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Recycling of Plastics in the United States: Plastic Material Flows and Polyethylene Terephthalate (PET) Recycling Processes

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Abstract

As efforts are made toward establishing a circular economy that engages in activities that maintain resources at their highest values for as long as possible, an important aspect is understanding the systems which allow recycling to occur. In this article a common plastic, polyethylene terephthalate, i.e., PET or plastic #1, has been studied because it is recycled at relatively high rates in the U.S. as compared to other plastics. A material flow analysis is described for PET resin showing materials collected, reclaimed for flake, and converted into items with recycled content. Imports/exports, reclaimer residue, and disposal with mismanaged waste are all shown for U.S. flows of PET. Barriers to recycling PET exist in the collecting, sorting, reclaiming, and converting steps, and this article describes them, offers some solutions, and suggests some research that chemists and engineers could focus on to improve the systems. This effort also models sorting at material recovery facilities (MRF) and reclaimers, with detailed descriptions of the material streams involved, to characterize the resource use and emissions from these operations that are key processes in the recycling system. Example results include greenhouse gas intensities of 8.58 kg CO_2 equiv per ton of MRF feed and 103.7 kg CO_2 equiv per ton of reclaimer PET bale feed. The results can be used in system analyses for various scenarios and as inputs in economic input-output and life cycle assessments.

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ASSOCIATED CONTENT
Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.1c06845.
Spreadsheet calculations for PET flows for material flow analysis (XLSX)
Spreadsheet calculations for MRF material calculations, MRF emissions and greenhouse gases, and reclaimer emissions and greenhouse gases (XLSX)

Complete contact information is available at: https://pubs.acs.org/10.1021/acssuschemeng.1c06845

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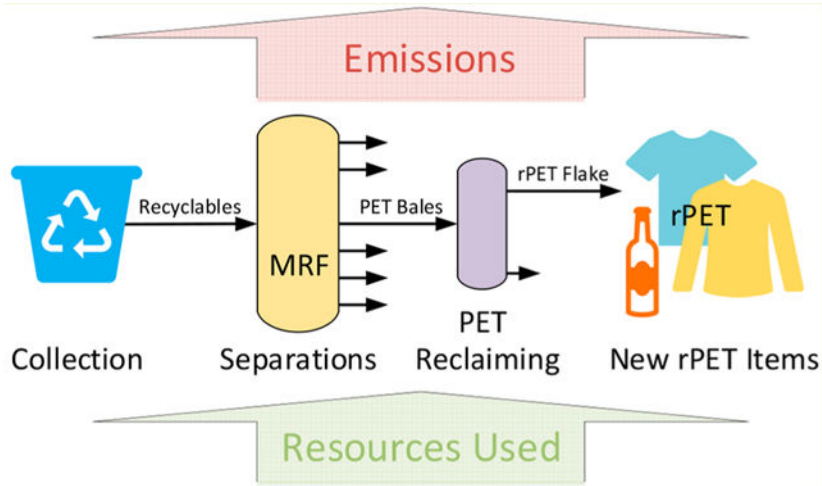
Graphical Abstract



Keywords

Plastics; Polyethylene terephthalate (PET); Recycling; Material recovery facilities (MRF); Processes; Resource use; Emissions

INTRODUCTION AND BACKGROUND

Plastics are used in many products throughout the world, making them economically important and a potential cause for environmental concern if managed improperly at the end of their life. Plastics are an important element in developing a sustainable world, one where the social, economic, and environmental aspects are recognized and effort applied to improve them. Plastics provide benefits due to their properties, from barriers, to flexibility, to ease of use, etc., and these properties are most often delivered at low cost. Since plastics are so ubiquitous in our society, this can pose issues including postconsumer municipal solid waste (MSW) management pollution, litter that can be found on land and at sea, and more recently how bits of plastic (i.e., microplastics) can enter food chains.

It is estimated that approximately 8 300 megatonnes (Mt) of plastic has been produced since the 1950s, and during this period, 6 300 Mt of plastic waste has been generated, most of which has been disposed in landfills.[1] Plastic demand in the 1950s was about 2 Mt/year,[1] whereas in 2019 it increased to 368 Mt/year,[2] and it is predicted that this demand will continue to increase, quadrupling by 2050.[3] This growth in plastic use will lead to a surge in the generation of plastic waste, and it is estimated that about 12 000 Mt of plastic waste will be in landfills or in the environment by 2050.[1] This poses a huge risk to the environment and wildlife in addition to the loss of enormous amounts of valuable materials. To address these risks, the Ellen MacArthur Foundation and others advocate efforts toward a circular economy, and before recycling they recommend opportunities to eliminate, reuse, or innovate the upstream plastic packaging systems that lead to so much plastic waste.[4]

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The large flows of postconsumer plastics also offer an opportunity for chemists, engineers, and material scientists to understand the current system and consider improvements. Chemists may develop new methods to integrate changes in chemistry into polymer chains and/or additives, improving properties and removing potential issues. Likewise, engineers and material scientists may discover new applications or processing to improve the products and systems for postconsumer management of plastics.

To understand potential changes to the product and system, a first step is to quantify the materials and processes involved. This article provides estimates of flows of materials and models of processes so that perceived barriers to innovation can be recognized and removed and thus improving systems. The idea of quantifying material flows is not new. Frosch and Gallopoulos,[5] two pioneers of industrial ecology, did early work on material flow analysis for platinum, and Graedel provides a recent review of history, methodologies, and uses of material flow analyses (MFA).[6] The idea of the analysis is to provide a description of how society uses a specific set of materials, if and how they are recycled, and the fate of materials whether they leak from the system or are managed. As Graedel defines its attributes, MFA studies the system of flows for a material (or group of materials), describing each flow, applying conservation of mass to the flows, and illuminating the results with diagrams and numbers.[6]

The flow of materials in society is also the focus of efforts with economic input-output models. These analyses describe the economy by sectors and model the flow of economic accounts through production and demand. The flows between sectors can be described with diagrams and tables showing final demands, inputs, value added, and intermediate flows.[7] An extension of input-output economic methods is the U.S. Environmentally-Extended Input-Output (USEEIO) model, which includes land, mineral, water, and energy use as well as releases of greenhouse gases, nutrients, and criteria and toxic emissions.[8] The USEEIO model supports U.S. Environmental Protection Agency efforts on sustainable materials management, i.e., using less materials and being the most productive with materials that are used, maintaining resources for today’s and tomorrow’s needs and reducing environmental impacts throughout the lifecycle.[9] As this article develops models that are within the recycling postconsumer plastics sector for the U.S., it also supports the USEEIO model.

