a limitless range of characteristics and colors, which can be further enhanced with additives[20].

3.1.1. Plastic Molding Methods

Plastic products can be manufactured by various molding methods. The most common molding methods are blow molding, injection molding, and extrusion.

In blow molding, plastic is melted and formed into a tube called a pre-form. The pre-form is clamped into the desired mold and air is pumped into it at high pressure. As a result of the air, the pre-form expands out to fill the dimensions and form of the mold. Once the plastic cools and hardens, the mold opens and the plastic product is ejected. Blow molded plastics are generally stiff and strong. Examples of blow-molded consumer plastics are bottles and jugs.

Injection molding is a process in which melted plastic of low viscosity fills the cavities of a mold. Once the plastic cools and hardens, it is removed from the mold. Plastic products that are made by injection molding include margarine tubs, toys, and packaging. Injection molding is often used for plastic products with complicated shapes.

Extrusion is a type of injection molding. In extrusion, melted plastic is forced through a mold called a die via an extrusion screw. Film plastics, such as shopping bags and shrink wrap, and styrofoam packaging are all formed by extrusion.

3.1.2 Plastic Additives

Additives are used in consumer plastic products to enhance the mechanical, chemical, and physical properties of plastic resins. Typical additives that are used in plastics are fillers, plasticizers, stabilizers, colorants, and flame retardants.

Fillers are added to plastics to improve physical properties such as tensile and compressive strengths, abrasion resistance, toughness etc. and chemical properties such as thermal stability. Fillers are less expensive than polymers therefore the addition of fillers drives down the cost of plastic end products[21].

Plasticizers are additives that are used to improve a plastic's ductility and flexibility. Plasticizers are used in PVC, which is an intrinsically brittle plastic. They are also commonly used in plastic film.

Some polymer-based materials are prone to mechanical deterioration as a result of either oxidation or UV radiation. To prevent this, stabilizers are added to plastics in order to counteract these deteriorative processes.

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[20] American Chemistry Council. "The Basics: Polymer Definition and Properties". 2012. Web.

[21] Callister, William D. Jr. *Materials Science and Engineering An Introduction*. 5th ed. John Wiley & Sons Inc, 2000. 498. Print.

Colorants impart a specific color to a polymer. Colorants are used in the form of either dyes or pigments. Dyes dissolve and become part of the polymer structure. Pigments, which are a type of filler material, don't dissolve but instead remain as a separate phase in the plastic.

Flame retardants reduce the flammability of plastics. Most polymers are flammable in their pure form. Exceptions are polymers that contain significant concentrations of chlorine and/or fluorine such as PVC. Flame retardants reduce the flammability of the plastic by either interfering with the combustion process through the gas phase or by initiating a chemical reaction that cools the combustion region and ends burning.

3.2 Plastic Resin Code

Due to the various molding methods and various additives that are used to make plastics, many plastic consumer products are unique unto themselves. In an effort to characterize this diverse material group, the Society of Plastics Industry (SPI) established the plastic resin code in 1988. The resin code identifies the different type of polymers most commonly found in MPW. Table 5 lists the seven resin categories of the plastic resin code. It should be noted that while the first six resin categories identify a specific chemical compound, the seventh resin category is considered a "catch-all" for miscellaneous resin types.

Table 5: Resin categories of SPI plastic resin code

Symbol	Number	Abbreviation	Resin Name
1 PETE	1	PET, PETE	Polyethylene Terephthalate
2 HDPE	2	HDPE	High Density Polyethylene
3 V	3	PVC, V	Polyvinyl Chloride
4 LDPE	4	LDPE, LLDPE	Low Density Polyethylene, Linear Low Density Polyethylene
5 PP	5	PP	Polypropylene
6 PS	6	PS	Polystyrene
7 Other	7	Other	Other Resin Types

Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

The SPI implemented the resin code to provide an industry-wide standard that would make it easier to identify and sort recyclable plastic[22]. Although all resins in the resin code are symbolized with "chasing

[22] RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 44. Print.

arrows", which is an internationally recognized symbol used to designate recyclable materials[23], most of the resins in the resin code are not designated for recycling under the DSNY's current recycling program. The following section explains which plastic resins are recycled in NYC and which are not.

3.3 Recyclable and Non-Recyclable Designated Plastics in NYC MPW

NYC only recycles #1-PET and #2-HDPE plastic bottles and jugs. Plastics of resins #3-7 and #1-PET and #2-HDPE plastics that are not bottles and jugs are not recycled. Table 6 specifies which plastic items are designated for recycling and which are not under the DSNY's current recycling program. The DSNY recycling guidelines for plastics apply only to NYC residents and food-service businesses. Businesses in the commercial sector, other than food-service operations, are not mandated by the DSNY to recycle plastic bottles and jugs[24].

Table 6: Recyclable designated and non-recyclable designated plastics in NYC

Recyclable designated plastics, RDP	Non-recyclable designated plastics, NRP
• Resin #1-7 bottles and jugs	• Rigid containers (i.e. deli food containers) • Plastic bags and film • Packaging • Styrofoam • Durable goods (i.e. toys) • Non-durable goods (i.e. cups and utensils) • Any item other than bottles and jugs

Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

There are several misconceptions about plastics recycling in NYC. One misconception is that NYC recycles all the plastic bottles and jugs that are collected by the DSNY. As mentioned above, NYC only recycles #1-PET and #2-HDPE bottles and jugs. The remaining bottles and jugs that are collected for recycling are discarded because the market for resins other than #1-PET and #2-HDPE is weak[25]. The market for #1-PET and #2-HDPE resins is stable because these resins produce high quality recycled products and they are in large enough quantities in NYC's MSW to satisfy the economies of scale in collection and processing[26].

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[23] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "Plastics Resin Codes". 2012. Web.

[24] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "What Plastics to Recycle in NYC". 2012. Web.

[25] Ibid.

[26] Ibid.

The DSNY collects all resin #1-7 bottles and jugs for recycling only to avoid confusion amongst waste generators[27]. In 2004, the DSNY guidelines designated only #1-PET and #2-HDPE bottles and jugs as recyclables. DSNY later reported that such specifications created confusion amongst waste generators. Since most bottles and jugs are made of resins #1-PET and #2-HDPE (DSNY reports that 95% of the collected plastic bottles and jugs are #1-PET and #2-HDPE and only 5% are made from resins #3-7)[28], to avoid further confusion, the DSNY changed its recycling guidelines back to collecting all plastic bottles and jugs for recycling.

A second misconception about plastics recycling is that #1-PET and #2-HDPE bottles and jugs are the only types of recyclable plastic products. On the contrary, the technology exists to recycle most kinds of plastics if carefully sorted out by type[29]. NYC chooses not to recycle all of its plastic waste largely because the economics of doing so make it impractical. The recycled products of plastic waste must compete in price and quality with alternate materials. The end market of a recycled plastic product must be stable and viable in order to cover the cost of collection and sorting of the plastic waste[30]. Currently, most plastic waste items, other than #1-PET and #2-HDPE bottles and jugs, do not have reliable markets and therefore they are not collected for recycling in NYC.[31] Instead, NYC chooses to landfill most of its plastic waste because it is currently cheaper than recycling[32].

Finally, one of the biggest misconceptions about plastics recycling is that the recyclability of a plastic item is solely based on its resin composition. While #1-PET and #2-HDPE plastics are generally more recyclable than #3-7 plastics, factors such as plastic molding process, types of plastic additives, and degree of contamination are also important in determining the recyclability of a plastic. In fact, the reason that #1-PET and #2-HDPE plastic bottles and jugs are recyclable and yet #1-PET and #2-HDPE tubs and trays are not lies in the difference between the molding processes used to make each of these products. Bottles and jugs are made by blow molding while tubs and trays are made by injection molding. Plastic products of the same resin but different molding process cannot be mixed together in the remanufacture of recycled content[33]. If plastic products of resin #1-PET and #2-HDPE, such as tubs and trays, were mixed with #1-PET and #2-HDPE bottles and jugs, the resulting mixture would not be usable for manufacturing a recycled material[34]. Since the current market for injection-molded #1-PET and #2-HDPE plastics is weak to non-existent, it isn't economical to recycle #1-PET and #2-HDPE plastics that are not bottles and jugs.

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[27] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "What Plastics to Recycle in NYC". 2012. Web.

[28] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "Why NYC Only Accepts Certain Plastics for Recycling". 2012. Web.

[29] RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 65.
[30] Ibid.
[31] Ibid, 63.
[32] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.
[33] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "Why NYC Only Accepts Certain Plastics for Recycling". 2012. Web.
[34] Ibid.

Table 7 lists plastic items commonly found in NYC MPW. The plastics are categorized based on resin type, molding method, consumer use, current recycling status in NYC, and recyclable product market status.

Table 7: Recyclability of plastic items in NYC MPW

Resin Code #	Name	Molding Method	Common Product Examples	Accepted for Recycling	Recyclable Product Market Status
1 PETE	Polyethylene Terephthalate	Blow Molding	Soda & Water Bottles	YES	HIGH
2 HDPE	High density Polyethylene	Blow Molding	Milk jugs, Detergent bottles	YES	HIGH
3 PVC	Polyvinyl Chloride	Blow Molding	Household cleaner & Shampoo bottles	YES	WEAK
4 LDPE	Low density Polyethylene	Blow Molding	Soft-sided juice bottles	YES	WEAK
5 Pp	Polypropylene	Blow Molding	Various Bottles & Jugs	YES	WEAK
7 OTHER	Any other type of plastic	Blow Molding	Various Bottles & Jugs	YES	WEAK
1 PETE		Injection Molding	Deli Containers	NO	WEAK
2 HDPE		Injection Molding	Take-out containers, yogurt cups, margarine tubs	NO	WEAK
3 PVC		Injection Molding	Various Tubs and Trays	NO	WEAK
4 LDPE		Injection Molding	Various Tubs and Trays	NO	WEAK
5 Pp		Injection Molding	Yogurt cups, Margarine tubs	NO	WEAK
7 OTHER		Injection Molding	Various Tubs and Trays	NO	NONE
2 HDPE or 4 LDPE Or no code	May be one of many different types of resins	Extrusion	Shopping and Grocery Bags	NO	WEAK
6 PS Or no code	Polystyrene (non-expanded)	Injection Molding	CD cases, Tamper proof packaging	NO	WEAK
None	Styrofoam	Extrusion	Cups & Plates, Mail order packaging	NO	WEAK
None	Other rigid packaging	Injection Molding (usually)	Caps, Lids, Crates	NO	WEAK
None	Single-use Packaging	Blow or injection molding	Disposable Cups, Plates & Cutlery	NO	WEAK
None	All other plastic durables	Injection Molding (usually)	House ware, Toys, Hardware	NO	WEAK
None	Other film plastic	Extrusion	Garbage bags, Baggies, Wraps	NO	WEAK

Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

3.4 Characterization of NYC MPW

3.4.1 Composition of NYC MPW

In 2010, NYC generated 750,538 short tons of MPW. Approximately 79% (589,838 tons) of the total MPW was residential plastic waste and the remaining 21% (160,700 tons) was commercial plastic waste. Calculations of NYC MPW tonnages are provided in *Appendix I: Municipal Plastic Waste Generation in NYC*.

Figure 6 shows the composition of NYC MPW. The composition of NYC's plastic waste was determined based on DSNY reported tonnages for 2010 and the DSNY's *2004-2005 NYC Residential and Streetbasket Waste Characterization Study* and *2004 Commercial Waste Management Study.* Calculations for Figure 6 are provided in *Appendix I: Composition of NYC's Municipal Plastic Waste*.

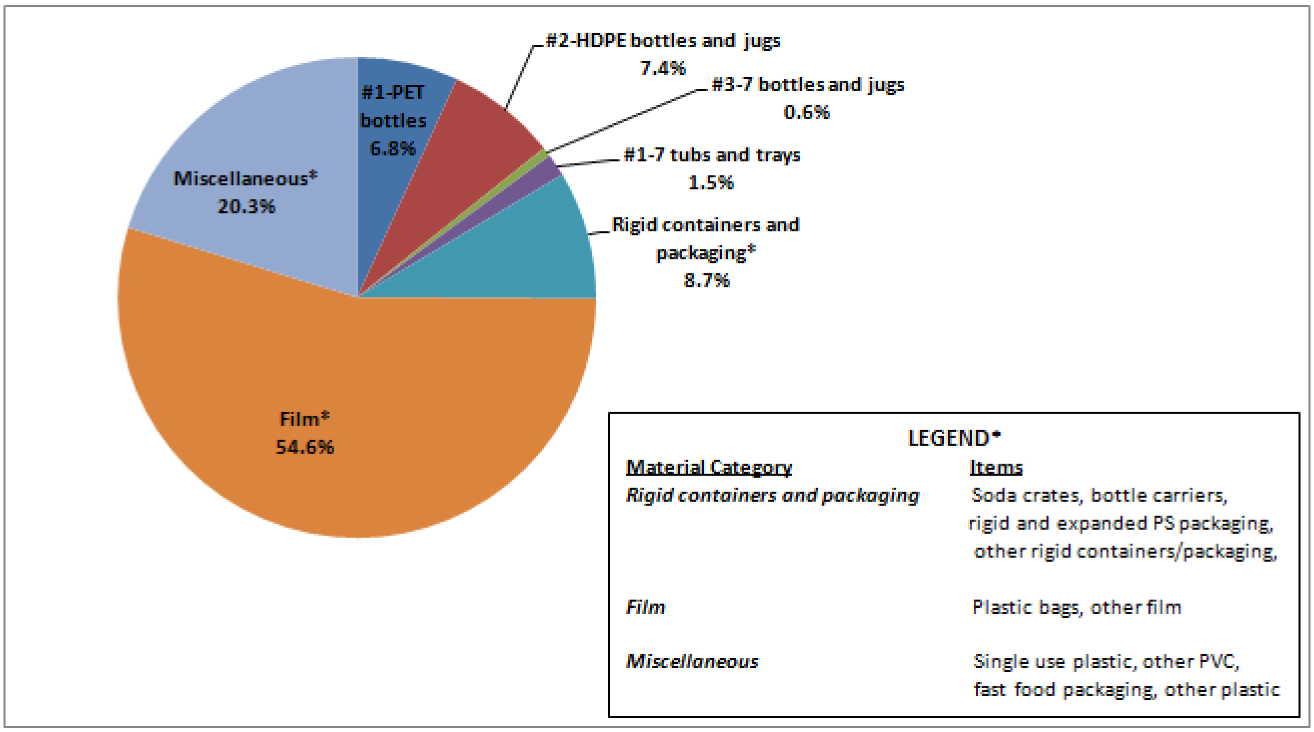

Figure 6: Composition of NYC MPW, 2010

Film plastics are the largest component of NYC MPW; they account for more than half of the total MPW. Examples of film plastics are shopping and grocery bags, trash bags, shrink wrap, and packaging. Film plastic items such as plastic bags are made of low density polyethylene (LDPE) resin. Other resins that are used to make film plastic items are high density polyethylene (HDPE) and linear LDPE (LLDPE). HDPE is stronger than LDPE because its chemical structure has less branching and is used to make plastic bags.

LLDPE is used to make plastic wrap, shrink wrap, and stretch wrap. Film plastics are non-recyclable designated therefore most film plastic waste generated in NYC is currently landfilled.

Miscellaneous plastics are the second largest component of NYC MPW. The miscellaneous category includes all plastic items that do not fall under any of the specific product categories listed in Figure 6. The miscellaneous plastic category includes a diverse range of plastics that vary in resin type, additive combinations, and molding method. Examples of miscellaneous plastics include fast food packaging and single-use plastics such as plastic plates and cups. Similarly to film plastic, miscellaneous plastics are not designated for recycling and therefore are currently disposed of in landfills.

The third largest component of NYC MPW is rigid containers and packaging. In the context of Figure 6, "Rigid containers" refers to any plastic containers that are not plastic bottles, jugs, tubs, and trays. Examples of rigid containers are coffee containers and deli food containers. "Packaging" refers to both rigid and flexible packaging. Polystyrene (PS) is a common resin that is used in packaging in both its rigid and expanded form. Examples of rigid packaging include caps and lids and examples of flexible packaging include mail order packaging. Since rigid containers and packaging are non-recyclable designated plastics, this material category of NYC MPW is also currently landfilled.

3.4.2 Recyclable and Non-recyclable Designated Plastics in NYC MPW

Figure 7 shows the breakdown of NYC MPW into recyclable designated and non-recyclable designated plastics (RDP and NRP, respectively) based on DSNY's current plastic recycling program. This graph shows how much of NYC's plastic waste could be recycled, and consequently diverted from landfills, if there was 100% participation in the DSNY's recycling program and if all participants followed the DSNY's recycling guidelines correctly. Calculations for Figure 7 are provided in *Appendix I: Recyclable and Non-Recyclable Designated Plastics in NYC Municipal Plastic Waste.*

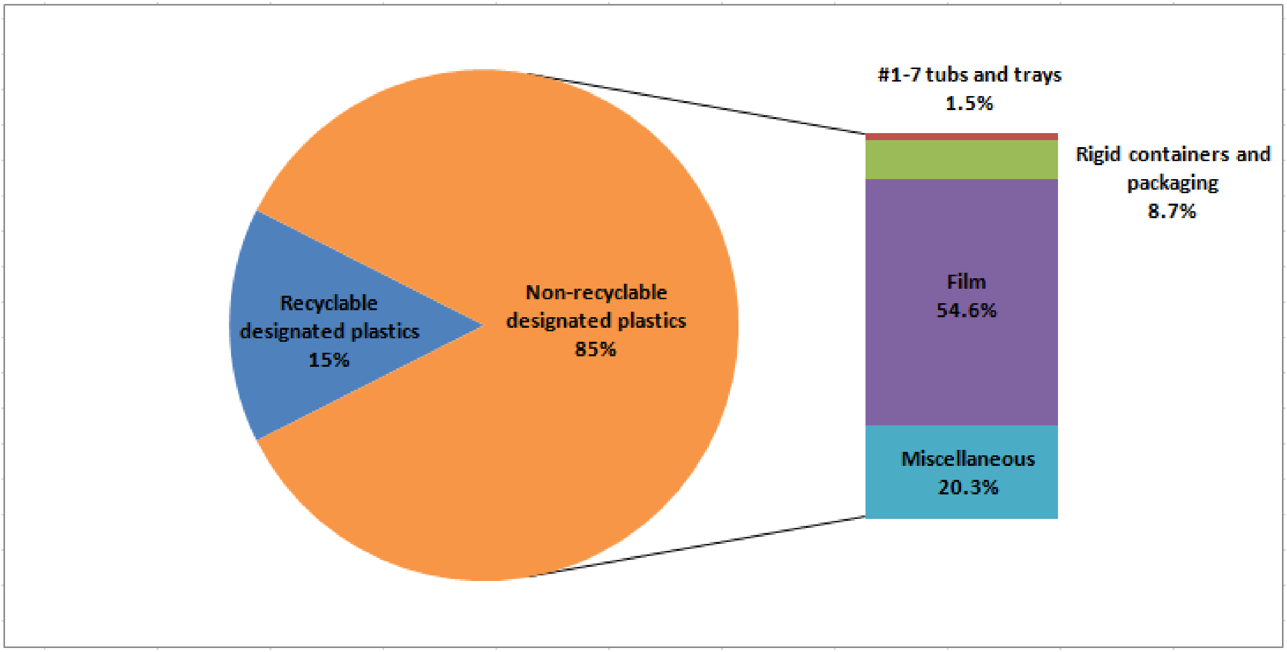

Figure 7: RDP and NRP in NYC MPW, 2010

Only 15% of NYC MPW is designated for recycling under the DSNY's current recycling program. Less than 15% of RDP is actually recycled due to carelessness on the part of waste generators.

Table 8 shows the tonnages of RDP and NRP present in the collected NYC residential waste streams (refuse, metals, glass, & plastic (MGP) recycling, and paper recycling). Tonnages are based on 2010 DSNY reported tonnages for the residential sector and plastic waste compositions provided in the DSNY's *2004-2005 Residential and Streetbasket Waste Characterization Study.*

Figure 8 shows the percentage of RDP and NRP present in the collected residential recycling and refuse streams.

