Technology, Energy Input, and Process Flow for Plastic Recycling: Optimization of Material Recovery and Environmental Impact Reduction in Circular Economy Systems

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ABSTRACT

Millions of tons of plastic are produced worldwide every year. The plastic waste may go down several paths through its life, including being sent to a landfill (85.5% in the US), recovered for energy (7.7%), or recycled (6.5%). This paper discusses current and prospective recycling methods, comparing primary and secondary mechanical recycling, technologically developing chemical recycling (including Idaho National Laboratory's ChemPren process), and energy recovery. Material and energy flows were created for nominal polyethylene terephthalate (PET),high density polyethylene (HDPE), andpolypropylene(PP) bottle recycling facilities in the United States. The energy and emission rates for these mechanically recycled plastics is significantly lower than with virgin pellet production, but has higher costs, including transportation and waste sorting. Energy recovery, although cheaper than landfills, produces the highest carbon dioxide emissions of all plastic end of life routes.

KEYWORDS: Plastic, PET, HDPE, PP, Recycling, ChemPren.

1. INTRODUCTION

Plastics are polymers, or molecules made of long chains of atoms, that have the capability of being molded into various shapes under the influence of heat and pressure [1]. They are typically made of either solely carbon or a combination of carbon with oxygen, nitrogen, or sulfur in the backbone chains, which can alter the properties of the plastic [1]. Plastics are commonly used because they typically have benefits such as low weight, durability and low-cost relative to other material types [2]. Various types of plastic polymers have numerous uses worldwide, from single use food packaging and toys, to medical equipment, and car components [3]. Millions of tonnes of plastic are produced per year – 24.6 million tonnes in the European Union in 2007 and 33.6 million tonnes in the United States in 2008 [2,4]. Approximately 50% of this plastic was produced for single-use applications such as packaging and disposable consumer items [2], which means that much of this plastic quickly becomes waste. There are a few different methods utilized to process the waste product at the end of their use. The most common is sending the plastic to landfills, as depicted in Table 1, comprisingthemajorityat85.5% (28.9 million tonnes) in the United States in 2008 [2,4]. However, with decreasing space and consequentially increasing costs to landfill usage, alternatives to landfills are currently being researched and developed [5].

Table 1. Percentage use of the end of life for plastics in Western Europe in 2003 and in the United States in 2008 [2,4].

	Western Europe, 2003	**United States, 2008**
Mechanical Recycling	15%	6.5%
Feedstock Recycling	2%	-
Energy Recovery	22%	7.7%
Landfill	61%	85.5%

Sending plastics to landfills can be especially detrimental for the environment as it takes many plastics hundreds, if not thousands, of years to degrade [2]. Even biodegradable plastics may take considerable amounts of time to degrade as the rate of degradation depends on many physical factors such as ultraviolet light exposure, oxygen, and temperature [2]. Alternatives to sending plastic to landfills include: downgauging

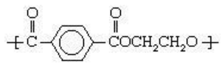
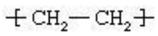
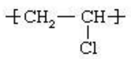
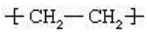
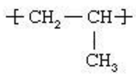
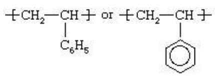
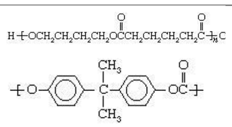
(reducing the amount of plastic), re-use of plastic packaging, and recycling. Reducing and reusing do not take considerable energy or produce any undesirable effects such as greenhouse gas emissions.

Recycling, on the other hand, does have an energy penalty and produces some emissions. The energy and emission penalty for recycling must be considered when comparing recycling techniques to landfill use. This paper will consider some of the many recycling techniques such as mechanical recycling, feedstock recycling, and energy recovery as shown in Table 1. It will also consider the energy and materials necessary to complete the process. Mechanical recycling processes plastic into flakes or pellets for future applications. Feedstock recycling is a form of chemical recycling where the plastic is first depolymerized and then repolymerized to be used as a feedstock in producing new petrochemicals and plastics [5]. This type of recycling is still a developing technology/ Although it is technologically possible to break down the plastic polymers for fuel, it is not economically feasible given the low cost of petrochemical feedstock [2]. Consequentially, only 2% of plastic waste was recycled with feedstock recycling in Western Europe in 2003, as shown in Table 1. Energy recovery is only partially considered a form of recycling, as no plastic remains, but the waste is incinerated and heat from that process is used as an energy source.

Not only are there several types of recycling, specific recycling techniques are highly dependent on the incoming plastic. Mechanical recycling, for example, relies on homogeneous or easily separable plastics [2]. Unfortunately, many types of products are made from highly mixed plastics, such as electronics [2], rendering it nearly impossible to mechanically recycle specific components.

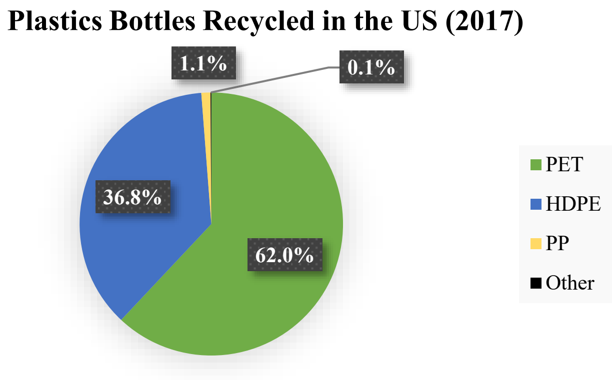
There are 7 common types of plastics with unique recycling numbers. Note there are many more types of plastics than these common ones. The recycling number is typically indicated on the product to show that it can be recycled. Recycling number 1 belongs to polyethylene terephthalate, commonly known as PET. This plastic is used for beverage bottles, textiles, and packaging films [6]. These PET bottles make up a considerable portion of possible recycling material - in the United States in 2017, for example, 1.27 million tonnes of plastic bottles were collected for recycling. This was only 29.3% of the total bottles disposed of, clearly indicating high development potential for this type of plastic to be recycled [7]. The other 6 recycling numbers are shown in Table 2, which includes the name of the plastic, its chemical composition, properties and common uses.