Postconsumer materials are managed in the U.S. under the Resource Conservation and Recovery Act, which establishes a framework for a national system of solid waste control. It provides the U.S. Environmental Protection Agency with specific regulatory authority for nonhazardous waste, while state governments play a lead implementing role and may have more stringent requirements. Due to challenges facing the U.S. recycling system, many organizations (federal, NGOs, environmental, industry) provided input in the development of a National Recycling Strategy.[10] This strategy is aligned with the National Recycling Goal to increase the recycling rate to 50% by 2030. There are five main objectives in the strategy: to improve markets for recycled commodities, to increase collection and improve materials management infrastructure, to reduce contamination, to enhance policies and programs to support circularity, and to standardize measurement and increase data collection. As this article aims to accurately describe aspects of plastics recycling, it is aligned with some of these objectives, and others will be recognized in barriers to increasing recycling with some suggestions for overcoming them. In accurately describing flows in recycling, this effort also supports another EPA mainstay, the Facts and Figures about Materials, Waste, and Recycling,[11] which for many years has described U.S. management pathways for postconsumer materials.

The management pathways for postconsumer materials can be improved through a concerted effort of sustainability conscious chemists and engineers, who focus research on improving the materials, products, and systems for recycling. Chemists might find opportunities for their efforts by understanding the flows and systems of plastics. For instance, development of new or improved stable catalysts with very high activity and selectivity is an important factor in improving current solvolysis processes in chemical depolymerization. Similarly, development of highly active stable enzymes for depolymerization of polymers with very high selectivity would be beneficial. In addition, to obtain pure monomers by depolymerization, it is critical to have optimized dissolution/precipitation processes to recover polymers (from plastic waste) that are free of additives.[12] In recent years, new plastics are designed with special features that allow them to be biodegraded, composted, and recycled with an emphasis of achieving a more sustainable plastics economy.[13] Polylactic acid (PLA) is a biopolymer which is most widely used in bioplastics production, and PLA is a potential replacement in conventional plastics applications such as cups, bottles, to-go containers, packaging, films, and textiles, etc. Bioplastics can potentially benefit the environment by replacing conventional fossil-derived feedstocks with renewable alternatives, reducing GHG emissions, and utilizing renewable resources.[14]

Some of the barriers for recycling plastics include contamination with a trace amount of different types of plastic materials, additives, catalysts, etc. To increase recycling, a solution could be to limit the types of plastic used to a single type for manufacturing products and packaging, which makes it easier to recycle. Another major barrier is the low cost of virgin monomer material produced from fossil feed stock when compared to recycled material. An alternate approach to overcome the low cost of virgin monomers is to convert the postconsumer plastic to high value-added chemicals or materials by upcycling. For example, use of waste plastic for manufacturing transparent conducting films for photovoltaics, battery electrodes, and carbon nanotubes. Specific oligomers produced by depolymerization can be used as additives.[12]

Before many barriers to recycling can be addressed, it is valuable to know how much plastic material is flowing through the economy. This study is not the first one to consider material flow analyses of plastics in the U.S. For PET, Kuczenski and Geyer created a map for the years 1996−2007.[15] More recently, studies have included several common polymers (including PET), which enabled them to show interactions between product types made of different materials, and they were able to follow durable goods to track the stocks of materials.[16,17] A European study of PE, PP, and PET flows used system dynamics to evaluate scenarios.[18] As Graedel points out, material flow studies are often linked to other analyses, for instance, economic input-output models, life cycle assessments, and scenario analyses.[6] Without specifically creating the linkages, it is expected that this study will further each of these types of analysis.

When contemplating the recycling of plastics, it is important to understand their composition, as there are two main categories: thermoplastics and thermosets. Thermoplastics can be melted into liquid whereas thermosets cannot. Thermoplastics constitute about 85% of plastic production,[19] and they include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and expanded polystyrene (EPS). Polyurethane (PUR) is the most produced thermoset.[2]

The composition of plastics includes more than the fossil-fuel derived polymer chains, as additives, such as antioxidants, light stabilizers, ultraviolet (UV) absorbers, flame retardants (FR), heat stabilizers, impact modifiers, plasticizers, compatibilizers, coupling agents, colorants, pigments, and whiteners, are added to polymers to provide increased functionality for broad ranges of plastic applications. In plastics manufacturing, additives are often used to enhance physical, mechanical, or chemical properties and to prolong the life of the product by protecting the polymer from the degradation effects of light, heat, or bacteria.[20] Since the information on the types and amounts of additives is largely confidential and proprietary,[21] public data sources do not have well-documented data, and it is estimated that the additives range from 6.4% to 10% by weight.[1,22] However, for specific types of polymers, a wider range of estimates are reported, as for example, the amounts of additives used in LDPE, HDPE, PP, PET, PS, and PVC have been estimated to be 25%, 25%, 15%, 25%, 6%, and 30%, respectively.[23] Additive amounts in plastic films, injection-molded goods, extrusion coatings, and plastic sheets are approximately 4−5%, 6−10%, 7%, and 15%, respectively.[24] The various percentages from these references confirm the large uncertainty regarding the amounts of additives in plastics.

Additives for plastics are divided into four main categories: (1) functional additives (stabilizers, antistatic agents, flame retardants, plasticizers, lubricants, slip agents, curing agents, foaming agents, biocides, etc.), (2) colorants (pigments, soluble azo-colorants, etc.), (3) fillers (mica, talc, kaolin, clay, calcium carbonate, barium sulfate), and (4) reinforcements (e.g., glass fibers, carbon fibers).[20] These additives, in most cases, are not chemically bound to the plastic polymer. Only the reactive flame retardants are bound to the plastic molecules and become part of the polymer chain. Several studies have been conducted to understand the potential release of various toxic substances like phthalates, brominated flame retardants (BFRs), BPA, bisphenol A dimethacrylate, lead, tin, cadmium, formaldehyde, acetaldehyde, 4-nonylphenol, MTBE (methyl *tert*-butyl ether), benzene, and many other volatile organic compounds from various plastic products.[20] During recycling processes of plastics, various potentially toxic substances (e.g., toxic metals, BFRs, POPs and PAHs) could be released throughout the application of recycling techniques: sorting, reprocessing, and remanufacturing.[20] It is in fact these stages that influence the final quality of the recycled material. Some additives could even have a direct impact on the recyclability of plastics. While additives offer benefits by mitigating an immediate challenge in reprocessing, they further complicate the recycling process. For example, antioxidants cause issues in waste sorting, migration, and aesthetics.