The tonnages in Table 8 and Figure 8 are based on the tonnages of residential plastic waste that are collected for recycling and are disposed at the curbside as refuse. Calculations of these tonnages are provided *in Appendix I: Fate of NYC Municipal Plastic Waste.*

Table 8: Tonnages of RDP and NRP in NYC's collected residential waste streams

		Refuse		Collected Recycling: Metals, glass, & plastic		Collected Recycling: Paper		MSW	
Material Subgroup	**Material Category**	**%**	**Tonnage**	**%**	**Tonnage**	**%**	**Tonnage**	**%**	**Tonnage**
#1 PET Bottles	PET bottles	0.90	32119	6.46	17564	0.07	273	1.21	51198
#2 HDPE Bottles	HDPE Bottles: Natural	0.28	9993	3.15	8564	0.01	39	0.46	19464
	HDPE Bottles: Colored	0.3	10706	3.27	8891	0.01	39	0.48	20310
#3-7 Bottles	#3 PVC Bottles	0.01	357	0.04	109	0.00	0	0.01	423
	#4 LDPE Bottles	0.01	357	0.01	27	0.00	0	0.01	423
	#5 PP Bottles	0.01	357	0.10	272	0.00	0	0.02	846
	#7 Other Bottles	0.07	2498	0.20	544	0.00	0	0.07	2962
TOTAL RECYCLABLE DESIGNATED PLASTICS (RDP)		**1.58**	**56,386**	**13.23**	**35,971**	**0.09**	**352**	**2.26**	**95,627**
#1-#2 Tubs/Trays/Other Containers	#1 PET tubs/trays	0.00	0	0.02	54	0.00	0	0.01	423
	#2 HDPE tubs/trays	0.05	1784	0.21	571	0.00	0	0.05	2116
#3-7 Tubs/Trays/Other Containers	#3 PVC tubs/trays	0.00	0	0.01	27	0.00	0	0.00	0
	#4 LDPE tubs/trays	0.01	357	0.01	27	0.00	0	0.00	0
	#5 PP tubs/trays	0.17	6067	0.42	1142	0.00	0	0.17	7193
	#7 Other tubs/trays	0.04	1428	0.06	163	0.00	0	0.04	1693
Other rigid containers/packaging	Soda crates and Bottle Carriers	0.01	357	0.07	190	0.00	0	0.01	423
	Rigid PS containers/Packaging	0.27	9636	0.28	761	0.01	39	0.24	10155
	Expanded PS Containers/Packaging	0.64	22840	0.10	272	0.04	156	0.54	22849
	Other rigid containers/packaging	0.79	28193	1.34	3643	0.04	156	0.75	31734
Film	Plastic Bags	3.22	114914	0.94	2556	0.23	898	2.73	115513
	Other film	5.44	194140	3.09	8401	0.71	2773	4.76	201408
Other Plastic Products	Single Use Plastic	0.6	21413	0.22	598	0.02	78	0.51	21579
	Other Plastic Materials	1.92	68520	3.54	9625	0.20	781	1.85	78278
	Other PVC	0.02	714	0.04	109	0.00	0	0.02	846
TOTAL NON-RECYCLABLE DESIGNATED PLASTICS (NRP)		**13.18**	**470,361**	**10.35**	**28,140**	**1.25**	**4,883**	**11.68**	**494,211**
TOTAL PLASTICS		**14.76**	**526,748**	**23.58**	**64,111**	**1.34**	**5,234**	**13.94**	**589838**

Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

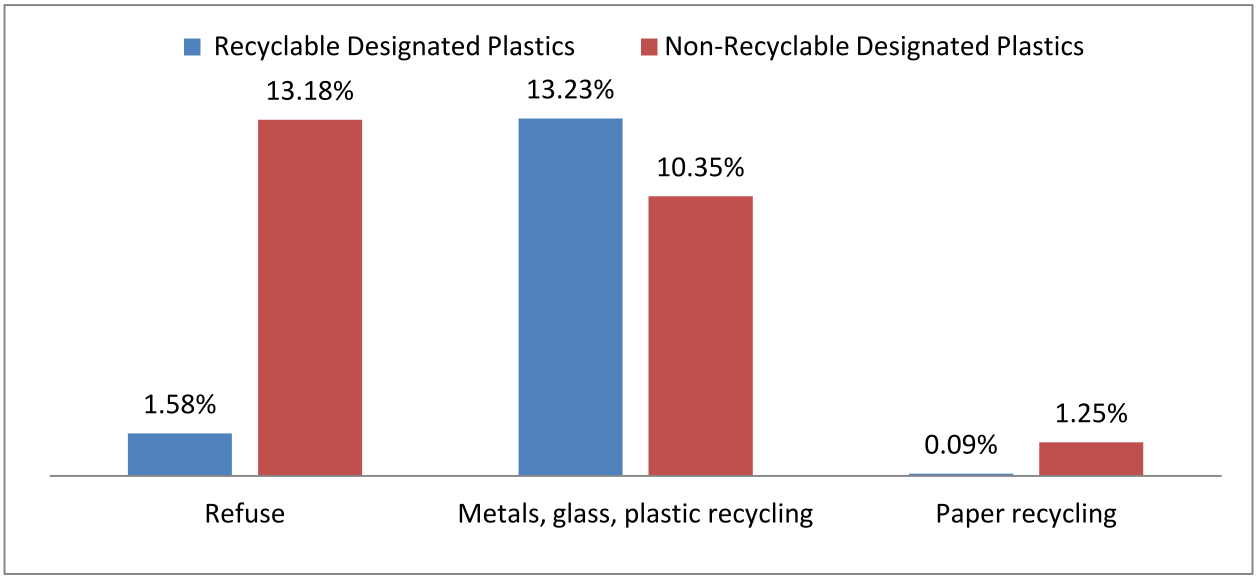

Figure 8: RDP and NRP in NYC's collected residential waste streams

As can be seen from Figure 8, approximately 2% of collected residential refuse consists of RDP that was disposed of instead of recycled. A small percent of collected paper recycling is RDP that was incorrectly disposed of in the paper recycling stream. This plastic residue is eventually disposed of in landfills after being sorted out at MRFs.

Approximately 10% of the metals, glass, & plastic (MGP) recycling collected by DSNY consists of NRP. Since plastics make up approximately 24% of the total MGP collection, this indicates that almost half of the total plastic waste collected for MGP recycling is non-recyclable. Such a statistic indicates that there is significant confusion amongst NYC residential waste generators about plastics recycling in NYC.

DSNY attributes confusion about plastics recycling to the fact that all rigid plastics have the chasing arrow recycling symbol printed on them[35]. While almost all rigid plastics can technically be recycled, the recyclability status of the product varies with location. Each city, county, and township chooses what they can recycle based on local factors. Plastic manufacturers print the recyclable symbol on their plastic products because what isn't collected for recycling in one community of their consumer base may be collected for recycling in another community of their consumer base[36]. In an effort to clarify the matter, the DSNY has been actively involved with GreenBlue's Sustainable Packaging Coalition in development of the new How2Recycle labels[37]. How2Recycle labels help consumers understand what products and packaging can

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[35] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "Plastics Resin Codes". 2012. Web.

[36] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "The How2Recycle Label". 2012. Web.

[37] Ibid.

and cannot be recycled based on where they live. The labels also remind consumers to check their local recycling programs before disposing of waste items[38].

In addition to the diversion rate, another performance metric that the DSNY uses to evaluate recycling performance is the capture rate. The capture rate is defined as follows:

Capture rate = Tons of recyclables collected/Tons of recyclables in total waste (refuse & recycling)[39]

The capture rate indicates how much of recyclable designated materials is actually being recycled. Table 9 shows the estimated capture rate of RDP for NYC's residential sector and the corresponding total capture rate for NYC, which was calculated by assuming 100% capture rate of RDP in the commercial sector. This assumption was made because plastics make up a small amount of commercial MSW; only food-service operations are required to recycle plastics, and, under NYC's Commercial Recycling Law, commercial businesses are charged a monetary penalty if they do not recycle according to DSNY recycling guidelines[40]. Calculations for the capture rates shown in Table 9 are provided in *Appendix I: Fate of NYC Municipal Plastic Waste.*

Table 9: Estimated capture rates for NYC's RDP, 2010

NYC residential plastics capture rate	37.6%
NYC total plastics capture rate	46.6%

Table 9 and Figure 9 show that NYC recycles only half of the RDP that it generates. The remainder of RDP ends up in landfills.

[38] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "The How2Recycle Label". 2012. Web.

[39] RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 4. Print.

[40] NYC Dept. of Sanitation Bureau of Waste Prevention, Reuse, and Recycling. "NYC Business Recycling: Enforcement & Penalties". 2012. Web.

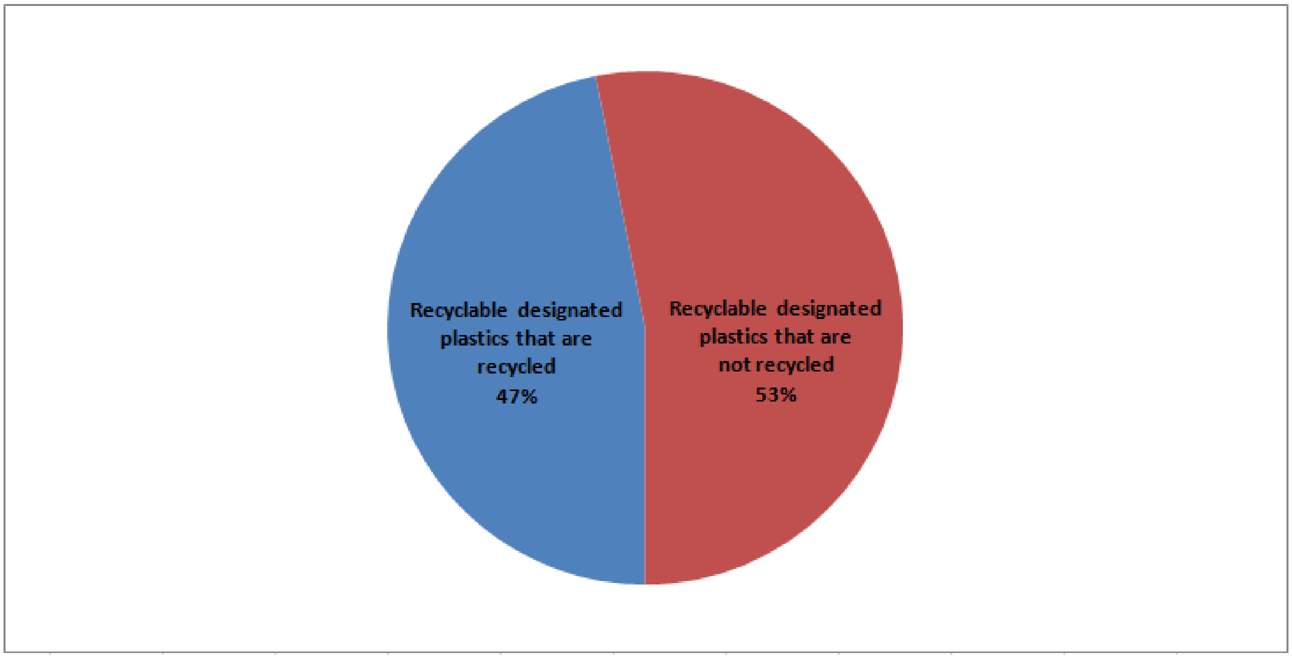

Figure 9: Fate of RDP in NYC MPW, 2010

3.4.3 Fate of NYC MPW: Tonnages Landfilled, Recycled, and Sent to Waste-to-Energy

In 2010, NYC generated 750,538 short tons of MPW. Of the total MPW, 84.0% (630,187 tons) was landfilled, 6.9% (52,041 tons) was recycled, and 9.1% (68,311 tons) was sent to waste-to-energy plants.

Table 10 shows the tonnages of NYC MPW from each sector that was landfilled, recycled, and sent to waste-to-energy plants. Figure 10 graphically shows the fate of NYC's total MPW based on the results in Table 10. Calculations for Table 10 and Figure 10 are provided in *Appendix I: Fate of NYC Municipal Plastic Waste*.

It should be noted that in Table 10, the category "Total MPW recycled" excludes the tonnage of NRP present in the collected recycling streams. This residue is accounted for in the "Total MPW landfilled" tonnage.

Table 10: Estimated tonnages of NYC MPW landfilled, recycled, and sent to waste-to-energy, 2010

		MPW in recycling collections				
	Estimated generation of MPW (tons/year)	In metals, glass, & plastic recycling (tons/year)	In paper recycling (tons/year)	Total MPW recycled (tons/year)	Total MPW sent to waste-to-energy (tons/year)	Total MPW landfilled (tons/year)
Residential Sector	589,838	64,111	5,234	35,971	57,892	495,975
Commercial Sector	160,700	16,070	0	16,070[1]	10,418	134,212
TOTAL	**750,538**	80,181	5,234	**52,041**	**68,311**	**630,187**

[1] :Assumed all commercial plastics collected for recycling are recycled

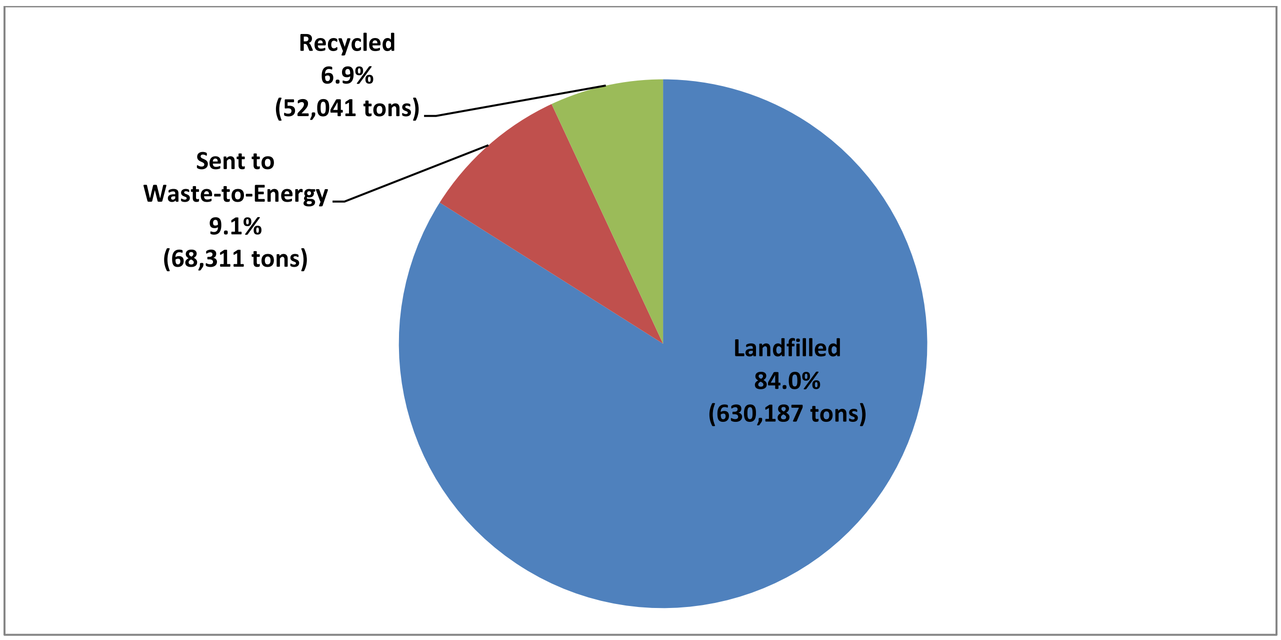

Figure 10: Fate of NYC MPW, 2010

3.4.4 Composition of NYC's NRP: The Potential Feedstock for Pyrolysis Technologies

In 2010, NYC generated approximately 698,498 short tons of municipal NRP waste. Approximately, 10% of NYC's NRP (68,311 tons) is sent to waste-to-energy plants for energy recovery and the remaining 90% (630,187 tons) is landfilled. Approximately 1,700 tons of NYC's municipal NRP waste is landfilled per day.

If the pyrolysis technologies discussed in this study were to be implemented in NYC, the city's landfill-bound NRP stream would be the feedstock for such technologies. Therefore, it is important to characterize NYC's NRP.

Figure 11 shows the composition of NYC's NRP. It should be noted that the composition provided in Figure 11 is for NYC's total NRP stream; this includes both waste-to-energy bound plastic and landfill-bound plastic. Calculations for Figure 11 are provided in *Appendix I: Composition of NYC's NRP*.

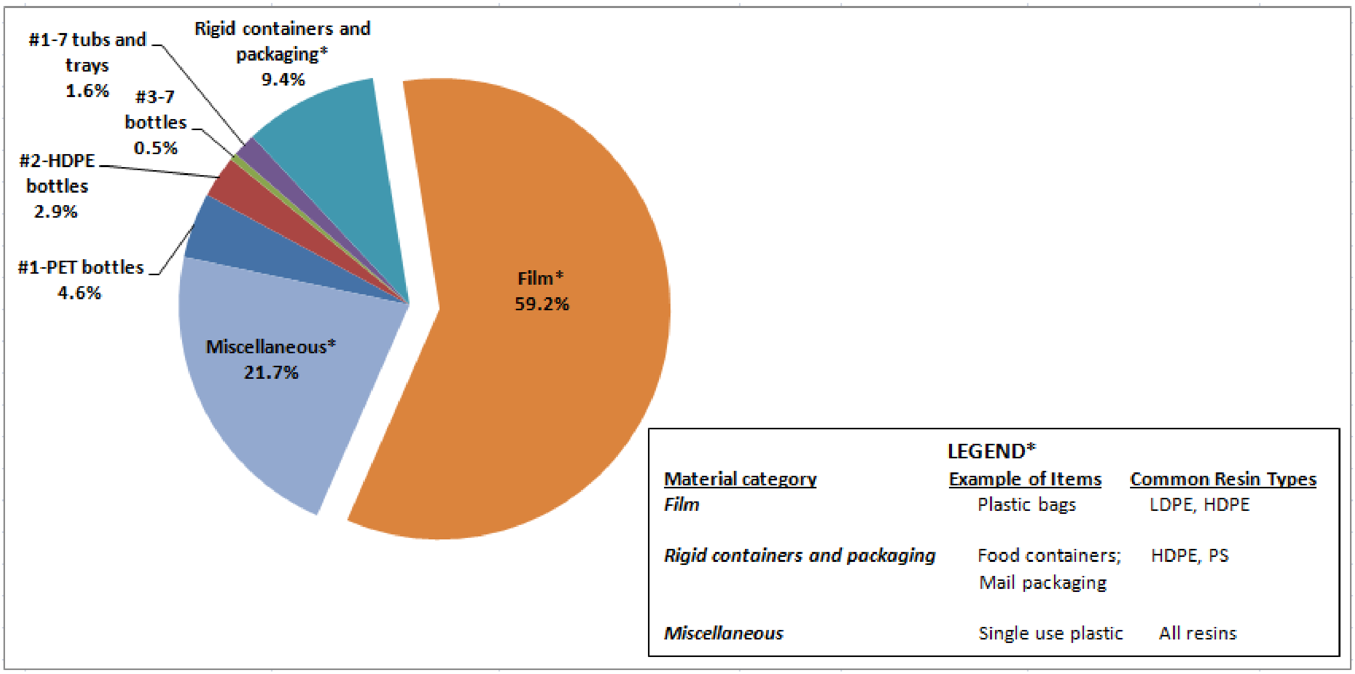

Figure 11: Composition of NYC's NRP: The potential feedstock for pyrolysis technologies

As is shown in Figure 11, most of NYC's NRP is made of film plastics, such as plastic bags. Film plastics are commonly made of low density and high density polyethylene resins (LDPE and HDPE, respectively).

3.5 Case Study – Plastic Residue from NYC's Sims Material Recovery Facility (NJ)

3.5.1 Sims Municipal Recycling

Sims Metal Management Ltd. is a global Australian-based company that specializes in metals recycling. In 2003, Sims expanded into curbside recycling in the United States and established the Sims Municipal Recycling division[41]. Sims Municipal Recycling sorts, processes, and markets all metal, glass, and plastics collected for recycling in NYC's five boroughs. Sims Municipal Recycling currently has one operating material recovery facility (MRF) called Claremont Recycling Center located in Jersey City, New Jersey. A second MRF is currently being constructed in Sunset Park, Brooklyn and is planned to open in Summer 2013. The Sunset Park MRF will process the majority of NYC's commingled curbside material[42].

In January 2012, the author of this study visited the Sims MRF located in Jersey City, NJ. The author met with Tom Outerbridge, the general manager of the Sims plant, and went on a tour of the facility. The purpose of the visit was to learn more about the plastic residue stream received at the MRF and to explore the possibility of using Sims plastic residue as test-run feedstock at a potential pyrolysis pilot plant in the New York metropolitan area. A summary report of the author's Jan. 2012 visit to the Sims MRF is provided in *Appendix II.*

3.5.2 Characterization and Quantification of Waste Output Stream at Sims MRF

Sims processes commingled recyclables from the curbside collection of the five boroughs of NYC. This waste is transported by truck from Staten Island and Lower Manhattan. The waste collected from Bronx, Queens and Brooklyn undergoes separation at the local transfer stations and only the plastic fraction is transported by boat to the Sims MRF. According to Mr. Outerbridge, the Sims MRF receives approximately 19,000 short tons of waste per month, which is equivalent to 633 tons per day. 11,000 tons are comingled recyclables and the remaining 8,000 tons are the plastic fraction of commingled waste pre-processed at the transfer stations in Queens, Bronx, and Brooklyn

Figure 12 shows the material composition of the processed waste output stream at the Sims MRF. The material breakdown is based on rough estimates provided by Mr. Outerbridge. Figure 12 also shows the estimated daily tonnage output of each material group from the Sims MRF. Tonnages were based on Mr. Outerbridge's estimate of an input stream of 633 tons of waste per day. It should be noted that the miscellaneous material category in Figure 12 includes milk cartons and aseptic packaging.

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[41] Sims Municipal Recycling. "History of Sims Municipal Recycling." 2012. Web.

[42] Sims Municipal Recycling. "State-of-the-Art Material Recovery Facility in Sunset Park, Brooklyn." 2012. Web.

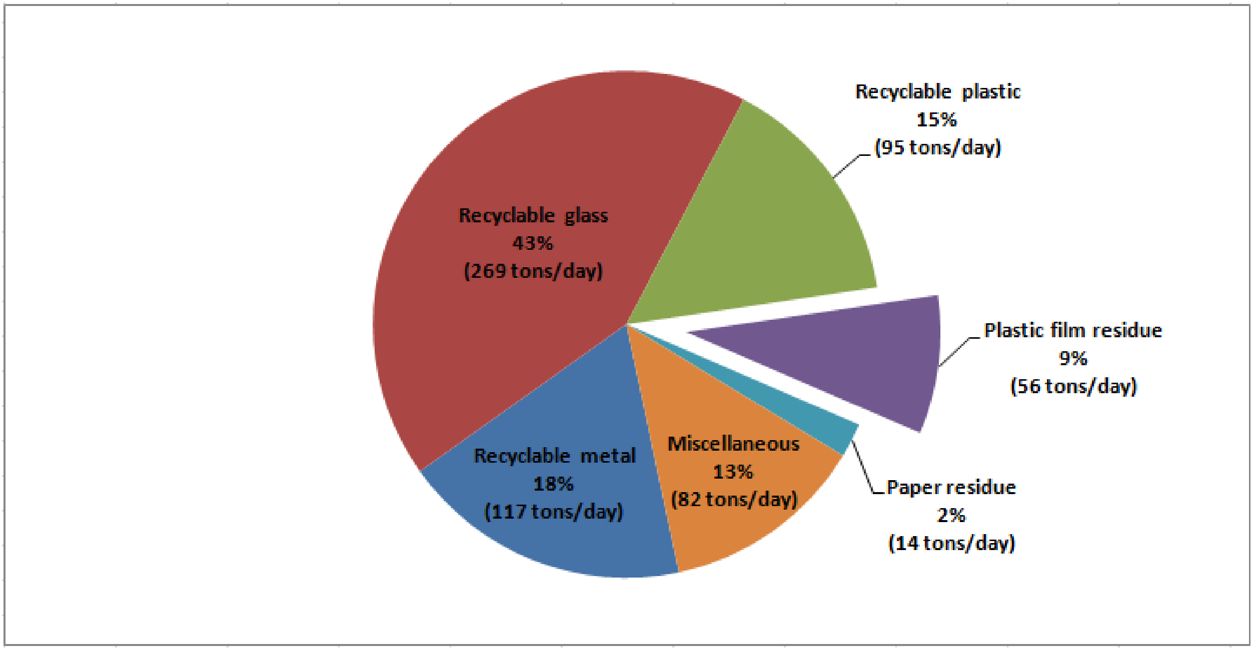

Figure 12: Material composition of waste output stream at NYC's Sims MRF, 2011

Sims MRF generates between 55-65 tons of plastic residue per day. According to Mr. Outerbridge, the resin composition of Sims residue is similar to the plastic refuse composition provided in DSNY's *2004-2005 Residential and Streetbasket Waste Characterization Study*. Therefore, most of the Sims plastic residue is made of film plastics, specifically plastic bags. Photos of the type of waste that is received at Sims MRF and of the output stream after processing are provided in the summary report in *Appendix II*. All plastic residue from Sims is currently disposed of in landfills.

