University of British Columbia

APSC 262

May 27, 2015

Contents

List of Illustrations

Introduction

The main purpose of this project is to perform a triple-bottom-line assessment of the different types of plastics used in common food handling at UBC. This project is important because it provides UBC procurement with a triple bottom line verified option for a more sustainable plastic to be used for food-safe containers. In addition, as UBC tries to deviate from land-fill destined goods to recyclable and compostable goods; this project delivers on providing a plastic which is the most recyclable and commonly accepted by Vancouver recycling centers with an emphasis on the sustainability of the recycling process. By performing this investigation we can further understand the social, economic, and environmental cost of these plastics in order to minimize their impact and select the most sustainable one. The plastics we selected for our analysis were polyvinyl chloride, polyethylene terephthalate, high density polyethylene, polystyrene, polypropylene, and low density polyethylene. To begin, we review the manufacturing and the end of life processes of each plastic and discuss their social, economic, and environmental implications. Next we compare the plastics based on triple bottom line indicators such as recyclability, manufacturing cost, manufacturing inputs, and health impacts. Finally, we present our recommendation for which plastic UBC procurement should implement further on campus.

Polyvinyl Chloride

PVC is a highly versatile polymer material that is used for a wide range of purposes. In western societies, approximately 60% of PVC produced is utilized in construction applications. In the food packaging industry its major applications are as a rigid film (60%), flexible film (11%), and closures (3) %. These come in the form of blisters and presentation trays, cling film, bottle sleeving and adhesive tape [5].

PVC is an amorphous polymer structure with carbon backbone and polar chlorine substituents. The chlorine substituents give PVC high mechanical stability, fire retarding properties, durability, and oil/chemical resistance. While the high melt viscosity of PVC limits the size of parts that can be injection molded, it's molten viscoelastic behavior is stable relatively independent of temperature giving rise to complex shapes. The exterior surface of PVC products is excellent and can be given a wide variety of surface treatments. Finally PVC's polar and amorphous characteristics mean it mixes excellently with additives, plasticizers, modifiers, and various other additives that can be used to tune its performance [5].

Manufacturing

The manufacturing process for PVC follows 4 main stages; PVC Resin Production, Commercial PVC Formulation, PVC Molding, and Painting. The individual processes involved in each of these stages are explored below and the environmental impact of those processes is quantified in Table 1[3].

PVC Resin Production

During this stage, PVC is taken from its raw materials, refined, and polymerized into PVC resin pellets. This stage can be broken down further into 5 processes:

- The production of petroleum feedstock
- The production of ethylene from petroleum feedstock
- The production of chlorine by the electrolysis of sodium chloride
- The production of vinyl chloride monomer
- The polymerization of the monomer into PVC

The PVC Resin Production stage constitutes a significant amount of the environmental impact of the process. This reinforces supports for high PVC recycling rates both economically and environmentally as replacing virgin resin with a recyclate cuts a high number of process inputs and outputs [3].

Commercial PVC Formulation

During the Commercial PVC Formulation stage, the generic PVC pellets are mixed with additives to refine end product properties. The stage is composed of 7 processes:

- Production of PVC resin by suspension polymerization
- Transportation of PVC resin to compounding site
- Production of various additives used in the compound
- Mixing/Compounding
- Packaging of PVC Formulation

The addition of additives to the mix is a very low energy consumption step, however the total waste created in the production and addition of additives is proportionally higher than that produced in pure PVC production. The addition of modifiers, plasticizers, and other such additives should therefore be minimized with the exception of additives that increase the recyclability of PVC [3].

PVC Molding

PVC Molding is the third stage of the process where the PVC arrives at its end shape. The stage is simply composed of:

- Transportation of Commercial Compound to designated molding vendor
- Molding of part

Molding is contributes significantly to total waste output, air emissions, and total primary energy inputs. The significant quantities of total waste and emissions produced are a reflection of the high-energy inputs required for the molding process and are therefore a function of the process energy source [3].

	Column Number		1	2	3
	Manufacturing Step		100% PVC Resin	Commercial Grade PVC with molding	PVC Molding
Inputs	**Raw Materials**	Units			
	Crude Oil (in ground)	kg	0.81	0.94	0.016
	Coal (in ground)	kg	0.34	0.81	0.26
	Lignite (in ground)	kg		0.049	0.031
	Natural Gas (in ground)	kg	1.0	1.2	0.027
	Uranium (in ground)	kg		6.7E-06	5.3E-06
	Limestone	kg	0.026	0.18	
	Sand	kg	0.0017	0.0014	
	NaCl	kg	1.2	0.93	
	Clay	kg		2.9E-06	
	Bauxite	kg	0.00038	0.00034	
	Iron Ore	kg	0.00063	0.00054	
	Ilmenite Ore	kg		0.095	
	Copper Ore				
	Ferromanganese	kg		1.5E-07	
	Wood	kg		1.5E-05	
	Water (cooling)	kg	n.a.	12	
	Water (process)	l	n.a.	0.97	
	Water (unspecified use)	l	34	41	0.0088
	Water (boiler)	l	n.a.	0.60	
	Total Water	l	34	55	0.0088
Outputs	**Air Emissions**				
	Particulate Matter (a)	g	6.7	7.3	0.51
	CO2 (a)	g	2998	4692	718
	CO (a)	g	4.3	5.4	0.13
	SOx (a)	g	22	31	5.9
	NOx (a)	g	26	30	3.1
	N2O (a)	g	n.a.	0.40	0.058
	NH3 (a)	g	n.a.	0.0024	0.00017
	Cl2 (a)	g	0.0017	0.0014	
	HCl (a)	g	0.41	0.57	0.13
	CH4 (a)	g	n.a.	2.6	0.23
	Non-Methane Hydrocarbons (a)	g	n.a.	18	6.8
	Hydrocarbons (a)	g	33	27	
	VOC (a)	g		1.1	
	Total Hydrocarbons	g	33	48	7.1
	Chlorinated Organics (a)	g	0.88	0.70	
	Aldehydes (a)	g	n.a.	0.012	0.0032
	H2S (a)	g		0.0012	
	Other Organic (a)	g		0.015	0.0062
	Fluorides (a)	g		6.7E-06	4.2E-06
	HF (a)	g		2.9E-06	
	Lead				
	Metals (a)	g	0.0051	0.0043	

Table 1: Life Cycle Impact of PVC manufacturing [3].

	Manufacturing Step		100% PVC Resin	Commercial Grade PVC with molding	PVC Molding
Outputs	**Water Effluents**	**Units**			
	BOD5 (w)	g	0.14	0.20	5.1E-05
	COD (w)	g	1.9	3.5	0.00015
	Chlorides (w)	g	72	58	1.0E-05
	Chlorinated Organics (w)	g	0.0051	0.0041	
	Dissolved Organics (w)	g	2.4	1.9	
	Dissolved Solids (w)	g	0.72	2.3	0.11
	Suspended Solids (w)	g	3.4	4.3	0.0017
	Oil (w)	g	0.086	0.12	0.0022
	Hydrocarbons (w)	g		0.0012	
	Iron (Fe2+ and Fe 3+) (w)	g	n.a.	6.4	1.6E-06
	Fluorides (w)	g		0.0017	0.00081
	Metals (w)	g	0.34	0.38	
	Nitrates (w)	g		0.00054	0.00019
	Nitrogen - NH3 (w)	g		0.0043	0.00038
	Nitrogen - TKN (w)	g	0.0051	0.010	0.00038
	Nitrogen - Organic (w)	g	0.0051	0.0056	
	Ammonium Hydroxide (w)	g		0.00019	
	Sodium Ions (w)	g	8.2	8.4	0.00013
	Sulfates (w)	g	2.6	7.4	0.00017
	Phosphates (w)	g		1.0E-05	
	Methanol (w)	g		0.0077	
	Phenol (w)	g		0.00013	
	Fibers (w)	g		0.0091	
	Other organic				
	Ca (w)	g	n.a.	0.60	
	Mg (w)	g	n.a.	2.6	
	Al (w)	g	n.a.	1.4	
	Mn (w)	g	n.a.	0.38	
Outputs	**Solid Waste**				
	Waste (hazardous)	kg	0.0060	0.0051	
	Waste (landfilled PVC)	kg		0.00053	0.00053
	Waste (mineral)	kg	0.10	0.083	
	Waste (non-haz. chemicals)	kg	0.019	0.015	
	Waste (slags and ash)	kg	0.021	0.017	
	Waste (unspecified)	kg	0.0034	0.36	0.17
	Waste Recovered	kg		0.044	0.027
	Total Waste	*kg*	0.15	0.53	0.19
Energy	Total Primary Energy	MJ	111	137	12
	Primary Energy - Fuels	MJ	59	80	12
	Primary Energy - Feedstock	MJ	52	56	
	Primary Energy - Non Renewable	MJ	110	135	12
	Primary Energy - Renewable	MJ	1.4	2.5	

Table 2: Life Cycle Impact of PVC manufacturing Continued Error! Bookmark not defined.

End of Life

There are three options for the disposal of used PVC products:

- Incineration with heat recovery
- Disposal in landfill
- Closed loop recycling

These three disposal routes are compared in order to determine the base motivations and realities behind PVC recycling [2].

Landfilling

When taken to the landfill, PVC is assumed to be inert and therefore the only inventory items associated with the disposal of PVC are the final PVC product waste as well as the burdens of the transportation process [2].

Incineration Heat Recovery

This incineration option is included for completeness sake only as the majority of Municipal Waste Combustion (MWC) facilities do not accept PVC making it a non-viable option. The PVC incineration model referenced is based on the composition of PVC as well as standard MWC conditions [2].

Recycling

When PVC is recycled, a significant amount of energy is used in the transportation, molding, and grinding of scrap but it is also returned by the reduction of further virgin PVC production [2].

		Units	Landfilling	Incineration	Recycling New data
Inputs	**Raw Materials**				
	Crude Oil (in ground)	kg	0.036	0.025	-1.10
	Coal (in ground)	kg	0.0002	-0.67	-0.67
	Natural Gas (in ground)	kg	0.0001	0.004	-1.48
	Limestone	kg		1.50	-0.24
	NaCl	kg			-1.22
	Water (unspecified use)	l	0.007	-0.008	-53.40
Outputs	**Air Emissions**				
	Particulate Matter (a)	g	0.15	33.59	-8.36
	CO2 (a)	g	115	2,400	-4,695.94
	CO (a)	g	0.41	1.07	-5.65
	SOx (a)	g	0.16	-13.01	-31.38
	NOx (a)	g	1.17	-4.17	-30.86
	NH3 (a)	g	0.0007	0.0143	0.00
	Cl2 (a)	g			-0.0018
	HCl (a)	g		299.50	-0.54
	Hydrocarbons (a)	g	0.31	-13.70	-49.41
	Other Organic (a)	g	0.00	-0.02	-0.92
	Water Effluents				
	BOD5 (w)	g	0.0002	0.0002	-0.26
	COD (w)	g	0.0006	0.0007	-4.56
	Chlorides (w)	g			-74.97
	Dissolved Solids (w)	g	0.42	0.48	-1.61
	Suspended Solids (w)	g	0.0002	-0.004	-5.58
	Oil (w)	g	0.005	0.007	-0.14
	Sulfates (w)	g			-9.69
	Nitrates (w)	g		-0.0004	
	Nitrogen - TKN (w)	g			-0.01
	Sodium Ions (w)	g			-10.95
	Metals (w)	g			-0.49
	Solid Waste				
	Waste (hazardous chemicals)	kg			-0.01
	Waste (landfilled PVC)	kg	2.26	0	0.02
	Waste (slag and ash)	kg		1.73	-0.02
	Waste (others)	kg	0.00005	-0.44	-0.36
	Total waste	*kg*	*2.26*	*1.29*	*-0.37*
Energy	Total Primary Energy	MJ	42	20	-115

(shaded) Best end-of-life option

Table 3: Life Cycle Impact of PVC Disposal Options

Environmental Impact

As shown by Figure 2, the recycling process represents a significant improvement in the lifecycle outputs of PVC and in doing so makes PVC a fairly sustainable option. PVC has the longest history of recycling among plastics and it is most advanced in mechanical recycling [5].

However, with that said, these figures are based on the use of recycling infrastructure designed for PVC. It is important to also understand how PVC is recycled when mixed with other plastics in municipal recycling centers. These municipal recycling centers like Cascades are far more concerned with the recycling of PET and HDPE as PVC bottles make up only a small fraction of bottles manufactured in our society as shown in Figure 3. This introduces problems, as PVC burns at a temperature lower than the melt temperature of PET. The burning PVC damages neighboring PET and equipment disrupting the recycling process. For PVC recycling to be as effective as these tables show, it must be separated from PET, and recycled separately. Unfortunately, dedicated recycling infrastructure is expensive and relatively small volume plastics like PVC don't reach the economy of scale necessary to justify infrastructure investments. As a consequence, 98% of all PVC containers go to landfills or incinerators [5].

PVC products must be collected separately and in volumes great enough to rationalize recycling infrastructure in order to avoid becoming part of environmentally harmful incineration and landfill waste streams.