As a case study, this article will examine PET resin, which along with HDPE is one of the two highly recycled plastics in the U.S. A very high-level schematic diagram of PET manufacture, product manufacture, use, collection, sorting, and recycling processes is shown in Figure 1. Although not shown in the figure, there are efficiency losses, resources used, and environmental releases from these processes. PET is manufactured by the condensation of chemical precursors terephthalic acid with ethylene glycol or by transesterification of dimethyl terephthalate and ethylene glycol followed by polymerization in the presence of a catalyst.[25] Since PET plastics are less susceptible to UV light, they are usually processed without protective additives. The production of PET is influenced by its demand for resin in packaging applications like bottles and various thermoforms and for polyester fibers in textiles, carpeting, and home goods. Virgin PET plastic has excellent mechanical properties, barrier properties, and processability.[26] Thus, PET resin plastic, the focus of this study, is a very widely used commodity-grade thermoplastic with high chemical and impact resistance at room temperature that is used extensively for injection-molded stretch-blown consumer packaging products such as water and soft drink bottles and as packaging for many other consumer products.[26] PET has many benefits as a recycled plastic whose melted polymer chains are compatible with virgin PET resin; thus, while PET containers must meet guidelines for crystalline melt point, color, labels, adhesives, etc., these attributes are attainable.[27] Postconsumer articles that go against these guidelines could be listed in the Barriers to Increasing Recycling of Polyethylene Terephthalate and Other Plastics section of this article; however, the intent is to list items that are not explicitly noted by the Association of Plastic Recyclers.

Various methods are available for handling postconsumer plastic, which include landfilling, combustion, and recycling, and a recent article by Lange has comprehensively reviewed these with some emphasis on a European context.[28] In the U.S. postconsumer PET plastic bottle recycling is done via curbside recycling, drop-off centers, as well as through reverse vending machines/collection points. There are two methods (see Figure 1) for recycling postconsumer PET plastic: (1) mechanical recycling and (2) chemical recycling.[29] In mechanical recycling, postconsumer PET plastic is sorted and reprocessed to produce a single type of polymer pellet, granule, or flake, intended to replace the virgin plastic in the market. This mechanical recycling process mainly involves melting and extruding the plastic without altering the chemical composition. Although the mechanical recycling process is economically viable when compared to chemical recycling, new materials produced by mechanical recycling are often of lower quality (as opposed to aluminum cans, for instance, which in theory can be recycled indefinitely). In addition, the presence of contaminants and additives complicates the mechanical recycling of plastics. In the chemical recycling process known as depolymerization, PET plastic ester groups are hydrolyzed at high temperature in the presence of certain catalysts such as manganese acetate, cobalt acetate, acetic acid, lithium hydroxide, sodium/potassium sulfate, and titanium(IV) *n*-butoxide to produce the basic monomer units.[30] Repolymerization of these pure monomers can produce high-quality products. However, depolymerization of PET plastic is not very widely used due to the unfavorable economic conditions relative to mechanical recycling.

This study will examine the systems for mechanical recycling processes for plastics and focus on barriers to increased recycling. It will propose ways to overcome some of these barriers. In addition to this study focusing on PET resin, we expect that experience with its systems will be useful for other plastics and products. The following items will be covered in the analysis below: (1) flows of plastics, for PET through U.S. production and recycling, and more generally various materials through material recovery facility (MRF) recycling, (2) simplified process models for material recovery facilities and PET reclaimers, which includes resource use and emission estimations, and (3) barriers to increasing recycling with some potential solutions.

Flows of Plastics: PET Case Study.

To understand the flows of materials such as plastics, it is reasonable to perform a material flow analysis. In this effort, PET was chosen as a material of interest because it is recycled at relatively high rates in the U.S. compared to other plastics, in part because PET can be collected as a relatively clean and once sorted homogeneous material, with enough quantity to make processing worthwhile. Also, efforts at recycling PET have been long-standing, creating a number of relevant references and data that are useful in tracking PET through the U.S. Even with these positive attributes, discovering flows for polymers in the U.S. often runs into roadblocks of confidential business information and the fact that there are many organizations that manufacture PET as well as in the recycling system performing collection, sorting, reclaiming, and converting.

One of the best sources for data about PET in the U.S. is the National Association for PET Container Resources (NAPCOR), the trade organization for PET packaging in North America.[31] NAPCOR information on 2018 bottle PET resin has been complemented with data for sheet and film, food, and nonfood uses of PET resin, calculations for U.S. mismanaged PET waste and other details as described in the Supporting Information. These values have been put together into a single diagram, Figure 2, to abstractly represent important aspects of the flows of PET resin in the U.S., while not recreating the Sankey diagram (i.e., literally proportional flows) developed by NAPCOR.[31] Not shown in Figure 2 is a calculated value for PET fiber in the U.S., 17 285 million lb (7 840 million kg) per year. Confirming this PET fiber amount is an approximation of 60% of commercially produced PET plastic is converted into fibers, 30% has been used in the production of bottles and 10% for other products.[32] Fiber is not a focus of this article, but it represents a very large amount of PET and may be researched in the future as an opportunity for recycling. Another focus for future work is uncertainty analysis, as it has not been considered in this effort.

Recycling of PET is described in Figure 2 through the flows of 1 816 million lb (824 million kg) of PET collected bottles and 6 270 million lb (2,844 million kg) of PET collected and uncollected bottle resin production per year. The ratio is an often-quoted recycling rate for PET, 29.0%.[31] Roughly two-thirds of the collected bottles are from curbside collection, i.e., 1209 million lb (548 million kg) per year. This same amount is assumed to be processed through MRFs, as described below.

Another ratio that can describe the efficiency of the recycling system is shown through Figure 2 in the values of U.S. Reclaimer Processed, i.e., 1 889 million lb (857 million kg) per year, and the U.S. recycled PET (rPET) flake, 1 238 million lb (562 million kg) per year. The ratio describes a reclaimer efficiency percentage, 65.5%. While this reclaimer efficiency certainly describes reclaimer processes as they make valuable rPET product, it is also influenced by the quality of PET bales fed to reclaimers. These factors will be discussed in more detail in the following sections. U.S. rPET flake is combined with imported quantities (about 60% of that imported is from Canada) to total rPET Converted in the U.S., which are then visualized in Figure 2 to produce various products including fiber (41%), food and beverage bottles (27%), sheet and film (17%), and others. While some bottles are exported and nonbottle material, imported bottles, and rPET flake enter the U.S. system, one could describe closed loop recycling of PET bottles by the flow of bottles produced from rPET, i.e., 441 million lb (200 million kg) per year and the initially collected bottles, 1 816 million lb (824 million kg) per year. This closed loop percentage equals 24.3%. Other versions of this indicator could be calculated using only U.S. rPET flake for the production of bottles or only including U.S. reclaimed bottles.