3.5.3 Use of Plastic Residue from Sims MRF as Test-run Feedstock for Pyrolysis Technologies

The possibility of sending Sims plastic residue to pyrolysis plants for material and energy recovery was discussed with Mr. Outerbridge during the author's visit. Mr. Outerbridge was familiar with some of the pyrolysis technologies discussed in this study and had even sent sample Sims residue to Climax Global Energy Inc. Mr. Outerbridge explained the current setbacks with pyrolysis and other plastic reclamation technologies from the standpoint of the Sims MRF.

Sims has enough material to run a full scale pyrolysis plant but, at the time of the visit, Mr. Outerbridge was not convinced about the economic viability of these plants. Mr. Outerbridge stated that, as general manager of Sims MRF, his biggest issue with all plastics-converting technologies is that their economic models currently don't seem viable because the market for plastics is constantly changing. Consequently, from his perspective, the economic models don't seem to compete with the current landfill disposal cost. Mr. Outerbridge also stated that Sims is constantly looking for markets to sell more recyclables.

In order to commit to a plastics-converting technology, they have to be offered a price competitive to the prices of the recyclables. Another concern Mr. Outerbridge had with the economics of these technologies is whether additional costs would result from environmental regulatory standards not being met by these new technologies.

When asked whether Sims would be willing to add non-recyclable designated plastics from curbside collection to their waste input stream at the MRF, Mr. Outerbridge said that they preferred not to. Sims already deals with large volumes of waste and it is problematic to handle non-recyclable designated plastics, especially film plastics. Mr. Outerbridge explained that the biggest issue with handling film plastics is the non-uniformity of the material and the fact that some fractions have high market value and some have no value at all.

The sections of this study that follow provide a detailed analysis and evaluation of three promising pyrolysis technologies that convert NRP into synthetic oil and other marketable petrochemical products. In the analysis, Sims plastic residue is assumed as the test-run feedstock for all three technologies. As part of the study's evaluation, the economics of one of the pyrolysis technologies is compared to that of landfilling to determine which method of plastic waste management is the least costly. Based on a comparison of the economic and environmental aspects of these waste management practices, a recommendation is made for improving waste management practices for NYC's municipal NRP.

4. PYROLYSIS TECHNOLOGIES FOR NON-RECYCLED PLASTICS

4.1 Motivation to Reuse NYC's Non-Recycled MPW

4.1.1 Economic and Environmental Drawbacks of Landfilling NYC MPW

In 2010, NYC landfilled approximately 630,187 short tons of MPW. This is equivalent to landfilling more than 1,700 tons of MPW per day. NYC landfills most of its MPW because it is currently the cheapest waste management solution available[43]. However, as more and more local landfills reach maximum capacity, the cost of landfilling NYC MSW is steadily increasing. NYC currently transports its MSW out of state via trucks, train, and barge to landfills in Pennsylvania, Ohio, Virginia, and South Carolina[44]. The increasingly farther distances that NYC waste has to travel to be disposed and the rising rates charged by landfill companies are making landfilling an increasingly more expensive waste management practice.

Landfilling is not a sustainable waste management solution because it pollutes the environment, it reduces green field space, and the land available for landfill use is limited. Furthermore, landfills are an aesthetic eyesore to surrounding communities and can be a source for disease-causing pathogens if improperly operated[45].

The waste in landfills is a viable source for material and energy recovery. Alternative waste management practices, such as waste-to-energy and mechanical recycling, utilize the material and energy resources available in waste and consequently reduce the total volume of generated waste that is disposed.

4.1.2 Waste Management Hierarchy

Since landfilling is not sustainable and is becoming more costly, it is important that NYC changes its waste management practices to more environmentally-friendly and economic alternatives. The hierarchy of waste management ranks waste management practices based on their respective environmental impacts. Figure 13 shows the expanded hierarchy of waste management proposed by Columbia University's Earth Engineering Center (EEC).

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[43] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

[44] Ibid.

[45] EPA. "Waste Management Options". 2012. Web.

Figure 13: Expanded hierarchy of waste management
Source: Themelis (2008)

As can be seen from Figure 13, waste reduction is the most favorable form of waste management because it has the least environmental impact. Other waste management practices that have relatively low environmental impacts compared to landfilling are mechanical recycling, composting of source-separated organics, and waste-to-energy. Waste-to-energy is a type of recycling where waste undergoes complete combustion for energy recovery. A small percentage of NYC MPW, approximately 9%, is currently sent to waste-to-energy plants.

4.1.3 Types of Recycling for MPW

There are four types of recycling for plastics: primary, secondary, tertiary, and quaternary recycling. Primary recycling converts post-consumer plastic waste back into its original product or a similar material. Primary recycling is desirable because it reduces the demand for virgin resins thus reducing the costs in plastics manufacturing[46]. This process is not widely used because it requires fairly clean feedstock of known composition. Therefore it is only feasible with semi-clean industrial scrap plastic[47].

[46] Themelis, Nickolas and Arsova, Ljupka. *Identification and Assessment of Available Technologies for Material and Energy Recovery From Flexible Packaging Waste (FPW).* New York: Columbia University, 2010. 3. Print.

[47] Ibid.

Secondary recycling, which is also known as mechanical recycling, uses mixed plastic waste to manufacture new plastic products. Unlike primary recycling, mechanical recycling can tolerate mixed plastic waste feedstock because the products of mechanical recycling have less demanding chemical and physical properties than the original pre-consumer plastic products[48]. In mechanical recycling, the mixed plastic waste does not need to be separated. It is converted into new plastic products via physical processes such as extrusion. Mechanical recycling is used to make recycled plastic bottles, recycled bags, and plastic lumber. Post-consumer film plastic is not a suitable feedstock for mechanical recycling technologies[49].

Tertiary recycling chemically breaks down plastic waste at elevated temperatures into its constituent monomers. The basic liquid and gaseous hydrocarbon products that are obtained can be used as fuel for heating or transport. Major tertiary recycling technologies for plastic waste are pyrolysis and gasification[50]. Both of these processes can tolerate mixed plastic waste feedstock with high levels of contamination and both processes have high yields of marketable petrochemical products. The major difference between pyrolysis and gasification is that pyrolysis occurs in the absence of oxygen while gasification occurs in an oxygenated environment.

Quaternary recycling recovers energy from plastic waste either through the production of engineered solid fuel or the direct combustion of plastic waste in waste-to-energy plants. Engineered solid fuel is produced by mixing high calorific plastic waste with MSW to yield a solid fuel of desired calorific value. The solid fuel can be burned as fuel in cement kilns, used in designated waste-to-energy plants, or co-fired with coal in power plants. Alternatively, plastic waste can be directly burned as fuel in waste-to-energy plants. The plastic waste undergoes complete combustion and the energy that is recovered from the process is used as heat and electricity. In waste-to-energy plants, plastic waste is mixed with MSW prior to being burned. This reduces the production of harmful oxide emissions, such as sulfur oxides (SOx) and nitrogen oxides (NOx), that result when plastics are combusted.

This study analyzes the potential application of pyrolysis technologies in the waste management of NYC's non-recycled MPW. Pyrolysis is a promising recycling process because it recovers the high calorific content of plastic waste without producing high emissions of NOx and SOx.

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[48] Themelis, Nickolas and Arsova, Ljupka. *Identification and Assessment of Available Technologies for Material and Energy Recovery From Flexible Packaging Waste (FPW).* New York: Columbia University, 2010. 24. Print.

[49] Ibid, 25.

[50] Ibid.

4.2 Pyrolysis

Pyrolysis is a process that thermally de-polymerizes plastics at elevated temperatures in an oxygen-depleted environment. Pyrolysis of plastic waste yields gaseous and liquid hydrocarbon products that can be used as fuel or as other petrochemical products, such as industrial waxes and lubricants. During pyrolysis, a solid residue by-product called char is also formed. Char contains inorganic materials from the plastic waste feedstock that are separated out during pyrolysis. The proportion and quality of the desired pyrolysis products and residue are directly related to the plastic waste feedstock composition, the pyrolysis operating conditions, and the pyrolysis reactor type[51].

Pyrolysis generally occurs between operating temperatures of 300 to 600 degrees Celsius at approximately atmospheric pressure. Increased yields of gaseous pyrolysis products are obtained at higher operating temperatures[52]. Reactor types that are used for pyrolysis processes include fixed beds, fluidized beds, and rotating kilns.

Pyrolysis is advantageous compared to other plastics recycling technologies because it can process highly contaminated mixed plastic waste and generate high yields of valuable marketable products with minimal waste generation[53]. Pyrolysis is advantageous over gasification because it occurs in an oxygen-depleted environment and therefore produces low emissions of NOx and SOx Also, there is lower heat loss in pyrolysis than in gasification because pyrolysis occurs at lower operating temperatures[54].

Some disadvantages of pyrolysis are that it usually requires an external energy source and the quality of the desired products may be inconsistent on a day to day basis due to the varying composition of the plastic waste feedstock[55].

There are three major types of pyrolysis: thermal, thermal-catalytic, and microwave pyrolysis. The following sections describe each of these pyrolysis processes in detail.

4.2.1 Thermal Pyrolysis

Thermal pyrolysis achieves decomposition of plastics at elevated temperatures. Thermal pyrolysis can achieve complete decomposition of pure plastic compounds at a minimum operating temperature of 400 degrees Celsius[56]. In order to achieve extensive plastic decomposition for mixed plastic waste, thermal pyrolysis operating temperatures must be greater than 1200 degrees Celsius and residence time must be

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[51] Themelis, Nickolas and Arsova, Ljupka. *Identification and Assessment of Available Technologies for Material and Energy Recovery From Flexible Packaging Waste (FPW).* New York: Columbia University, 2010. 26. Print.

[52] Ibid.

[53] Ibid, 25.

[54] Ibid, 38.

[55] Ibid, 31.

[56] Bhatti, Jawad. *Current State and Potential for Increasing Plastics Recycling in the US*. New York: Columbia University, 2010. 50. Print.

long[57]. The discrepancy in operating temperatures for the thermal pyrolysis of pure plastic compounds versus plastic waste is attributed to the difference in contamination level. Thermal pyrolysis generally yields wax-like petrochemical products that solidify at room temperature[58].

4.2.2 Thermal-Catalytic Pyrolysis

Thermal-catalytic pyrolysis utilizes a catalyst in the pyrolysis process. In general, the catalyst reduces the pyrolysis reaction temperature, increases the rate of de-polymerization, and allows for more specificity and control of the end product parameters[59]. Thermal-catalytic processes are generally faster and less energy intensive than thermal pyrolysis. The minimum operating temperature for thermal-catalytic processes is approximately 200 degrees Celsius[60].

Catalysts may be added to the plastic feedstock in either a homogeneous or heterogeneous phase. Homogeneous catalysts are difficult to separate from the final pyrolysis products. Heterogeneous catalysts are easy to separate but present difficulties in deactivation because they suffer from coking[61]. Catalysts are an added expense to thermal-catalytic pyrolysis processes because they deactivate after a certain period of time and thus they must be periodically replenished with a new batch of catalyst.

4.2.3 Microwave Pyrolysis

Microwave pyrolysis uses microwave radiation to heat plastic feedstock to the elevated temperatures required for thermal degradation of the plastics. Microwave radiation is a beneficial method of heating because it provides a uniform distribution of heat and allows greater control over heating[62].

Plastics are poor absorbers of microwave radiation because they have low dielectric constants[63]. Therefore high, microwave absorbent materials such as graphite carbon are added to the plastic waste feedstock. The graphite absorbs the microwave radiation and heats up the surrounding plastics via conduction.

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[57] Bhatti, Jawad. *Current State and Potential for Increasing Plastics Recycling in the US*. New York: Columbia University, 2010. 49. Print.

[58] Ibid.

[59] Ibid, 50.

[60] Ibid.

[61] Ibid.

[62] Ibid.

[63] Sharobem, Timothy. *Tertiary Recycling of Waste Plastics: An Assessment of Pyrolysis by Microwave Radiation.* New York: Columbia University, 2010. 27. Print.

For plastic waste products coated with aluminum, such as packaging for snacks, some microwave pyrolysis processes are reported to achieve 100% aluminum recovery[64].

4.2.4 Commercial Pyrolysis Technologies

Pyrolysis is a well-established technology that has been applied in the area of waste management over the past forty years. Major developments in pyrolysis waste management applications were made in the 1990s. Although pyrolysis is an established and proven technology, it still struggles to compete as a commercially viable alternative for industrial scale plastic waste management. Improvements in energy input, purity of products, and feed capacity are required to make pyrolysis technologies more competitive at an industrial scale[65].

The following sections of this study provide a detailed analysis of three promising pyrolysis technologies for the treatment of non-recycled plastics (NRP). The technologies are thermal, thermal-catalytic, and microwave pyrolysis and were developed by Agilyx, JBI Inc., and Climax Global Energy Inc (CGE), respectively. All companies currently operate demonstrational scale pyrolysis plants. Agilyx also operates a commercial facility, which has been in operation for the past two years. JBI Inc. is currently in the process of constructing their first commercial facility and CGE is starting up its first commercial facility.

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[64] Themelis, Nickolas and Arsova, Ljupka. *Identification and Assessment of Available Technologies for Material and Energy Recovery From Flexible Packaging Waste (FPW).* New York: Columbia University, 2010. 59. Print.

[65] Ibid, 27.

4.3 JBI Inc.'s "Plastic2Oil" Process

4.3.1 Overview

JBI Inc.'s "Plastic2Oil" (P2O) process is a continuous thermal-catalytic pyrolysis process that converts plastic waste to synthetic fuel. JBI Inc. is a publicly owned company that was founded in 2006 by John Bordynuik and is located in Niagara Falls, NY. JBI Inc. began developing the P2O process in 2009 and it is currently a patent-pending process. JBI Inc currently operates a demonstrational scale facility in Niagara Falls, NY and is in the process of constructing a 144-short ton per day commercial facility in Jacksonville, FL.

In September 2012, the author of this study visited JBI Inc's demonstration facility. The author met with Mr. Bordynuik and was given a tour of one of the company's 48-ton per day processing units. The purpose of the visit was to learn more about the company's P2O process and to consider its potential for application in NYC. Findings from the author's visit to JBI Inc. are provided in this section.

The P2O process converts plastic waste into fuel via thermal-catalytic pyrolysis. The process accepts almost all plastic waste as feedstock except for #3-PVC and nylons. The primary consumer products of the process are No. 6 oil, No. 2 oil, and naphtha. The No. 6 and No. 2 oils are in-spec and can be sold directly to the consumer. The primary residue of this process is petcoke.

The P2O process is a continuous closed-loop process that is powered by the off-gas produced during pyrolysis. The footprint of the current fifth generation P2O unit is 10 ft. long x 120 ft. wide x 20 ft. high and its maximum feed capacity is 48 tons per day. The fifth generation unit operates at 75% availability. Based on the 2011 performance metrics provided by JBI Inc., it was calculated that the P2O fifth generation unit produces approximately 4.4 barrels of oil and 8.2 kg of petcoke per ton of plastic waste feed.

The following sections include a detailed technical description of the P2O process, results of calculated mass and energy balances on the P2O system, a discussion of the emissions and environmental impacts of the process, and an economic analysis of the company's business model for a 31,700-ton per year P2O commercial facility.

4.3.2 Process Description

4.3.2.1 Plastic Feedstock

The current fifth generation P2O unit at the Niagara Falls demonstration facility can process up to 48 tons of plastic waste per day at maximum capacity. Its current sources of feedstock are commercial and industrial waste streams. JBI Inc. is looking into partnering with local universities and MRFs to provide plastic waste from the residential stream as well. The P2O process accepts a wide array of plastic wastes with regard to resin type, product type, and degree of contamination.

The P2O unit processes the following plastic resins: #2-HDPE, #4-LDPE, #5-PP, and #7-Other. The unit also processes items that don't have a designated resin code. The unit can tolerate small amounts of

#1-PET but it is not a desired feedstock because when pyrolyzed it generates terephthalic acid, which corrodes process equipment. JBI Inc. does not accept #3-PVC or nylon as feedstock primarily because they yield harmful pyrolysis products that pollute the environment.

The P2O unit can handle a wide variety of plastic waste products. Examples include food containers, gas tanks, wine bags, automotive plastic, and consumer waste plastic film. When a new type of plastic waste product is received at the facility, it is tested on site for suitability as feedstock. Based on the test results, the plastic waste is either incorporated into the feed or shipped back to the supplier.

The P2O unit accepts unwashed and unsorted plastic waste, composites, and commingled materials. The P2O unit can process plastic waste with food and oil residue and plastic waste that is commingled with metal.

When plastic waste arrives at the Niagara Falls facility, it is temporarily stored in large plastic totes on skids. The waste is not chemically prepared prior to being fed to the P2O unit. Mechanical preparation of the waste feed is required only if the size of the plastic waste items exceeds the 24-inch diameter of the feed intake receiver. Items exceeding 24 inches in diameter are shredded prior to being fed to the P20 unit. Examples of plastic waste that don't require shredding are items from the food and beverage industry, pill bottles, shampoo bottles, markers and crayons. Examples of plastic waste that do require shredding are items from the automobile industry such as gas tanks and bumpers. JBI Inc. shreds its plastic waste in a JBI Inc. owned plastic shredder located at a material recovery facility (MRF) in Thorold. Ontario, Canada.

4.3.2.2 P2O Process

The P2O unit operates continuously and is fed up to 2 short tons (4,000 lb) of plastic waste per hour using a forklift. The plastic waste stored in a reusable tote is dropped into a hopper and is continuously loaded into a jacketed cylindrical rotating kiln called the pre-melt tank. The pre-melt tank is operated at a temperature between 300 and 500 degrees Celsius. Prior to entering the pre-melt tank, the plastic feed in the hopper is purged with nitrogen in order to remove any oxygen that is present. The hopper is intended to hold approximately 1 ton (2,000 lb) of plastic waste with a bulk density of approximately 25 lb/ft^3 (specific gravity: 0.4)

JBI Inc. takes pride in being able to maintain a continuous feed rate to the pre-melt tank. Plastic feed enters the tank approximately every 2 minutes via a feed screw and slide gates. The feed screw is of JBI Inc.'s own design and according to them, is the reason why the tank can be fed continuously. The controlled feed rate is timed perfectly so that the heated plastic doesn't harden before entering the pre-melt tank thus avoiding a major mechanical issue that is often encountered with plastic extruders.

Once in the pre-melt tank, the plastic feed is directly heated by 2 burners located at each end of the tank. The fuel source for the burners is recycled off-gas from the process itself. The off-gas is combusted in the jacket chamber of the pre-melt tank. During the pre-melt stage, the plastic feed is liquefied and mixed with a liquid recycle stream containing JBI Inc.'s proprietary catalyst. Steel, which is commingled with plastic waste from automobile manufacturing, and metal are separated out during the pre-melt stage.

Any steel and metal that is present in the P2O feedstock remains in the pre-melt tank and is backed out every 70 tons (140,000 lb) of plastic feed. The steel and metal are removed in conjunction with petcoke residue, which is generated in the pyrolysis reactor. Residue from the hopper, pre-melt kiln, and pyrolysis reactor are collected in a container located below the hopper. Currently, residue removal doesn't require complete shut-down. However, during removal, feeding is stopped and the kilns are cooled off. In 2012, JBI Inc. added a third kiln to the P2O unit and an automatic slide gate directly below the hopper to improve residue removal rate. The third kiln is designed to condition the residue to remove it in real time at a rate of 70 lb/hr.

After the pre-melt stage, the liquefied plastic is transported to a jacketed pyrolysis reactor via a screw. Like the pre-melt tank, the pyrolysis reactor is also a cylindrical rotating kiln. In the reactor, the plastic undergoes pyrolysis at an operating temperature between 300 and 500 degrees Celsius. During pyrolysis, the plastic feed is mixed with the same proprietary catalyst that is used in the pre-melt stage. The burners in the pyrolysis reactor are fueled by the off-gas generated by the process. JBI Inc. employs in-situ hydrogenation in the pyrolysis reactor to assure that the final fuel products don't contain any alkenes and are consequently in-spec.

The petroleum gas products from the pyrolysis reactor flow through a cyclone to remove any particulate matter and then enter Reactor Tower 1 where the gases are further pyrolyzed. The cracked gases are then sent to Towers 2, 3, and 4 where No. 6 oil, No. 2 oil, and naphtha are separated out. Light gaseous hydrocarbons from Towers 4 are compressed to approximately 2 psig and the compressed off-gas is used as fuel for the pre-melt and pyrolysis burners. The composition of the off-gas includes methane, ethane, propane, butane, and hydrogen.

The final products of the P2O process are collected from the reactor towers, cooled, and sent for storage. Prior to storage, naphtha is passed through an oil/water coalescer to knock out any additional water still in the product.

The separation systems installed in the four reactor towers are completely automated. This allows JBI Inc. to closely control the composition of their fuel output. The degree of control that JBI Inc. can employ in their P2O process has allowed them to produce consistently in-spec No. 6 and No. 2 fuels that can be sold directly to the consumer. Naphtha is currently sold to a fuel blending site where it is injected with additives to turn it into gasoline.

All oil products of the P2O process are analyzed at the company's on-site laboratory to make sure that the oils are in-spec with the current market products.