Table 2. Plastics with recycling numbers: composition, properties and common uses [1,6]

Plastic Name	Rec. #	Composition	Properties	Common Uses
Polyethylene Terephthalate (PET)	1		Moderately crystalline, high strength and stiffness	Beverage bottles (transparent), textiles, packaging films, recording tape
High Density Polyethylene (HDPE)	2	 (linear chains)	Highly crystalline, high strength, moderate stiffness	Milk bottles, automotive components, injection molding for toys
Polyvinyl Chloride (PVC)	3		Rigid, low flammability	Vinyl, pipe, shower curtains, boots, medical tubing
Low Density Polyethylene (LDPE)	4	 (branched chains)	Partially crystalline, highly flexible	Food packaging film, reusable bags
Polypropylene (PP)	5		Like Polyethylene but stiffer, higher melting temperature, oxidative-sensitive	Bottles, Car components, yogurt/food containers, toys, office supplies
Polystyrene (PS)	6		Rigid, brittle	Styrofoam™, eating utensils
Polyurethane (PUR), Polycarbonate (PC), Others	7		Versatile – multiple plastic types	Plastic glass, sponge, insulation, safety glasses, compact discs

The focus of this study is on recycling numbers 1, 2, and 5, or PET, HDPE, and PP, which are common plastics made for consumer bottles. As shown in Figure 1, the US predominately recycles PET and HDPE bottles, combined forming 98.8% of plastic bottles recycled in 2017, with PP at 1.1%, and other types at a minimal 0.1% [7]. Though it is possible to recycle all these plastic types, the US does not commonly recycle PVC, LDPE, PS, or other. Some plastics that the US does not recycle in large quantities are exported to other countries for recycling, such as LDPE and PVC [7].

Figure 1:



Plastic bottle types commonly recycled in the US in 2017 [7]

2. RECYCLING PROCESSES

As described by Hopewell, there are four main recycling processes: primary (mechanical), secondary (mechanical), tertiary (chemical), and quaternary (energy recovery).

Mechanical Recycling

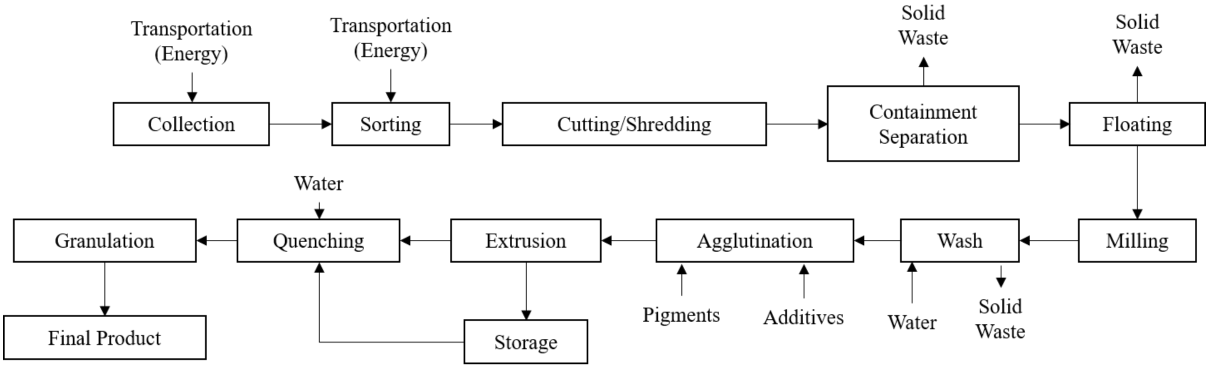
Primary recycling, also known as closed loop recycling, involves all recycled plastics being reused for their original purpose as they are not degraded during the recycling process. This type of recycling is best because it can completely replace virgin plastics (plastic that has not been recycled), reduce waste and lower the amount of plastic that must be produced. Popular types of plastic used in this method are clear PET bottles (i.e. water bottles), HDPE milk bottles, and clean industrial scrap materials. The mechanical recycling process is shown in Figure 2 (described later), with an additional step of recreating the original product from the plastic flakes or pellets. Unfortunately, a drawback to this type of recycling is that the polymer constituents must be pure or easily separable and not degrade during reprocessing. It can be extremely difficult to obtain homogenous plastic and have facilities that can separate plastic with enough precision to form plastics of virgin-level quality, hence why this process is mainly done for PET and HDPE pure bottles.

The most common form of recycling is secondary recycling, or downgrading [2]. This is also mechanical recycling, but the plastic is typically used for a different product post processing that allows for downgrades in the plastic's quality during recycling. Downgrading comes from heat and energy supplied causing photo-oxidation and mechanical stresses to the plastic [5]. This process can be done for single-polymer plastics, not suitable to be primarily recycled, but are still homogeneous and separable: including PET, HDPE, and PP. The biggest challenge for mechanical recycling is the inability to recycle mixed plastics, severely limiting the products that may be recycled in this way. However, given the best economic prospects, this type of recycling is the most common form of recycling, accounting for 15% of the total for plastic waste [2].

The process for mechanical recycling is shown in Figure 2 [2,5]. The process begins with the collection of recyclable material from either drop-offs at a recycling facility or curbside collection from individual residents.