In addition, the colors of Figure 2 provide information about the PET recycling system. Yellow represents the production of nonbottle "thermoform" resin, blue collected bottles, and light red uncollected bottles. Uncollected bottles combine with most of the yellow nonbottle resin to become materials destined for disposal (dark red). In this article, an assumption was made that 2% of this for disposal postconsumer material is littered, and 0.66% is assumed to be illegally dumped,[33] thus, forming U.S. mismanaged waste in Figure 2. In this figure, one can easily see that very little nonbottle resin enters the recycling system in the U.S. Also, only a relatively small fraction of PET bottles is collected. These blue and yellow streams do combine to form reclaimed PET, flake, and converted rPET, although the relative amount is not that large. As one would expect, the counter combination of U.S. reclaimer residue (gray), disposal, and U.S. mismanaged waste (dark red) is large, together representing opportunities to improve the systems of collection, sortation, reclaiming, and converting, as described in the sections below.

RESULTS AND DISCUSSION

Plastic recycle flows begin with collection of recyclable postconsumer materials. Collection often includes cardboard, paper, glass, ferrous and aluminum cans, and plastic containers and packaging. Common contamination in the collected recycle stream includes trash, food, plastic bags and other plastic film, unwanted plastics, and assorted large items. The following sections will describe the flow of these materials through MRFs and PET reclaiming processes and provide a discussion on barriers to increasing recycling.

Flows of Plastics through Recycling Systems.

The process of recycling materials includes collecting desirable items, identifying materials correctly, sorting them appropriately, purifying streams of material, and processing a desirable quantity of material for further use.[34] Each of these steps is found within the process of collecting and sorting materials at a MRF. Normally, materials are collected curbside, at drop-off centers, or by commercial organizations and sent to MRFs for sorting and processing quantities of recyclable materials. These collected materials can be extensive, as described in the collection information presented in Table 1. The basis for Table 1 is the curbside collection of PET bottles, found to be 1 209 million lb per year in Figure 2, and other values in Table 1 determined in relation to this flow rate, with details described in the Supporting Information. Note that sometimes, other plastics #3−7 are purposely collected as recyclables, while other times they are collected as contamination, which is reflected in Table 1. An example is polypropylene (#5), which in some areas around the country is collected to be recycled and not in others.

The purpose of a MRF is to take collected recyclables and sort them into useable streams, although bales of sorted materials may need further purification or reprocessing before they are sent for manufacturing into recycled products. While the basis for the amounts in this table is the amount of PET bottles, as shown in the Supporting Information, a number of other references were used in defining relative flows. The recyclables listed in Table 1 are from the ASTRX Review of Material Flow at MRFs and Reprocessors,[35] while a combination of Oregon Metro Single-Family Recycling and Waste Composition Studies 2014−15[36] and Oregon Metro Commercial Mixed Recyclables Composition Study[37] were scaled to the 16.9% average contamination level found in the State of the Curbside Recycling Report.[38] For the purposes of this effort, Table 1 provides a reasonable representation of recyclables processed at MRFs. A more complete analysis could generate state-level data for collected recyclables or survey more MRFs to obtain a more complete picture of flows and variability.

Note that this listing of MRF sorted flows does not represent all recycled materials. Figure 2 shows that approximately a third of PET bottles are collected through deposit systems.[31] There are other methods used for additional materials. Commercial paper collection can be larger than the combination of curbside and drop-off collection.[39] For instance, Rumpke indicates that 46% of old corrugated containers (OCC) enter their MRF as clean commercial material.[40] This material does not get processed in the MRF, but it is combined with sorted OCC for baling. Other materials, like glass, might be collected separately, or in some communities not collected at all. Thus, Table 1 presents an average description of MRF inbound materials, but not a complete or nuanced one for specific communities.

Materials collected for recycling are most commonly acquired through curbside recycling collection, drop-off centers, container deposit return systems, and commercial organizations. The amount of curbside collection for the U.S. has been estimated by the Recycling Partnership at 11.9 million tons.[38] Curbside recycling is most likely to be contaminated, as described in a recent report from the Recycling Partnership, where an average inbound contamination rate of 16.9% (see Table 1) was found for curbside collections.[38] These contaminated materials create problems for MRF operators, from large objects, to food waste, to plastic films that can clog operating lines. Some contamination is particularly dangerous, like lithium batteries which can lead to MRF fires. The inbound contamination rate is differentiated from residues after processing at the MRF, with the amount of residue proportional to the amount of contamination in case studies.[41]

Inputs to MRFs include collected recyclables, electricity, fuels, and baling wire.[42] Resources used and a high-level summary of emissions are shown in Table 2, augmented by details described in the Supporting Information. Fitzgerald et al. report that natural gas is used for space heating at some MRFs located in colder climates, where they present the intensity of natural gas use for a MRF (presumably in the U.S. upper Midwest) as half that of electricity usage (i.e., electricity was converted to GJ and is roughly twice the GJ value reported for natural gas).[43] Other MRFs do not report space heating, so an engineering approximation is that 25% of U.S. MRFs in colder climates have space heating. Another engineering approximation is that where space heating occurs, it is used for 25% of the year. Thus, an average U.S. MRF will use natural gas at a rate half that of electricity usage multiplied by 25% for colder climates and 25% for fraction of the year. Outputs of MRFs include products and waste, in addition to air emissions and water releases.

Models of MRFs have been created by researchers who describe individual split factor estimations for materials and equipment.[44] A MRF separation table between inbound materials and products based on a U.S. MRF has been developed by Damgacioglu et al.[45] and was the starting point for calculations described in the Supporting Information. This analysis builds off of the inbound materials shown in Table 1. Nine of the products were determined to be (from largest to smallest flow) mixed paper, glass, OCC, PET, steel cans, mixed rigid plastics, HDPE colored, aluminum cans, and HDPE natural. Unfortunately for MRF operators, the largest flows have the least value, and the smallest flows have the most value. Other products are sometimes sorted as separate products, namely, aseptic and gable-top cartons, film, residential paper, and plastics #3−7. In the model, shown in Supporting Information, cartons and residential paper are sorted predominantly to mixed paper, film is separated out (as possible) into a distinct outbound material, and plastics #3−7 are assumed to be split among mixed rigid plastics and other streams. To develop this model, separation factors from Damgacioglu et al.[45] were augmented with some from the Oregon DEQ.[46] Separation factors are used to transform the inputs (inbound streams) into products and waste streams. While complete results are shown in the Supporting Information, an example shown through PET will demonstrate the product results. PET bales as product are determined to be 89.0% PET bottles, 6.8% nonbottle PET, and 1% or less of other unacceptable materials, steel cans, aluminum cans, etc. A range of compositions for PET bottle bales is presented by DSM Environmental Services, 91.1−99.3% PET.[47] An analysis was performed on the effects of reducing the contamination level shown in Table 1 of 16.9% in half, but PET bales only improved in that the product was made up of 89.5% bottles (other materials decreased by small amounts). Increasing the contamination shown in Table 1 by 50% did not have a large effect on PET either; however, other unacceptable materials increased to 1.7% in the product, which is above the specification for PET bales. In the Barriers to Increasing Recycling of Polyethylene Terephthalate and Other Plastics section below, additional discussion will consider the effects of contamination.