Figure 14 is a flowsheet of JBI Inc.'s P2O process.

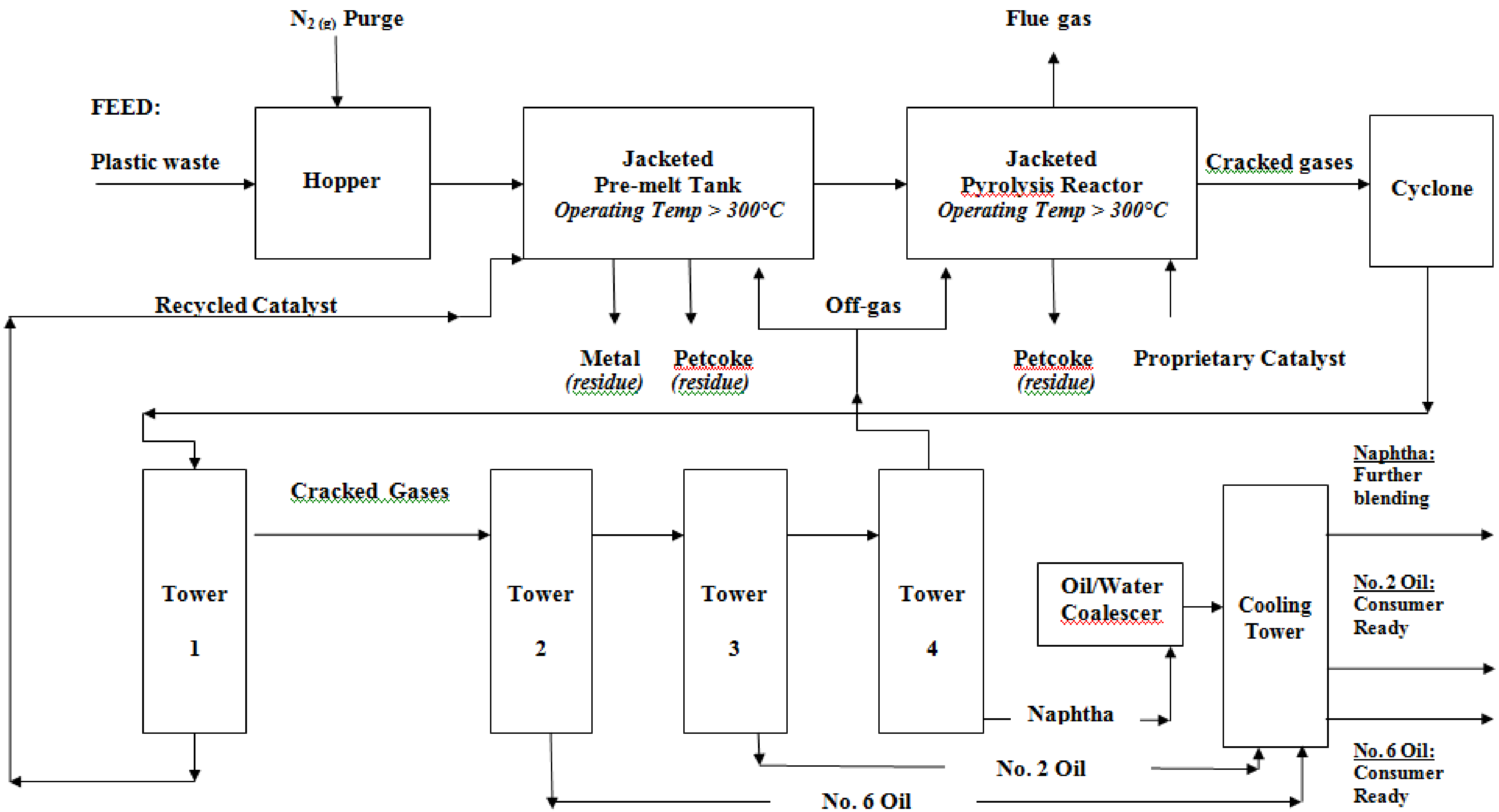

Figure 14: JBI Inc.'s Plastic2Oil process

4.3.2.3 Input and Output
The material inputs of the P2O process are:

- Plastic waste (except for #3-PVC and nylons)
- Proprietary catalyst
- Water (minimal)

The plastic waste is the feedstock for the P2O process. The proprietary catalyst helps achieve certain specific operating parameters that allow for the production of in-spec fuels. The water is used for cooling the equipment; the process uses approximately 1,000 gallons per day.

The material outputs of this process are:

- No. 6 oil
- No. 2 oil
- Naphtha
- Petcoke (by-product)
- Steel (by-product)
- Off-gas (a combustible mixture of methane, ethane, propane, butane, and hydrogen)

No. 6 oil is used as fuel in industrial boilers and ships. No. 6 oil is consumer-ready directly from the process; it doesn't require further blending. It is the company's most demanded product because it is one of the cleanest No. 6 oils available on the market. While the industry regulations allow for the sulfur content in No. 6 oil to be up to 30,000 parts per million (ppm), JBI Inc's No. 6 oil has less than 16 ppm of sulfur. JBI Inc. currently sells their No. 6 oil to US Steel and Indigo Energy.

No. 2 oil can be used as fuel for industrial boilers or, with the addition of additives, it can be used as diesel transport fuel. Similar to No. 6 oil, No. 2 oil is also consumer-ready directly from the P2O process. The P2O process includes an in-line injection of additives to make diesel fuel when desired. JBI Inc. currently sells its No. 2 oil to Coco Paving Inc. and US Steel.

Naphtha is used in high or regular grade transport fuels. Naphtha product from the P2O process requires further blending before it can be sold to the consumer. Naphtha produced at the Niagara Falls facility is sold directly to GTI Oil and Chemical for blended fuel distribution.

Petcoke is a by-product that is formed in the P2O process. The petcoke that is formed is a very fine black powder with highly uniform particle size. JBI Inc. is currently looking to sell their petcoke residue either as pigment, to be used in manufacturing, or to be used in the coking processes of steel companies.

Steel is an additional byproduct of the P20 process. Steel is separated from the plastic feed during the pre-melt stage. JBI Inc. recovers a significant amount of steel because it is often commingled with plastic waste from the automobile industry. JBI Inc. sells the removed steel to Metallico Inc. for which they receive a scrap metal fee.

The off-gas of the P2O process is composed of hydrogen and light hydrocarbons . The off-gas that is generated during pyrolysis is recycled and used to fuel the burners in the pre-melt tank and pyrolysis reactor.

4.3.3 Material and Energy Balances

4.3.3.1 Material Balance

JBI Inc. reports the following mass yields for its P20 process:

- 86% marketable fuel product
- 10-12% off-gas (recycled)
- 2-4% petcoke

JBI Inc. controls the output of the P2O process based on the fuel demand of its clients. In terms of mass percent, the process can yield 80:20 No. 2 oil-light naphtha, 70:30 No. 6 oil-light naphtha, or 100% light naphtha.

JBI Inc. provided the author of this study with performance metrics of the fifth generation P20 unit for the operation period of June to December 2011. Based on these metrics, a mass balance on the system was calculated. Table 11 compares the reported yields of the P2O process to the calculated yields from the mass balance.

Table 11: Comparison of reported and calculated yields for P2O process

	JBI Inc.'s Reported Yields **Tons/ ton of plastic**	**Calculated Yields[1]** **Tons/ ton of plastic**
Mass of crude oil	0.86	0.65
Mass of petcoke	0.02-0.04	0.01
Mass of off-gas	0.10-0.12	0.08
Mass of non-hydrocarbons[2]	Not given	0.27
TOTAL	1 ton	1 ton

1: Yields calculated by D. Tsiamis
2; Calculated as the difference between plastic tonnage processed and hydrocarbon products reported by JBI Inc. for the operating period of June-December 2011 (presumed to be moisture, inorganics and paper in feedstock)

As is shown in Table 11, the calculated mass balance estimates a lower yield of crude oil per ton of plastic than is reported by JBI Inc. JBI Inc. reports that 1 ton of plastic feed will yield 0.86 tons of crude oil. However, based on the mass balance, it was calculated that 1 ton of plastic feed yields only 0.65 tons of crude oil. The discrepancy in the reported and calculated yields can be attributed to the presence of residue in the plastic feed. Plastic waste contains metals, paper fibers, and organic residues. Based on the mass balance, residue accounts for 27% of the mass of the plastic feed. Therefore, the presence of residue consequently lowers the yield of crude oil produced per ton of plastic feed. It would be more accurate for JBI Inc. to report that the 86% yield of crude oil is only based on the hydrocarbon content of the plastic waste feed.

Based on the results of the calculated mass balance, it was determined that the P2O process yields approximately 4.4 barrels of crude oil and 8.2 kg of petcoke per ton of plastic waste. Table 12 shows the calculated yields of the P2O process in terms of barrels of oil and mass of residue per 1 ton of plastic waste.

Table 12: Calculated yields of P2O process

Total synthetic oil	**4.4 barrel (bbl) oil/ ton plastic**
No. 2 oil	*1.6 bbl oil/ ton plastic*
No. 6 oil	*1.0 bbl oil/ton plastic*
Light naphtha	*1.8 bbl oil/ton plastic*
Total petcoke residue	**8.2 kg/ton of plastic**

4.3.3.2 Energy Balance

The energy inputs of the P2O process are:

- Natural gas (for start-up)
- Electricity
- Off-gas (recycled)

JBI Inc. uses 5-8 million British Thermal Units (BTU) of natural gas to start up the P20 process. It uses approximately 53 kilowatts (kW) of electricity daily (1.3 MWh/day) to power fans, pumps, and small motors. The off-gas generated during the P2O process is recycled and is used to fuel the burners in the pre-melt tank and pyrolysis reactor.

An energy balance was calculated based on the performance metrics of 2011. The lower heating values (LHV) of the plastic waste feed and process products were taken from a previous EEC study for the American Chemistry Council and they are as follows:

- Non-recycled plastics: 14,000 Btu/lb
- Crude oil: 18,400 Btu/lb
- Petcoke: 12,700 Btu/lb
- Off-gas (assumed mostly CH_4): 20,300 Btu/lb

It should be noted that the LHV of non-recycled plastics, which was assumed to be equivalent to the LHV of MPW, is only 76% of the LHV of crude oil. This discrepancy is attributed to the fact that plastic waste is contaminated with residue which consequently reduces the energy content of waste. Table 13 shows the calculated energy distribution that is achieved in the P2O process.

Table 13: Energy distribution in P2O process

	Heating value (Btu/ton of plastic feedstock)	**% Distribution of heating value of feedstock**
IN		
Plastic waste	28,000,000	100.0%
OUT		
Crude oil	23,855,211	85.2%
Petcoke	229,109	0.8%
Hydrocarbon gas combusted to heat process[1]	3,915,680	14.0%
TOTAL	28,000,000	100.0%

1: Calculated as the difference between the heating value of plastic feedstock processed and the hydrocarbon products reported by JBI for June-December 2011

In the P2O process, most of the chemical energy that is stored in the plastic waste feed is recovered in the crude oil product. Approximately 14% of the stored chemical energy is used to power the P2O process via the combustion of the off-gas.

4.3.4 Environmental Emissions

Emissions from the P2O process come from the flue gas that is generated during pyrolysis. The flue gas goes through a stack before it is released into the environment. The reported emissions of greenhouse gases for the P2O process are: 0.02 ppm SO_2, 15.1 ppm NOx, and 3.1 ppm CO. CO_2 emissions from the P2O process are estimated to be approximately 1,129 short tons CO_2 per year. (These emissions are based on a P2O unit processing approximately 36 tons of plastic waste per day at 75% availability).

The electricity consumption of a 48-ton per day P20 unit is approximately 1.3 MWh per day (53 kW/day). Assuming 75.3% availability (275 days/year) of the P2O unit, the total annual electricity consumption of P2O unit is estimated to be approximately 350 MWh per year. Assuming that the electricity provided to the process is generated from coal, the CO_2 emissions from the electricity consumption are estimated to be approximately 364 tons CO_2 per year (this is based on the Energy Information Administration's estimate that coal derived electricity produces on average 2.08 lb CO_2/kWh). Therefore, the overall CO_2 emissions of a P2O unit are estimated to be approximately 1,493 tons CO_2 per year.

The P2O process passed multiple Conestoga-Rovers & Associates (CRA) stack tests that were conducted in 2010 and 2011. Air emissions were well within the regulatory criteria established by the New York State Department of Environmental Conservation (NYSDEC) thus reaffirming that the P2O process is a clean "green" process. JBI Inc. received an air permitting exemption from the environmental protection agency for the new commercial facility that will be constructed in Jacksonville, FL.

The primary waste product generated by the P2O process is petcoke. JBI Inc. is currently seeking Beneficial Use Determination (BUD) for the purposes of potential sale of the petcoke residue.

Although the P2O process uses cooling water for the equipment, no wastewater is generated. The cooling water runs in a closed loop and is never in contact with the chemicals in the process.

4.3.5 Economic Analysis

In 2012, JBI Inc. commissioned SAIC Energy, Environment, and Infrastructure, LLC to conduct an independent review of the P2O process and its business model. The economic analysis provided in this study is based on the SAIC report and only provides a rough estimate of the expenses and revenues of the P2O process.

The SAIC base case business model for 2013 is based on a commercial facility consisting of 3 P2O units operating at 75.3% uptime (275 days/year) with an 80% yield. The annual processing capacity of the facility is approximately 31,700 tons per year and the product stream of the facility is 70:30 No. 6 oil-naphtha. No. 2 oil generation and sale is not included in this business model. Table 14 compares the P2O costs provided in SAIC business model with costs estimated by Earth Engineering Center (EEC) for a pyrolysis plant of the same capacity. In both cases, the oil yields calculated from the mass balance were used.

Table 14: Economic Analysis of P2O Process

		SAIC Report	**EEC estimate**
Plant capacity	*tons/year*	31,700	31,700
Capital investment	*$ (total)*	7,838,415	9,500,000
	$/ton of annual capacity	247	300
Annual capital charge (APR 4%, 10 years)	*$/year*	783,842	950,000
	$/ton processed	25	30
Cost of collecting/sorting/delivering PW to plant[1]	*$/year*	Not provided	1,595,000
Variable operating costs	*$/year*	562,348	634,000
Fixed operating costs	*$/year*	444,180	1,000,000
General and Administrative	*$/year*	20,000	200,000
Total operating costs	*$/year*	1,026,528	3,429,000
TOTAL CAPITAL + OPERATING COSTS	*$/year*	1,810,370	4,379,000
	$/ton processed	57	138
Operating Revenues	*$/barrel of No. 6 oil*	100	100
	$/barrel of naphtha	80	80
No. 6 oil[2]	*barrels/ton of PW[3]*	3.1	3.1
Naphtha[4]	*barrels/ton of PW*	1.3	1.3
Total Oil Products[5]	*barrels/ton of PW*	4.4	4.4
Revenues from No. 6 oil	*$/ton*	310	310
Revenues from Naphtha	*$/ton*	104	104
TOTAL REVENUES	*$/year*	13,123,800	13,123,800
	$/ton processed	414	414
NET INCOME (REVENUE-COSTS)	*$/year*	11,313,430	8,744,800
	$/ton processed	357	276

1: Arsova L. and Nickolas J. Themelis, "Collection and processing of plastic wastes for use as pyrolysis feedstock", (2012)
2,4,5:Yields calculated by D.Tsiamis
3: PW indicates plastic waste

Based on the SAIC business model, a 31,700-ton per year commercial P2O facility operating at approximately 75% availability is estimated to generate a net income of $357 per ton of plastic waste. Meanwhile, the EEC analysis estimates a net income of $276 per ton of plastic waste. EEC estimates that the costs of the P2O facility, specifically the capital cost, fixed operating costs, and general administrative costs, should be higher than those provided in the SAIC model. Furthermore, the EEC analysis takes into account the additional cost of collection, sorting, and delivery of plastic waste to the pyrolysis plant.

The business model of JBI Inc. is to develop processor partnerships with clients who generate large volumes of plastic waste. From this partnership, the client would avoid the cost of tipping fees (which are fees for transporting and disposing waste in landfills) and would have access to affordable clean burning fuels. JBI Inc. owns and operates all of its P2O units; it does not sell units. The fuel products that are generated by the P2O process are sold to fuel retailers, fuel brokers, and directly to end-users.

4.3.6 Current Status

JBI Inc. is currently in the process of constructing its first commercial facility. The facility will initially operate with 3 P2O units (total 144 ton per day capacity). Eventually, JBI Inc. plans to install 24 P2O units and have the facility operate at a maximum capacity of approximately 1,150 tons per day. The commercial facility will be located in Jacksonville, FL and will be used by Rock-Tenn, a paperboard and packaging manufacturer. To date, JBI Inc. has produced 461,000 gallons of fuel with its P2O process

4.4 Agilyx

4.4.1 Overview

Agilyx uses a patented thermal pyrolysis batch process to convert plastic waste to synthetic fuel. Agilyx (formerly known as Plastic2Fuel) is a private company located in Portland, OR that was founded in 2006 by Kevin Dewhitt and Chris Ulum. Agilyx currently operates a demonstrational scale facility located in Tigard, Portland, OR and a commercial facility located near Portland, OR.

In May 2012, a research associate of Columbia University's Earth Engineering Center (EEC) visited Agilyx's demonstration facility. The EEC associate met with Mr. Dewhitt and Mr. Ulum and took a tour of one of Agilyx's fourth generation processing units. Some of the findings from the EEC associate's visit to Agilyx are reported in this section.

The Agilyx process converts plastic waste into fuel via thermal pyrolysis. The process accepts all plastic waste types and resins as feedstock. The primary yield of the process is a low-sulfur content crude oil that is sold to refineries. The by-products of this process are char and light gases. The char is sold as low grade char. The light gases are burned in open flare and are an emission of the process. Agilyx is currently looking into recycling the light gases for use as a heat source for its process.

The Agilyx process is a batch process that is powered by an external energy source. A single processing unit at the Agilyx facility is called a base system. The feed capacity of a base system is approximately 30 tons per day. Base systems can be used in parallel in unlimited increments to increase total processing capacity[66]. Based on calculations from the EEC associate's summary report on Agilyx, it was determined that the Agilyx process produces approximately 4.1 barrels of oil per ton of plastic waste feed.

The following sections include a detailed technical description of the Agilyx process, results of calculated mass and energy balances on the fourth generation Agilyx system, and a discussion of the emissions and environmental impacts of the process. Economic data was not provided by Agilyx therefore an analysis of the Agilyx business model could not be performed.

4.4.2 Process Description

4.4.2.1 Plastic Feedstock

The Agilyx base system can process up to 30 short tons of plastic waste per day. Base systems can be used in parallel in unlimited increments to increase the total processing capacity of the process. The Agilyx system accepts all plastic waste types (rigid containers, film plastics, etc.) and plastic resins #1-7 as feedstock. The unit also processes items that don't have a designated resin code.

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[66] Agilyx, *Convert Waste Plastic into Crude Oil*. Agilyx, 2012. Print.

Sources for Agilyx's feedstock are material recovery facilities (MRFs), plastic aggregators, and plastic manufacturers (manufacturers provide floor-sweep and off-spec material). Agilyx runs tests on samples of the plastic waste in the company's on-site laboratory prior to processing it. If the lab test results prove that the material is suitable for the Agilyx process, Agilyx does a trial run in the demonstration plant to test the yields and feasibility of using the client's plastic waste as feedstock for the Agilyx system[67].

Mechanical preparation of the plastic waste feedstock is required for the Agilyx process. Rigid plastics are shredded and film plastics are shredded, granulated, and pelletized prior to being fed to the Agilyx system.

4.4.2.2 Agilyx Process

Prepared plastic waste feed is put into a cartridge and the cartridge is inserted into a large insulated vessel called a plastics reclamation unit. Within the reclamation unit, air is heated via a natural gas burner and is circulated around the cartridge. The cartridge is heated by the air and, via heat transfer, the plastics inside the cartridge are heated and liquefied.

The liquefied plastics occupy a series of manifolded tubes within the cartridge called candles. The liquefied plastics are pyrolyzed in the candles. The structural design of the candles maintains the proper surface area to volume ratio for adequate cracking. In the Agilyx system, the plastics are pyrolyzed at an operating temperature between 300 and 600 degrees Celsius[68].

The resultant gaseous pyrolysis products are filtered for char and then transferred to a condenser where they are directly water sprayed to remove heat. In the condenser, buffer agents and caustics are added to remove halogens and organic acids from the pyrolysis products. The emulsion from the condenser is moved into a coalescing vessel to separate the oil from the aqueous fraction. The oil product goes through 1-2 more settlers to remove any remaining aqueous fraction and then is transferred to a final holding tank.

Figure 15 shows a schematic of the Agilyx process.

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[67] Arsova, Ljupka. "Report from the visit of Agilyx headquarters and demonstration facility". EEC Summary Report, 2012. 5-6. Print.

[68] Ibid, 4.