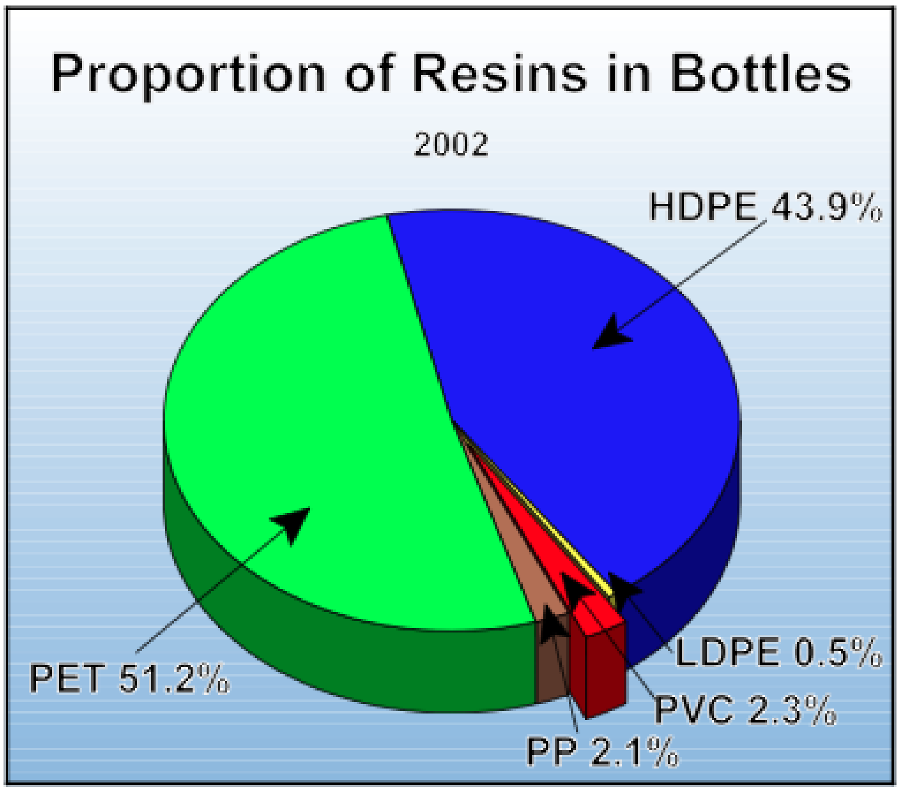

Figure 1: Proportion of Resins in Bottles

Social Impact

The production of PVC in Canada has dropped off considerably in the past 20 years. This is linked primarily to the risks inherent in the production of vinyl chloride. Vinyl chloride is carcinogenic and poses an occupational risk to PVC factory workers as well as an environmental exposure risk to the general population through contaminated air, ingestion of contaminated drinking water, and use of PVC consumer products. After the two vinyl chloride manufacturing plants in Canada shut down, the majority of PVC plants soon followed. Currently Canadian PVC demand is met through imports from the United States [6].

Economic Impact

PVC cost is mid-range among other plastics alternatives. The comparison is illustrated in Figure 4. The PVC and vinyl chloride plants in Canada have for the most part closed and been moved to china where more lax environmental and worker safety laws allow them to operate unimpeded. This has resulted in the loss of hundreds of Canadian jobs [4].

Polyethylene Terephthalate

PET is highly valued polyester because it is strong, light, cost-effective and recyclable numerous times (31% of PET products were recycled in the US and 52% were recycled in Europe in 2012). PET is incredibly popular in the food industry as it has good diffusion barrier properties that ensure food or drinks remain fresh for longer periods of time and it is FDA certified as an inert material so it is harmless if ingested, inhaled or touched.   In comparison, PET provides almost 9 times more protection against gas diffusion than does PLA and over 40 times more than HDPE.

Manufacturing

The scientific process for the manufacture of PET is described in the flow diagram below. Basically, two raw materials, ethylene glycol and terephthalic acid, are combined under high temperatures and low vacuum pressures to form long chains of a polymer. The resulting chains are then quickly cooled and cut to get PET pellets which can be liquefied later to assume a certain shape.

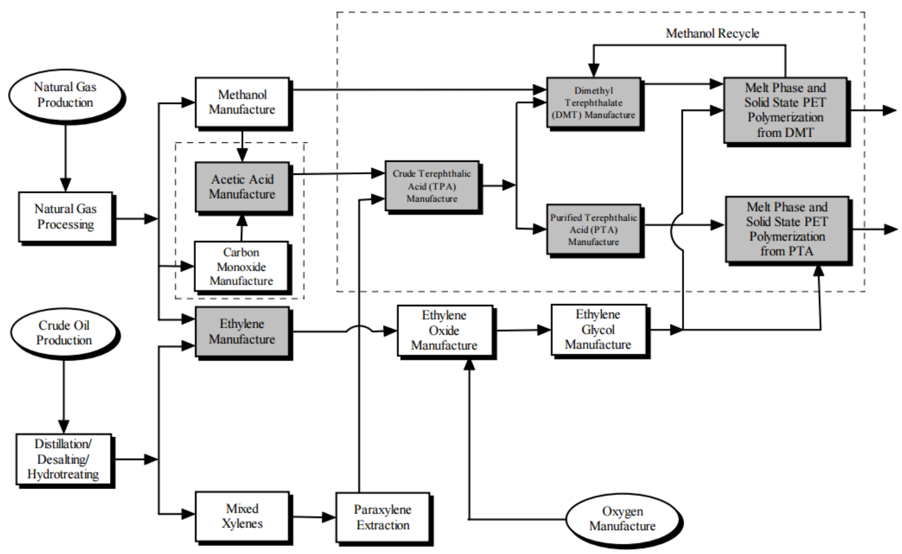

Figure 6-1. Flow diagram for the manufacture of virgin polyethylene terephthalate(PET) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted rectangle are included in an aggregated dataset.

Figure 2. Flow diagram for the manufacture of PET [11]

After the pellets are formed, there are two main methods that are used to transform the pellets into useable containers depending on the application.

The first method is called blow molding and it involves re-heating the pellets into a gooey form before blowing high pressure air into the mold cavity to inflate it. The plastic is then quickly cooled which causes the polymer chains to quickly solidify in their current orientation, leading to a very tough structure that is flexible and shatterproof. This process results in a wide but thin layered plastic container with a narrow opening, making it ideal for use as a plastic water bottle.

The second method is called thermoforming and in this process, the PET pellets are initially molten to their liquid form and formed over a mold before being left to cool slowly. This results in a plastic that is opaque, rigid and able to withstand heat from a microwave or oven. This makes it ideal for creating large containers since the size of the container, as well as the thickness can be changed as desired.

End of Life

One of the advantages of using PET is that it does not have to be incinerated, or thrown into a landfill once it has reached its end of life. It is 100% recyclable and it can be recycled an unlimited amount of times. Approximately 1.5 billion bottles are collected and recycled in the US, making it the most recyclable plastic in America [11]. Due to the high volume of PET being recycled, the US has heavily invested in this area and virtually all recycling programs in the US accept PET bottles and containers which are easily recognized by the image in Figure 2.

If the PET container or bottle is contaminated and cannot be cleaned safely to return it to a sterile state, then it can be safely and efficiently thermal recycled. This means that it can be burned as an energy source.

Figure 3. Symbol denoting PET containers or bottles [11]

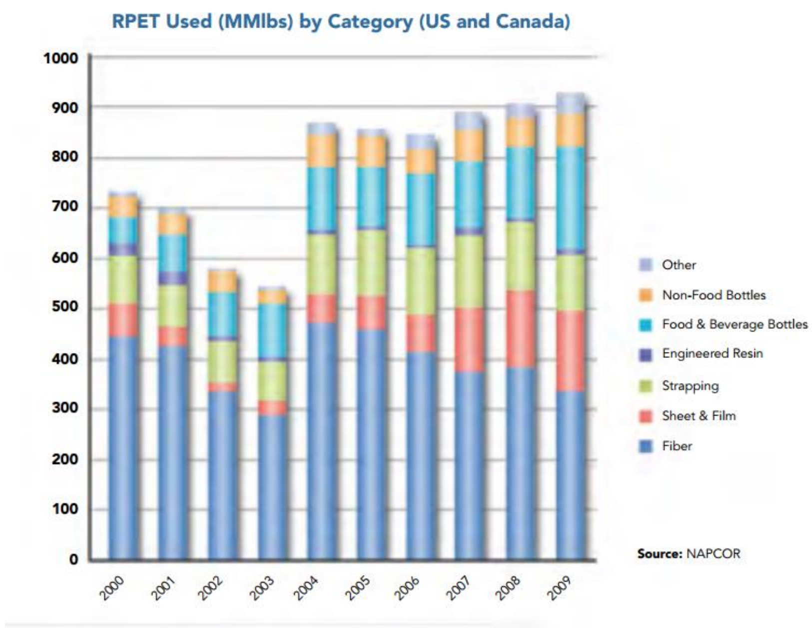

Figure 4. Amount of Recycled PET used (in MMlbs) separated by category [9]

Recycling

One of the reasons why PET is so popular is because of how economically efficient and environmentally friendly PET is to recycle. The recycling process uses very little energy and very little greenhouse emissions. Life Cycle Inventory study shows that for every pound of recycled PET used, energy use is reduced by 84% and greenhouse gas emission by 71%. Figure 4 shows the value of the US PET recycling assets. Since about 2003, the US has exceeded its capacity of recycled bottles made from PET and its reclamation assets is expected to exceed $300 million over the next few years.

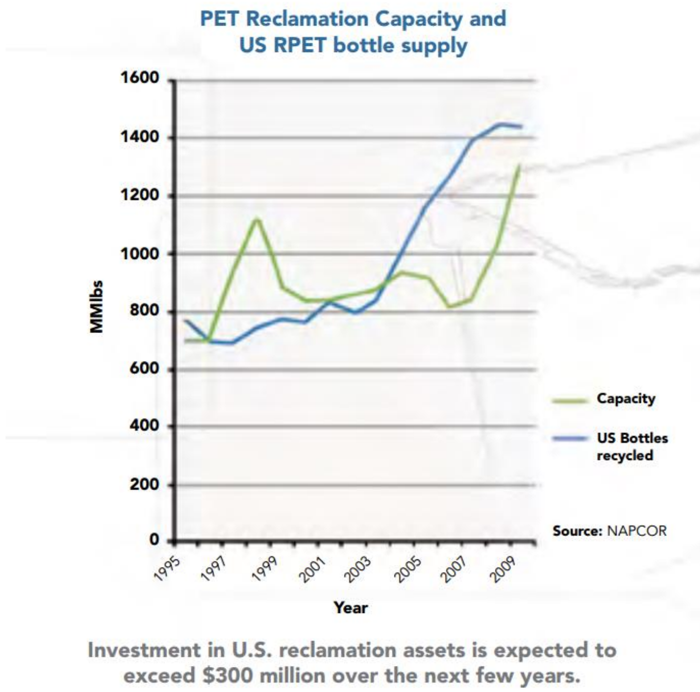

Figure 5. PET Reclamation Capacity and US RPET bottle supply [9]

Table 3-1. Energy and Water Use for Recycled PET Resin
(million Btu of energy and gallons of water per 1,000 pounds of resin)

	Process	Transport	EMR	TOTAL	% of Total	Water Use
PET - Cut-off, weight-based collection						
Collection (weight-based)	0.026	0.51	0	0.53	11%	0
Sorting/Separation	0.10	0.045	0	0.15	3%	0
Reclaimer Processing to Flake	3.77	0.44	0	4.21	86%	47.3
Total for PET Flake	3.90	1.00	0	4.89		47.3
Percent by Category	80%	20%	0%			
Conversion of Flake to Pellet	2.33	0	0	2.33		0
Total for PET Pellet	6.22	1.00	0	7.22		47.3
Percent by Category	86%	14%	0%			
PET - Cut-off, volume-based collection (50% compaction)						
Collection (50% compaction)	0.026	0.72	0	0.74	15%	0
Sorting/Separation	0.10	0.045	0	0.15	3%	0
Reclaimer Processing to Flake	3.77	0.44	0	4.21	83%	47.3
Total for PET Flake	3.90	1.21	0	5.10		47.3
Percent by Category	76%	24%	0%			
Conversion of Flake to Pellet	2.33	0	0	2.33		0
Total for PET Pellet	6.22	1.21	0	7.43		47.3
Percent by Category	84%	16%	0%			
PET - Open-loop, weight-based collection						
Allocated Virgin Resin Production (2010)	7.45	0.33	8.18	16.0	87%	0
Collection (weight-based)	0.013	0.25	0	0.27	1%	0
Sorting/Separation	0.051	0.022	0	0.073	0.4%	0
Reclaimer Processing to Flake	1.88	0.22	0	2.11	11%	23.7
Total for PET Flake	9.40	0.83	8.18	18.4		23.7
Percent by Category	51%	4%	44%			
Conversion of Flake to Pellet	1.16	0	0	1.16		0
Total for PET Pellet	10.56	0.83	8.18	19.6		23.7
Percent by Category	54%	4%	42%			
PET - Open-loop, volume-based collection (50% compaction)						
Allocated Virgin Resin Production (2010)	7.45	0.33	8.18	16.0	86%	0
Collection (50% compaction)	0.013	0.36	0	0.37	2%	0
Sorting/Separation	0.051	0.022	0	0.073	0.4%	0
Reclaimer Processing to Pellet	1.88	0.22	0	2.11	11%	23.7
Total for PET Flake	9.40	0.93	8.18	18.5		23.7
Percent by Category	51%	5%	44%			
Conversion of Flake to Pellet	1.16	0	0	1.16		0
Total for PET Pellet	10.56	0.93	8.18	19.7		23.7
Percent by Category	54%	5%	42%			

	Total Energy	% of Virgin
Virgin PET production burdens (2010 resin data)	31.9	
Recycled PET flake		
PET - Cut-off, weight-based collection	4.89	15%
PET - Cut-off, volume-based collection (50% compaction)	5.10	16%
PET - Open-loop, weight-based collection	18.4	58%
PET - Open-loop, volume-based collection (50% compaction)	18.5	58%

Source: Franklin Associates, A Division of ERG

Table 4. Energy and Water Usage for Recycled PET [8]

Environmental Impact

PET is very sustainable for the environment. Even though the raw materials needed for creating PET are made from petroleum compounds, the environmental impact of PET is much better than most plastics, glass or aluminum. Less than 4% of the world's oil production goes to producing all types of plastics and PET accounts for less than 0.5% of 1 %. [13]. As table 1 shows, PET can be recycled numerous times at a relatively low energy cost using the closed loop recycling method. The key to PET's energy efficiency is its capacity-to-weight ratio which allows manufacturers to put more product in less packaging which results in less fuel during transportation.