MRFs were also modeled for their resource use and emissions. According to Pressley et al., the electricity, diesel, and baling wire usage at single-stream MRFs are 6.2 kWh, 0.7 L, and 0.6 kg per metric ton (t) of recyclables fed.[42] For wire usage, Civancik-Uslu et al. cite the use of 2.102 kg of binding wire per ton of plastic, metal, and carton MRF feed.[48] Rumpke indicates that in their MRF they use 1.974 kg of wire per ton of MRF tipping floor and commercially separated feed.[40] An average of these three values gives 1.559 kg of wire per ton of MRF feed. For wastewater, Civancik-Uslu et al. report 0.631 L of wastewater per ton of plastic, metal, and carton MRF feed.[48] For electricity, additional values are reported by Chester et al. as 27 MJ/t of MRF feed (7.5 kWh/t),[49] Fitzgerald et al. cite 13.8 kWh/t,[43] and Rumpke at 27.3 kWh/t.[40] Thus, there is a large range of electricity use in MRFs, which may be due to different activities occurring inside. Averaging the four references for electricity gives 13.7 kWh per ton of MRF feed. For diesel storage and use, three values were averaged: the Pressley et al. value above, one from Chester et al. of 52 MJ of diesel/t (1.358 L/t) of MRF feed,[49] and one from Rumpke of 0.178 L/t.[40] The average is 0.75 L diesel/t MRF feed, which multiplied by a ton of diesel/1182 L diesel, gives 0.635 kg of diesel/t MRF feed. Methods for estimating emissions for diesel storage and combustion of natural gas and diesel are presented by Smith et al.[50] and are described and referenced in the Supporting Information. To calculate the storage emissions of diesel, one needs to estimate a rate of diesel use based on a MRF feed rate per year. For a process operating at 100 000 tons of MRF feed/year × 0.635 kg diesel/t MRF feed = 63 500 kg diesel/year, assuming 2 000 work hours per year, the rate of use is 31.8 kg diesel/hour and emissions are 2.3×10^{-6} kg of diesel emissions/t of MRF feed. For natural gas (NG) used at MRFs for space heating, Fitzgerald et al. report 0.0256 GJ of NG/t MRF feed-month.[43] Calculations in the Supporting Information show that this amounts to 18.2 scf of NG/t-year (0.516 scm of NG/t-year). Emissions from burning natural gas are also shown in the Supporting Information. Regarding other emissions, additives are added to plastics that are collected and processed in MRFs, and the processing could lead to some emissions, although due to additives being confidential business information their emissions are not approximated in this analysis. Finally, Fitzgerald et al. report a GHG intensity of 11.07 kg CO_2 equiv/t of MRF feed.[43] In this article, the calculations (shown in the Supporting Information using U.S. average grid values) determine a GHG intensity of 8.58 kg CO_2 equiv/t of MRF feed. For a 100 000 ton/year MRF, this amounts to 858 000 kg CO_2 equiv per year.

Process Models for Reclaiming PET.

As shown in Figure 2, where U.S. Reclaimer Processed is central to the PET recycling process between collection and end use, reclaimers take postconsumer materials and process them into feedstocks or ready-to-use materials. In the case of PET, reclaiming means to take MRF outbound PET bales and process them by opening bales, sorting out unwanted materials, grinding the plastic flow, washing it, allowing it to separate due to density differences in water, followed by drying, and finally air sifting to remove light contaminants like film, paper, and/or fines. A newly installed process is described as having sorters, a wet grinder, washers, float-sink tanks, a centrifuge, and dryers.[51] Larrain et al. report that 3% of plastic yield is lost during processing.[52] Analysis shown below details that 78.0% of PET bales are actually PET, so a 3% loss of 78.0% gives 75.7% yield of rPET based on original PET bale content. In a separate analysis, Perugini et al. report 1.32 kg of feed yielding 1.00 kg of PET flake, i.e., 75.8% yield based on PET bales.[53] A summary of content results for PET bottles and bales is shown in Table 3.

Roosen et al. report that the average residue (i.e., dirt and moisture) level in PET bottles is 6.4% (after washing, drying, and reweighing).[54] Of the remaining 93.6% captured with PET bottles, the materials are PET (81.4%), PE (7.5%), PP (3.4%), EVA (0.9%), and paper (0.4%). (While the most common, using PET bottles as the standard is a bit optimistic as PET trays have less PET than bottles.) Similarly, Roosen et al. report that halogens were found at an average concentration of 303 ppm (0.6 ppm fluorine found in labels, and 302 ppm of chlorine found nearly proportionally in PET, caps, and labels). Metals (i.e., Cr, Sr, Sb, Ti, Mg, Fe, Na, Al, and Ca) and food contact regulated metals (i.e., Ba, Co, Cu, Fe, Li, Mn, and Zn) were found at average concentrations of 512 and 25.1 ppm, respectively.[54] According to this effort (calculated results in the Supporting Information), PET bales outbound from an average MRF have 4.2% other materials in the bale. (A relatively similar value is reported by the Plastic Recycling Corporation of California in its PET Bale Specifications−grade A, which indicate a 4% maximum contamination, and no more than 1% of any type of contamination.)[55] Subtracting 4.2% from PET bales, the remaining is 95.8% PET bottles. Another 6.4% of PET bottles is bottle residue (i.e., of the original PET bales, 6.1% is residue).

However, PET bottles are not only made of PET. Other materials are part of PET bottles, identified as 12.2% of PET bottles.[54] From the perspective of PET bales, this is 11.7% other materials. Adding up the parts of PET bales, 4.2% other materials in the bale, 6.1% bottle residue, and 11.7% other materials as part of PET bottles, totaling 22.0% other materials and bottle residue in PET bales (i.e., 78.0% of PET bales is PET). This reasonably aligns with the 34.5% U.S. Reclaimer Residue calculated earlier from Figure 2. If only 22.0% of PET bales is not PET, then a 34.5% U.S. Reclaimer Residue points to an opportunity to improve reclaiming processes. If the 34.5% residue value is accurate and necessary, and with the knowledge that PET has been a focus of the Association of Plastic Recyclers and others to improve recycling over many years, this U.S. Reclaimer Residue marks a potential problem for other plastics that could be recycled. Some reclaimers report even lower values of clear PET in PET bales, i.e., 50−55% clear.[51] The Plastics Recycling Corporation of California has studied a discrepancy between their own analysis of PET bales, 90% clear PET, and California reclaimers, who indicated an average bale is 65% clear PET.[56]