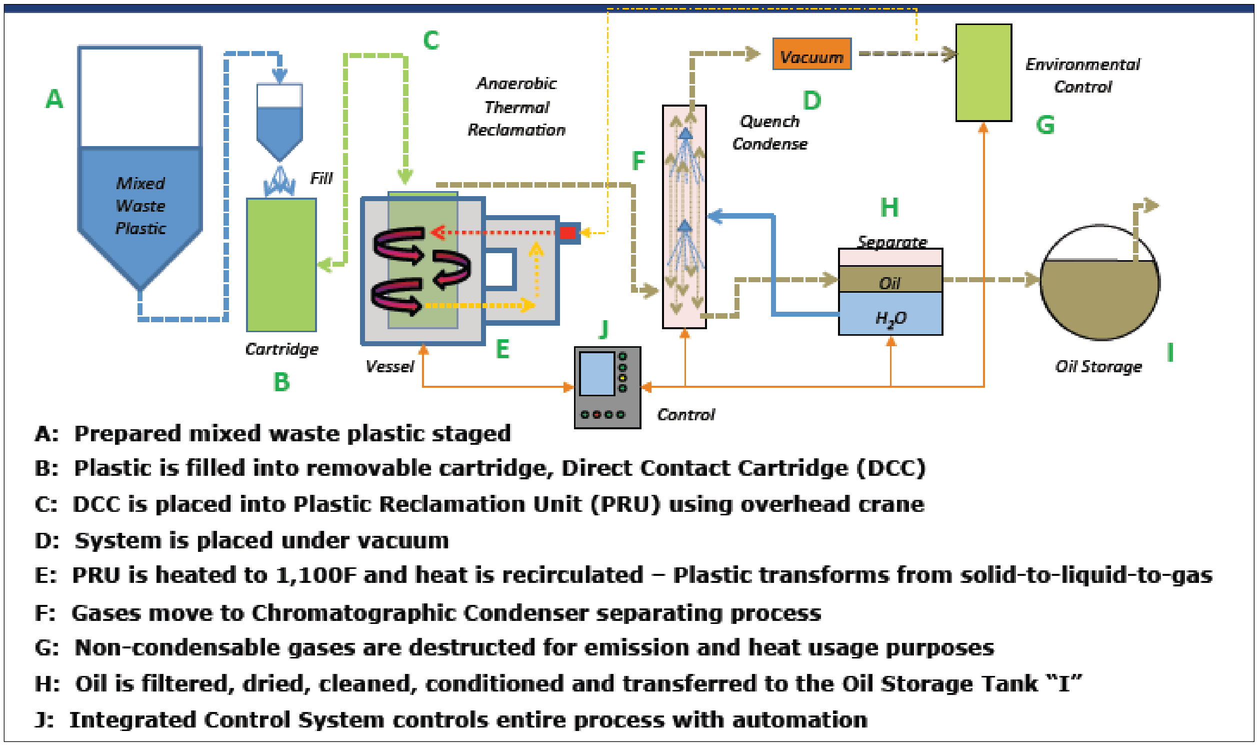

Figure 15: Agilyx process
Source: Arsova, (2012)

4.4.2.3 Input and Output

The material inputs of the Agilyx process are:

- Plastic waste (all types and resins)
- Air
- Water
- Buffer agents and caustics

The plastic waste is the feedstock for the Agilyx process. Air is used as a heating medium to heat the plastics inside the cartridges. Water is used in the condenser to remove heat from the gaseous pyrolysis products. Buffer agents and caustics are used to remove halogens and organic acids from the gaseous pyrolysis products.

The material outputs of this process are:

- Low-sulfur crude oil
- Char (by-product)
- Light gases (a combustible mixture of methane, ethane, propane, butane and hydrogen)

The synthetic crude oil product of the Agilyx systems meets petroleum specifications and has low sulfur, low residuum, high API gravity, high PONA, and high calorific value[69]. Agilyx currently sells its crude oil to US refineries[70].

The char residue from the Agilyx process is sold as low-grade char. The light gases produced during pyrolysis are currently emissions of the Agilyx process. Agilyx is looking into reusing the light gases as an energy source for heating in the pyrolysis process[71].

4.4.3 Material and Energy Balances

4.4.3.1 Material Balance

Agilyx reports the following mass yields for its thermal pyrolysis process[72]:

- 80% crude oil
- 10% light gases
- 10% char

A mass balance could not be performed on the Agilyx system because performance metrics were not provided in the EEC summary report.

Agilyx reports that its process yields between 4.8 to 5.6 barrels of oil per ton of plastic waste (yields depend on the plastic waste feedstock)[73]. To check this claim, the oil production rate of the Agilyx system was calculated based on the plastic composition of Agilyx's feedstock (which was provided by Agilyx) and the energy contents of the plastics, crude oil, light gases, and char that are reported in the EEC literature. In the calculations, it was assumed that 80% of the plastic waste was converted to oil and it was assumed that the light gases were primarily composed of methane. Table 15 shows the comparison between Agilyx's reported oil production yields and the yields calculated by EEC.

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[69] Agilyx, *Convert Waste Plastic into Crude Oil*. Agilyx, 2012. Print.

[70] Arsova, Ljupka. "Report from the visit of Agilyx headquarters and demonstration facility". EEC Summary Report, 2012. 3. Print.

[71] Ibid, 6.

[72] Ibid.

[73] Agilyx, *Our Technology: FAQ*. 2013. Web.

Table 15: Comparison of reported and calculated yields for Agilyx process

	Agilyx's Reported Yield	Yield Calculated by EEC
Barrels of oil/ ton of plastic waste	4.8 to 5.6	4.1

Even if the Agilyx process achieved 100% conversion of plastic waste into oil, Agilyx's reported yield of 5.6 barrels of oil per ton of plastic waste is not feasible based on the energy content of Agilyx's feedstock and the energy content of crude oil. The calculated maximum number of barrels of oil that could be produced from 1 ton of Agilyx plastic waste feed is only 5.14 barrels.

4.4.3.2 Energy Balance

The energy inputs of the Agilyx process are:

- Natural gas or Propane
- Electricity

The specific amounts of natural gas/propane and electricity that are used for the Agilyx process were not provided in the EEC summary report.

An energy balance was performed on the Agilyx system assuming the EEC estimate that 4.1 barrels of oil are generated from 1 ton of plastic waste in the Agilyx process. The calculations were based on the plastic composition of Agilyx feedstock and the energy contents reported in the EEC literature. In the calculations, it was assumed that the conversion of plastic waste into char and the light gases was of the same magnitude and it was assumed that the light gases were composed primarily of methane. Table 16 shows the calculated energy distribution that is achieved in the Agilyx process.

Table 16: Energy distribution in Agilyx process

	Heating value (Btu/ton of plastic feedstock)	% Distribution of heating value of feedstock
IN		
Agilyx plastic waste feedstock	29,810,000	100.0%
OUT		
Crude oil	21,973,530	73.7%
Char	5,116,744	17.2%
Light gases	8,178,732	27.4%
TOTAL	35,269,006	118.3%

The discrepancy in the energy balance of Table 16 may be due to incorrect assumptions about the composition of Agilyx light gases or the assumed conversion of the plastic waste feed into char and light gases. However, the EEC estimate for crude oil yield and the energy contents of Agilyx plastic waste feed and crude oil are accurate. Therefore, it can be concluded that approximately 74% of the chemical energy stored in plastic waste is recovered in the crude oil product of the Agilyx process. The remaining 26% of the stored energy is accounted for in the stored energy of the char, the chemical energy available in the light gases, and the heat losses of the process.

4.4.4 Environmental Emissions

The air emissions of the Agilyx process are due to the combustion of natural gas and the flaring of the light gas product of pyrolysis. Agilyx claims that the total greenhouse gas (GHG) emissions from a 40-ton per day Agilyx facility are 8,159 short tons of CO_2 per year[74]. If Agilyx's next generation processing unit can use the light gas product to heat the pyrolysis reactor, Agilyx estimates that the GHG emissions for a 40-ton per day facility would be reduced to 6,732 tons of CO_2 per year[75]. Agilyx currently has air permits in Oregon, California, and Florida[76].

Additional emissions of the Agilyx system come from the electricity consumption of the process. Since both Agilyx and JBI Inc's processes are based on thermal pyrolysis, it can be assumed that the Agilyx process consumes as much electricity as the P2O process at a minimum; the Agilyx system has a greater external energy demand than the P2O process because it does not recycle its light gases product for use as an energy source of its process. Assuming that an approximately 40-ton per day Agilyx system uses at minimum 1.3 MWh per day (at reported power input of 53 kW) and operates at 92% availability, the estimated annual CO_2 emissions from electricity production are estimated to be approximately 444 tons of CO_2 per year (this is based on the Energy Information Administration's estimate that coal derived electricity produces on average 2.08 lb CO_2/kWh). The minimum estimated annual CO_2 emissions of the Agilyx process is approximately 8,603 tons of CO_2 per year.

In addition to air emissions, the Agilyx process also generates wastewater. The water used in the spray down of the gaseous products of pyrolysis is mixed with buffer agents and caustics. Agilyx re-uses approximately 80% of its water in its process. However, prior to disposal, this water must be treated because it contains halogens and organic acids. Adequate waste water treatment and increased recycling of water in the Agilyx process are necessary to maintain low environmental impacts of this process[77].

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[74] Agilyx. *Fact Sheet for Air Regulators*. 1. Print.

[75] Ibid.

[76] Arsova, Ljupka. "Report from the visit of Agilyx headquarters and demonstration facility". EEC Summary Report, 2012. 7. Print.

[77] Ibid, 8-9.

4.4.5 Current Status

Agilyx has been operating a commercial facility near Portland, OR for the past two years. In 2012, Agilyx completed installation of its first 40-ton per day commercial facility. This commercial facility is located in Minnesota and will be used by Rational Energies[78]. Since the time of the EEC associate's visit, Agilyx has developed and begun operation of its fifth generation base system.

[78] Arsova, Ljupka. "Report from the visit of Agilyx headquarters and demonstration facility". EEC Summary Report, 2012. 3. Print.

4.5 Climax Global Energy Inc. (CGE)

4.5.1 Overview

Climax Global Energy Inc. (CGE) uses a patented continuous microwave pyrolysis process to convert plastic waste to synthetic petroleum. Distillation of the synthetic petroleum from the CGE process yields marketable fuel and wax. CGE was founded in 2005 and is a private company. CGE has a research and development (R&D) plant located in Allendale, SC and has completed construction of a 10-ton per day commercial unit in Barnwell County, SC. which is in start-up phase. The commercial unit will be a part of CGE's new commercial facility, which will include 3-4 units and is planned to operate at a maximum feed capacity of 30-40 tons per day.

In November 2011, a research associate of Columbia University's Earth Engineering Center (EEC) visited CGE's R&D plant. The EEC associate met with John Griffith, the CEO of CGE, and took a tour of the company's 3-ton per day unit. The findings from the EEC associate's visit to CGE are reported in this section. It should be noted that the findings from the EEC associate's summary report on CGE include performance metrics of the company's 3-ton per day unit as well as projections for the company's new 10-ton per day commercial unit. (The commercial unit was being constructed during the time of the EEC associate's visit).

The CGE process converts plastic waste into synthetic petroleum via microwave pyrolysis. The feedstock for the CGE process is mixed plastic waste. The primary products of the process after distillation are diesel range fuel and wax. By-products of the CGE process are char and light gases. Some of the light gases are re-used for heating the CGE reactor. The remaining light gases are burned in open flare and are an emission of the process. CGE is currently looking into recycling the light gases for use as an electricity source in its process.

The CGE process is continuous and is powered by a microwave generator. The microwave electricity consumption of CGE's 10-ton per day commercial unit is estimated to be approximately 3.2 megawatt-hours (MWh) per day. The new CGE commercial unit is planned to operate at a maximum total feed capacity of 10 tons per day at 85% availability. The claimed yields for the CGE process are approximately 5 barrels of synthetic petroleum per ton of plastic waste feed.

The following sections include a detailed technical description of the CGE process, results of calculated mass and energy balances on the CGE system, and a discussion of the emissions and environmental impacts of the process. Economic data was not provided by CGE therefore an analysis of the CGE business model could not be performed.

4.5.2 Process Description

4.5.2.1 Plastic Feedstock

The CGE reactor at the R&D plant can process up to 3 short tons of plastic waste per day. CGE's new commercial unit is planned to operate at a maximum total feed capacity of 10 tons per day.

The CGE process accepts mixed plastic waste as its feedstock. Sources for CGE feedstock include material recovery facilities (MRFs), dirty MRFs, and any other source that generates a constant supply of plastic waste.

Shredding of the plastic waste feedstock is required for the CGE process. The new CGE commercial facility will use an automated system to transport the shredded plastic feed to the reactor.

4.5.2.2 CGE Process

Prepared plastic feed is dropped into a reactor where it falls by gravity to the lower part of the reactor. The lower part of the reactor is at all times partially filled with melted plastic material that is continuously mixed.

Microwaves from a generator are introduced into the top portion of the reactor. Optimal expansion of the microwave radiation is achieved by the specific reactor geometry. The top part of the reactor has a hot oil jacket for reactor temperature control while the lower part's thermal insulation is secured with burners at the bottom. The melted plastic material in the reactor is pyrolyzed at an operating temperature of approximately 350 to 400 degrees Celsius.

The pyrolyzed gaseous products exit the reactor and go through two steps of condensation. First, the gas goes through a hot water scrubber where the heaviest fraction of petroleum is condensed out and the main product is extracted as wax. Next, the remaining gas goes through a cold water scrubber where a lighter fraction is condensed and extracted. The remaining light gases are re-circulated and some of the gas is utilized for heating of the lower part of the reactor. The leftovers are burned in open flare. Further development of the CGE process will look into recycling the light gases for use in electricity production for the pyrolysis plant.

The microwave generator for the commercial unit has a capacity of 200 kW and is designed to pyrolyze up to 0.35 tons (333 kg) of plastic waste feed per hour.

Figure 16 shows a picture of the CGE commercial unit.

Figure 16: Climax Global Energy Inc.'s Commercial Unit
Source: Climax Global Energy Inc. (2013)

4.5.2.3 Input and Output

The material inputs of the CGE process are:

- Mixed plastic waste
- Carbon (for start-up)
- Water

The plastic waste is the feedstock for the CGE process. The carbon is used as microwave-absorbent material in the start-up of the process. Water is used for the scrubbers.

The material outputs of this process are:

- Synthetic petroleum
- Char (by-product)
- Light gases (a combustible mixture of methane, ethane, propane, butane and hydrogen)

CGE's synthetic petroleum can be distilled into a diesel fraction and a wax fraction. The diesel can be blended into diesel tanks at fuel terminals. The wax can be sold to refiners for upgrading. CGE plans to utilize the light gases generated during pyrolysis for electricity production at the commercial facility.

4.5.3 Material and Energy Balances

4.4.3.1 Material Balance

CGE reports the following mass yields for its microwave pyrolysis process:

- 75% raw wax (corresponding to 25% diesel range fuel, 50% lubricating oils and waxes)
- 15% light gases
- 10% char

A mass balance on the CGE system could not be performed because performance metrics for the process were not provided in the EEC summary report. Table 17 shows the reported oil production yields for the CGE process per 1 ton plastic waste.

Table 17: Reported yields of CGE process after distillation

Total Raw Wax Product:	***5.0 barrel (bbl) synthetic petroleum/ton of plastic***
Diesel range oil	1.7 bbl oil/ ton plastic
Wax	3.3 bbl oil/ton plastic

4.3.3.2 Energy Balance

The energy inputs of the CGE process are:

- Electricity

CGE's 10-ton per day commercial unit is designed to have two heat inputs: microwave energy and heat provided by recovered off-gas. Depending on operating parameters, the unit may run at varying levels of microwave and thermal inputs. Assuming that 50% of the capacity of the 10-ton per day unit is derived from the microwave input and 50% is derived from the off-gas heat input, the electricity required for the microwave input is estimated by CGE to be approximately 3.2 MWh per day.

An energy balance was performed on the CGE system based on the reported yields. The energy content of the light gases was provided by CGE and was estimated to be approximately 20,000 Btu/lb (the light gases have an energy density similar to that of propane). The energy contents of the plastic waste feed and the raw wax product were based on values provided in the EEC literature. Table 18 shows the calculated energy distribution that is achieved in the CGE process.

Table 18: Energy distribution in CGE process

	Heating value (Btu/ton of plastic feedstock)	**% Distribution of heating value of feedstock**
IN		
Plastic waste	28,000,000	100.0%
OUT		
Raw wax	27,600,000	98.6%
Char	2,540,000	21.4%
Light gases	6,000,000	9.1%
TOTAL	36,140,000	129.1%

Table 18 shows that there is a discrepancy in the energy balance for the CGE process. The error in the energy balance may be attributed to an incorrect assumption about the energy composition of the raw wax. Since the energy content of the light gas was provided by CGE, it can be concluded that approximately 9% of the plastic feed's stored chemical energy is converted to energy that can be recovered through the combustion of the light gases. The remaining 91% of the stored energy is accounted for in the stored energy of the raw wax product, the stored energy of the recycled char, and the heat losses of the process.

4.5.4 Environmental Emissions

Emissions from the CGE process are generated from flaring of the light gases. Additional emissions are associated with the electricity consumption of the process. The estimated electricity consumption of CGE's 10-ton per day commercial unit is approximately 3.2 MWh per day. As such, at a capacity factor of 85%, the annual electricity consumption of the facility is estimated to be approximately 1 GWh per year. Assuming that the electricity provided to the facility is generated from coal, the CO_2 emissions from electricity consumption are estimated to be approximately 1,033 short tons CO_2 per year (this is based on the Energy Information Administration's estimate that coal derived electricity produces on average 2.08 lb CO_2/kWh). The overall CO_2 emissions of the CGE process are estimated to be greater than 1,033 tons CO_2 per year.

4.5.5 Current Status

CGE has completed construction and is starting up its first 10-ton per day commercial unit in Barnwell County, SC.

4.6 Comparison of Pyrolysis Technologies to Landfill Disposal of NYC MPW

4.6.1 Landfill Disposal of NYC MPW

NYC currently disposes its non-recycled MSW in landfills located in Virginia, South Carolina, Ohio, and Pennsylvania. The waste is primarily transported by tractor trailers but NYC plans to shift its mode of waste transport in the near future to rely more heavily on train and barge. Currently, about 900 23-ton tractor trailers transport NYC MSW to landfills every day.[79] On a daily basis, the tractor trailers travel an approximate total of 500,000 miles and consume a total of 6,500 gallons of fuel[80]. DSNY estimates that the amount of greenhouse gas (GHG) emissions generated by landfilling NYC MSW is equivalent to the amount of GHG emissions generated by Con Edison in supplying electricity to half of its NYC customers.[81] Con Edison generates approximately 25 billion kilowatt-hours (kWh) per year to power half of its customers[82]. Therefore, based on the Energy Information Administration's average metric of 2.08 lb of CO_2/kWh for coal-derived electricity[83], the annual CO_2 emissions of landfilling are estimated to be approximately 26,000,000 short tons of CO_2 per year. In addition to air emissions, approximately 140 acres of land per year are destroyed by landfilling.

The current cost of landfilling for NYC for residential and institutional waste is approximately $92/ton of waste. The NYC Office of Budget and Management projects that, in the next few years, the annual cost of landfilling NYC's residential and institutional waste will increase by nearly 50% (from $305 million in 2013 to $450 million in 2016)[84]. DSNY reports that the cost of landfilling waste is rising because the space available for landfill use is decreasing and, since 80% of the land commercially available for landfill use east of the Mississippi is owned by only 2 companies, the fee for landfilling is increasing[85].

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[79] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

[80] Ibid.

[81] Ibid.

[82] Con Edison. "Con Edison's Electricity System". Web.

[83] US E.I.A. "Frequently Asked Questions: How much carbon dioxide is produced per kilowatt-hr when generating electricity with fossil fuels?". Web.

[84] New York City, Department of Sanitation. *New and Emerging Conversion Technology.* 2013. Web

[85] *The Wrong Bin*. Dir. Krishnan Vasudevan. 2011. Documentary.

4.6.2 Evaluation of Pyrolysis Technologies and Comparison to Landfill Disposal

Table 19, on the following page, shows a comparison of the pyrolysis technologies of JBI Inc., Agilyx, and CGE based on the performance metrics and environmental impacts of each process. Table 19 also shows the economics of the P2O process. It should be noted that the total costs, total revenues, and net incomes shown in Table 19 are rough estimates based on the business models provided by JBI Inc.

The pyrolysis technologies discussed in this study generate approximately 2 to 4 barrels of oil per ton of plastic waste processed. Although the technologies process the same type of feedstock, the difference in yields can be attributed to the differences in operating conditions for the technologies. The high yields of JBI Inc's P2O process can be attributed to the presence of its proprietary catalyst during pyrolysis reactions. The catalyst lowers the operating temperature for the pyrolysis reaction and consequently increases the rate of depolymerization. Meanwhile, the relatively low oil yields of the CGE process indicate that extensive separation of the oil product from the melted plastic feed is not easily achieved in this process. This can be attributed to factors such as possible non-uniformity in the heating of the plastic feed and the limited types of plastic waste that can be used as feed in the CGE process.

Of the three pyrolysis technologies analyzed, JBI Inc.'s P2O process has the least negative environmental impact. JBI Inc. significantly reduces the carbon footprint of its process by recycling the off-gas that is produced during pyrolysis and using it to heat the process. Agilyx does not recycle its off-gas and therefore its process has higher air emissions than JBI Inc.'s. The high electricity demand of the CGE process indirectly contributes to the air emissions of the process. If CGE were to recycle its off-gas and use it to produce electricity for the system, then the total electricity demand of the process would decrease. Thus, recycling of the off-gas in the CGE process would significantly reduce its carbon footprint. In general, all of the pyrolysis technologies have significantly low negative environmental impacts, as indicated in Table 19.

JBI Inc's P2O process generates a significant net income per ton of plastic waste. In a previous study, the Earth Engineering Center (EEC) at Columbia University estimated that the additional cost of collection and processing MPW at a material recovery facility is approximately $50 per ton of plastic waste[86]. This additional cost is taken into account in JBI Inc's total estimated cost shown in Table 19 which is $138 per ton of plastic waste processed. This estimated cost is comparable to the current cost of landfilling which is approximately $92/ton of waste[87]. The P2O process is an economically viable alternative to landfill disposal because it produces a marketable product that generates a significant net income.

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[86] Arsova L. and Nickolas J. Themelis, "Collection and processing of plastic wastes for use as pyrolysis feedstock", EEC Report to Flexible Packaging Association, December 2012. Print.

[87] New York City, Department of Sanitation. *New and Emerging Conversion Technology.* 2013. Web.