Social Impact

PET has been widely accepted for the past 30 years as a safe plastic to use and there are numerous studies, regulatory approvals and scientific testing to prove this theory. PET has also been approved by the FDA, the U.S. Food & Drug Administration, Health Canada, and the EU's European Food Safety Authority as an inert plastic which does not react with biological materials such as food so the public perception of this particular plastic is also very positive [12].

Economic Impact

Since PET is one the most sustainable plastics to manufacture and recycle in the world it is not surprising that it is so popular around the world with the largest consumers of PET being the US and China. Furthermore, the recycling process also creates thousands of domestic jobs at PET recycling facilities which also generates billions in domestic tax revenue [7].

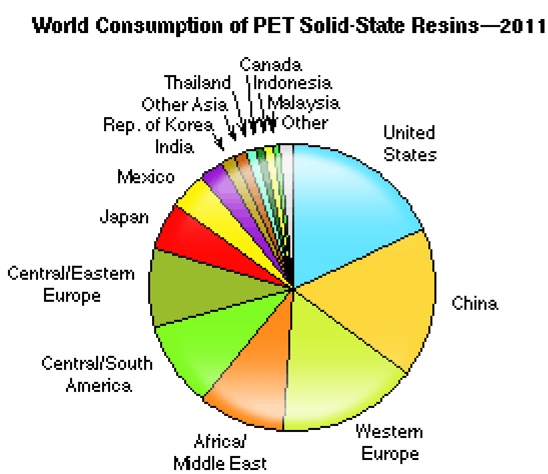

Figure 6. World Consumption of PET

High-Density Polyethylene

High-density polyethylene (HDPE) is a very versatile plastic. HDPE is widely used for the production of packaging materials, bottles, household goods, and construction products. In 2014, HDPE achieved US$61.8 billion worldwide [15].

High-density polyethylene is the largest of the three polyethylenes due to its linear structure with only a few short side branches leading to a higher density range and a more crystalline structure, resulting in higher strength [16].

Manufacturing

More prevalent processing methods of HDPE are as follows:

Extrusion

This technique is more prevalent in Asia-Pacific countries due to the high film production and the strong construction industry. Since film and rigid packaging are the largest applications, extrusion is the most prevalent processing method of HDPE. In fact, the capacity of HDPE extrusion is expected to increase in the next few years [15].

Most commercial HDPE is produced in multiple reactor configurations allowing for optimum resin structure. This leads to lower capital and production cost [16].

Blow molding

This technique is more prevalent in Western Europe. Blow-molding applications such as bottles for milk and other non-carbonated drinks, fuel tanks for automobiles and household goods [16].

Injection molding

This technique is more prevalent in Western Europe. Injection molding is used for pallets, packaging containers, and pipes [16]. Demand for HDPE is speculated to grow at 5.5%/year. Over the past quarter, the price/kg of HDPE resin fluctuated with an average, highest and lowest prices of US$2.66, US$2.82, and US$2.44 respectively [17].

End of Life

According to Plastics Europe, mechanical or feedstock recycling is the preferred end-of-life management for HDPE. Alternatively, for residual streams energy recovery can be conducted in special designed plants. Recycling HDPE requires 0.84MTCO$_2$E/Short ton less than using virgin inputs (1.19 MTCO$_2$E/Short ton – 0.35 MTCO$_2$E/Short ton) [19].

Combustion is also possible although it produces waste and pollution. 84.3% of HDPE is converted into CO_2 through combustion, while only 17.8% efficiency can be achieved [19].

Landfilling might not result in CO_2 emission but it is less of a solution and more of avoiding the problem altogether.

Environmental Impact

Figure 7 below shows the environmental impact from the production of 1 kg of HDPE.

Input parameters

Indicator	Unit	Value
Non-renewable materials		
• Minerals	g	2.6
• Fossil fuels	g	1,595.7
• Uranium	g	0.006
Renewable materials (biomass)	g	8.704
Water use[1)]	g	3,378
Non-renewable energy resources[2)]		
• for energy	MJ	21.7
• for feedstock	MJ	54.3
Renewable energy resources (biomass)[2)]		
• for energy	MJ	0.8
• for feedstock	MJ	0
[1)] This indicator comprises only process water. Cooling water is not included. [2)] Calculated as upper heating value (UHV).		

Output parameters

Indicator	Unit	Value
GWP	kg CO_2 eq	1.96
ODP	g CFC-11 eq	n/a[3)]
AP	g SO_2 eq	6.39
POCP	g Ethene eq	1.23
NP	g PO_4 eq	0.43
Dust/particulate matter	g PM10	0.64
Total particulate matter	g	0.64
Waste		
• Non-hazardous	kg	0.032
• Hazardous	kg	0.006
[3)] Relevant LCI entries are below quantification limit.		

Figure 7: Environmental Impact from the Production of 1kg of HDPE [19]

In Figure 1, it is clear that most of the energy needed as inputs is derived from non-renewable energy resources of 76MJ, compared to 0.8MJ from renewable energy resources. Non-renewable materials are also consumed much more than renewable materials. The Global-Warming-Potential is reported to be approximately twice the standardized value.

In addition, ethylene, the monomer of HDPE, can be produced from a petrochemical source or from alternative sources like syngas and biomass [19].

Social Impact

HDPE is well recognized for maintaining a long shelf life of dairy food products [19].

REGIONAL CAPACITY BREAKDOWN Table 2

	Ethylene capacity, tpy		Change	
	Jan. 1, 2012	Jan. 1, 2011	tpy	%
Asia-Pacific	42,631,000	42,631,000	—	—
Eastern Europe	7,971,000	7,971,000	—	—
Middle East, Africa	24,557,000	23,357,000	1,200,000	5.14
North America	34,508,000	34,508,000	—	—
South America	6,383,500	5,083,500	1,300,000	25.57
Western Europe	24,904,000	24,904,000	—	—
Total capacity	**140,954,500**	**138,454,500**	**2,500,000**	**1.81**

Figure 8: Regional Capacity Breakdown [18]

While it is difficult to pinpoint the social impact HDPE has had, it is still possible to consider an overall picture of the working conditions across regions that make up most of the global HDPE suppliers.

In Figure 2, the global production of capacity of ethylene, including HDPE, is categorized into various regions. Asia-Pacific leads the world with 42 million in 2012, while North America, the Middle East and Western Europe lag behind by 10-20 millions[18].

While half of the suppliers are developed countries, which have better working conditions and minimum wage, the other half consists of developing countries that are growing quickly like China. With the economic support, it is a matter of time for the facilities and regulations to follow. Overall, HDPE contributes positively socially.

Economic Impact

It is very clear that HDPE has a massive economic impact. The evidence can be seen in products across many industries; all the way from consumer applications to heavy-duty industrial applications. Besides creating HDPE recycling businesses, the sustainability of a number of HDPE's applications also provides economic advantages in the long term as follows:

- Trenchless pipe systems
- UN containers
- Foldable crates

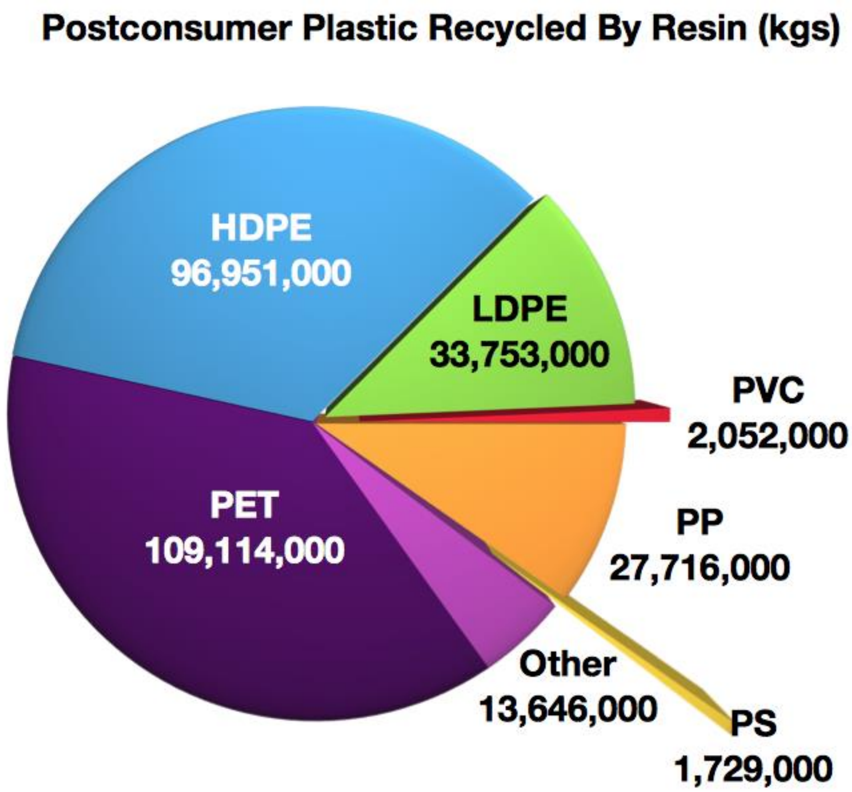

Figure 9: Postconsumer Plastic Recycled by Resin (kgs) [20]

Despite an enormous 96000 tons of postconsumer HDPE gets recycled in Canada, North American re-claimers still report an even stronger domestic demand [21].

Polystyrene

Polystyrene is a petroleum-based plastic that can come in two forms: rigid or foamed. Polystyrene is one of the most commonly used plastics in the world, with over a billion kilograms produced each year. Polystyrene is often confused with the Styrofoam, which is the trade name of a form of polystyrene foam used for insulation. Polystyrene is also a very light-weight material, with about ninety-five percent of its weight being air. [22]

Polystyrene is very prevalent in packaging and as food service material. Foam polystyrene is commonly used to make cups, plates, trays, and bowls. Rigid polystyrene is commonly used in yogurt containers, cutlery, and drinking cups. Due to its good insulation properties, Polystyrene is an excellent choice for a material that keeps food and water warm and protects packages during shipment [24].

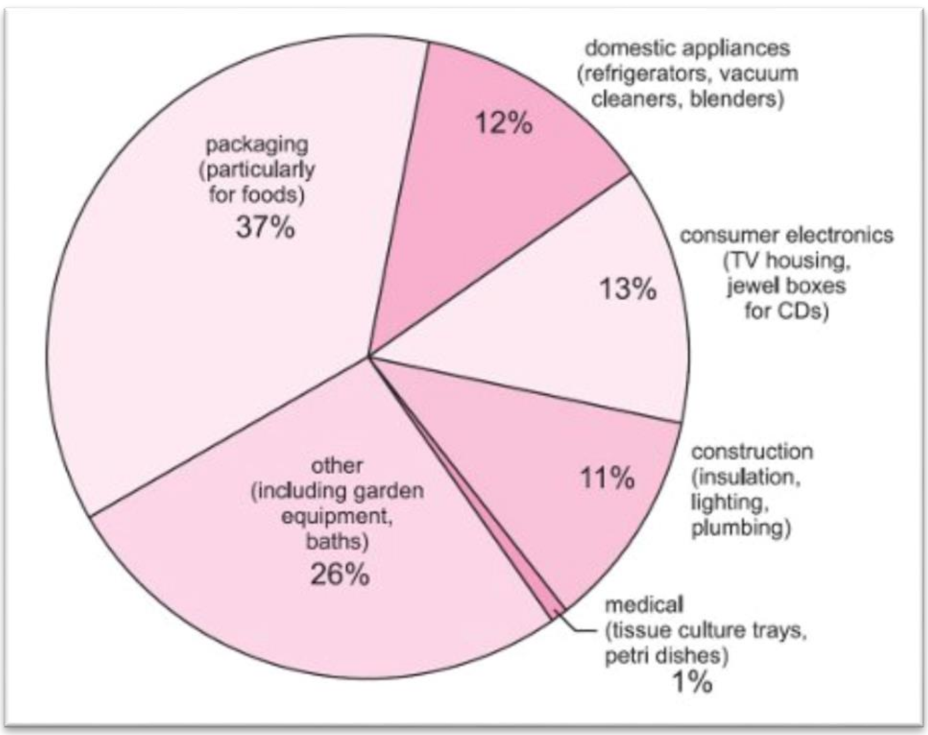

Figure 10: Pie chart showing the distribution of polystyrene in products [26]

World	14.6 million tonnes
Europe	3.4 million tonnes
US	4.0 million tonnes
Russia	0.27 million tonnes

Table 2: A breakdown of the consumption of polystyrene in 2014 [26]

Manufacturing Process

The manufacturing for Polystyrene follows a seven step process: making Styrene, making polystyrene, preparing the beads, making expanded polystyrene foam, molding, cutting bonding and coating. Next, we will explore the individual processes in slightly more detail. [25]