Reclaiming processes were modeled for their resource use and emissions. Civancik-Uslu et al. report electricity and water usage for mechanical recycling of PP rigids, PS rigids, and mixed polyolefin rigids, with electricity use as 0.586 MWh, 0.504 MWh, and 0.201 MWh per ton of each plastic fed.[48] Water inputs provided by them are 0.238 tons, 0.078 tons, and 0.247 tons water per ton of each plastic fed. An average of these three values gives a water use of 0.188 ton of water per ton of plastic fed. A processor reports their water usage on a newly installed reclaimer line as one pint per pound of PET flake produced,[51] converting units and using 75.7% overall yield for PET bales, this amounts to only 0.00036 tons of water use per ton of feed. While improved water use may be available (and hopefully common in the future), for this analysis 0.188 tons of water per ton (188 L per ton) of PET bale will be used. The same amount will be assumed as the quantity of wastewater. Additional electricity use values come from Larrain et al. (137.3 kWh/ton PET flake)[52] and Perugini et al. (1.05 MJ electricity/kg PET flake),[53] converted, respectively, to 103.9 kWh/ton and 220.8 kWh/ton of PET bales fed. Using an average of the above values from Civancik-Uslu et al. provides a third value of electricity use of 430.3 kWh/ton of PET bales fed.[48] An average from these three research groups gives 251.7 kWh/ton of PET bales fed.

Welle[57] cites that washing is done with 2−3% caustic (NaOH), which will be averaged here as a 2.5% concentration. Based on the tons of water per ton of plastic fed, the caustic input is estimated as 0.0047 tons caustic per ton of plastic fed. Detergents are also used, but an amount is not reported by Welle.[57]

For diesel use and natural gas, one research group has posted natural gas usage for reclaiming PET. Perugini et al. provide a value of 2.5 MJ of natural gas usage for a kg of PET flake product (0.051 scm of NG/ton of feed, as calculated in the Supporting Information).[53] An assumption has been made that diesel use per ton of feed is the same for reclaimers as it is for MRFs. As with MRFs, emissions for reclaimers (e.g., 2.5×10^{-6} kg of diesel emissions/t of feed) are described in the Supporting Information. These include emissions from natural gas combustion, diesel usage and storage, and electricity (GHGs only). Electricity has many more emissions which are not reported here, although Franklin & Associates describe life cycle assessment estimates of resource use[58] and emissions.[59] Another potential source of emissions from reclaiming PET are the additives that become part of the PET material, which when shredded, washed, dried, and separated could release additives; however, due to the confidentiality of information on additives, these potential releases have not been estimated here. GHG calculations for reclaimers follow in the format for MRFs, with the resulting intensity of 103.7 kg CO_2 equiv/t of PET bale feed. One large difference between the GHG results for MRFs and reclaimers is the much larger electricity usage at reclaimers. Another difference is in the magnitude of the feed into reclaiming, where 100 000 tons fed per year into MRFs produces 5 000 tons of PET bale reclaimer feed per year. Thus, the magnitude of the GHG results for reclaiming are 519 000 kg CO_2 equiv per year. This is less than the MRF (858 000 kg CO_2 equiv per year), but the MRF results could be allocated among its various products. A 5% PET bale allocation for the MRF is 42 900 kg CO_2 equiv per year.

The above calculations, summarized in the flows of Figure 2 and tables, provide reinforcement for the qualitative information discussed in the next section, both as to the scale of the barriers to increasing recycling and the need for improvements to the systems involved.

Barriers to Increasing Recycling of Polyethylene Terephthalate and Other Plastics.

Addressing barriers and solutions to overcoming challenges to recycling of polyethylene terephthalate and other plastics is necessary to strengthen recycling programs. This discussion will consider three areas: consumers and infrastructure, mandates and packaging choices, and chemistry and engineering efforts.

Consumers and Infrastructure.—Collecting more recyclable materials is a first step to increasing recycling. Recycled materials are necessary for companies to meet the New Plastics Economy Global Commitment, as laid out by the Ellen MacArthur Foundation.[60] The Recycling Partnership reports that 20 million tons of recyclable materials are disposed of each year in the U.S. (i.e., only one-third of potential materials are collected) and that a combination of needs for more access, participation, and individuals capturing recyclables are limiting the amount collected.[38] Collected garbage is reported to have 14% recyclables, including 2% plastics.[36] The reasons people give for not recycling vary, with the top reasons in order: no service/recycle bin (21%), do not have recyclables (11%), no time (9%), lazy (9%), do not feel the need to (9%), inconvenient (8%), no interest (8%), and do not know/no reason (8%).[38] To expand the collection of recyclables, one could address these concerns, i.e., provide service and bins more widely, make it easy, promote its importance to the three aspects of sustainability, shift responsibility to producers via extended producer responsibility (EPR), and generally to educate people to recycle more.

Consumers may be unaware of the usefulness, demand for, and value of recycled plastics. Currently, the onus is on the consumer to learn their municipality standard operating procedures for recycling programs and collection. There is inadequate consumer education regarding plastics recycling. A Covanta survey has found that 62% of Americans are not confident about recycling correctly; over half “wishcycle” by erroneously recycling items they want to be recyclable, while only 31% always recycle appropriate items.[61] There is confusion over inconsistent recycling guidelines, unclear labels, and instructions. Public education campaigns have failed, particularly regarding cleaning and preparing plastics for recycling. By not properly cleaning plastics that are being recycled, the contaminated bins of recyclables will most likely cause materials to be landfilled. While some types of plastic items are recyclable, and others are not, people are receiving confusing/contradictory messages. As an example, most U.S. counties do not explicitly name PET items as recyclable but rather show pictures of bottles (e.g., water bottles), leaving consumers to guess. Consistent and standardized labels are needed to have clear messaging.

Correct labeling is insufficient, as waste disposal infrastructure varies by location in the U.S., with unequal access to convenient recycling programs for households. Forty million U.S. households, many of whom live in multifamily housing (including apartment complexes with many renters) or in rural areas, experience no or inequitable access to recycling.[62] The 6% of households in the U.S. with no access to recycling represent a loss of as much as 280 million pounds of recycled PET each year.[60] Availability of recycling options for plastics varies across different regions in the U.S. In general, recycling programs located along the East and West Coasts and in the upper Midwest collect the widest variety of plastics.[63] Due to export market changes, #3−7 plastics (or most plastic packaging that is not PET (#1) or high-density polyethylene (HDPE) (#2) bottles) have been the focus of elimination in some community programs, as they require additional separation post-MRF sorting.[60] Different approaches to collecting and managing materials can pose challenges, especially for consumers. For example, differences in the materials accepted or collected within the same geographic area can result in lack of access to recycling for some communities.[64] This confusion can increase the contamination rate and negatively impact local, regional, and national markets for recycled materials.