This step requires transportation (which requires fuel), especially for curbside collection. Next, the plastic is sent to a sorting facility and is either manually or automatically (or a combination of the two) sorted based on desired plastic to be recycled. Automatic sorting is constantly developing, using methods such as Fourier transform near-infrared (FT-NIR) spectroscopy or lasers. After the material is sorted it is cut/shredded into small flakes and contaminates are removed. In contaminant separation, a cyclone is typically used to separate out paper, dust, and other impurities. Multiple methods are used to separate the plastic. Floating is a method where the plastic pieces are separated based on their density, which can be used to separate polyolefins (PP, HDPE, LDPE) from PVC, PET, and PS [2]. Separation techniques includesorting based on material properties and visual based techniques. After floating, the separated single polymer plastics are milled together. The milled together plastic is then pre-washed and dried with water to clean it. Sometimes a chemical wash is used in order to remove items such as glue (from labels). The wash may also involve supercritical fluid extraction (typically carbon dioxide) to separate the polymer from other fibers [8]. After sorting and cutting, the plastic pieces are collected together (agglutination) and processed with pigments and additives. After this step, the plastic may be sold as flakes or further processed. The analysis in this paper shows the energy inputs and emissions for various recycling processes which include processing plastic into pellets using extrusion, quenching, and granulation. Extrusion involves heating the plastic into strands, which are then quenched by water-cooling. After the strands are cooled, they are granulated to into pellets. The final product is the single plastic in pellet form. There are many applications that these pellets can be used for, so the consideration for recycling the plastic ends at the pellet stage.

Figure 2:



Mechanical recycling process for plastics [2,5]

Chemical Recycling

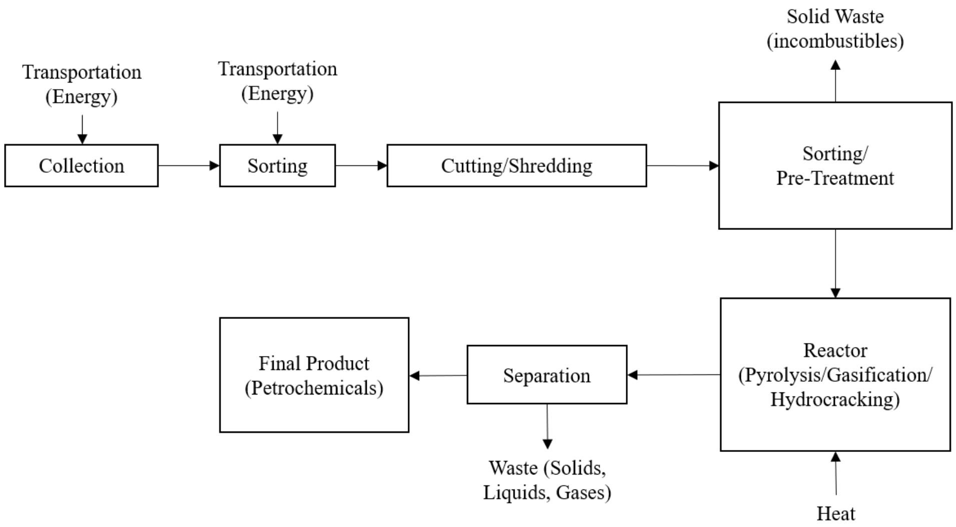
The third type of recycling is called tertiary recycling or feedstock recycling [2]. This is chemical recycling where the polymer is depolymerized (to a monomer) and then repolymerized to produce petrochemicals that may be reprocessed into a new plastic. Technologies to up-convert waste plastics to petrochemicals for the production of new plastics and materials, have been developed in the U.S., Japan, and Korea [9-12]. This type of recycling's main advantage is the ability to treat heterogeneous and contaminated polymers with limited pre-treatment [5]. Unfortunately, this process is still relatively expensive (when compared to petrochemical feedstock) and less energetically favorable than mechanical recycling [13]. An analysis of the inputs and outputs was not performed as this technology remains expensive and uncommonly used.

There are several processes for feedstock recycling [3,5]. The beginning of the process matches mechanical recycling, with collection, sorting, and pre-processing work. The chemical recycling processes then diverge byinvolving thermolysis, or treatment of the plastics with heat under controlled temperatures without catalysts. Figure 3 shows the basic thermolysis chemical recycling process. First, pyrolysis utilizes thermal cracking of polymers in inert atmospheres to produce fuels. The operating temperature ranges from 350 – 900 °C depending on the specific process and input materials. Next is gasification, which produces fuels or combustible gases from plastic solid waste using air or pure oxygen. The temperature for this process must be at least 500 °C (and up to 1200 to 1500 °C using the most common Texaco gasification process). Waste solids, liquids (tars) and gases are produced from the plastic during both processes. Another process for chemical recycling is hydrocracking,

which uses the high partial pressures of hydrogen to depolymerize the polymer. Again, these processes range from pilot scale to industrial capacity proven but are not widely utilized due to costs.

Developments in chemical recycling include fabricating new polymers specifically designed for energetically favorable degradation to lower costs [14]. There are also developments in combining biology and chemistry and using microbes for depolymerization. Finally, catalytic chemical recycling processes are being developed to decrease pretreatment (including sorting and separation) while lowering temperature/energy requirements to make chemical recycling economically viable. One of these catalytic processes currently being researched is Idaho National Laboratory's ChemPren process.