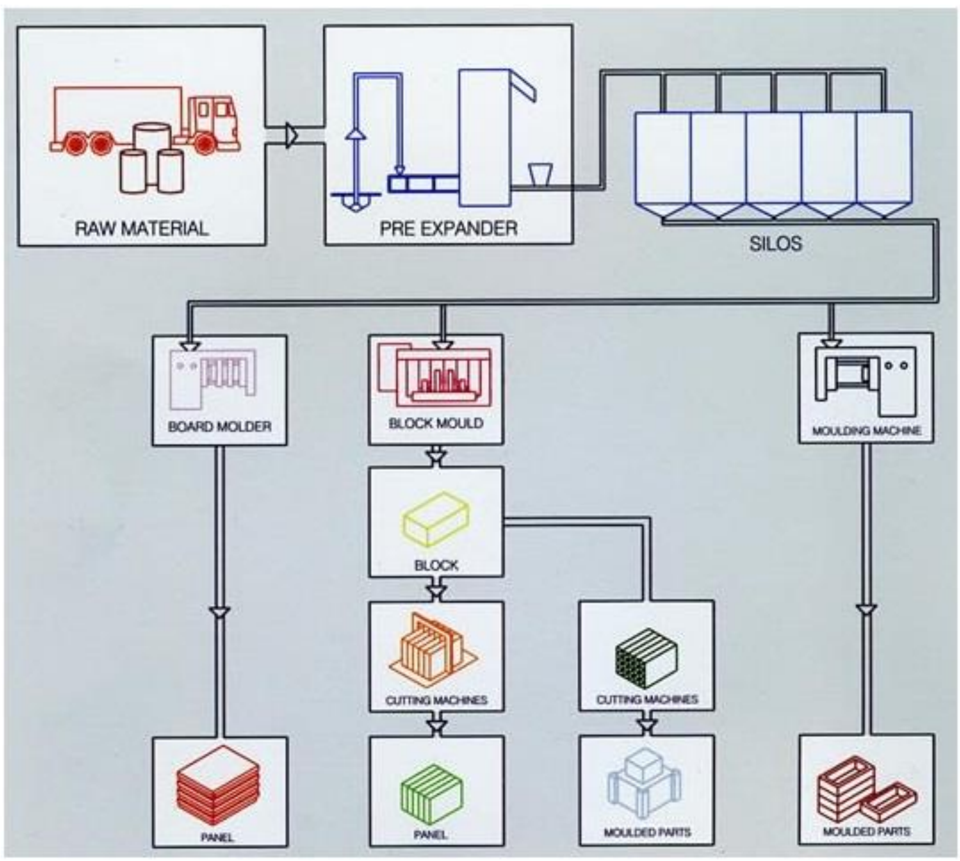

Figure 11: A typical production cycle in a Polystyrene plant [23]

Making Styrene

Styrene is made through the combination of ethylene and benzene. It is then dehydrogenated (the hydrogen is removed) at 600 - 650 degrees Celsius to form Styrene [25].

Making Polystyrene

The styrene is then treated to a process where it is completely surrounded by water and a mucilaginous (thick gluey substance produced by plants and microorganisms, used in storage of food and water) substance, which produces uniform droplets of polystyrene [25].

Preparing the Beads

The resulting polystyrene formation is chain-like consisting of beads. This mixture is then cooled, washed out and dried. The beads are often fed through a filter to separate the large beads from the small beads. [25]

Making Expanded Polystyrene Foam

After the filtering, the beads are expanded to achieve a desired density, a process known as pre-expansion. This is done by heating the polystyrene using steam or hot air. The beads are then aged for at least 24 hours to allow them to fill up with air, cool down, and harden [25].

Molding

The beads are then placed into molds in order to achieve a desired shape. Low pressure steam is infused into the beads to expand them once more and fuse them together. The formation is then cooled down again by being circulated through water, allowing it to harden [25].

Cutting, Bonding, and Coating

The polystyrene is then cut into its proper shape and often coated with protective epoxy to keep it non-flammable [25].

End of Life

There are two options available for the disposal of polystyrene, namely, taking it to a landfill, or taking it to a specialized polystyrene recycling plant.

Landfill

Polystyrene foam is often disposed of in a landfill. The dangers of this approach is that polystyrene often breaks very easily and is left behind if not carefully disposed of. This means that animals who get ahold of the material may eat it, causing a blockage in their digestive system [22].

Recycling

While recycling polystyrene is the more sustainable options, the number of recycling centers that have the technology necessary to properly recycle polystyrene is getting smaller. The biggest cost involved in recycling polystyrene is actually transporting it to the recycling centers, because as previously mentioned, it is 95% air and takes up a lot of space. Many recycling centers have also stopped accepting Polystyrene [22].

Environmental Impact

The issue with polystyrene products is that they are meant for short-term uses, and are disposed of very quickly. This creates a problem because polystyrene is not easily or affordably recycled, so it is often thrown into landfills. Even when in the landfills, the large size of these products means that a lot of space needs to be allocated for polystyrene products [24].

Hydrocarbons, used in the production of polystyrene foam, are released into the air during manufacturing. Hydrocarbons form tropospheric ozone once they reach the upper layers of Earth's atmosphere. This creates a serious air pollution problem on the ground level. The National Bureau of Standards Center for Fire Research found 57 harmful chemical byproducts that were released into the atmosphere during the combustion of polystyrene foam [24].

The other danger with disposing polystyrene is that it is not biodegradable. It takes a couple decades for the polystyrene to fully decompose into the environment. Due to its lightweight nature, a strong wind can blow the polystyrene outside of the landfill, where it is possible that animals can come into contact with it. If the animals eat the polystyrene, it can potentially block their digestive system [24].

Economic Impact

Polystyrene is the most expensive plastic to manufacture by weight of the ones reviewed here making it less desirable than alternatives. It is manufactured in Canada and around the world so where jobs are created depends on where the plastic is sourced from. If UBC procures polystyrene from local Canadian factories then local jobs will be provided.

Social Impact

Styrene, which is one of the materials in Polystyrene, is a toxin and likely carcinogen. The US Food and Drug Administration has concluded that polystyrene containers leak Styrene when they come in contact with warm food or liquids. This poses a direct threat to people who eat or drink out of these containers, as their bodies get contaminated with Styrene, which is difficult to get rid of. Health effects of Styrene contamination include irritation of the skin, eyes, and upper respiratory tract, and gastrointestinal effects [23].

Low Density Polyethylene

Low Density Polyethylene (LDPE) belongs to the polyolefin family of plastics, first produced in the year 1931 by Imperial Chemical Industries (ICI). Due to LDPE's versatility, it is widely utilized for applications such as packaging for food and non-food items, protective coating for various materials, and insulation for electrical cables (Insert Exxon Mobil Reference). In 2013, LDPE generated revenues of approximately US $33 Billion globally, with a speculative expected sales increase of 1.3% until 2021[27].

LDPE has the lowest density in comparison to the other polyethylene plastics such as HDPE. The lower density is due to the presence of small branching of the carbon atoms which leads to LDPE having a loose crystalline structure. LDPE is produced in opaque and translucent variations; it is extremely robust, flexible, chemically unreactive at room temperature, and resilient to temperatures upwards of 80 degrees Celsius [28].

Manufacturing

The main manufacturing process used for the production of LDPE: Autoclave and tubular high pressure technology.

The starting raw material for the production of LDPE is Ethylene. The Ethylene is brought up to reaction pressure to initiate process of polymerization using the LP (Low Pressure) Compressor and HP (High Pressure) Compressor. A precise combination of reaction temperature (160-360 Degrees Celsius), pressure (130 – 200 MPa), and co-monomers (vinyl/butyl acetate) are used to control density and other physical characteristics of LDPE [29].

Once the process is terminated at the bottom of the reactor; the LDPE mixture then heads for the high pressure and low pressure separators where it is cooled and the unreacted Ethylene heads for the recycle compressor. There it is re-compressed and recycled back to begin the process over again. The resulting polymer with a density of < 940 kg/m is mixed with enhancing additives and extruded into pellets for package and delivery [30].

End of Life

There are four options available for the disposal of used LDPE products:

- Solvent-based recycling
- Closed loop recycling
- Landfilling
- Combustion

Solvent-Based Recycling

According to experiments conducted on virgin LDPE pellets by the National Technical University of Athens, the results of solvent (using concentrated solution of Toluene) based recycling revealed outstanding recovery of the polymer and solvent solution with negligible effect to the mechanical properties and performance. The resulting recycled grade rivals the virgin pellets and can be used in various applications [31].

Closed Loop Recycling

According to Plastics Europe mechanical or feedstock recycling is the recommend end-of-life management for LDPE waste due to its economic and environmental feasibility [30].

Landfilling

LDPE does not contain any biodegradable carbon therefore it does not generate methane emissions when landfilled. The transportation of LDPE waste materials which generates the carbon emissions and the waste material itself are the only final product waste [32].

Combustion

Combustion of LDPE is another method of disposal. Through the process of combustion 98% of the Carbon in LDPE is converted into CO_2 and produces 2.79 ($MTCO_2E$/Short Ton) of CO_2 emissions. [32].

Observing the input parameters figure we can deduce that fossil fuels, a non-renewable material, are used as the major raw material, 1591.3g, for the production of LDPE in comparison with 10.787g of biomass, a renewable material. This disproportionality is also noticed when comparing the non-renewable and renewable energy resources required in the production process. Non-renewable energy resources account for 76.9 MJ while renewable energy resources account for a miniscule 1.2 MJ [32].

Additionally, analyzing the output parameters figure we can conclude that GWP of 2.13 (Global Warming Potential) is a little more than twice the standardized value. The AP of 7.74 (Acidification Potential) which causes the phenomenon of acid rain is approximately eight times the standardized value. Lastly, the POCP of 1.19 (Photochemical Oxidant Formation) which causes production of ground-level ozone is slight more than standardized value [30].

Environmental Impact

The two figures below summarize the environmental performance indicators related to the production of 1 Kg of LDPE.

Output parameters

Indicator	Unit	Value
GWP	kg CO_2 eq	2.13
ODP	g CFC-11 eq	n/a[3)]
AP	g SO_2 eq	7.74
POCP	g Ethene eq	1.19
NP	g PO_4 eq	0.50
Dust/particulate matter	g PM10	0.69
Total particulate matter	g	0.70
Waste		
• Non-hazardous	kg	0.034
• Hazardous	kg	0.005

[3)] Relevant LCI entries are below quantification limit.

Input parameters

Indicator	Unit	Value
Non-renewable materials		
• Minerals	g	4.2
• Fossil fuels	g	1,591.3
• Uranium	g	0.009
Renewable materials (biomass)	g	10.787
Water use[1)]	g	2,934
Non-renewable energy resources[2)]		
• for energy	MJ	25.3
• for feedstock	MJ	51.6
Renewable energy resources (biomass)[2)]		
• for energy	MJ	1.2
• for feedstock	MJ	0

[1)] This indicator comprises only process water. Cooling water is not included.
[2)] Calculated as upper heating value (UHV).

Figure 12: Environmental impact from the production of LDPE

Observing the input parameters figure we can deduce that fossil fuels, a non-renewable material, are used as the major raw material, 1591.3g, for the production of LDPE in comparison with 10.787g of biomass, a renewable material. This disproportionality is also noticed when comparing the non-renewable and renewable energy resources required in the production process. Non-renewable energy resources account for 76.9 MJ while renewable energy resources account for a miniscule 1.2 MJ [30].

Additionally, analyzing the output parameters figure we can conclude that GWP of 2.13 (Global Warming Potential) is a little more than twice the standardized value. The AP of 7.74 (Acidification Potential) which causes the phenomenon of acid rain is approximately eight times the standardized value. Lastly, the POCP of 1.19 (Photochemical Oxidant Formation) which causes production of ground-level ozone is slight more than standardized value [30].

Social Impact

LDPE has been in consumption for the past 84 years with uses ranging from film applications for food packaging and non-food packaging purposes to extrusion coating for packaging liquids. Its demand and use is on the rise as Asia-Pacific region countries begin to adopt food packaging techniques and standards seen in the west [32].

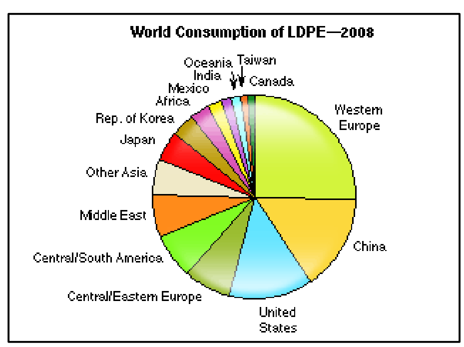

Figure 13: World consumption of LDPE-2008

Economic Impact

The Asia-Pacific and Middle East are the largest growth markets for the production of LDPE. In 2013, the Asia-Pacific region handled 7.1 million tons of LDPE with China accounting for 58% of the consumption. With other plastics (such as: LLDPE and HDPE) entering the market, the growth rate and future demand for LDPE is on a steady decline. In the Middle East LDPE output is estimated to rise at 5% per year due to petrochemical projects coming online in the region. Throughout Western Europe LDPE production is expected to decline due to closure of manufacturing sites and stagnant capacity [27].

Polypropylene

Polypropylene is a thermoplastic polymer with a wide range of uses. It is commonly used for bottle caps, food containers, and drinking straws. Other uses include textiles, stationery, and packaging and labeling.

Polypropylene is normally tough and flexible, and has an intermediate level of crystallinity, between low-density polyethylene and high-density polyethylene. An advantage of polypropylene is it's resistance to high heat, making it suitable for many of the applications it's currently used for. Although it is fairly unreactive chemically, it is slightly more susceptible to strong oxidizing agents than other plastics. Its high melting point and strength makes it the most used plastic packaging in the US and UK.

Manufacturing

Polypropylene is made from propene, which is an organic compound produced from gas, oil, and propane. The most common methods for processing of polypropylene are through molding and extrusion. Another method makes polypropylene into a film for fibrous products.

The most common method, injection molding, is used for a majority of polypropylene products. This is made into a wide range of things, from car bumpers and dashboards, to housewares and consumer products. Polypropylene can also be extruded, being made into pipes and cables.

Most fibrous products made of polypropylene use polypropylene that is manufactured into melt-blown fibers. These are micro-fibers (2 to 4 µm) that are made by fast moving air blows molten polypropylene from an extruder die tip onto a take-up screen to form a self-bonding web. This gets made into things like face masks, food packaging films, and textiles [40].