Table 19: Technical, environmental, and economic comparison of pyrolysis technologies

	Performance Metrics				Environmental Impacts				Economics		
Waste Management Practice	**Types of Plastic Waste Accepted**	**Maximum Operating Capacity of a Single Processing Unit (Tons of plastic waste/day)**	**Estimated Total Number of Units Required to Process NYC's Non-Recycled MPW[1]**	**Product Yields (Barrels of oil/ton of plastic waste)**	**Air Emissions (Tons CO_2/ton of plastic waste)**	**Emissions associated with electricity consumption (Tons CO_2/ton of plastic waste)**	**Overall emissions (Tons CO_2/ton of plastic waste)**	**Waste Generated**	**Estimated Total Cost ($/ton of plastic waste)**	**Estimated Total Revenue ($/ton of plastic waste)**	**Estimated Net Income ($/ton of plastic waste)**
JBI Inc. (thermal -catalytic pyrolysis)	All plastic waste except #3-PVC and nylons	48	36	4.4	0.11	0.04	0.15	Petcoke (potentially marketable)	138	414	276
Agilyx (thermal pyrolysis)	All plastic waste types and plastic resins (#1-7)	30	58	4.1	0.57	Info. not available	>0.57	Wastewater	Info. not available	Info. not available	Info. not available
CGE (microwave pyrolysis)	Mixed plastic waste	10	173	5[2]	Info. not available	0.33	>0.33	Char	Info. not available	Info. not available	Info. not available

1: Total tonnage of landfill-bound NYC non-recycled MPW is approximately 1,727 tons per day.
2: Distilled to approx. 1.7 bbl of diesel range oil and 3.3 bbl of wax.

While landfilling is a significant expense for a plastic waste generator, like NYC, and it generates no income, JBI Inc's P2O process, if adopted, could generate a net income of approximately $280 per ton of plastic waste processed.

The principle advantage of pyrolysis over landfill disposal is the production of economically valuable oil products. The major environmental advantage is the reduced use of fossil fuel and also the saving of green fields from landfill use. Pyrolysis will have an economic advantage over landfill disposal for a municipality that sorts out non-recyclable plastics (NRP). Specifically, if a pyrolysis facility is set up in NYC, it would produce marketable fuel products that would generate a profit for the plastic component of the waste, as shown in the business model of the P2O process examined in this study. Currently, NYC is incurring an expense for the disposal of the plastic waste through landfilling and, in the next few years, the cost of landfilling for NYC for residential and institutional waste is expected to increase by nearly 50% (from $305 million in 2013 to $450 million in 2016)[88].

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[88] New York City, Department of Sanitation. *New and Emerging Conversion Technology.* 2013. Web

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Current Status of Plastic Waste Management in NYC

Currently, the primary waste management practice for NYC MSW is landfill disposal. Based on DSNY's most recent annual report (which was for 2011), the Bureau of Waste Prevention, Reuse, and Recycling is not making any major moves at this time to shift NYC's waste management practices to alternatives that have a lower negative environmental impact than landfilling. Instead, the major milestones in NYC solid waste management in 2011 were the near completion of the new Sims material recovery facility (MRF) in South Brooklyn and the commencement of the initial phase of the "New York City Comprehensive Commercial Waste System Analysis and Study"[89].

In a 23 year contract with the DSNY, Sims Municipal Recycling will process all of the designated metals, glass, and plastic recyclables collected by DSNY in its new MRF located in South Brooklyn. This MRF will also process up to 150,000 tons of commingled paper within the next five years. The Sims South Brooklyn MRF is expected to begin operation sometime between December 2012 and June 2013.

The "New York City Comprehensive Waste System Analysis and Study" is an on-going DSNY study on NYC's commercial waste stream. The goals of this study are to assess the current recycling capabilities of NYC's commercial establishments, to determine potential improvements in current commercial recycling practices, and to assess the possibility of adding additional mandated items for recycling by commercial establishments[90]. In January 2011, the DSNY commenced the initial phase of this study called "Promoting the Sustainable Maximization of the Recovery of Recyclables from the Commercial Sector". In this phase of the study, the DSNY will characterize and assess the commercial putrescible waste stream.

DSNY made major strides in 2011 towards improving recovery of designated recyclable items in NYC waste. Unfortunately, based on the annual 2011 DSNY report, it seems that no major developments have been made with regards to the material and energy recovery of designated non-recyclable items in NYC MSW. As landfilling becomes increasingly more expensive and as the land available for landfill disposal becomes more sparse, the need for a major change in NYC's waste management practices becomes urgent. Serious efforts should be made by DSNY in the following years to consider application of alternative practices and technologies in NYC's waste management infrastructure that re-use NYC's waste and consequently reduce NYC's reliance on landfill disposal.

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[89] New York City. Department of Sanitation. "2011 Annual Report." Print.

[90] Ibid.

5.2 Recommended Plastic Waste Management Practice for NYC

It is recommended that NYC consider the application of pyrolysis technologies in its management of NYC's non-recycled MPW. Based on a preliminary comparison of the pyrolysis technologies examined in this study, JBI Inc.'s thermal catalytic pyrolysis technology appears to be the most advantageous. JBI Inc's P2O process is a highly automated process that accepts a wide array of plastic waste and consistently yields high quality consumer-ready fuels. The P2O process generates approximately 4.4 barrels of oil per ton of plastic waste processed and is estimated to generate a net income of approximately $280 per ton of plastic waste.

JBI Inc's P2O process is advantageous compared to the pyrolysis technologies of Agilyx and CGI because it has the highest operating capacity at a low footprint, it has the highest oil production yield, and it has the least environmental impacts. Furthermore, JBI Inc. is the only company that has managed to successfully recycle all of its light combustible gaseous products of pyrolysis for energy use in its process. This significantly reduces the overall external energy demand of the process as well as overall CO_2 emissions. The P2O process is an economically competitive alternative to landfill disposal because it has a low total estimated cost and it generates a significant net income per ton of plastic waste processed.

JBI Inc's P2O unit has a maximum operating capacity of 48 tons of plastic waste per day. Based on this capacity, JBI Inc. could easily handle the plastic residue tonnage from Sims material recovery facility (MRF), which is approximately 60 tons per day. It would take approximately 36 P2O units to process NYC's total daily tonnage of municipal landfill-bound non-recycled plastics (NRP), which is approximately 1,700 tons per day (this tonnage includes Sims MRF plastic residue). The footprint of a single P2O unit is approximately 1,200 square ft. therefore an estimated minimum of 43,200 square ft. would be required to process all of NYC's municipal NRP. The P2O process accepts film plastics, which account for approximately 60% of NYC's municipal NRP.

In conclusion, pyrolysis is a favorable alternative to landfill disposal in the waste management of NYC's non-recycled MPW. Unlike landfill disposal, pyrolysis taps into the material and energy resources of post-consumer waste and creates a market for materials that would otherwise be disposed. As landfill disposal becomes increasingly more expensive, pyrolysis becomes a more economically competitive alternative. Furthermore, pyrolysis has a less negative environmental impact than landfill disposal. Pyrolysis has not been widely applied in the field of waste management because of its drawbacks which include high external energy demand, high capital cost, and inconsistent product quality. JBI Inc.'s P2O process seems to have overcome these disadvantages because of its highly automated system and its ability to recycle its off-gas product for energy use. Therefore, JBI Inc.'s P2O process is a pyrolysis technology that should be seriously considered for application in NYC plastics waste management. It offers all the benefits of pyrolysis without any of the major drawbacks.

5.3 Future Research

Waste management in NYC is a very complex system and this study only addresses one aspect of it. Innovative plastic reclamation technologies are obsolete unless a consistently high volume plastic feedstock stream can be provided. Therefore, future research should look into the collection and processing of NYC's MPW waste and assess the feasibility of adding non-recycled plastics (NRP) to the collected recycling streams that are sent to NYC's material recovery facilities (MRFs). Analysis of the plastic waste handling required prior to the reclamation technologies would provide a more accurate estimate of total cost associated with these alternatives and would address the bigger problem of plastics waste management in NYC.

Further research on the pyrolysis of NYC's NRP should also include a feasibility study for the siting, building and operation of a pyrolysis plant of initial capacity of 60 tons per day (21,900 tons per year), which would process plastic residue from the Sims MRF.

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APPENDIX I: Calculations

A. MSW GENERATION IN NYC (2010)

1) Residential Sector:

Basis: Approx. 11,600 tons of residential MSW collected by DSNY per day
Source: New York State. Department of Sanitation. *DSNY Annual Report: Curbside Municipal Refuse and Recycling Statistic*. 2011.

Calculations:

Table 20: DSNY Residential Curbside Collections, 2010

Waste Type	***Tons/day***
Organics	4.2
Metals, glass, plastic recycling	744.9
Paper recycling	1070.2
Refuse	9733.2
TOTAL	11592.5

Source: DSNY Annual Report, Fiscal Year 2010: Curbside Municipal Refuse and Recycling Statistics

$$11{,}592.5\ \frac{tons\ of\ MSW}{day} \times 365\ \frac{days}{yr} = 4{,}231{,}262\ \frac{tons\ of\ MSW}{yr}$$

Result:
Annual Tonnage of MSW Generated by NYC Residential Sector in 2010: ***4.23 million tons/yr***
Daily Tonnage of MSW Generated by NYC Residential Sector in 2010: ***11,593 tons/day***

2) Commercial Sector:

Source: HDR P.C.. *Commercial Waste Management Study, Volume II: Commercial Waste Generation and Projections.* 2004. 24.

Calculations:

Commercial waste in this study is broken into the following two categories:

1) Putrescible: Principally office and retail waste, also includes restaurant waste (includes waste that is both recycled and disposed)
2) Non-Putrescible: C&D waste
3) Fill Material

For this study, non-putrescible waste and fill material were not accounted for in commercial waste generation estimates:

Table 21: NYC commercial waste generation in 2010

New York City	2010 (Tons)
Generation	3,214,000

Source: Commercial Waste Management Study

Result:
Annual Tonnage of MSW Generated by NYC Commercial Sector in 2010: ***3.21 million tons/yr***
Daily Tonnage of MSW Generated by NYC Commercial Sector in 2010: ***8,806 tons/day***

**Note: C&D and fill account for approx. 6.9 million tons of commercial waste in 2010. Including these categories makes total commercial waste generation for 2010 approx. 10.1 million tons.*

3) NYC: Net Generation

Basis:
Residential MSW Generation: 4,231,262 tons/yr
Commercial MSW Generation: 3,214,000 tons/yr

Calculations:

$$4{,}231{,}262.5\ \frac{tons\ residental\ MSW}{yr} + 3{,}214{,}000\ \frac{tons\ commercial\ MSW}{yr} = 7{,}445{,}262\ \frac{tons\ MSW}{yr}$$

$$7{,}445{,}262\ \frac{tons\ MSW}{yr} \div 365\ \frac{days}{yr} \approx 20{,}398\ \frac{tons\ MSW}{day}$$

Result:

Net Annual MSW Generation by NYC (2010): ***7.45 million tons/yr***
Net Daily MSW Generation by NYC (2010): ***20,398 tons/day***

**Note: Net Annual MSW Generation by NYC IN 2010 Including C&D and Fill: 14.3 million tons/yr*

B. MATERIAL COMPOSITION OF NYC MSW

1) Residential Sector:

Basis: 4.23 million tons of NYC residential MSW, 2010
Source: RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 2

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Calculations:

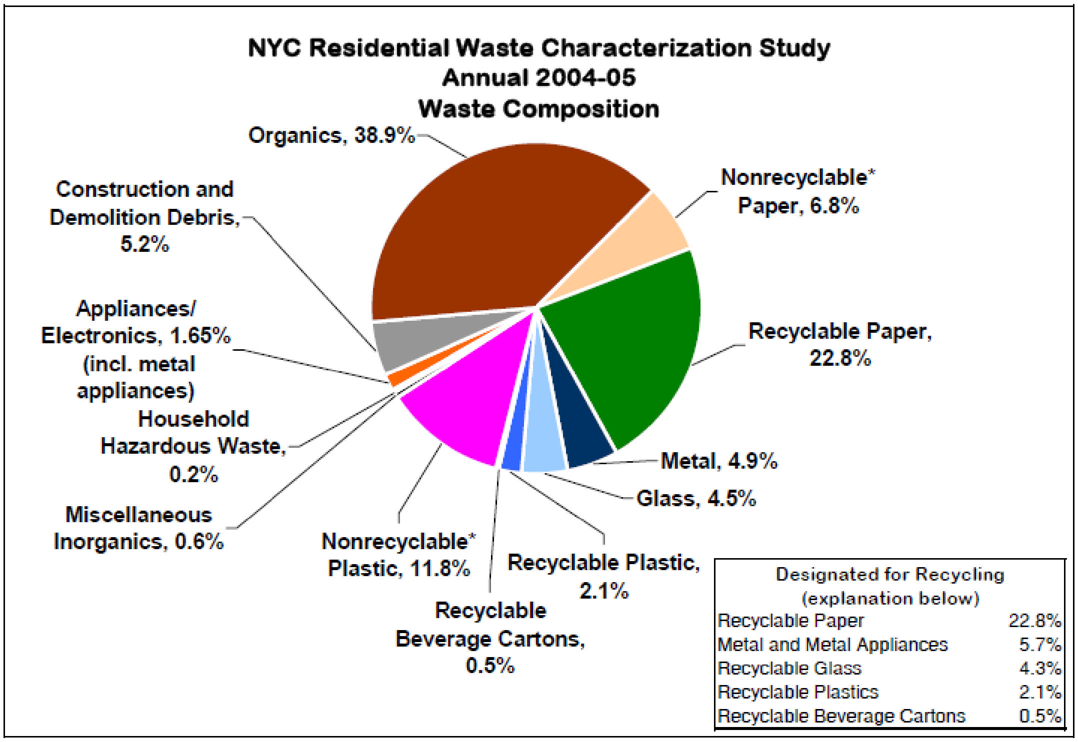


Figure 17: NYC Residential MSW composition
Source: DSNY 2004-2005 Waste Characterization Study

Results:

Table 22: Material tonnages in residential MSW, 2010

Material Category	% of Residential MSW	Million tons	Tons
Paper	29.6	1.25	1252080
Glass	4.5	0.19	190350
Metal	4.9	0.21	207270
Plastic	13.9	0.59	587970
Organics	38.9	1.65	1645470
Miscellaneous*	7.95	0.34	336285
Hazardous	0.25	0.01	10575
TOTAL	**100**	**4.23**	**4230000**

**Miscellaneous: Beverage cartons, miscellaneous inorganics, C&D debris, appliances and electronics*

2) Commercial Sector:

Basis: 3.21 million tons of NYC commercial MSW, 2010
Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.

Calculations:

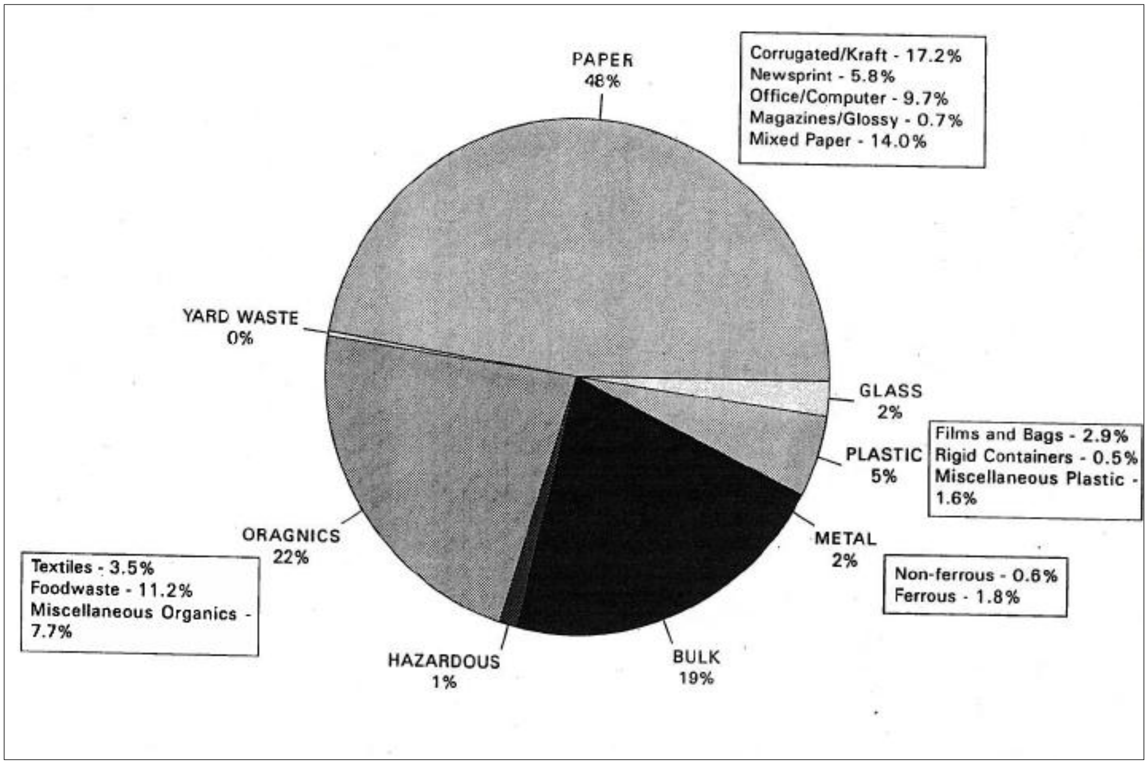


Figure 18: Material composition of commercial MSW
Source: DSNY 1989-1990 Waste Composition Study

Results:

Table 23: Material tonnages in NYC commercial MSW, 2010

Material Category	% of Commercial MSW	Million tons	Tons
Paper	48	1.54	1540800
Glass	2	0.06	64200
Metal	2	0.06	64200
Plastic	5	0.16	160500
Organics	22	0.71	706200
Miscellaneous*	20	0.64	642000
Hazardous	1	0.03	32100
TOTAL	**100**	**3.21**	**3210000**

**Miscellaneous: Bulk*

3) NYC MSW: Overall Composition

Basis:

a) 2.1% of NYC residential MSW is recyclable plastic, 11.8% is non-recyclable plastic
b) 0.5% of NYC commercial MSW is recyclable plastic (rigid plastics), 4.5% is non-recyclable plastic

Source:

RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 2

New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.

Results:

Material Category	Million tons	% of Total MSW
Paper	2.79	38.3
Glass	0.25	3.5
Metal	0.27	3.7
NRP	0.51	6.9
RP	0.09	1.2
Organics	2.35	32.3
Miscellaneous	0.98	13.4
Hazardous	0.04	0.6
TOTAL	**7.28**	**100**

C. RECYCLABLE AND NON-RECYCLABLE DESIGNATED ITEMS IN NYC MSW

1) Residential Sector:

Basis: 4.23 million tons of NYC residential MSW, 2010
Source: RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 3.

Calculations:

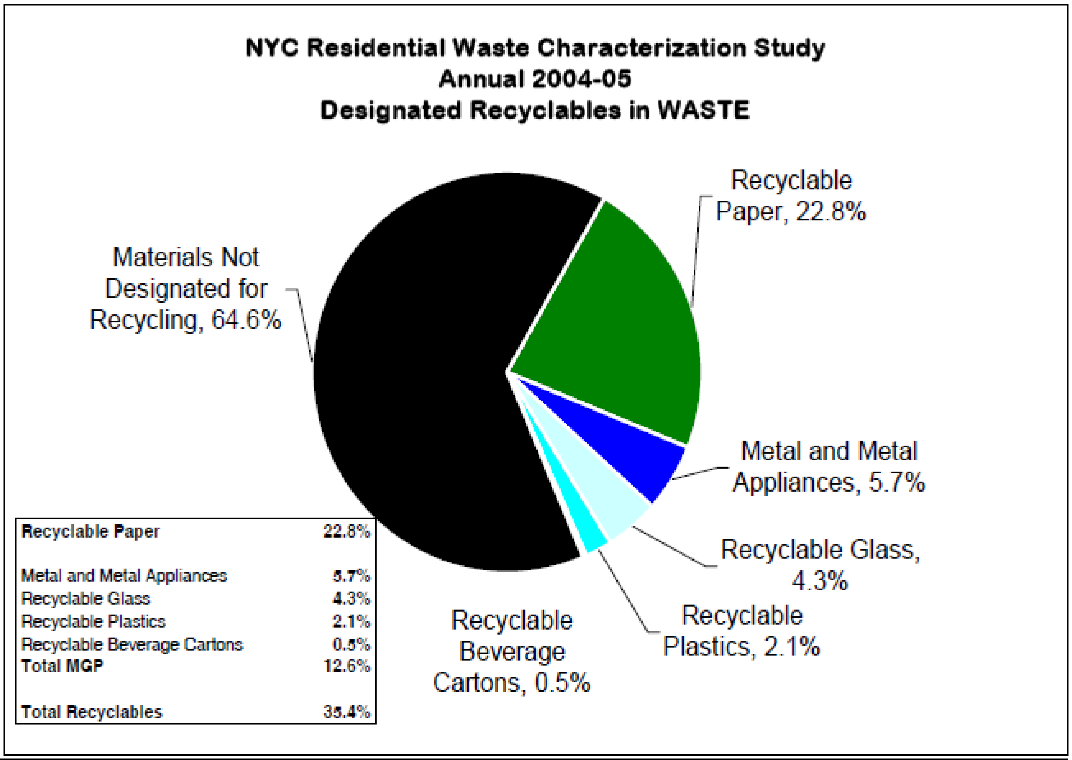


Figure 19: Recyclable and non-recyclable designated items in NYC residential MSW
Source: DSNY 2004-2005 NYC Residential Waste Characterization Study

Results:
Table 24: Tonnages of recyclable and non-recyclable items in residential MSW, 2010

Material Category	% in Residential MSW	Million tons	Tons
Non-recyclable Items	64.6	2.73	2732580
Recyclable Items	35.4	1.50	1497420
TOTAL	**100**	**4.23**	**4230000**
Recyclable Beverage Cartons	0.5	0.02	21150
Recyclable Plastics	2.1	0.09	88830
Recyclable Glass	4.3	0.18	181890
Recyclable Metal and Metal Appliances	5.7	0.24	241110
Recyclable Paper	22.8	0.96	964440
TOTAL	**35.4**	**1.50**	**1497420**

2) <u>Commercial Sector:</u>

Basis: 3.21 million tons of NYC commercial MSW, 2010
Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.