Figure 3:

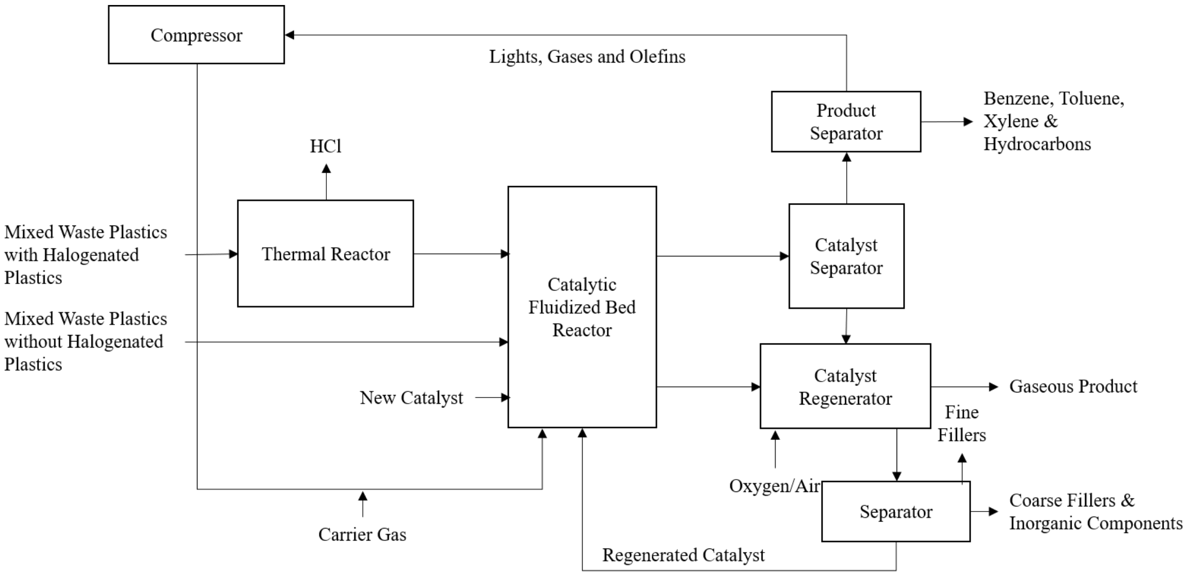


Basic chemical/feedstock recycling process. Note that the non-plastic components in the reactor (i.e air, oxygen, or hydrogen content) depend on the feedstock recycling process [5]

Idaho National Laboratory's ChemPren Technology

A recent technological innovation in feedstock recycling is called ChemPren. ChemPren is a technique that combines pyrolysis with a solid catalyst component made of zeolite with a modifier and metal alloy (Group VIII and transition metals) [15]. This fluid bed cracking occurs at around 538 °C [16]. The outcome is the same as pyrolysis in that it produces various petrochemicals, including Benzene, Toluene and Xylene (BTX) [15]. The overall process is shown in Figure 4. Note the mixed waste is pre-cut into pieces less than 1 cm to maximize surface area in contact with the catalyst [15]. The ChemPren process offers an advantage over previously considered chemical recycling processes because it can recycle mixed solid waste, including thermosets (such as polyurethane) with thermoplastics (such as polyethylene). It also has a minimal sorting step (reducing costs) because organic waste such as wood and paper are not detrimental to the recycling process [15].

Figure 4:



ChemPren recycling process [15]

Catalytic conversion of waste plastics to BTX was initially developed by ARCO chemical in the early to mid-1990s [9,10]. The BTX mixture is a versatile feedstock and can be used for the production of polyethylene terephthalate (PET), polycarbonates, polyurethanes, nylons, SBR, ABS and other polymers which are in turn used to produce beverage bottles, clothing, carpeting, automotive components and a broad range of other products. Intellectual property for improvements in the process and catalyst to up convert waste plastics to BTX was recently signed over to Idaho National Laboratory (INL) [15]. This technology will advance under DOE BETO funding if INL's encouraged pre-proposal is awarded as a full proposal to advance the technical readiness level from the current level of 4 to a level of 7 with the project culminating in demonstrating at least 1000 hours of pilot plant operation.

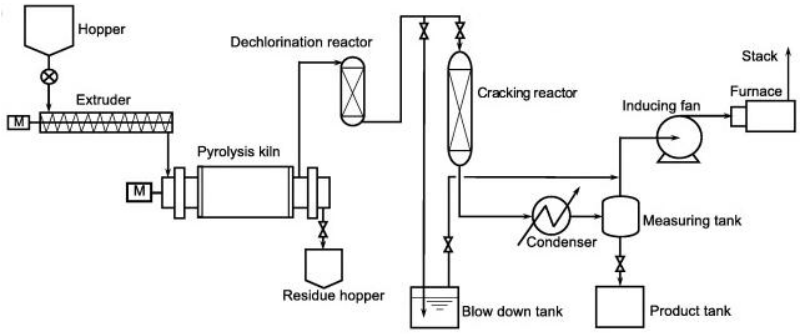
Although a 10 kg/hr pilot plant was built and operated recently in Japan [17], the system suffered many short comings including catalyst deactivation, pyrolysis kiln fouling and poor dechlorination. The pilot plant design was based on operation and testing of a 1 kg/hr bench system that used polypropylene as a feedstock [17]. That feedstock had order-of-magnitude lower levels of ash and chlorine compared to the mixed waste plastic that forced an early shutdown of the pilot plant at just 170 hours of operation.
In the proposed project INL would initially work with a 0.5 kg/hr bench scale system utilizing mixed plastics expected from typical non-recyclable materials. Project development efforts will focus on:

1. Pyrolysis kiln with residual solids removal,
2. Pyrolysis vapor dechlorination or optionally to be replaced by a supercritical solvent processing step to achieve dichlorination,
3. Stable and attrition resistant BTX catalysts or optionally to be replaced by other catalysts targeting other end products other than BTX depending on customer and market drivers,
4. Development of a reactor-regenerator process, and
5. Mass-Energy balance model to obtain preliminary TEA/LCA.

Once stable, the bench scale system will be operated for a minimum of 1000 hours.

Pending successful outcome of the bench scale demonstration, a 5 kg/hr pilot unit will be developed and operated for a minimum of 1000 hours. A potential schematic of the pilot system is shown in Figure 5.

Figure 5:



Potential BTX process flow [11]

The purpose of scale testing and analysis will be to develop engineering scale measurements to support process scale up, to develop sound TEA and LCA data, and to obtain an operational database and operational experience. Specific engineering data will focus on the pyrolysis kiln, the dechlorination reactor and the cracking reactor. The primary focus will be on the cracking reactor with data collection centered on catalyst reaction/regeneration cycles, catalyst make-up rates, and catalyst attrition issues.