The following figure shows the breakdown of what polypropylene is made into:

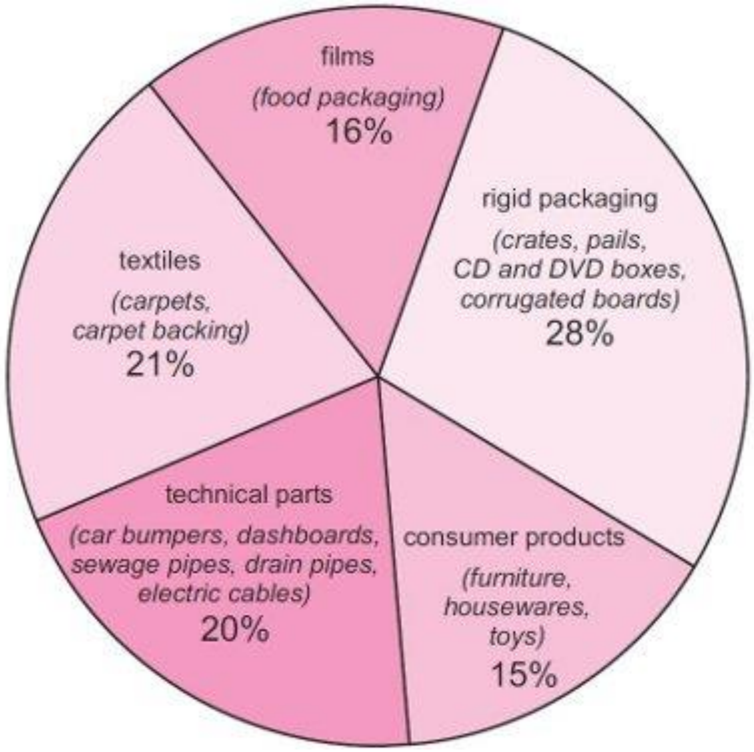

Figure 14: How polypropylene resin is used in manufacturing [34].

End of Life

According to recycling figures provided by American Chemistry Council, polypropylene is one of the least recycled plastics, at a rate below 1% for post-consumer recycling. Overall polypropylene recycling (not just post-consumer), however, is higher. In the US, recycling rates have gone up from 3% of all polypropylene recycled in 2004 to 18% in 2010, and it continues to rise [35].

It is considered a challenging plastic to recycle, as there as issues with decontamination and removing odor and taint. However, recycling companies have recently come up with new ways to decontaminate food grade polypropylene to re-use in food packaging. This is considered a significant improvement in the polypropylene recycling industry and recycling rates are rising quickly as a result [38].

More recently for the year of 2013, out of the 195 million pounds of polypropylene bottles produced in the US, 62 million pounds (or 31.8%) have been recycled, showing that the rates of polypropylene recycling are indeed rising [39].

Environmental Impact

Polypropylene products that don't get recycled degrade slowly in landfills and take 20-30 years to get completely decomposed. This poses a negative effect on our environment as additives added to the plastic when it's produced contain toxins such as lead and cadmium, which can have harmful consequences for a number of bio-systems. The following charts show the detailed environmental impact of producing polypropylene:

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Ammonia	0.0015	lb	0.0015	kg
Antimony	8.7E-07	lb	8.7E-07	kg
Arsenic	1.1E-07	lb	1.1E-07	kg
Benzene	0.074	lb	0.074	kg
Carbon Dioxide - Fossil	73.0	lb	73.0	kg
Carbon Monoxide	0.30	lb	0.30	kg
Carbon Tetrachloride	5.8E-07	lb	5.8E-07	kg
CFC 13 (Methane, trichlorofluoro-)	9.3E-06	lb	9.3E-06	kg
Chlorine	1.0E-04	lb	1.0E-04	kg
Chromium	2.9E-07	lb	2.9E-07	kg
Ethylbenzene	0.0087	lb	0.0087	kg
Ethylene Dibromide	1.8E-06	lb	1.8E-06	kg
HCFC-22	1.0E-06	lb	1.0E-06	kg
Hydrogen	0.0052	lb	0.0052	kg
Hydrogen Chloride	1.0E-06	lb	1.0E-06	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	0.29	lb	0.29	kg
Lead	1.0E-12	lb	1.0E-12	kg
Methane	6.40	lb	6.40	kg
Nickel	2.5E-06	lb	2.5E-06	kg
Nitrogen Oxides	0.19	lb	0.19	kg
Nitrous Oxide	0.0045	lb	0.0045	kg
Non-Methane Hydrocarbons	0.26	lb	0.26	kg
Other Organics	0.011	lb	0.011	kg
Particulates (PM10)	0.11	lb	0.11	kg
Particulates (PM2.5)	0.0098	lb	0.0098	kg
Particulates (unspecified)	0.031	lb	0.031	kg
Polyaromatic Hydrocarbons (total)	2.4E-05	lb	2.4E-05	kg
Sulfur Dioxide	1.54	lb	1.54	kg
Sulfur Oxides	0.0041	lb	0.0041	kg
Toluene	0.11	lb	0.11	kg
VOC	0.59	lb	0.59	kg
Xylene	0.066	lb	0.066	kg
Zinc	1.0E-06	lb	1.0E-06	kg

Waterborne Wastes

m-Xylene	8.5E-06	lb	8.5E-06	kg
1-Methylfluorene	1.7E-08	lb	1.7E-08	kg
2,4-Dimethylphenol	8.1E-06	lb	8.1E-06	kg
2-Hexanone	1.9E-06	lb	1.9E-06	kg
2-Methylnaphthalene	4.4E-06	lb	4.4E-06	kg
4-Methyl-2-Pentanone	6.4E-07	lb	6.4E-07	kg
Acetone	1.5E-06	lb	1.5E-06	kg
Acid (benzoic)	2.9E-04	lb	2.9E-04	kg
Acid (hexanoic)	6.1E-05	lb	6.1E-05	kg
Alkylated benzenes	5.5E-05	lb	5.5E-05	kg
Alkylated fluorenes	3.2E-06	lb	3.2E-06	kg
Alkylated naphthalenes	9.0E-07	lb	9.0E-07	kg
Alkylated phenanthrenes	3.7E-07	lb	3.7E-07	kg
Aluminum	0.027	lb	0.027	kg
Ammonia	0.0096	lb	0.0096	kg
Antimony	1.7E-05	lb	1.7E-05	kg
Arsenic	5.6E-05	lb	5.6E-05	kg
Barium	0.36	lb	0.36	kg
Benzene	3.2E-04	lb	3.2E-04	kg
Beryllium	3.5E-06	lb	3.5E-06	kg
BOD	0.046	lb	0.046	kg
Boron	9.1E-04	lb	9.1E-04	kg
Bromide	0.036	lb	0.036	kg
Cadmium	8.7E-06	lb	8.7E-06	kg
Calcium	0.60	lb	0.60	kg
Chlorides	7.44	lb	7.44	kg

Calcium	0.41	lb	0.41	kg
Chlorides	4.99	lb	4.99	kg
Chromium (unspecified)	0.0068	lb	0.0068	kg
Cobalt	4.2E-06	lb	4.2E-06	kg
COD	1.64	lb	1.64	kg
Copper	5.1E-05	lb	5.1E-05	kg
Cyanide	4.9E-09	lb	4.9E-09	kg
Dibenzofuran	1.3E-08	lb	1.3E-08	kg
Dibenzothiophene	1.0E-08	lb	1.0E-08	kg
Dissolved Solids	5.23	lb	5.23	kg
Ethylbenzene	1.4E-05	lb	1.4E-05	kg
Fluorides	5.1E-05	lb	5.1E-05	kg
Fluorene	9.7E-07	lb	9.7E-07	kg
Iron	0.033	lb	0.033	kg
Lead	9.8E-05	lb	9.8E-05	kg
Lead 210	2.0E-14	lb	2.0E-14	kg
Lithium	0.036	lb	0.036	kg
Magnesium	0.081	lb	0.081	kg
Manganese	1.2E-04	lb	1.2E-04	kg
Mercury	2.3E-07	lb	2.3E-07	kg
Metal Ion (unspecified)	4.5E-06	lb	4.5E-06	kg
Methyl Chloride	2.7E-09	lb	2.7E-09	kg
Methyl Ethyl Ketone	5.5E-09	lb	5.5E-09	kg
Molybdenum	4.3E-06	lb	4.3E-06	kg
Naphthalene	3.4E-06	lb	3.4E-06	kg
n-Decane	5.4E-06	lb	5.4E-06	kg
n-Docosane	7.3E-08	lb	7.3E-08	kg
n-Dodecane	1.0E-05	lb	1.0E-05	kg
n-Eicosane	2.8E-06	lb	2.8E-06	kg
n-Hexacosane	4.5E-08	lb	4.5E-08	kg
n-Hexadecane	1.1E-05	lb	1.1E-05	kg
Nickel	4.5E-05	lb	4.5E-05	kg
n-Octadecane	2.8E-06	lb	2.8E-06	kg
p -Xylene	2.0E-06	lb	2.0E-06	kg
o -Xylene	2.0E-06	lb	2.0E-06	kg
o-Cresol	5.4E-06	lb	5.4E-06	kg
Oil	0.0095	lb	0.0095	kg
p-Cresol	5.8E-06	lb	5.8E-06	kg
p-Cymene	6.8E-09	lb	6.8E-09	kg
Pentamethylbenzene	5.1E-09	lb	5.1E-09	kg
Phenanthrene	1.5E-07	lb	1.5E-07	kg
Phenol/Phenolic Compounds	3.9E-04	lb	3.9E-04	kg
Phosphates	5.1E-04	lb	5.1E-04	kg

	English units (Basis: 1,000 lb)	Total Energy Thousand Btu	SI units (Basis: 1,000 kg)	Total Energy GigaJoules
Material Inputs (1)				
Refined Petroleum Products	357 lb		357 kg	
Processed Natural Gas	643 lb		643 kg	
Water Consumption	161 gal		1,344 liter	
Energy Usage				
Process Energy				
Electricity (grid)	46.2 kwh	492	102 kwh	1.15
Electricity (cogeneration)	142 cu ft (3)	159	8.85 cu meters	0.37
Natural Gas	1,759 cu ft	1,970	110 cu meters	4.59
Gasoline	0.0021 gal	0.29	0.017 liter	6.8E-04
Diesel	0.0018 gal	0.28	0.015 liter	6.6E-04
Internal Offgas use (2)				
From Oil	66.2 lb	1,884	66.2 kg	4.39
From Natural Gas	118 lb	3,350	118 kg	7.80
Recovered Energy	2.30 thousand Btu	2.30	5.35 MJ	0.0054
Total Process		7,853		18.3
Transportation Energy				
Propylene Products				
Pipeline-Petroleum Products	19.5 ton-miles		62.8 tonne-km	
Electricity	0.43 kwh	4.35	0.94 kwh	0.010

Figure 15: Inputs and Emissions from making 1000 kg of Polypropylene [37]

Some important points to highlight from this are that there is an emission of 73 kg of Carbon Dioxide for every 1000 kg of polypropylene produced. It can also be seen that 18.3 GJ of total energy is needed to produce that 1000 kg of polypropylene.

Social Impact

It is difficult to determine the social impact of polypropylene production. A good way to go about this would be to look at the production rates of polypropylene by country, as where it is produced can tell you a lot about worker compensation and working conditions.

The chart for the production of polypropylene by country for 2012 is shown below:

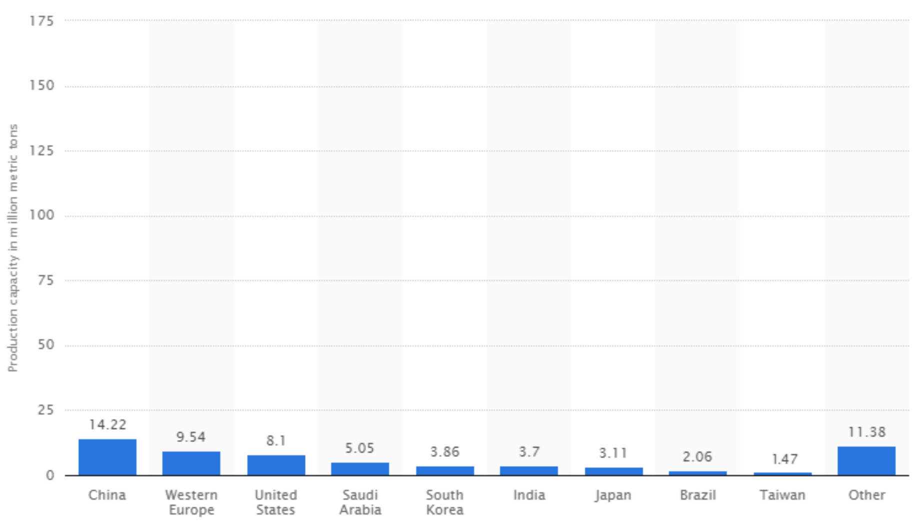

Figure 16: Production Capacity of Polypropylene by Country

As can be seen, China leads the way in polypropylene production, with 14.22 million metric tons of it being produced there in 2012. While no specific data is available on the conditions of the workers in polypropylene producing plants in China, there is plenty of information on the conditions of the workers in other factories in China, and they have a history of having poor treatment. The next two highest producers are in more developed countries and have a reputation for having better working conditions than China. For these reasons we can say that compared to the other plastics, working conditions for polypropylene production would be somewhere in the middle.

In 2008, Canadian researchers claimed that ammonium biocides and oleamide were leaking out of polypropylene lab equipment, affecting their experimental results. Knowing that polypropylene is used in many food containers, Health Canada said they will be reviewing the findings to determine what steps are needed to protect consumers [36].