Calculations:

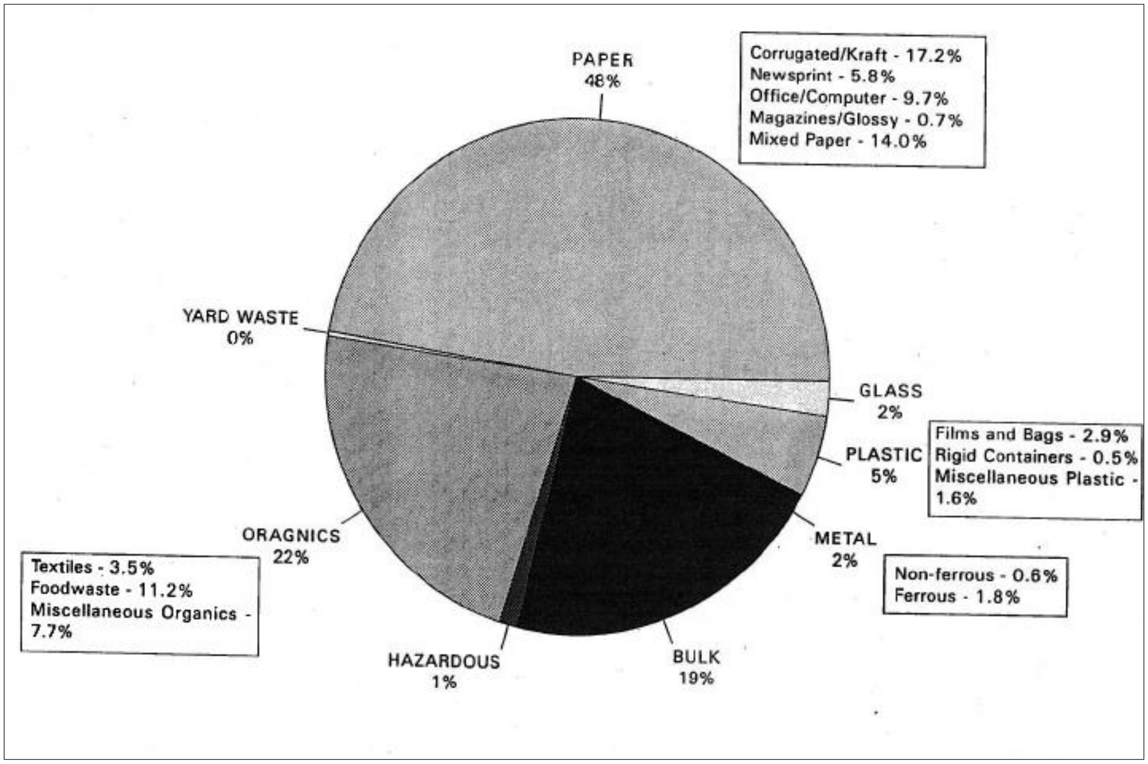


Figure 20: Recyclable and non-recyclable designated items in NYC commercial MSW
Source: DSNY 1989-1990 NYC Waste Composition Study

Assumptions:

- All paper, glass, and metal in commercial MSW is recycled
- From the plastics material group, only rigid plastics (0.5% of commercial MSW) are recycled

Results:

Material Category	% in Commercial MSW	Million tons	Tons
Non-recyclable Items	47.5	1.52	1524750
Recyclable Items	52.5	1.69	1685250
TOTAL	**100**	**3.21**	**3210000**
Recyclable Glass	2	0.06	64200
Recyclable Paper	48	1.54	1540800
Recyclable Metal	2	0.06	64200
Recyclable Plastic	0.5	0.02	16050
TOTAL	**52.5**	**1.68525**	**1685250**

3) NYC MSW: Overall Composition

Results:

Material Category	% in NYC MSW	Million tons	Tons
Non-recyclable Items	57.22	4.26	4,257,330
Recyclable Items	42.78	3.18	3,182,670
TOTAL	**100**	**7.44**	**7,444,000**
Recyclable beverage cartons	0.28	0.02	21,150
Recyclable Glass	3.31	0.25	246,090
Recyclable Paper	33.67	2.51	2,505,240
Recyclable Metal	4.10	0.31	305,310
Recyclable Plastic	1.41	0.10	104,880
TOTAL	**52.5**	**3.18**	**3,182,670**

D. FATE OF NYC MSW (2010)

TONNAGES RECYCLED:

1) Residential Sector

i. Metals, Glass, and Plastic Stream (Collected)

Basis: 744.9 tons Metals, Glass. &Plastic (MGP) recycling collected/day
Source: New York State. Department of Sanitation. *Annual Report: New York City Curbside Municipal Refuse and Recycling Statistics.* 2011

Calculations:

$$744.9 \ \frac{tons\ MGP\ collected}{day} \times 365\ \frac{days}{yr} = 271{,}888\ \frac{tons\ MGP\ collected}{yr}$$

Result:
Annual Tonnage of NYC Residential MGP Collected in 2010: ***0.27 million tons/yr***

Daily Tonnage of NYC Residential MGP Collected in 2010: ***745 tons/day***

ii. Paper Stream (Collected)

Basis: 1,070 tons paper recycling collected/day
Source: New York State. Department of Sanitation. *Annual Report: New York City Curbside Municipal Refuse and Recycling Statistics.* 2011

Calculations:

$$1070\ \frac{tons\ paper\ recycling\ collected}{day} \times 365\ \frac{days}{yr} = 390{,}623\ \frac{tons\ paper\ recycling\ collected}{yr}$$

Result:
Annual Tonnage of NYC Residential Paper Recycling Collected in 2010: ***0.39 million tons/yr***

Daily Tonnage of NYC Residential Paper Recycling Collected in 2010: ***1,070 tons/day***

iii. Residue in Metals, Glass, and Plastic and Paper Recycling Streams

Basis:
Net Annual Metals, Glass, and Plastic Tonnage Collected: 271,888 tons
Net Annual Paper Recycling Tonnage Collected: 390,623 tons
Source: NYC Department of Sanitation Bureau of Waste Prevention Reuse and Recycling. "Marketable Materials: What's in NYC's Residential Recycling?". 2012. Web.
<http://www.nyc.gov/html/nycwasteless/html/resources/reports_recycomp_calc.shtml>

Calculations:
Net tonnages were input into the online calculator which then outputs a tonnage breakdown of the recycling streams, including the residue tonnages.

Results:
Annual Tonnage of Residue in NYC Residential Collected Paper Recycling (2010):
19,922 tons/yr
Daily Tonnage of Residue in NYC Residential Collected Paper Recycling (2010):
55 tons/day

Annual Net Tonnage of Residue in NYC Residential Collected MGP Recycling (2010):
54,650 tons/yr
Daily Net Tonnage of Residue in NYC Residential Collected MGP Recycling (2010):
150 tons/day

- Annual Tonnage of Non-Recycled Plastic Residue in MGP: ***29,092 tons/yr***
  Daily Tonnage of Non-Recycled Plastic Residue in MGP: ***80 tons/day***

- Annual Tonnage of Other Residue in MGP: ***25,558 tons/yr***
  Daily Tonnage of Other Residue in MGP: ***70 tons/day***

iv. Total Recycled Residential Waste (Excludes Residue)

Basis:
Net Annual Collected MGP Tonnage: 271,888 tons
Net Annual Collected Paper Recycling Tonnage: 390,623 tons
Net Residue Tonnage (MGP & Paper): 74,571 tons

Calculations:

$$271{,}888\ \frac{tons\ \ MGP\ collected}{yr} + 390{,}623\ \frac{tons\ \ paper\ recycling\ collected}{yr} - 74{,}571\ \frac{tons\ \ of\ residue}{yr} = 587{,}940\ \frac{tons\ MSW\ recycled}{yr}$$

Result:
Annual Tonnage of NYC Residential MSW Recycled in 2010***: 0.59 million tons/yr***

Daily Tonnage of NYC Residential MSW Recycled in 2010***: 1,611 tons/day***

2) Commercial Sector

i. Total Recycling Collected

Basis: 858,000 tons of commercial putrescible waste was collected for recycling in 2010
Source: HDR. *Commercial Waste Management Study, Volume II: Commercial Waste Generation and* Projections. 2004. Table 3.7-3: *Recycling of Commercial Putrescible Waste by Borough, 2003 through 2024.*

Result:
Annual Tonnage of NYC Commercial Recycling Collected in 2010***: 0.86 million tons/yr***

Daily Tonnage of NYC Commercial Recycling Collected in 2010: ***2,351 tons/day***

ii. <u>Paper Stream (Collected)</u>

Basis: a) 48% of commercial stream is paper
b) 37.5% of commercial refuse is paper
Source: a) New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.
b) Kaufman, Scott. *Analysis of Technology and Infrastructure of the Paper Recycling Industry in New York City*. New York: Columbia University. 2004. 17.

Calculations:

$$3{,}214{,}000\ \frac{tons\ commercial\ MSW}{yr} \times 0.48 = 1{,}542{,}720\ \frac{tons\ of\ paper\ in\ commercial\ MSW}{yr}$$

$$\{3{,}214{,}000\ \frac{tons\ commercial\ MSW}{yr} - 858{,}000\ \frac{tons\ commercial\ recycling}{yr}\} \times 0.375 = 883{,}500\ \frac{tons\ of\ paper\ in\ commercial\ refuse}{yr}$$

$$1{,}542{,}720\ \frac{tons\ of\ paper\ in\ commercial\ MSW}{yr} - 883{,}500\ \frac{tons\ of\ paper\ in\ commercial\ refuse}{yr} = 659{,}220\ \frac{tons\ of\ commercial\ paper\ recycling}{yr}$$

Result:
Annual Tonnage of NYC Commercial Paper Recycling Collected in 2010: ***0.66 million tons/yr***

Daily Tonnage of NYC Commercial Paper Recycling Collected in 2010: ***1,806 tons/day***

iii. <u>Metals, Glass, and Plastic Stream (Collected)</u>

Calculations:

$$858{,}000\ \frac{tons\ commercial\ recycling}{yr} - 659{,}220\ \frac{tons\ commercial\ paper\ recycling}{yr} = 198{,}780\ \frac{tons\ commercial\ MGP}{yr}$$

Result:
Annual Tonnage of NYC Commercial MGP Collected in 2010: ***0.20 million tons/yr***

Daily Tonnage of NYC Commercial MGP Collected in 2010***: 545 tons/day***

iv. **Total Recycled Commercial Waste (Excludes Residue)**

Assumption: Since there is no information available about the residue tonnages present in the commercial recycling stream, it was assumed that all commercial recycling collected was recycled.

Result:
Annual Tonnage of NYC Commercial MSW Recycled in 2010***: 0.86 million tons/yr***

Daily Tonnage of NYC Commercial MSW Recycled in 2010: ***2,351 tons/day***

3) NYC: Net Recycled MSW

Basis: Net Annual Residential MSW Recycled Tonnage: 587,940 tons/yr
Net Annual Commercial MSW Recycled Tonnage: 858,000 tons/yr

Calculations:

$$587{,}940\ \frac{tons\ residential\ \ MSW\ recycled}{yr} + \ 858{,}000\ \frac{tons\ commercial\ MSW\ recycled}{yr} = 1{,}445{,}940\ \frac{tons\ \ MSW\ recycled}{yr}$$

Result:
Annual Net Tonnage of NYC MSW Recycled in 2010: ***1.45 million tons/yr***

Daily Net Tonnage of NYC MSW Recycled in 2010: ***3,961 tons/day***

TONNAGES SENT TO WASTE-TO-ENERGY PLANTS:

1) Residential Sector

Basis: 9% of residential MSW is sent to Waste-to-energy facilities
Source: Todd, Claire. *Technical and Economic Analysis of NYC Recycling System*. New York: Columbia University. 2002. 8

Calculations:

$$4,,231{,}262\ \ \frac{tons\ \ residential\ MSW}{yr} \times 0.09 = 380{,}813\ \frac{tons\ \ WTE - bound\ residential\ MSW}{yr}$$

Result:
Annual Tonnage of NYC Residential MSW Sent to WTE Facilities: ***0.38 million tons/yr***

Daily Tonnage of NYC Residential MSW Sent to WTE Facilities:***1,043 tons/day***

2) Commercial Sector

Basis:

a) 0.55 million tons of total NYC MSW sent to Waste-to-energy facilities (Source: Themelis)

b) 0.38 million tons of WTE-bound waste comes from residential sector (calculated)

Calculations:

$$0.55\ \frac{million\ tons\ \ of\ total\ \ WTE-bound\ NYC\ MSW}{yr} - \ 0.38\ \frac{million\ tons\ \ of\ WTE-bound\ residential\ MSW}{yr}$$

$$= 0.17\ million\ \frac{tons\ \ WTE-bound\ commercial\ MSW}{yr}$$

Result:

Annual Tonnage of NYC Commercial MSW Sent to WTE Facilities: ***0.17 million tons/yr***

Daily Tonnage of NYC Commercial MSW Sent to WTE Facilities: ***464 tons/day***

3) NYC: Net Waste-to-Energy Bound MSW

Basis: 0.55 million tons of total NYC MSW is sent to Waste-to-energy facilities annually
Source: Themelis

Result:

Annual Net Tonnage of NYC MSW Sent to Waste-to-Energy Facilities in 2010***: 0.55 million tons/yr***

Daily Net Tonnage of NYC MSW Sent to Waste-to-Energy Facilities in 2010: ***1,507 tons/day***

TONNAGES LANDFILLED:

1) Residential Sector

Basis:

Net Annual Residential Generation Tonnage: 4,231,262 tons
Net Annual Recycled Tonnage: 587,940 tons
Net Annual WTE-Bound Residential MSW Tonnage: 380,813 tons

Calculations:

$$4{,}231{,}262\ \frac{tons\ residental\ MSW}{yr} - 587{,}940\ \frac{tons\ recycled}{yr} - \ 380{,}813\ \frac{tons\ \ WTE-bound}{yr}$$

$$= 3{,}262{,}508\ \frac{tons\ landfilled}{yr}$$

Results:

Annual Tonnage of NYC Residential MSW Landfilled in 2010: **3.26** ***million tons/yr***

Daily Tonnage of NYC Residential MSW Landfilled in 2010: ***8,938 tons/day***

2) <u>Commercial Sector</u>

Basis:
Net Annual Commercial Generation Tonnage: 3,214,000 tons
Net Annual Recycled Tonnage: 858,000 tons
Net Annual WTE-Bound Commercial MSW Tonnage: 169,186 tons

Calculations:

$$3{,}214{,}000\ \frac{tons\ commercial\ MSW}{yr} - 858{,}000\ \frac{tons\ recycled}{yr} - 169{,}186\ \frac{tons\ \ WTE - bound}{yr} = 2{,}186{,}814\ \frac{tons\ landfilled}{yr}$$

Results:
Annual Tonnage of NYC Commercial MSW Landfilled in 2010: **2.19 *million tons/yr***

Daily Tonnage of NYC Commercial MSW Landfilled in 2010: ***5,991 tons/day***

3) <u>NYC: Net Landfilled MSW</u>

Basis:
Net Annual Landfilled Residential MSW: 3,262,508 tons/yr
Net Annual Landfilled Commercial MSW: 2,186,814 tons/yr

Calculations:

$$3{,}262{,}508\ \frac{tons\ landfilled\ residental\ MSW}{yr} + 2{,}186{,}814\ \frac{tons\ landfilled\ commercial\ MSW}{yr} = 5{,}449{,}323\ \frac{tons\ landfilled\ MSW}{yr}$$

Result:
Annual Net Tonnage of NYC MSW Landfilled in 2010: ***5.45 million tons/yr***

Daily Net Tonnage of NYC MSW Landfilled in 2010: ***14,930 tons/day***

E. MUNICIPAL PLASTIC WASTE GENERATION IN NYC (2010)

1)Residential Sector:

Basis: 13.94% of residential MSW is plastic
Source : RW Beck. *Results Highlights: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007.

Calculations:

$$4{,}231{,}262.5 \ \frac{tons\ residential\ MSW}{yr} \times 0.1394 = 589{,}838 \ \frac{tons\ of\ plastic\ in\ residential\ MSW}{yr}$$

Result:
Annual Tonnage of Plastic in NYC Residential MSW in 2010: ***589,837 tons/yr***

Daily Tonnage of Plastic in NYC Residential MSW in 2010: **1,616 *tons/day***

2) Commercial Sector:

Basis: 5% of commercial MSW is plastic
Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.

Calculations:

$$3{,}214{,}000 \ \frac{tons\ commercial\ MSW}{yr} \times 0.05 = 160{,}700 \ \frac{tons\ of\ plastic\ in\ commercial\ MSW}{yr}$$

Result:
Annual Tonnage of Plastic in NYC Commercial MSW in 2010: ***160,700 tons/yr***

Daily Tonnage of Plastic in NYC Commercial MSW in 2010: ***440 tons/day***

3)NYC: Net Generation

Basis:
Residential Plastic Waste Generation: 589,837 tons/yr
Commercial Plastic Waste Generation: 160,700 tons/yr

Calculations:

$$589{,}837 \ \frac{tons\ residental\ plastic\ waste}{yr} + \ 160{,}700 \ \frac{tons\ commercial\ plastic\ waste}{yr} = 750{,}538 \ \frac{tons\ plastic\ MSW}{yr}$$

Result:
Net Annual Municipal Plastic Waste Generation by NYC in 2010: ***750,538 tons/yr***

Net Daily Municipal Plastic Waste Generation by NYC in 2010: ***2,056 tons/day***

F. COMPOSITION OF NYC'S MUNICIPAL PLASTIC WASTE

1) Residential Sector:

Basis: 589,837 tons of residential plastic waste generated in 2010
Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67. See table below.

material subgroup	material category	annual percent in the waste stream			
		Refuse	MGP	Paper recycling	WASTE
#1 PET Bottles	PET Bottles	0.90%	6.46%	0.07%	1.21%
# 2 HDPE Bottles	HDPE Bottles: Natural	0.28%	3.15%	0.01%	0.46%
	HDPE Bottles: Colored	0.30%	3.27%	0.01%	0.48%
#1-#2 Tubs/Trays/Other Containers	#1 PET tubs/trays	0.00%	0.02%	0.00%	0.01%
	#2 HDPE tubs/trays	0.05%	0.21%	0.00%	0.05%
#3-#7 Bottles	#3 PVC Bottles	0.01%	0.04%	0.00%	0.01%
	#4 LDPE Bottles	0.01%	0.01%	0.00%	0.01%
	#5 PP Bottles	0.01%	0.10%	0.00%	0.02%
	#7 Other Bottles	0.07%	0.20%	0.00%	0.07%
#3-7 Tubs/Trays/Other Containers	#3 PVC tubs/trays	0.00%	0.01%	0.00%	0.00%
	#4 LDPE tubs/trays	0.01%	0.01%	0.00%	0.00%
	#5 PP tubs/trays	0.17%	0.42%	0.00%	0.17%
	#7 Other tubs/trays	0.04%	0.06%	0.00%	0.04%
Other Rigid Containers/Packaging	Soda Crates and Bottle Carriers	0.01%	0.07%	0.00%	0.01%
	Rigid PS Containers/Packaging	0.27%	0.28%	0.01%	0.24%
	Expanded PS Containers/Packaging	0.64%	0.10%	0.04%	0.54%
	Other Rigid Containers/Packaging	0.79%	1.34%	0.04%	0.75%
Film	Plastic Bags	3.22%	0.94%	0.23%	2.73%
	Other Film	5.44%	3.09%	0.71%	4.76%
Other Plastic Products	Single Use Plastic	0.60%	0.22%	0.02%	0.51%
	Other Plastics Materials	1.92%	3.54%	0.20%	1.85%
	Other PVC	0.02%	0.04%	0.00%	0.02%
TOTAL PLASTICS IN 22 CATEGORIES		**14.74%**	**23.54%**	**1.35%**	**13.92%**

Figure 21: Product composition of NYC residential plastic waste
Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

Calculations:
Based on the net tonnage of plastic waste generated by the residential sector and the percent composition of residential waste provided in Figure 21 (last column), the plastic product tonnages in the residential plastic stream were determined.

Result:

Table 25: Tonnages of plastic products in NYC residential plastic waste

Plastic Products	**Tons**
#1-PET bottles	51198
#2-HDPE bottles and jugs	39774
#3-7 bottles and jugs	4654
#1-7 tubs and trays	11424
Rigid containers and packaging	65161
Film	316922
Miscellaneous	100704
TOTAL	**589838**

2) <u>Commercial Sector:</u>

Basis: 3,214,000 tons of commercial MSW generated in 2010
Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.See table below.

Table 26: Plastic composition of commercial MSW

Material Category	**% of Commercial MSW**	**Examples of plastic items**
Films and bags	2.9%	Plastic wrap, refuse bags
Rigid containers	0.5%	Milk and beverage containers
Miscellaneous	1.6%	Fast food packaging

Result:

Table 27: Plastic product tonnages in commercial MSW

Material Category	% of Commercial MSW	Tons
Films and bags	2.9	93206
Rigid containers	0.5	16070
Miscellaneous	1.6	51424
TOTAL	**5**	**160700**

3) NYC Municipal Plastic Waste: Overall Composition

Result:

Table 28: Total plastic product tonnages in NYC MSW

Plastic Products	% of Total Plastic Waste	Tonnages
#1-PET bottles	6.8	51198
#2-HDPE bottles and jugs*	7.4	55844
#3-7 bottles and jugs	0.6	4654
#1-7 tubs and trays	1.5	11424
Rigid containers and packaging	8.7	65161
Film	54.6	410128
Miscellaneous	20.3	152128
TOTAL	**100.0**	**750538**

*It was assumed that the commercial rigid containers were #2-HDPE bottles and jugs

G. RECYCLABLE AND NON-RECYCLABLE DESIGNATED PLASTICS IN NYC MUNICIPAL PLASTIC WASTE

1) Residential Sector:

Basis:
a) 589,837 tons of residential plastic waste generated in 2010
b) Only #1-#7 bottles and jugs are recyclable designated

Result:

Table 29: Tonnages of recyclable and non-recyclable designated plastics in residential MSW

	Tonnage
Recyclable Designated Plastics	95627
Non-Recyclable Designated Plastics	494211
TOTAL	589838

2) Commercial Sector:

Basis: Assumed that only the plastic rigid containers of commercial MSW were recyclable designated.