INL has existing resources for bench scale studies and the 5 kg/hr pilot unit. The bench scale studies will be conducted at INL's Energy Innovation Laboratory (EIL). The existing automated solid/vapor catalyst testing system with integrated on-line analysis (GC/FID – GC/MS) will be modified for the BTX conversion reaction and process. Scale-up studies will employ the existing gas/solid reaction system located at the Bonneville County Technology Center (BCTC) (Figure 6). At BCTC, INL facilities include an integrated prototype system that provides gas flows of 5 liters per minute and pressure of 96 bar. The automated system includes an integrated Data Acquisition and Control System (DACS) that monitors, logs and controls temperatures, pressures and process stream flows along with product analysis by on-line fiber optic coupled Raman spectrometer.

Figure 6:

BCTC prototype gas-solid process system

As a second phase of INL's proposed technology, a novel low-temperature chemical approach to deconstructing and upcycling mixed waste plastic streams utilizing the heat and electricity generated from nuclear power plant (NPP). The key to achieving this vision is a novel non-thermal plasma reactor integrated with nanostructured zeolite-based catalysts to produce chemical building blocks of energy-dense fuels and valuable chemicals at low temperatures (< 300 °C) and low pressures.

In this new plasmachemical reactor, waste plastic stream is first deconstructed via breaking the C–C and C–H bonds by the highly energetic (1-10 eV) electrons generated from gas discharges in a high voltage electric field[18]. The intermediate species formed in the deconstruction process will then adsorb on the surface of the

zeolite-based catalysts and convert into various hydrocarbon products including paraffins, olefins, aromatic compounds, etc. In this configuration, the applied electric field controls the concentration of the hot electrons driving the formation kinetics of activated intermediates from plastic degradation. INL hypothesizes that incorporating zeolite-based catalysts into the discharge region will selectively stabilize the key reaction intermediates, H and C_xH_y, necessary for the production of paraffins, olefins, and aromatics while suppressing the deep decomposition or coke accumulation. By co-feeding hydrogen, oxygen, or water with the plastic stream, it is possible to further functionalize the hydrocarbon molecules into value-added oxygenate chemicals. When integrated with the low-carbon-footprint nuclear and renewable power sources, this unique approach could be disruptive both technically and economically by upcycling abundant waste plastics to valuable chemicals and fuels. The successful implementation of this technology will have high impact on the future energy horizon and to the environment.

The INL team has performed some proof of concept studies in the conversion of mixed waste plastic to marketable products and developed thermal catalysis-based ChemPren technology, which involves the fluid bed cracking of mixed plastic with a modified ZSM-5 catalyst at about 538 °C [16,19].A continuous process was proven viable which can produce gasoline and olefins with attractive economics. When combined with non-thermal plasma activation, it is anticipated that further improvement in the rate of waste plastic degradation by at least 50% and remaining solid less than 20% at much lower temperatures (<200 °C) could be achieved by the end of the project period.

The proposed plasmachemical approach has several unique advantages over the existing technologies, especially thermal pyrolysis, for the degradation and upcycling of waste plastics. First, the plasma-derived hot (highly energetic) electrons are highly efficient for breaking down the chemical bonds of plastics without significant input of thermal energy, thus allowing for much lower operating temperatures (<300 °C). Due to its non-equilibrium features, the non-thermal plasma could improve the reaction activity and product selectivity by enabling some thermodynamically unfavorable reaction channels/pathways that are not attainable via conventional pyrolysis. Second, compared with the plasma-only pyrolysis, the incorporation of highly efficient catalytic materials in the plasma reactor could selectively convert the intermediates from plastic degradation into more valuable chemicals and fuels, thus improving the energy efficiency and process economics. Third, the operating conditions of the plasma-catalytic process can be precisely controlled and the reaction time with non-thermal plasma is relatively short, which makes the process rapid, flexible, and potentially cost-effective.

The key technical risks/issues associated with the proposed technology development lie in the following thrusts: 1) the design and development of new advanced catalysts with improved activity and selectivity for depolymerization/cracking of plastics and coupling reaction of hydrocarbon intermediates; 2) the development of high performance non-thermal plasma reactor with homogeneous and non-filamentary discharges as well as facile incorporation of solid catalyst materials. A systematic approach will be employed to address materials and engineering aspects of the development. With the anticipated DOE funding support, this proposed work will engage multidisciplinary experts from both Idaho National Laboratory and industrial partners to investigate both the basic science needs and practical application requirements for conversion of waste plastics. The concerted efforts will ultimately promote innovative technologies that can utilize waste plastics as economical feedstock and accelerate the nation's transformation to sustainable future through collaborative research.

Energy Recovery

The final type of recycling is quaternary recycling or valorization [2]. It is also called energy recovery, as the process involved incinerating the plastic waste and converting the heat produced from this process into energy. This type of recycling has the highest carbon emissions associated with it, and only has advantage in reducing the volume of plastic waste to go into a landfill. It is best for highly mixed plastics such as electronic and electrical waste or automotive shredder reside, as these are not recyclable otherwise. It has the highest CO_2, SO_x, and NO_x emissions of all recycling techniques- typically even higher than leaving plastic in a landfill, and can also release other harmful substances such as heavy metals and other carcinogenic products.