Economic Impact

Prices for polypropylene fell 14% from December 2014 to January 2015. It is now valued at $1,165 per metric ton [35]. This now means that polypropylene is becoming a cheaper and more ready readily accessible plastic for many products.

Conclusion

Economically, PET seems to be the best plastic to use, as it has the lowest average cost to manufacture, and it's very lightweight, meaning that it lowers the shipping costs. There are also local manufacturers in Vancouver, such as Ampak, that produce PET, which would also help contribute to a lower overall shipping and manufacturing cost. Figure 9 shows an example of

Environmentally, we found that HDPE was on average the most environmentally friendly plastic out of the ones we researched. The manufacturing process used a fairly low amount of energy compared to the other plastics, and it also produced a very small amount of hydrocarbons. It also has a high recycling rate in the US and Canada, and the plastic itself is nearly 100% recyclable.

For social factors, we found that most of the plastics had very low health risks in these areas, except for PVC and Polystyrene. PVC and Polystyrene both contained a list of known carcinogens.

After conducting a thorough analysis on which plastics UBC should consider using, we have decided that PET was the most sustainable plastic for food containers. Referring back to our table, we noticed that PET was the most energy efficient; it was 100% recyclable, produces the least amount of solid waste, and is already actively recycled across Canada and the United States. We are in the process of evaluating if there are opportunities for UBC to transition from less sustainable plastics to PET for items such as food containers.

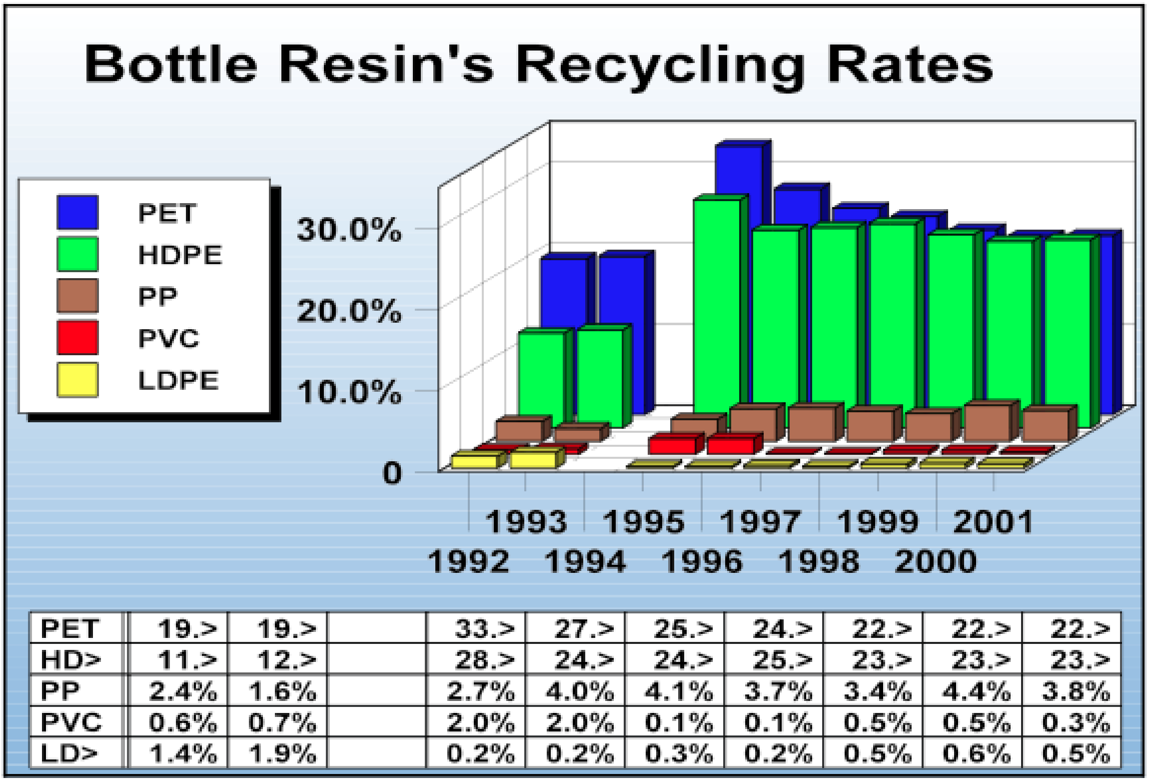

Figure 17: Bottle Resin's Recycling Rates

Recommendations

PET was determined to be the best plastic considering its environmental, social, and economic impacts. UBC should take advantage of PET's low impact by selecting it as the material for campus plastic products wherever possible. Although some products are already made from PET, there still exists room for continued development.

Our team recommends sourcing PET-based coffee cup lids, takeaway containers, and cutlery. Doing so can make major improvements to UBC on-campus sustainability as these items are for the most part thrown away after a single usage and at the moment, the majority of them are made from polypropylene and polystyrene. HDPE containers such as milk jugs and detergent containers should not be replaced as the attempt to source PET-based alternatives could potentially be very difficult and HDPE is actually a very sustainable alternative to PET.

References

Our references are sorted alphabetically and grouped per plastic.

PVC

[1] *Anderson, P. (2004). Message in a Bottle: The Impacts of PVC on Plastics Recycling.*

[2] *Brinkley, A., Kirby, J. R., Wadehra, I. L., Besnainou, J., Coulon, R., & Goybet, S. (1995). Life cycle inventory of PVC: Disposal options for a PVC monitor housing. Paper presented at the 145-151.*

[3] *Brinkley, A., Kirby, J. R., Wadehra, I. L., Besnainou, J., Coulon, R., & Goybet, S. (1996). Life cycle inventory of PVC: Manufacturing and fabrication processes. Paper presented at the 94-101.*

[4] *Fort Saskatchewan losing 170 jobs (9:40 a.m.). (n.d.). Retrieved April 9, 2015, from http://www.canada.com/story.html?id=f269fbdf-09dd-4096-98f0-dc44c812e18c#__federated=1*

[5] *PVC's Physical Properties (2014). Retrieved Feb 12, 2015, from http://www.pvc.org/en/p/pvcs-physical-properties*

[6] *Vinyl Chloride. (n.d.). Retrieved April 9, 2015, from http://www.carexcanada.ca/en/vinyl_chloride/*

PET

[7] Dunham, John and Associates. (2013). Scrap Recycling Industry Impact Summary and Methodology. Scrap Recycling Industry Impact Summary and Methodology. Retrieved from http://www.isri.org/docs/default-source/recycling-analysis-%28reports-studies%29/economic-impact-study-u-s-based-scrap-recycling-industry-2013.pdf?sfvrsn=8

[8] Franklin Associates. (2010). Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin From Postconsumer Containers and Packing. Retrieved: http://www.napcor.com/pdf/FinalReport_LCI_Postconsumer_PETandHDPE.pdf

[9] *PET Basics. (2014). Retrieved March 18, 2015, from http://www.napcor.com/pdf/v4-*11_NAPCOR_PET_Interactive.pdf

[10] PET Recycling. (2014). Retrieved March 18, 2015, from http://www.napcor.com/PET/landing_petrecycling.html

[11] PET Recycling. (2015). Retrieved March 18, 2015, from http://www.petresin.org/recycling.asp

[12] PET Safety & Use. (2015). Retrieved March 18, 2015, from http://petresin.org/safety_uses.asp

[13] Sustainabilty. (2015). Retrieved March 18, 2015, from http://petresin.org/sustainability.asp

[14] What is PET? (2014). Retrieved March 18, 2015, from http://www.napcor.com/PET/whatispet.html

HDPE

[15] Ceresana (2015, March). Market Study: Polyethylene - HDPE. Ceresana. Retrieved March 2015, from http://www.ceresana.com/en/market-studies/plastics/polyethylene-hdpe/

[16] ICIS (2007, November). Polyethylene – High Density (HDPE) Uses and Market Data. ICIS. Retrieved March 2015, from http://www.icis.com/resources/news/2007/11/06/9076152/polyethylene-high-density-hdpe-uses-and-market-data/

[17] Moore Recycling (2014, February). 2012 Postconsumer Plastics Recycling in Canada. Retrieved March 2015, from http://www.moorerecycling.com/2012_Canada_Plastic_Recycling_Report_Final_3.4.14.pdf

[18] Oil and Gas Journal (2012, February). Global Ethylene Capacity Continues Advance in 2011. Retrieved March 2015, from http://www.ogj.com/articles/print/vol-110/issue-07/special-report-ethylene-report/global-ethylene-capacity.html

[19] Plastics Europe (2008, November). High Density Polyethylene. Retrieved March 2015, from http://www.plasticseurope.org/Documents/Document/20100312112214-FINAL_HDPE_280409-20081215-017-EN-v1.pdf

[20] RecycleInMe (2015, April). HDPE Resin Prices. Retrieved March 2015, from http://www.recycleinme.com/scrapresources/DetailedPrice.aspx?psect=2&cat=Resin+Prices&subcat=HDPE

[21] United States Environmental Protection Agency (2010, October). Plastics. Retrieved March 2015, from http://www.epa.gov/climatechange/wycd/waste/downloads/plastics-chapter10-28-10.pdf

Polystyrene

[22] Green Restaurant Association. Polystyrene Foam Report. Retrieved from: http://www.earthresource.org/campaigns/capp/capp-styrofoam.html

[23] Maul, J., Frushour, B. G., Kontoff, J. R., Eichenauer, H., Ott, K.-H. and Schade, C. (2007). Polystyrene and Styrene Copolymers. Ullmann's Encyclopedia of Industrial Chemistry. Retrieved from: http://onlinelibrary.wiley.com/doi/10.1002/14356007.a21_615.pub2/abstract

[24] Recycling Polystyrene. Retrieved from: http://www.plastics.ca/Recycling/Polystyrene/index.php

[25] Expanded Polystyrene Foam. Retrieved from: http://www.madehow.com/Volume-1/Expanded-Polystyrene-Foam-EPF.html

[26] The Essential Chemistry Industry. (January 2014). Polystyrene. Retrieved from: http://www.essentialchemicalindustry.org/polymers/polyphenylethene.html

Low Density Polyethylene

[27] http://www.ceresana.com/en/market-studies/plastics/polyethylene-ldpe/

[28] http://www.dynalabcorp.com/technical_info_ld_polyethylene.asp

[29] http://www.bkvibro.com/en/download/publications/case-stories/ldpe-reactor-mixer-bearing-faults-part-1/ldpe-manufacturing-process.html

[30] http://www.plasticseurope.org/Documents/Document/20100312112214-FINAL_LDPE_270409-20081215-018-EN-v1.pdf

[31] http://www.sciencedirect.com/science/article/pii/0921344994900051

[32] http://www.epa.gov/climatechange/wycd/waste/downloads/plastics-chapter10-28-10.pdf

[33] http://chemical.ihs.com/nl/Public/2009/0907/0907.html

Polypropylene

[34] Polypropylene. (2014, January). Retrieved March 2015, from Essential Chemical Industry: http://www.essentialchemicalindustry.org/polymers/polypropene.html

[35] Why Polypropylene? (2015). Retrieved March 2015, from Milliken Chemical: http://millikenchemical.com/why-polypropylene/

[36] Canwest News Service. (2008, November 6). Scientific tests skewed by leaching plastics. Retrieved March 2015, from Canada Classic Edition: http://www.canada.com/chilliwacktimes/story.html?id=be27d48b-ef01-4e78-b2bf-c108801884c2

[37] Franklin Associates. (2011, August). LifeCycle Inventory of 9 Plastics Resins and 4 Polyurethane Precursors. Retrieved March 2015, from American Chemistry: http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-APPS-Only

[38] LeBlanc, R. (2013). An Overview of Polypropylene Recycling. Retrieved March 2015, from About Recycling: http://recycling.about.com/od/Paper/a/An-Overview-Of-Polypropylene-Recycling.htm

[39] *Recyclers, T. A. (2013). 2013 United States National Post-Consumer Plastics Bottle Recycling Report. Retrieved March 2015, from American Chemistry:* *http://plastics.americanchemistry.com/Education-Resources/Publications/2013-National-Post-Consumer-Plastics-Bottle-Recycling-Report.pdf*

[40] *Silva, E. (2010). The Melt-Blowing Process. Retrieved March 2015, from Academia:* *http://www.academia.edu/440299/The_melt-blowing_process_-_Nonwovens*

Appendix A

The below graphs were constructed from data received from the "Cradle-To-Gate life cycle inventory of nine plastics resins and four polyurethane precursors"(http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-APPS-Only).