MRFs have reported on their concerns regarding contaminated inbound materials.[41] Plastic bags and film top the survey, as 25−50% of residents have reported putting plastic bags into their recycling cart. It is common for residents to not understand that plastics marked with a triangular recycle symbol are often not recyclable in their communities through curbside collection. Plastic bags and film often clog the MRF equipment, sometimes necessitating multiple shutdowns a day of the recycling line. Another issue is that plastic films can surround other recyclables and confuse the sorting systems.[47] When residents learn why plastic bags and film are an issue, they often improve their behavior. Other common issues are needles and batteries, which can be dangerous or cause a fire in a MRF.[65] In addition to specific issues with contamination of collected recyclables at MRFs, the cost of MRF processing increases with contamination (i.e., some people put garbage in the recyclables collection). DSM Environmental Services found that 37% of manual sorting labor at MRFs is due to 3.7% of the inbound contamination.[47] The increased MRF costs make it less likely that communities will institute recycling programs or collection of apparently problematic materials that lead to increased contamination and cost. A report by the World Economic Forum, the Ellen MacArthur Foundation, and McKinsey & Company in 2016 estimated that around 14% of plastic packaging is collected for recycling worldwide; however, due to the costs of sorting and reprocessing, only 5% of the material value is retained for future usage.[66]

A 2017 analysis by Closed Loop Partners and Resource Recycling Systems (RRS) showed that the cost of processing bottle-grade rPET was slightly more than the price of virgin PET.[67] This appears to be a continued trend with most plastics.[68] The price of virgin plastic is directly influenced by the price of oil, the principal feedstock for plastic production.[69] Due to factors such as changes in international waste trade, exports, tariffs, changes in the waste stream due to SARS-CoV-2, and fluctuating oil prices, recycled plastics remain more expensive than virgin plastics.[68] However, investments to increase supply, quality, and quantity of bottle collection as well as investments in MRFs could improve rPET cost, therefore making the use of postconsumer resin a more competitive option to virgin resin. The low economic value of secondary plastics disincentivizes any improvements that would be needed to upgrade systems.[60] There are also high upfront costs associated with switching to recycled plastics, which may include new testing, product design, and establishing supply chains. If national supply chains for recycled materials are not reliably available, this would result in an impractical system and the need to import or otherwise source the materials.

Even with the above limitations, there has been a recent surge in reuse and reclamation. In the last several years, Oregon moved to increase the recovery of beverage containers in the state.[70] In 2017, the state doubled the deposit on redemption bottles to 10 cents each, with the result being an increased redemption rate, from 59% to 82%. Then in 2018, the state increased the beverage containers included in the redemption program to include juice, tea, and other beverages. The combination increased the redemption rate to 90%. Similarly, in New York, the state has a redemption bottle bill that has retailers and other redemption centers collect and sort aluminum cans, PET, and glass (although sorting is often provided by reverse vending machines), and materials are processed into bales for shipment to reclaimers.[71] By extending this type of redemption to other types of packaging and materials, the recycling system could be expanded. Traceability of plastics from cradle to grave has been a continued barrier in tracking the lifecycles of plastics. However, new reuse/refill tracking systems have established a route to trace plastic reuse. For example, Chilean startup Algramo makes products including detergent in affordable quantities via smart vending machines and reusable containers. RFID tags on the bottles allow consumers to earn discount credits with each use, incentivizing them to refill. They also have an app that consumers can track their packaging and review their environmental impact.[72] Other examples include TerraCycle's Loop reusable packaging service, PepsiCo's SodaStream, Unilever Food Solutions, Cif ultraconcentrated refills for its Power & Shine spray bottles, and many more pilot projects and initiatives.

Mandates and Packaging Choices.—One method to increase recycling is to mandate it by law or to meet brand goals set by beverage companies.[73] Two U.S. states, Maine and Oregon, have passed extended producer responsibility laws for plastic packaging, and in addition, California has created a mandate for recycled content. Bottles in the state redemption program must average certain amounts of postconsumer recycled plastic: 15% in 2022, 25% in 2025, and 50% in 2030. This should increase the demand for recycled postconsumer plastics and thereby create a market through the system of manufacturers and reclaimers to invest and operate to satisfy this end demand. California has also passed a law defining the export of scrap mixed plastics as disposal, rather than recycling, and since Californians must divert material from disposal this law enforces recycling behavior.[74] Resource Recycling indicates that 97% of California's deposit system bottles are PET and that manufacturers will have to report on their amounts used to CalRecycle.[75] As shown in Figure 2 above, there is a substantial amount of PET resin that is not being recycled, representing an opportunity to increase rPET availability. Beverage companies have also committed to support the cause. While the average postconsumer recycled content in plastic packaging is 6.2%, Coca Cola, Keurig Dr. Pepper, Nestle, and Pepsi have announced higher rPET and portfolio goals for recycled content.[73]

Packaging producers are increasing their use of lightweight and composite plastics that are difficult to recycle.[76] Unlike PET, these materials do not get collected, sorted, processed, or sold into markets with ease. The reasoning for choosing packaging often does not consider its recyclability. For a complete environmental evaluation, one should consider a life cycle assessment, which can help determine if more recycling with different and heavier packaging is better. If the lightweight packaging falls into the sort known as flexible plastic packaging, i.e., pouches, bags, films, etc., then research on newer processing equipment at MRFs might provide an answer.[77] Some screens allow less film plastic to get wrapped around the equipment, which normally would lead to clogging issues. If the clogging by thin film plastics can be mitigated, it opens an opportunity to intentionally collect more flexible plastic packaging via single-stream recycling, and it could lead to the generation of plastic film bales. In addition to not clogging the screens, optical sorters are needed to separate the flexible plastic packaging from the fiber streams in a MRF. Unfortunately, small packaging will still (often) fall through disc screens and would still represent contamination.

Brand owners can also improve the recycling system through choices for their packaging. For instance, Coca Cola is changing green Sprite bottles to clear, thus improving the value of the bottles. Another change by brand owners is requiring cooperation between colorant companies and brands. Black plastics have problems being identified by optical sorters. PolyOne is working with Unilever and optical sorting companies to develop black colorants that meet brand needs and sorting abilities.[78] If necessary, the optical sorting company could find a way to identify aspects of new colorants. Thus, this effort represents an example of both packaging choices and chemistry/engineering research that improves the recycling system. In general, this emphasizes the role that chemistry and engineering can play; as described earlier, additives are ubiquitous in plastics, and figuring out how to change the packaging or the system the plastics and additives are recycled through are necessary for increasing recycling. Additional chemistry and engineering efforts are considered next.