It has been proven possible to net fewer emissions with energy recovery when compared to landfill, but only in cases where fossil fuels are the alternatives to landfill [20]. Non-recyclable plastics produce around 2.4 kg CO_2

equivalent/kg plastic when incinerated (for energy recovery). When considering the avoided heat and electricity from landfills, incineration can produce up to 4.1 kg CO_2 eq/kg plastic incinerated, averaging 1.7 kg CO_2 eq/kg plastic [20]. Mixed plastics produce around 2.55 kg CO_2 eq/kg plastic when incinerated. Also considering the avoided heat and electricity from landfills, incineration can produce up to 4.6 kg CO_2 eq/kg, also averaging 1.7 kg CO_2 eq/kg plastic incinerated [20]. Eriksson showed it was possible to see incineration have lower emissions than sending plastic to a landfill, but this only occurred once for each case (non-recyclable and mixed plastics) where fossil fuels were the alternative fuel. With an average of 1.7 kg CO_2 eq/kg plastic incinerated, energy recovery is worse for the environment than landfills when considering emissions; only having the advantage of limiting volume of waste stored in landfills.

3. MECHANICAL RECYCLING OF POST-CONSUMER BOTTLES

Material and Energy Balances

Material and energy balances were considered for the three most commonly recycled plastic bottle types: PET, HDPE, and PP. Note that analysis was not done for LDPE and PVC as these plastics are typically exported from the US [7]. Given that the most common type of recycling was secondary mechanical recycling, this is discussed in more detail in this study. Secondary mechanical recycling involves the production of plastic pellets of a lower quality than that of the virgin plastic. Inputs and outputs were calculated given nominal recycling plant sizes for each type of plastic [7,13,21]. Data for the inputs and outputs was collected as averaged from collection of the plastic to pellet (considered the final product). The process for mechanical recycling is virtually the same for each type of plastic (see Figure 2).

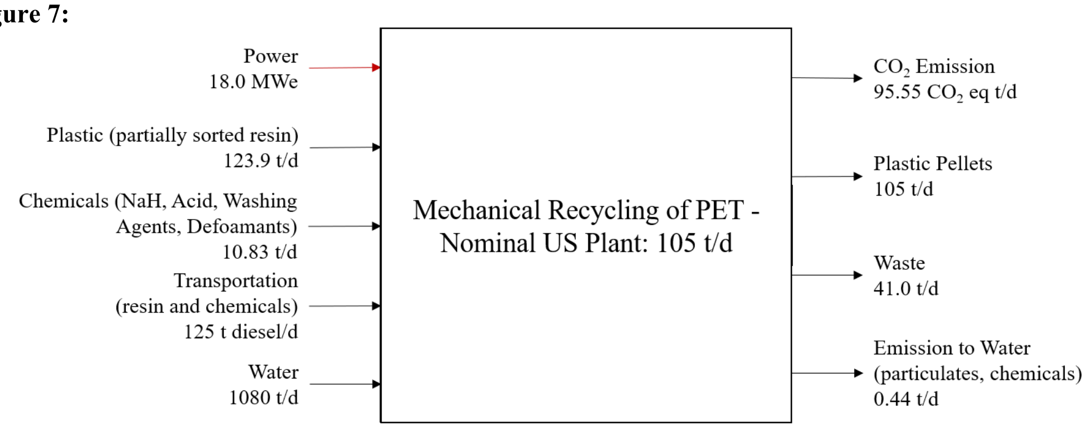
Nominal US plant size for each plastic is based on the total collected plastic waste size (in 2017) [7] divided by the total number of recycling plants existing for each plastic [21]. The results of this analysis are shown in Table 3. The nominal US plant is given in terms of the daily output of recycled material. Inputs include: amount of input material given to the nominal plant, chemicals for treatment (including NaH, acids, washing agents, and defoamants), average mass of diesel used for transporting both the plastic from single-stream collection and chemicals required for treatment, electrical energy use in the recycling plant, and water used for washing and quenching. Outputs include: Carbon dioxide emissions, particulates and chemicals emitted to used water, solid wastes, and the recycled pellet (equal to nominal US plant size).

Table 3. Common plastics with inputs and outputs for secondary mechanical recycling method and nominal plant size [13,21].

Plastic	Nominal US Plant (t/d)	Inputs: Material (per nominal output in t/d)	Input: Chemicals (t/d)	Input: Transportation (t diesel/d)	Input: Energy (MWe)	Input: Water (t/d)	Output: CO_2 (t CO_2 eq /d)	Output: Emission to Water (t/d)	Output: Solid Waste (t/d)	Output: Finished Product (t/d)
PET	105	123.9	10.830	125	18.0	1080	95.55	0.4427	41.0	105
HDPE	47	55.9	0.295	121	4.7	160	26.32	0.0644	23.5	47
PP	1.4	1.6	0.005	3.3	0.14	6.5	0.74	0.0006	0.7	1.4

Figure 7 shows anominal PET plant energy and material flow process diagram. The PET plant recycles the most amount of plastic per day given there were a similar numbers of plants recycling each type of plastic. PET consists of more than half of all recycled bottles. Therefore, a nominal plant processes around 105 tons/day, consuming 18 MWe of power.

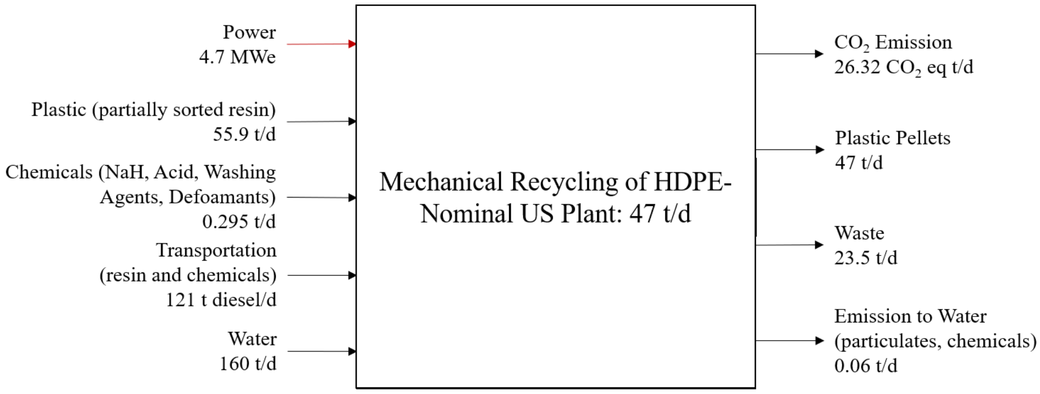
Figure 7:



Energy and material flow process diagram for mechanical recycling of PET

For secondary recycling of HDPE (mainly milk bottles), the energy and material process flow diagram is shown in Figure 8. The HDPE plant is smaller than the nominal PET plant, as again a similar total number of plants exist with fewer plastic to be recycled. Recycling HDPE requires significantly less power than the PET plant relative to the amount of recyclable material.