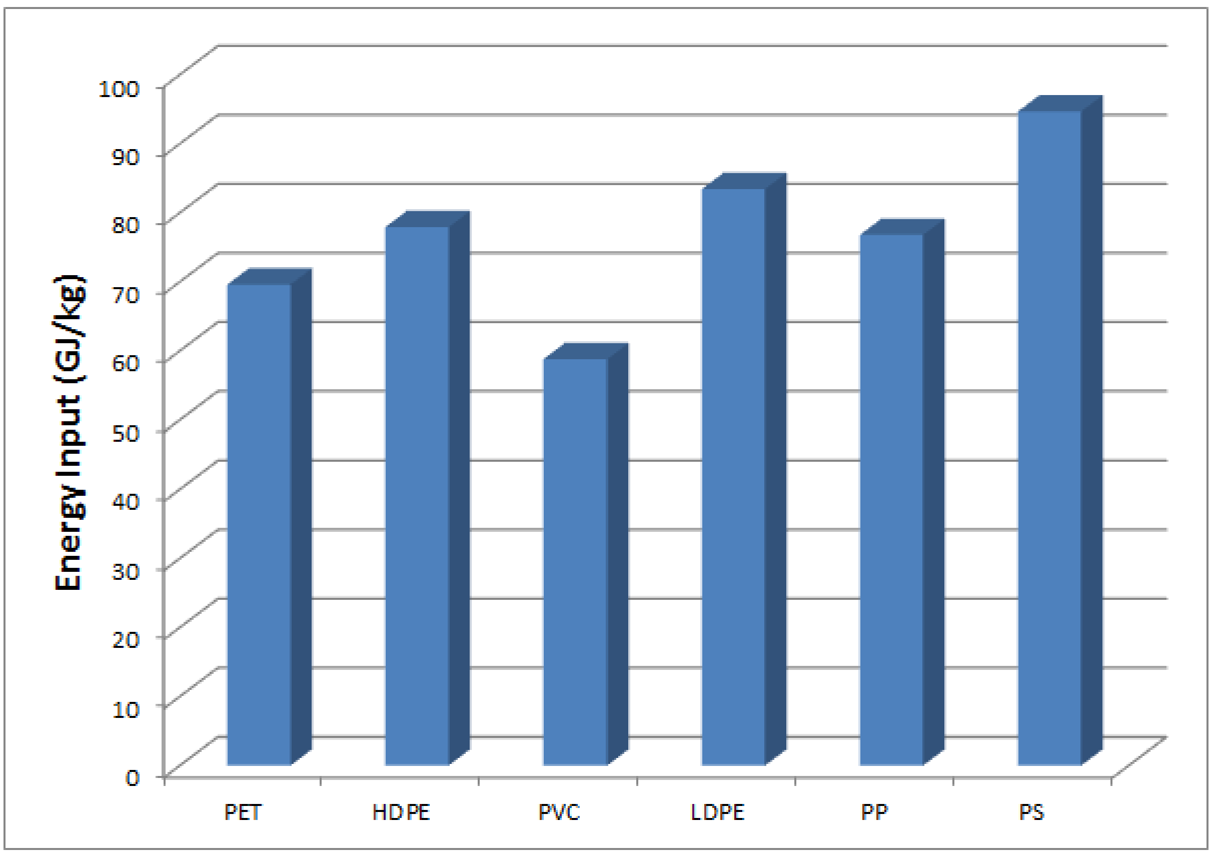

Figure 1: Energy consumed for the entire manufacturing process of each plastic

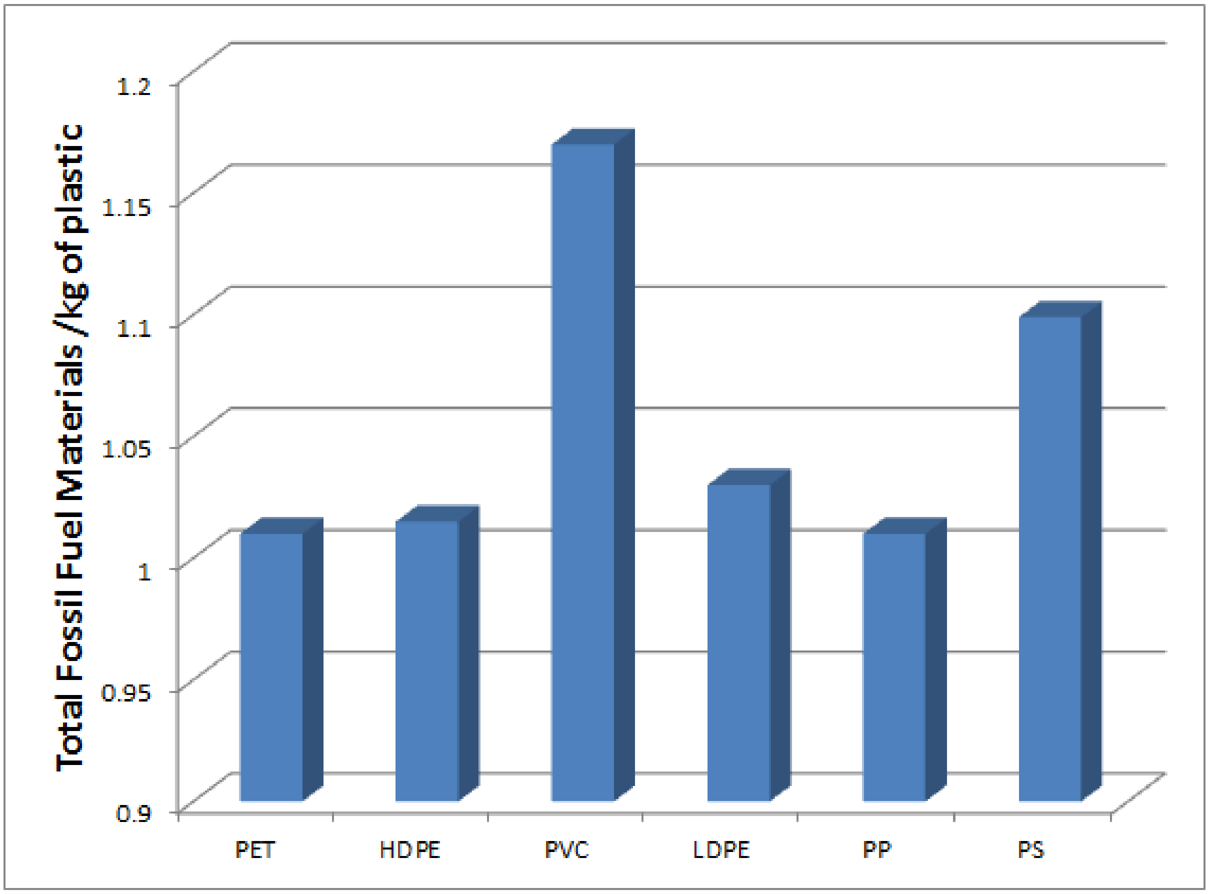

Figure 2: Kilograms of raw fossil fuel produced for every kilogram of plastic produced

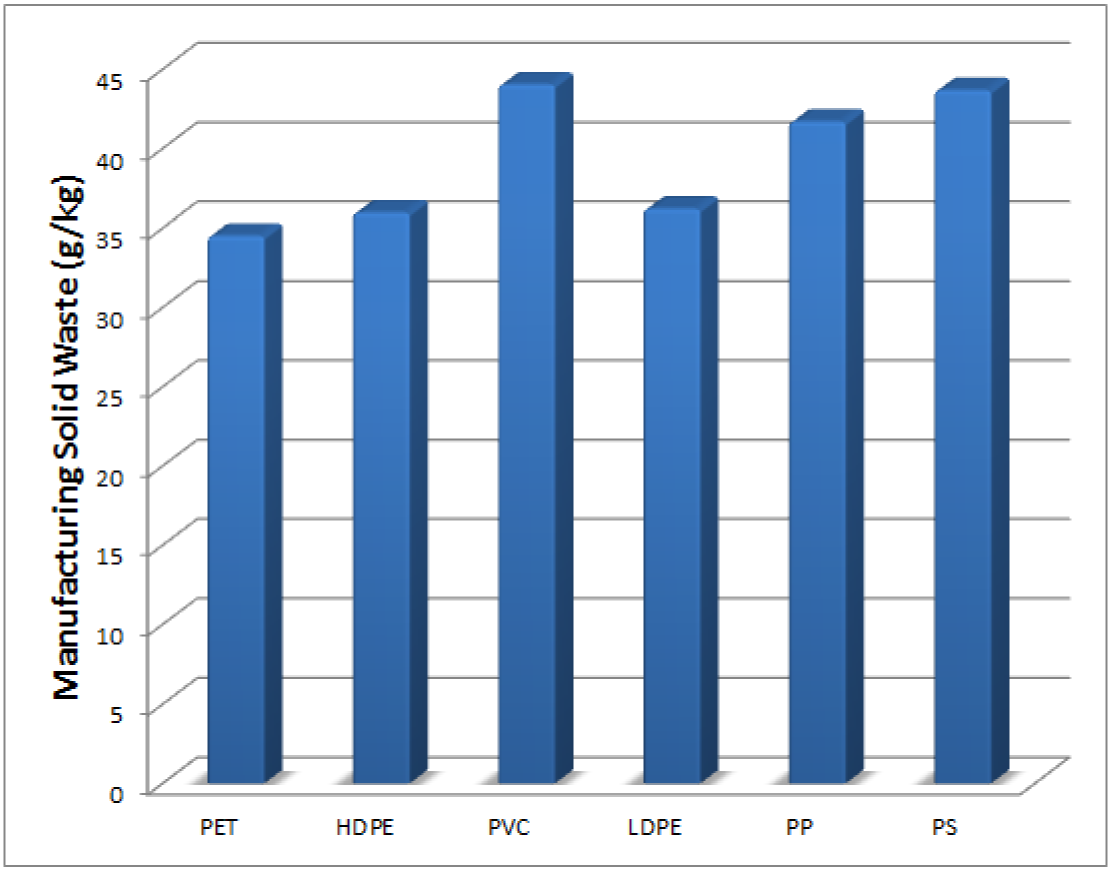

Figure 3: Grams of solid waste produced for each kilogram of plastic produced during the manufacturing cycle