Result:

Table 30: Tonnages of recyclable and non-recyclable designated plastics in commercial MSW

	Tonnage
Recyclable Designated Plastics	16070
Non-Recyclable Designated Plastics	144630
TOTAL	160700

3) NYC: Overall Composition

Result:

Table 31: Tonnages of recyclable and non-recyclable designated plastic in NYC MSW

	Tonnage
Recyclable Designated Plastics	111697
Non-Recyclable Designated Plastics	638841
TOTAL	750538

H. FATE OF NYC MUNICIPAL PLASTIC WASTE (2010)

TONNAGES RECYCLED:

1) Residential Sector

i. **Metals, Glass, and Plastic Stream (Collected)**

Basis: 23.58% of residential MGP is plastic waste
Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

Calculations:

$$271{,}889\ \frac{tons\ residential\ MGP}{yr} \times 0.2358 = 64{,}111\ \frac{tons\ of\ plastic\ in\ residential\ MGP}{yr}$$

Result:
Annual Tonnage of Plastic in NYC Residential MGP Collected in 2010: ***64,111 tons/yr***

Daily Tonnage of Plastic in NYC Residential MGP Collected in 2010: ***176 tons/day***

ii. **Paper Stream (Collected)**

Basis: 1.34% of residential paper recycling is plastic
Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

Calculations:

$$390{,}623\ \frac{tons\ residential\ paper\ recycling}{yr} \times 0.0134 = 5{,}234\ \frac{tons\ of\ plastic\ in\ residential\ paper\ recycling}{yr}$$

Result:
Annual Tonnage of Plastic in NYC Residential Paper Recycling Collected in 2010: ***5,234 tons/yr***

Daily Tonnage of Plastic in NYC Residential Paper Recycling Collected in 2010: **14** ***tons/day***

iii. **Residue in Metals, Glass, & Plastic and Paper Recycling Streams**

- **MGP Stream**

  Basis: 10.35% of residential MGP is non-recyclable designated plastic residue
  Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

Calculations:

$$271{,}888.5\ \frac{tons\ residential\ MGP}{yr} \times 0.1035 = 28{,}140.45975\ \frac{tons\ of\ plastic\ residue\ in\ residential\ MGP}{yr}$$

Result:
Annual Tonnage of Plastic Residue in NYC Residential MGP in 2010: ***28,140 tons/yr***

Daily Tonnage of Plastic Residue in NYC Residential MGP in 2010: ***77 tons/day***

- **<u>Paper Stream</u>**

Basis: 1.34% of residential paper recycling is plastic
Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

Calculations:
All plastic in paper recycling stream, whether it is recyclable designated or not, is residue.

Result:
Annual Tonnage of Plastic Residue in NYC Residential Paper Recycling Collected in 2010: ***5,234 tons/yr***

Daily Tonnage of Plastic Residue in NYC Residential Paper Recycling Collected in 2010: **14 *tons/day***

- **<u>Total Residue</u>**

Basis:
Net Annual Tonnage of Plastic Residue in NYC Residential MGP in 2010:
28,140 tons/yr
Net Annual Tonnage of Plastic Residue in NYC Residential Paper Recycling in 2010:
5,234 tons/yr

Calculations:

$$28{,}140\ \frac{tons\ of\ plastic\ residue\ in\ residential\ MGP}{yr} + 5{,}234\ \frac{tons\ of\ plastic\ residue\ in\ residential\ paper\ recycling}{yr} = 33{,}375\ \frac{tons\ of\ plastic\ residue\ in\ residential\ recycling}{yr}$$

Result:
Annual Net Tonnage of Plastic Residue in NYC Residential Recycling in 2010:
33,375 tons/yr

Daily Net Tonnage of Plastic Residue in NYC Residential Recycling in 2010:
91 tons/day

iv. **Total Plastics Recycled (Excludes Residue)**

Basis:
Annual Tonnage of Plastic in Collected MGP: 64,111 tons/yr
Annual Tonnage of Plastic in Collected Paper Recycling: 5,234 tons/yr
Annual Net Tonnage of Plastic Residue: 33,375 tons/yr

Calculations:

$$64{,}111\ \frac{tons\ plastic\ in\ \ MGP\ collected}{yr} + 5{,}234\ \frac{tons\ plastic\ in\ \ paper\ recycling\ collected}{yr} - 33{,}375\ \frac{tons\ \ of\ plastic\ residue}{yr} = 35{,}971\ \frac{tons\ plastic\ recycled}{yr}$$

Result:
Annual Tonnage of NYC Residential Plastic Waste that was Recycled in 2010***: 35,971tons/yr***

Daily Tonnage of NYC Residential Plastic Waste that was Recycled in 2010***: 99 tons/day***

Residential Plastics Capture Rate : ***37.6%****

*35971 tons plastic recycled/95627 tons of recyclable designated plastics = 0.376

2) Commercial Sector

i. Total Plastic Recycled

Basis:
a) Assume that only rigid plastic containers in commercial waste are recyclable designated
b) Assume all plastic rigid containers collected for recycling in commercial waste are actually recycled

Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.

Result:
Annual Tonnage of NYC Commercial Plastic waste that was Recycled in 2010: ***16,070 tons/yr***

Daily Tonnage of NYC Commercial Plastics that was Recycled in 2010: ***44 tons/day***

3) NYC: Net Recycled Plastic Waste

Basis: Annual Tonnage of NYC Residential Recycled Plastic Waste: 35,971 tons/yr
Annual Tonnage NYC Commercial Recycled Plastic Waste: 16,070 tons/yr

Result:
Net Annual Tonnage of NYC Recycled Plastic Waste in 2010: ***52,041 tons/yr***

Net Daily Tonnage of NYC Recycled Plastic Waste in 2010: ***143 tons/day***

TONNAGES SENT TO WASTE TO ENERGY FACILITIES:

1) Residential Sector

Basis:

a) 553,867 tons of plastic residential refuse
b) Assume same percent distribution of residential plastic refuse as was applied to overall residential refuse (10.45% is WTE-bound)

Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

Calculations:

$$553{,}867\ \frac{tons\ residential\ plastic\ refuse}{yr}\ x\ 0.1045\ =\ 57{,}892\ \frac{tons\ WTE-bound\ residential\ plastic}{yr}$$

Result:

Annual Tonnage of NYC Residential WTE-Bound Plastic Waste in 2010: ***57, 892 tons/yr***

Daily Tonnage of NYC Residential WTE-Bound Plastic Waste in 2010: ***159 tons/day***

2) Commercial Sector

Basis:

a) 144,630 tons of plastic commercial refuse
b) Assume same percent distribution of commercial plastic refuse as was applied to overall commercial refuse (7.20% is WTE-bound)

Calculations:

$$144{,}630\ \frac{tons\ commercial\ plastic\ refuse}{yr}\ x\ 0.0720\ =\ 10{,}418\ \frac{tons\ WTE-bound\ commercial\ plastic}{yr}$$

Result:

Annual Tonnage of NYC Residential WTE-Bound Plastic Waste in 2010: ***10,418 tons/yr***

Daily Tonnage of NYC Residential WTE-Bound Plastic Waste in 2010: ***44 tons/day***

3) NYC: Net WTE-Bound Plastic Waste

Basis: Annual Tonnage of NYC WTE-Bound Residential Plastic Waste: 57,892 tons/yr
Annual Tonnage NYC WTE-Bound Commercial Plastic Waste: 10,418 tons/yr

Result:

Net Annual Tonnage of NYC WTE-Bound Plastic Waste in 2010: ***68,311 tons/yr***

Net Daily Tonnage of NYC WTE-Bound Plastic Waste in 2010: ***187 tons/day***

TONNAGES LANDFILLED:

1) **Residential Sector**

Basis:
Annual Residential Plastic Generation Tonnage: 589,838 tons
Annual Residential Recycled Plastics Tonnage: 35,971 tons
Annual Residential WTE-Bound Plastics Tonnage: 57,892 tons

Calculations:

$$589{,}838\ \frac{tons\ residental\ plastic\ waste}{yr} - 35{,}971\ \frac{tons\ recycled}{yr} - 57{,}892\ \frac{tons\ \ WTE - bound}{yr}$$
$$= 495{,}975\ \frac{tons\ landfilled}{yr}$$

Results:
Annual Tonnage of NYC Residential Landfilled Plastics in 2010: ***495,975 tons/yr***

Daily Tonnage of NYC Residential Landfilled Plastics in 2010: ***1,359 tons/day***

2) **Commercial Sector**

Basis:
Annual Commercial Plastics Generation Tonnage: 160,700 tons
Annual Commercial Recycled Plastics Tonnage: 16,070 tons
Annual Commercial WTE-Bound Plastics Tonnage: 10,418 tons

Calculations:

$$160{,}700\ \frac{tons\ commercial\ plastic\ waste}{yr} - 16{,}070\ \frac{tons\ recycled}{yr} - 10{,}418\ \frac{tons\ \ WTE - bound}{yr}$$
$$= 134{,}212\ \frac{tons\ landfilled}{yr}$$

Results:
Annual Tonnage of NYC Commercial Landfilled Plastics in 2010: ***134, 212 tons/yr***

Daily Tonnage of NYC Commercial Landfilled Plastics in 2010: ***368 tons/day***

3) NYC: Net Landfilled Plastic Waste

Basis:
Annual NYC Residential Landfilled Plastics Tonnage: 495,975 tons/yr
Annual NYC Commercial Landfilled Plastics Tonnage: 134,212 tons/yr

Calculations:

$$495{,}975\ \frac{tons\ landfilled\ residental\ plastic}{yr} + 134{,}212\ \frac{tons\ landfilled\ commercial\ plastic}{yr} = 630{,}187\ \frac{total\ tons\ landfilled\ plastic}{yr}$$

Result:
Total Annual Tonnage of NYC Plastic Waste that was Landfilled in 2010: ***630,187 tons/yr***

Total Daily Tonnage of NYC Plastic Waste that was Landfilled in 2010: ***1,727 tons/day***

I. COMPOSITION OF NYC MUNICIPAL PLASTIC REFUSE (2010)

1) Residential Sector

Basis:
Annual Tonnage of MSW Generated by NYC Residential Sector in 2010: 4,231,262 tons/yr
Annual Tonnage of NYC Residential MGP Collected in 2010: 271, 889 tons/yr
Annual Tonnage of NYC Residential Paper Recycling Collected in 2010: 390,623 tons/yr
Annual Tonnage of NYC Residential Refuse in 2010: 3,568,751 tons//yr

Source: RW Beck. *Focus on Residential Plastics: 2004-2005 NYC Residential and Street Basket Waste Characterization Study*. 4 vols. 2007. 67.

material subgroup	material category	annual percent in the waste stream			
		Refuse	MGP	Paper recycling	WASTE
#1 PET Bottles	PET Bottles	0.90%	6.46%	0.07%	1.21%
# 2 HDPE Bottles	HDPE Bottles: Natural	0.28%	3.15%	0.01%	0.46%
	HDPE Bottles: Colored	0.30%	3.27%	0.01%	0.48%
#1-#2 Tubs/Trays/Other Containers	#1 PET tubs/trays	0.00%	0.02%	0.00%	0.01%
	#2 HDPE tubs/trays	0.05%	0.21%	0.00%	0.05%
#3-#7 Bottles	#3 PVC Bottles	0.01%	0.04%	0.00%	0.01%
	#4 LDPE Bottles	0.01%	0.01%	0.00%	0.01%
	#5 PP Bottles	0.01%	0.10%	0.00%	0.02%
	#7 Other Bottles	0.07%	0.20%	0.00%	0.07%
#3-7 Tubs/Trays/Other Containers	#3 PVC tubs/trays	0.00%	0.01%	0.00%	0.00%
	#4 LDPE tubs/trays	0.01%	0.01%	0.00%	0.00%
	#5 PP tubs/trays	0.17%	0.42%	0.00%	0.17%
	#7 Other tubs/trays	0.04%	0.06%	0.00%	0.04%
Other Rigid Containers/Packaging	Soda Crates and Bottle Carriers	0.01%	0.07%	0.00%	0.01%
	Rigid PS Containers/Packaging	0.27%	0.28%	0.01%	0.24%
	Expanded PS Containers/Packaging	0.64%	0.10%	0.04%	0.54%
	Other Rigid Containers/Packaging	0.79%	1.34%	0.04%	0.75%
Film	Plastic Bags	3.22%	0.94%	0.23%	2.73%
	Other Film	5.44%	3.09%	0.71%	4.76%
Other Plastic Products	Single Use Plastic	0.60%	0.22%	0.02%	0.51%
	Other Plastics Materials	1.92%	3.54%	0.20%	1.85%
	Other PVC	0.02%	0.04%	0.00%	0.02%
TOTAL PLASTICS IN 22 CATEGORIES		**14.74%**	**23.54%**	**1.35%**	**13.92%**

Figure 22: Product composition of NYC residential plastic waste
Source: DSNY Bureau of Waste Prevention, Reuse, and Recycling

Calculations:
Based on the net tonnage of plastic waste generated by the residential sector and the percent composition of residential waste provided in Figure 22, the plastic product tonnages in the residential plastic stream were determined.

Non-recycled plastics include all plastics in the refuse and paper stream and all non-recyclable designated plastics in the MGP stream.

Results:

Table 32: Tonnages of plastics in NYC residential refuse (includes residue from recycling streams)

Plastic Product Type	Plastics in Collected Refuse (tons)	Plastics in Collected Paper Recycling (tons)	Non-recyclable Plastics in Collected MGP Recycling (tons)
#1 bottles	32119	273	0
#2 bottles	20699	78	0
#3-7 bottles	3569	0	0
#1-7 tubs and trays	9636	0	1985
Rigid containers and packaging	61026	352	4867
Film	309054	3672	10957
Miscellaneous	90646	859	10332
TOTAL	**526748**	**5234**	**28140**

2) Commercial Sector

Basis:
Annual Tonnage of MSW Generated by NYC Commercial Sector in 2010: 3,214,000 tons/yr
Source: New York State. Dept. of Sanitation. *New York City Waste Composition Study (1989-1990), Commercial Sector, Volume IV*. 4-5.See table below.

Table 33: Plastic composition of commercial MSW

Material Category	% of Commercial MSW	Examples of plastic items
Films and bags	2.9%	Plastic wrap, refuse bags
Rigid containers	0.5%	Milk and beverage containers
Miscellaneous	1.6%	Fast food packaging

Calculations: It was assumed that only films and bags and miscellaneous items were disposed of in the commercial refuse stream.

Results:

Material Category	% of Commercial MSW	Tonnage
Films and bags	2.9	93206
Miscellaneous	1.6	51424
TOTAL	**4.5**	**144630**

3) NYC: Net Plastic Tonnages in Refuse

Results:

Plastic Product Type	% of Total Plastic Refuse	Tonnage
#1 bottles	4.6	32392
#2 bottles	2.9	20777
#3-7 bottles	0.5	3569
#1-7 tubs and trays	1.6	11620
Rigid containers and packaging	9.4	66244
Film	59.2	416889
Miscellaneous	21.7	153261
TOTAL	**100.0**	**704752**

APPENDIX II: Summary Report of Sims MRF Visit

REPORT FROM THE VISIT OF THE SIMS MATERIAL RECOVERY FACILITY

JERSEY CITY, NJ, JANUARY 23RD, 2012

By Demetra Tsiamis & Ljupka Arsova

Introduction

On Monday, Jan. 23rd 2012, two research associates of Columbia University's Earth Engineering Center, Ljupka Arsova and Demetra Tsiamis, visited the SIMS material recovery facility (MRF) located in Jersey City, NJ. Ms. Arsova and Ms. Tsiamis met with Tom Outerbridge, the general manager of the SIMS plant, Maite Quinn, the business development and marketing manager, and Eadaoin Quinn, who is involved in the municipal recycling at SIMS. After the meeting, SIMS representatives took Ms. Arsova and Ms. Tsiamis on a tour of the MRF of the comingled stream of recyclables at the SIMS recycling site.
The purpose of this visit was to learn more about the non recyclable plastic stream they currently have on the MRF and to explore the possibility to include the flexible packaging waste in the comingled recyclables coupled with processing of these materials on pyrolysis plants such as Climax Global Energy (CGE) and Agilyx.

Description of the plant

SIMS recycling processes comingled recyclables from the curbside collection of the five borrows of New York City. This waste is transported by trucks from Staten Island and Lower Manhattan. The waste collected from The Bronx, Queens and Brooklyn undergoes separation on the local transfer stations and only plastic fraction is transported to this MRF by boats.

Comingled waste goes first through a trommel screen with two sizes of sieves, 2 inches followed by 8 inches. The fraction separated through the 2 inches sieves is the glass fraction and all packaging containers are separated through the 8 inches sieve. The material that is left from the trommel is oversize items including film plastic and some paper. This fraction goes through manual sorting station but it is not efficient and a lot of recyclable containers end up in it. They are planning to change the manual sorting with automatic that is more efficient.

The fraction that gets separated through the 8 inches sieve still contains plastic film and has to go through ballistic separator to separate 2D from 3D items. The containers get separated as 3D items and go through magnetic separator to separate the metal containers and after that through a series of optical separators that separate PET, natural and colored HDPE and aseptic cartons.

As output of this facility they have the following fractions:

- PET

- Natural HDPE

- colored HDPE

- metal

- glass

- aseptic cartons

- mixed plastic (3-7)

- film plastic and paper

All the fractions except the last one (film plastic and paper) are sold for recycling. The film plastic and paper refuse is comprised of 80:20 (or sometimes, 70:30) plastic film vs. paper. Mr. Outerbridge estimated that the SIMS plant receives approximately 19,000 tons of waste/month (approx. 633 tons/day). The SIMS plant process around 11,000 tons of comingled recyclables and the remaining 8,000 tons are the plastic fraction from the comingled waste preprocessed on the transfer stations in Queens, the Bronx and Brooklyn. At the time, Mr. Outerbridge could not give a number for the NRP residue generated by the MRF that is sent to landfills. The rough estimation is that 1900 t/month are sent to landfills. However, he did give the following rough breakdown of the input stream composition: 17- 20 wt% metal, 45-50% glass (of which 5% is also small plastic waste), 10% plastics, 10-12% residue waste (we will need to confirm this composition breakdown since the current breakdown doesn't add up to 100%). Due to the large scale of waste that SIMS handles already, Mr. Outerbridge was opposed to adding non-recyclable designated plastics to the curbside program.

Discussion

Mr. Outerbridge was familiar with the pyrolysis technologies and had even sent some plastic waste from the SIMs MRF to Climax Global Energy few years ago. Mr. Outerbridge explained the setbacks with the plastic-converting technologies from the standpoint of the SIMS MRF. The main issue is that the economic model of the plastics-converting technologies currently doesn't seem viable because the market for plastics is constantly changing and consequently the economic model still doesn't seem to compete with the landfill disposal cost. Also they are constantly looking for markets to sell more recyclables and in order to commit to a plastic converting technology they have to be offered a price competitive to the prices of the recyclables. Another concern with the economics of these technologies is whether additional costs would come from environmental regulatory standards not being met by these new technologies.

SIMS recycling already has enough material to build a full scale pyrolysis plant but is not convinced regarding the economics of these plants.

SIMS is currently developing a new MRF plant in Brooklyn that will have additional technology for film plastic separation on the front end. This plant is developed by RRT Design and Construction.

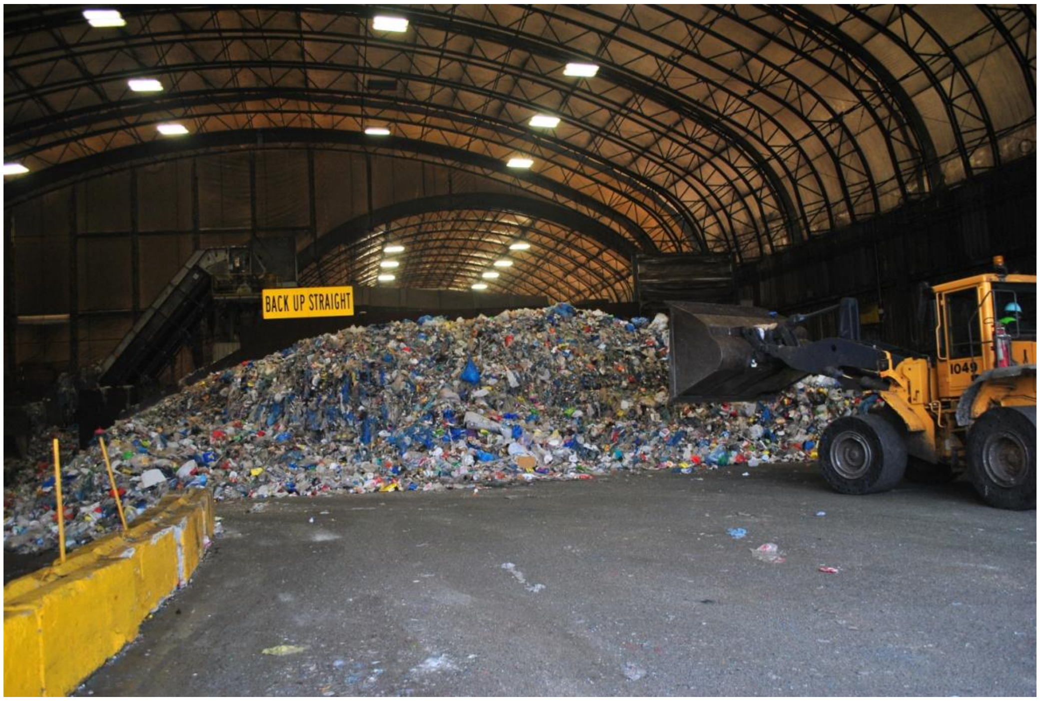
Mr. Outerbridge said that they prefer not to have any more NRP on the plant, especially not film plastic waste, because it is problematic to handle. The biggest issue with handling film plastic waste as recyclables is the non-uniformity of the material and the fact that some fractions have high market value and some have no value at all.

The following photos were taken by the Earth Engineering Center representatives during the tour:

Plastic Waste from Bronx, Queens, and Brooklyn

Waste to be Further Separated at SIMS or Sent to 3rd Party MRFS

Film plastic and paper leftover fraction



Comingled recyclable waste from Staten Island and Lower Manhattan

Unit separating the film plastic from the containers

Separation lines for colored and natural HDPE

Balling of the separated waste streams

PET separation line

Manual sorting cabin

Separation stations for metal cans and mixed plastic

Aseptic cartons separation line

Manually Separated Plastic Film Residue

End Product: Resin 1 and 2 Bottles and Jugs

End Product: Resin 3-7 with some Resin 1 and 2

Plastic, Glass, and Metal Respectively to be Landfilled

Film plastic and paper waste to be landfilled