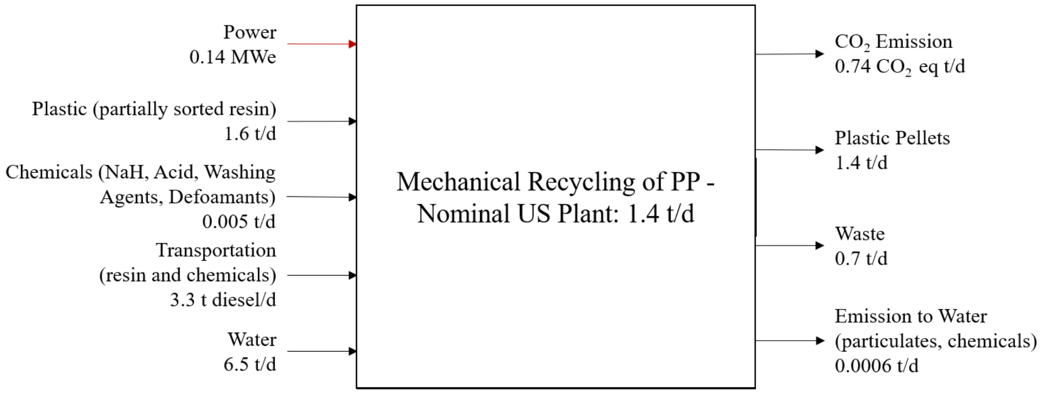
Figure 8:



Inputs and outputs for a nominal US plant recycling HDPE

Figure 9 describes the inputs and outputs for a PP plant, nominally outputting the smallest amount of recycled material per day. As the PP plant is nominally the smallest, it requires the lowest amount of power.

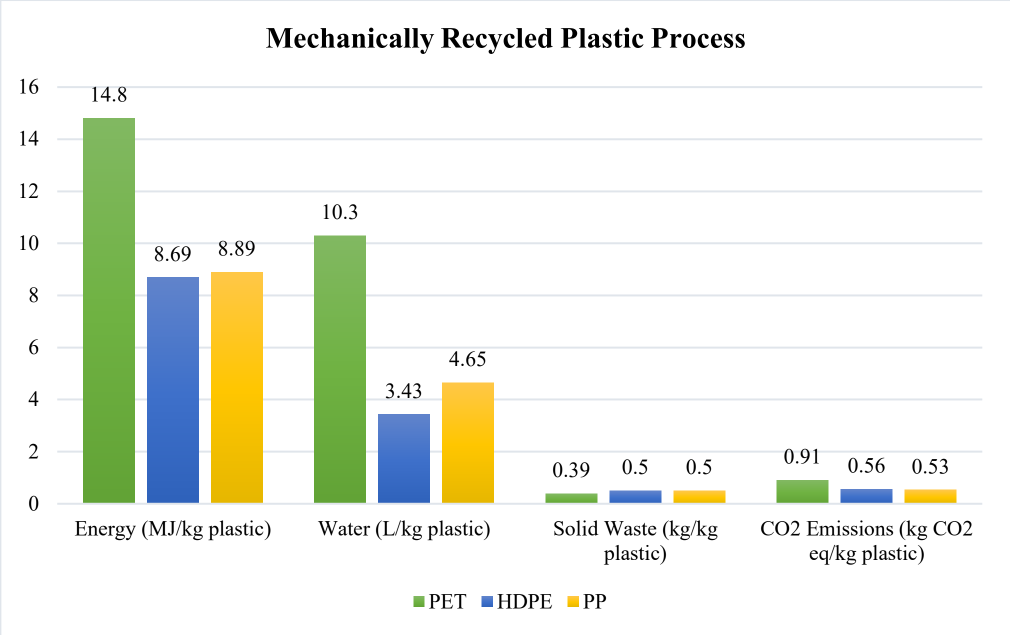
Figure 9:



PP nominal US recycling plant inputs and outputs

Figure 10 shows the direct comparison of inputs and outputs for the mechanical recycling plant process. This compares the direct quantity of energy, water, or solid waste per kg of recycled material. It is clear from the diagram that PET recycling takes in the most energy and water while having the highest carbon dioxide equivalent emissions but produces the least amount of solid waste. HDPE and PP have similar amounts of waste and emissions, but HDPE has the lowest energy and water requirements. It should be noted that all recycled material requires either less than or a similar amount of water and energy and produce lower carbon dioxide emissions than manufacture of virgin plastics [13]. However, recycling does consistently produce more solid waste than virgin plastic production [13], due to the required separation process.

Figure 10:



Comparison of inputs (energy and water) and output (solid waste and CO_2 emissions) per kg of plastic recycled for PET, HDPE, and PP.

Cost Analysis

The current price of recycled resin for PET, HDPE, and PP in pellet form is shown in Table 4 and compared to virgin pellet price[22]. The recycled resin is taken as the price of a post-consumer pellet for PET and HDPE, and industrial pellet for PP (which is assumed to be similar to the post-consumer pellet). The virgin plastic price is estimated from the price of bottle resin for PET, blow molding homopolymer (dairy) for HDPE, and extrusion fiber for PP [22].