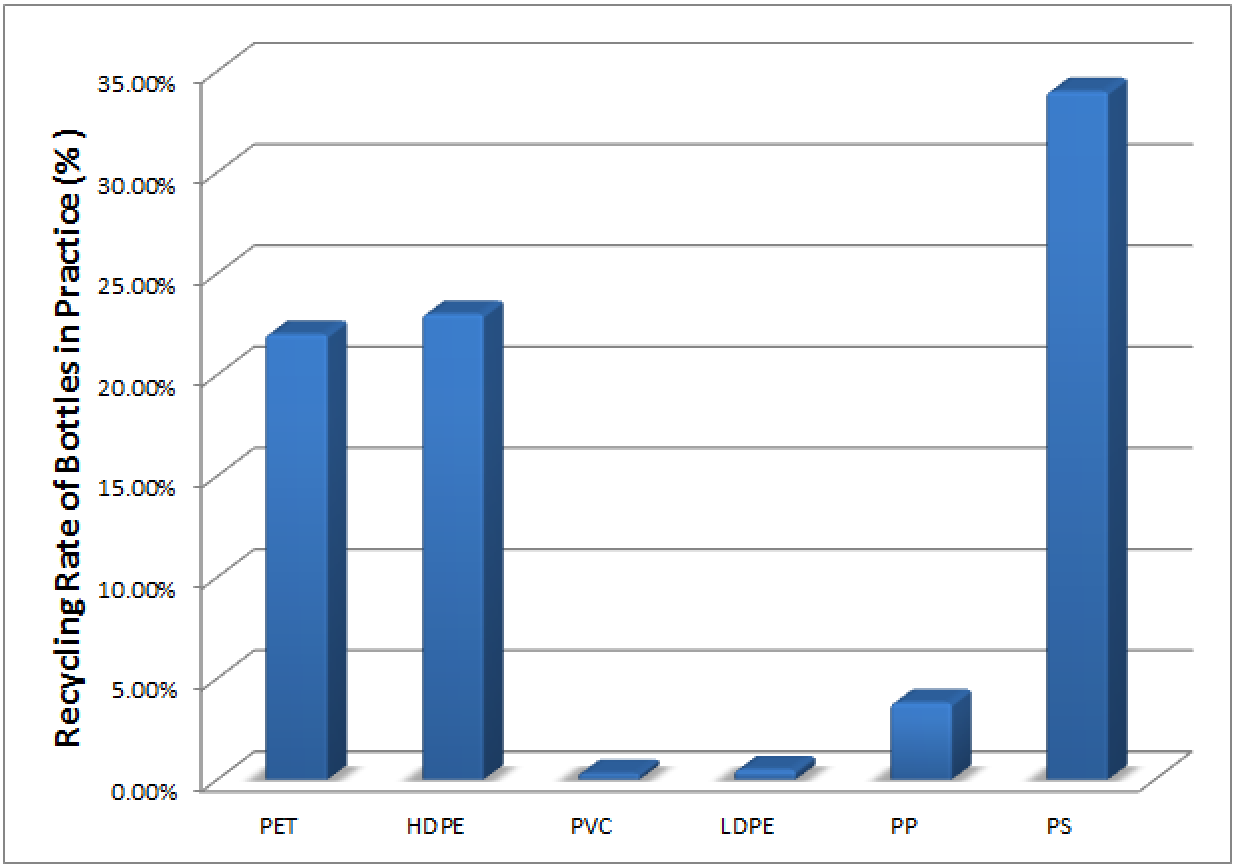

Figure 4: Percentage of all bottles recycled amongst each plastic group

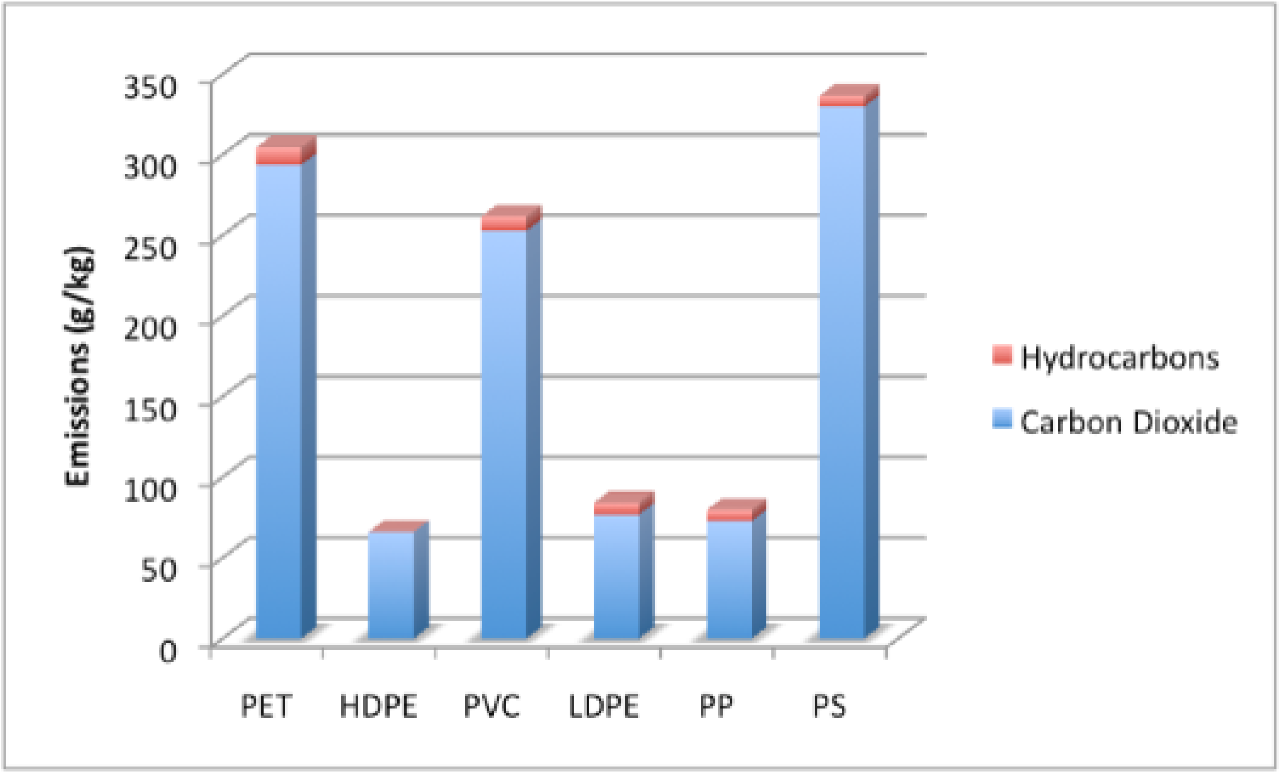

Figure 5: Manufacturing Emissions

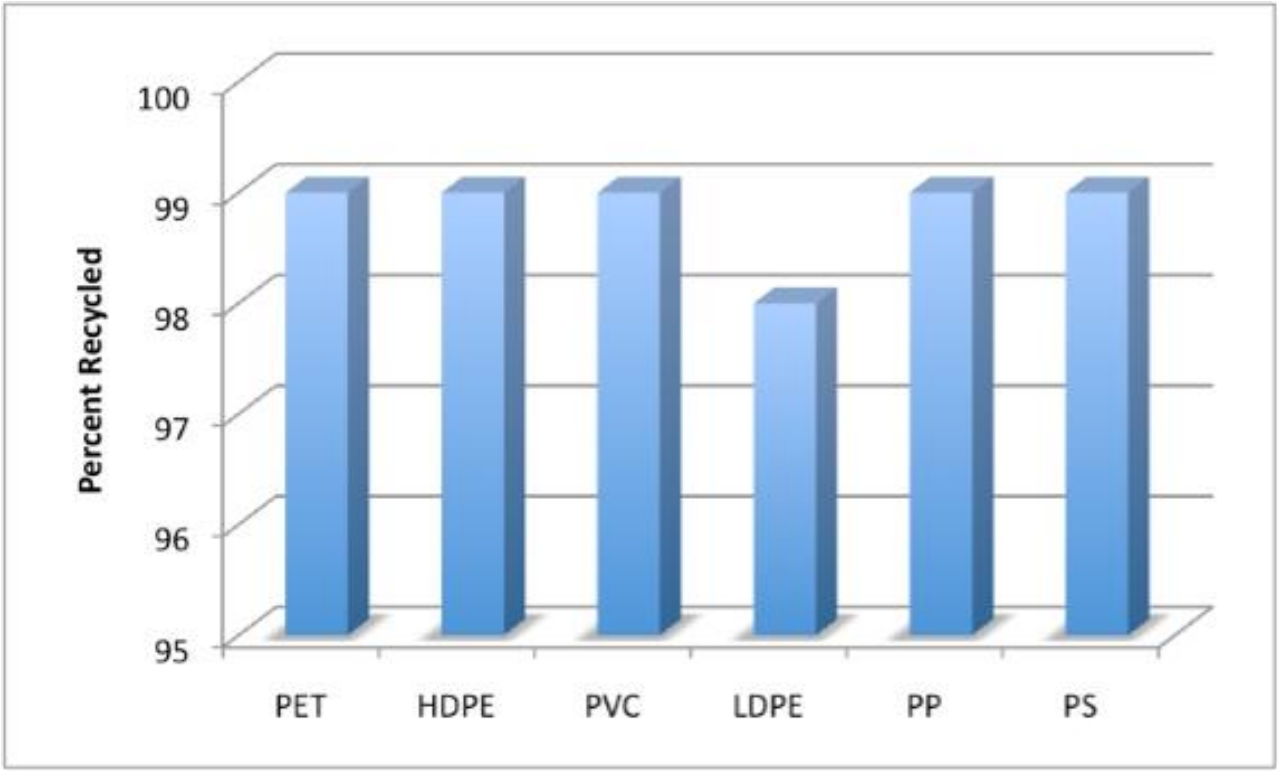

Figure 6: Recyclability

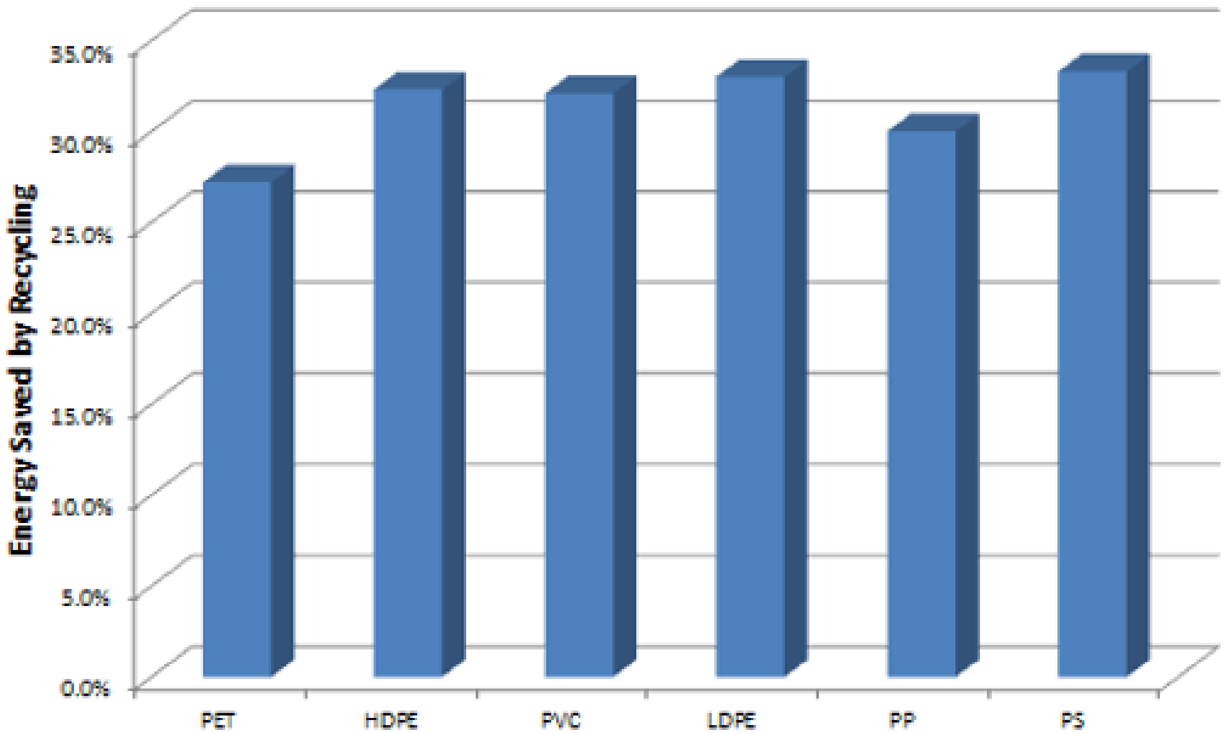

Figure 7: Energy Saved by Recycling

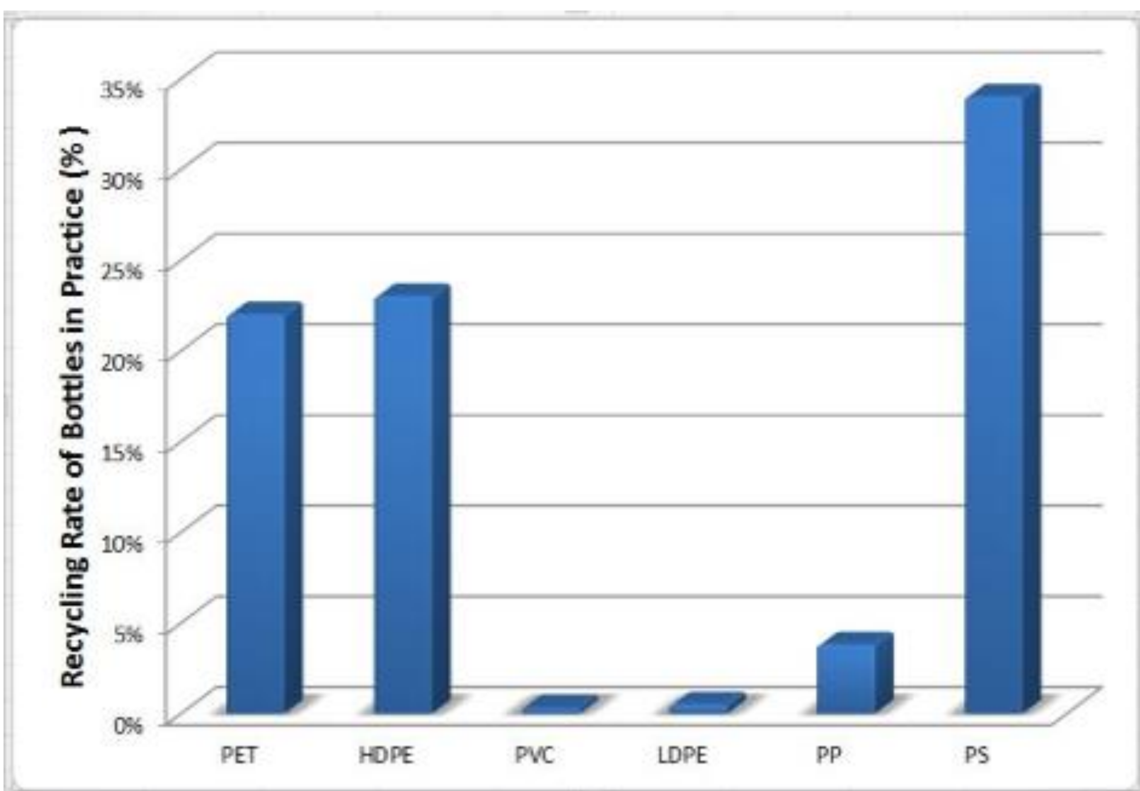

Figure 8: Recycled Rate of Plastic Bottles

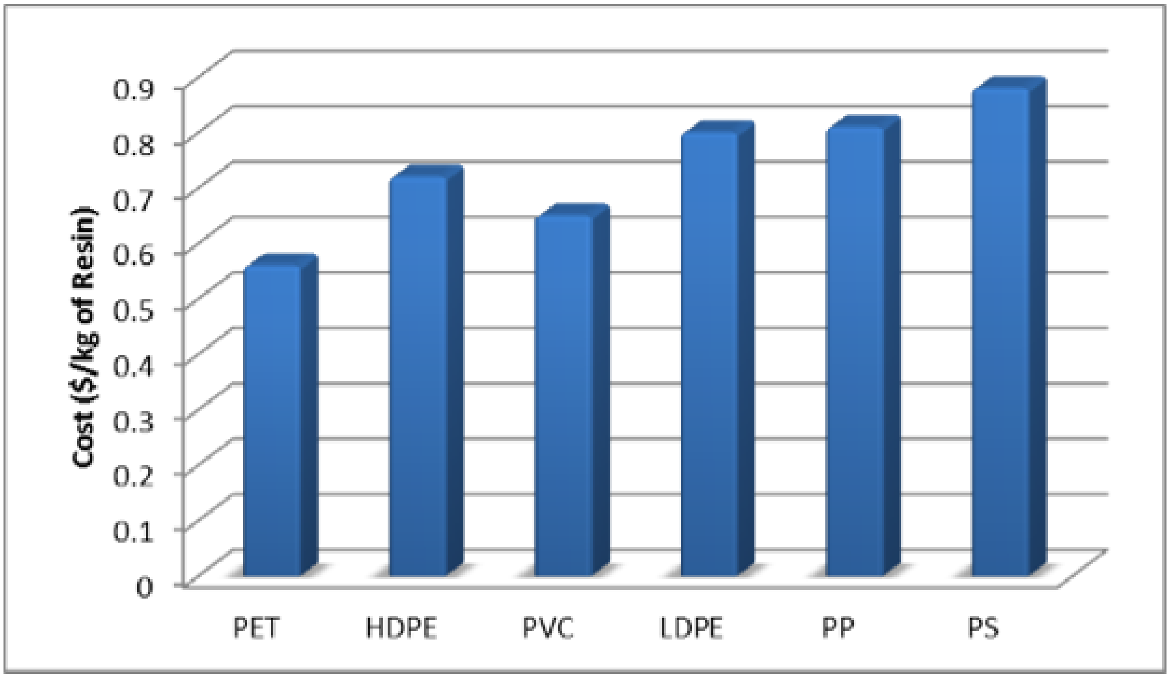

Figure 9: Manufacturing Cost