It is difficult to quantify the cost of taking materials to landfills, as it varies by region. It is also difficult to estimate the cost of transportation, as transportation of recyclable materials from curbside pickup makes up a large portion of the total cost. Additionally, sorting can be expensive during the recycling process. A 2017 study estimates the cost of recycling plastic from municipal solid waste [23]. In this study it was estimated that the cost of recycling was US $93.89 per ton compared to incineration costing $14.53 per ton and landfill $72 per ton. Note that these are estimates for a mid-size city (population of 87,000) generating 0.058 kg plastic per person per day. The cost of recycling is significantly higher than either energy recovery or landfill, given these averages. Energy recovery is the cheapest option given revenue from incinerated plastic energy but has highest emissions.

The cost of recycled material is also dependent on the price of virgin materials. In the past, recyclables have been economically viable with subsidies from the cities the recycling is picked up in and with proper

infrastructure in place. The price of recycled resin is typically less due to the lower quality of plastic produced during the recycling process. However, it is more energy efficient to recycle (see Table 5) which can bring total costs down, indicating recycled plastic still holds value with significantly lower energy requirements.

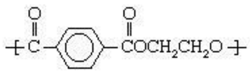
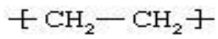
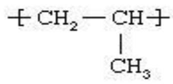
Table 4. Price of virgin and recycled plastic pellets, in US $/t[22]

Plastic	Virgin Pellet Price (US $/t)	Recycled Pellet Price (US $/t)
PET	1708-1752	1500-1675
HDPE	1455-1565	970-1124
PP	1378-1424	992-1080

Costs for plastic recycling could be dramatically reduced with smaller plants requiring less transportation. The average plant consumes 125, 121, and 3.3 tons of diesel per day for PET, HDPE, and PP, respectively. Assuming the average cost of diesel hovers around $3/gal [24], this corresponds to an average cost of $112,000, $108,000, and $3,000 per day for PET, HDPE, and PP in transportation expenses alone. Collection and some sorting typically does not occur at the same location as the recycling process, leading to additional transportation expenses. If new, small recycling plants were built near or at these collection sites, there are potential savings to make plastic recycling more cost effective.

Summary
A summary of the recycling of PET, HDPE, and PP is shown in Table 5. This table also includes the percentages by weight each plastic takes up in an average truck load of recyclable materials for single stream collection (consisting 91.8 of total collected material) [7]. From that analysis, 2.8% of every truckload was PET, 1.5% HDPE, 0.3% PP, other plastics 0.9%, non-plastic recyclables such as paper, aluminum, steel, and glass makes up 83.8%, and non-recyclables 10.7%, respectively [7]. From these statistics it is clear these plastics only make up a small fraction of total recyclable material. Table 5 also includes a comparison of the energy and water requirements as well as solid waste produced, carbon dioxide emissions and price per pellet for virgin pellet production (including feedstock energy) and recycled pellet production [7]. When compared to the virgin pellet, less energy is required for all plastics, and less water is required with the exception of PET recycling. More solid waste is produced with recycled material, which is due to wastes from sorting and chemical separation.

Table 5. Mechanical plastic recycling with comparison to virgin plastic production

	PET		**HDPE**		**PP**	
Composition			 (linear chains)			
Common Uses	Beverage bottles (transparent), textiles, packaging films, recording tape		Milk bottles, automotive components, injection molding for toys		Bottles, Car components, yogurt/food containers, toys, office supplies	
% of Bottles Recycled	62.0%		36.8%		1.1%	
Weight Percent Per Truck Load of Recyclables	2.8%		1.5%		0.3%	
Pellet	**Virgin**	**Recycled**	**Virgin**	**Recycled**	**Virgin**	**Recycled**
Energy (MJ/kg plastic)	69.8	14.8	75.3	8.69	74.4	8.89
Water (l/kg plastic)	9.89	10.3	8.33	3.43	8.58	4.65
Solid Waste (kg/kg plastic)	0.14	0.39	0.07	0.5	0.078	0.5
CO_2 Emissions ($kgCO_2$/kg plastic)	2.78	0.91	1.89	0.56	1.84	0.53
Price of Pellet (US $/t)	1708-1752	1500-1675	1455-1565	970-1124	1378-1424	992-1080

4. CONCLUSION

In this study the focus was on energy inputs and process flow for plastic recycling. Since mechanical recycling is predominantly used, it was analyzed in detail. A mechanical recycling plant is a better option for the environment (producing fewer emissions and requiring less energy) than a virgin plastic plant, for the cases studied (PET, HDPE, and PP). However, recycling is costly and typically provides lower quality material than virgin plastics. PET, mainly seen in water bottles, makes up the majority of recycled plastic, followed by HDPE, which makes milk bottles, and then PP, seen in other beverage bottles and other food containers. A nominal PET plant requires the most energy and water and produces the highest CO_2 emissions per unit mass of plastic recycled, when compared to HDPE and PP.

Chemical or feedstock recycling has an advantage over mechanical recycling in that it can recycle heterogeneous and non-separable plastics, but it does not have a high technological readiness level (pilot scale). It is also not cost effective due to the low cost of petrochemicals. Technology is advancing for chemical recycling through processes such as INL's ChemPren. Energy recovery releases higher CO_2 emissions than placing plastic waste in a landfill. It is used because of volume savings and some energy production, and may be a more economical option. In the future, with technological advancements and efficiency increases for both mechanical and chemical recycling, these pose significant advantages over plastic waste filling up landfills. With the large amounts of plastic being produced every year, it is important to have recycling methods. These methods are not perfect, and still intake energy and release some emissions. However, they are typically better for the environment than sending plastic waste to a landfill. Current mechanical recycling technologies are also economically viable in the current state, given subsidies and the price of oil.

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