Chemistry and Engineering Efforts.—The overall mechanical recycling methods used in recycling facilities are not designed to deal with complex and highly variable plastics coming through waste streams today. Communication between the manufacturers of new materials and products and the recycling industry needs to be enhanced to prepare for and optimally manage the recycling of new materials.[79] Some types of plastics are difficult to recycle. For example, polystyrene is hard to recycle because it is often contaminated by the food it contained.[80] In addition, mixed plastic recycling can have negative consequences. For example, a small amount of PVC contaminant present in a PET recycle stream will degrade the recycled PET resin. Conversely, PET in a PVC recycle stream will form solid lumps of undispersed crystalline PET, which significantly compromises and reduces the value of the recyclate.[69]

Another example is for engineers, who the Polypropylene Recycling Coalition is pushing to develop methods to sort and recycle more polypropylene. Equipment such as optical sorters and robotics can be used to separate polypropylene from MRF streams.[81] Modifying equipment for use with new plastics is a project for engineers to identify and sort the materials. Additional sorting could also be used to increase the value of other components of the plastics #3−7 stream, whether materials can be positively or negatively sorted, an increased purity will improve the value of many MRF product bales. Robotics are also within the purview of engineers, who with a penchant for machine learning and artificial intelligence, can help improve robotics in their abilities to sort MRF materials. In addition, chemists and engineers can both research aspects that will improve the economics of recycling. Chemical reactions that utilize currently unwanted or underutilized MRF product streams will create new opportunities. Engineers can put effort into reducing costs for sorting and other steps along the recycling chain of processes.

While this paper has focused on mechanical recycling, depolymerization of PET and chemical recycling continue to be active areas of research. Recently, investigators at the Pacific Northwest National Laboratory depolymerized PET bottles with mixed waste of pigments, labels, adhesives, and polypropylene rings.[82] At relatively mild conditions, and using no catalyst, the chopped PET was converted in both ethylene glycol and ethanol in water to generate 97−98% pure terephthalic acid monomer. Examples of other research have examined chemical recycling as pyrolysis of HDPE[83] and pyrolysis and gasification of polypropylene.[84] Determining the benefits/disadvantages of real-world processes will continue to be of interest for potential recycling systems.

PET thermoforms are an interesting subject in the current recycling system. Thermoforms are molded into shape, used as food containers, like clam shells and berry containers, and can be recycled with PET bottles. However, the properties of thermoforms differ from bottles, and so it is undesirable to have a large percentage of PET thermoforms in PET bottle bales. Thermoforms can be processed, however, with solid state reactors that improve the molecular weight and intrinsic viscosity of the material. That is not the end of the issues with thermoforms though. Some thermoforms are made of other plastics, like polylactic acid or polyvinyl chloride, and the mixes of plastics can cause problems for end users. Unlike bottles, which are easily recognizable as to their brand, thermoform packaging does not have an obvious brand, and so no one currently feels responsible for the inability to deal with thermoform issues, nor the labels and glue that can hinder recycling.[85] These packages appear ripe for improvements, as brands can do their part, or laws can start to enforce behavior, but also that chemists and engineers have opportunities to cut costs, improve chemistries, optimize systems, and develop thermoform recycling the way PET bottle recycling has improved over the years. As this article has shown, PET bottle recycling still has huge opportunities ahead, maybe only surpassed by the opportunities available for PET thermoforms.

CONCLUSION

This article has described U.S. flows of PET resin through collection, sorting, reclamation, and converting steps. The amounts of materials represent opportunities for recycling, with a fraction of PET bottles collected and almost no nonbottle PET collected. While 29.0% of PET bottles are collected for recycling, collected material is processed for conversion to products at a 65.5% efficiency. Mismanaged waste represents 2.66% of PET that would go to disposal, seemingly small, but on an absolute basis, 183 million pounds.

The processes for MRF sortation and PET reclamation were modeled, sortation with separation efficiencies to describe internal MRF flows and both MRFs and reclaimers according to their resource use and emissions. Results describe MRF inbound flows for individual recyclables and contaminants. PET bales are only 78.0% PET, while reclaimer residue is 34.5% of PET bales, thus representing an opportunity for process improvement. Among the emissions, GHGs were calculated for MRFs and reclaimers. MRFs have 858 000 kg CO_2 equiv emissions for a 100 000 ton feed process (reduced to 42 900 kg CO_2 equiv when allocated for PET only), and reclaimers have 519 000 kg CO_2 equiv emissions for processing 5 000 tons of PET bales, where all of these feed rates and emissions are on an annual basis.

In a vision toward increasing recycling, this effort described many substantial barriers, potential solutions, and research opportunities. One report pointed out that 40 000 million pounds of recyclables are disposed of each year, but at the same time Oregon was able to increase its redemption rate of beverage containers to 90%. Many of the barriers are a matter of investments in system availability and commitments. Other barriers are really opportunities for research, including collection and sorting of polypropylene, depolymerization of PET, and multiple needed advances for PET thermoforms. Perhaps optimization is warranted, as the barriers are known, and efforts are underway.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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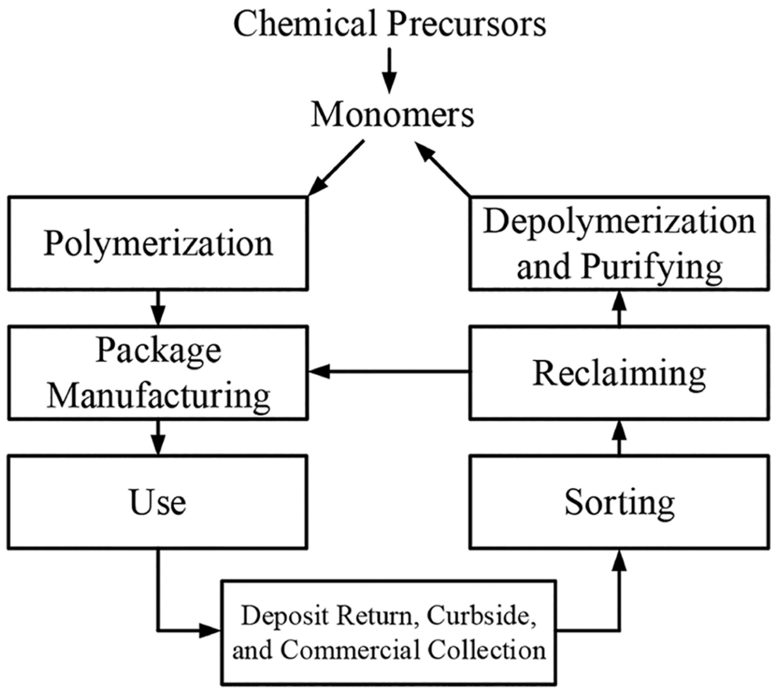

Figure 1.

Steps in the polymerization, manufacturing and recycling of PET resin plastics. Directly transferring PET flakes from reclaiming to package manufacturing is known as mechanical recycling. Depolymerization and purifying of monomers is a form of chemical recycling appropriate for PET.

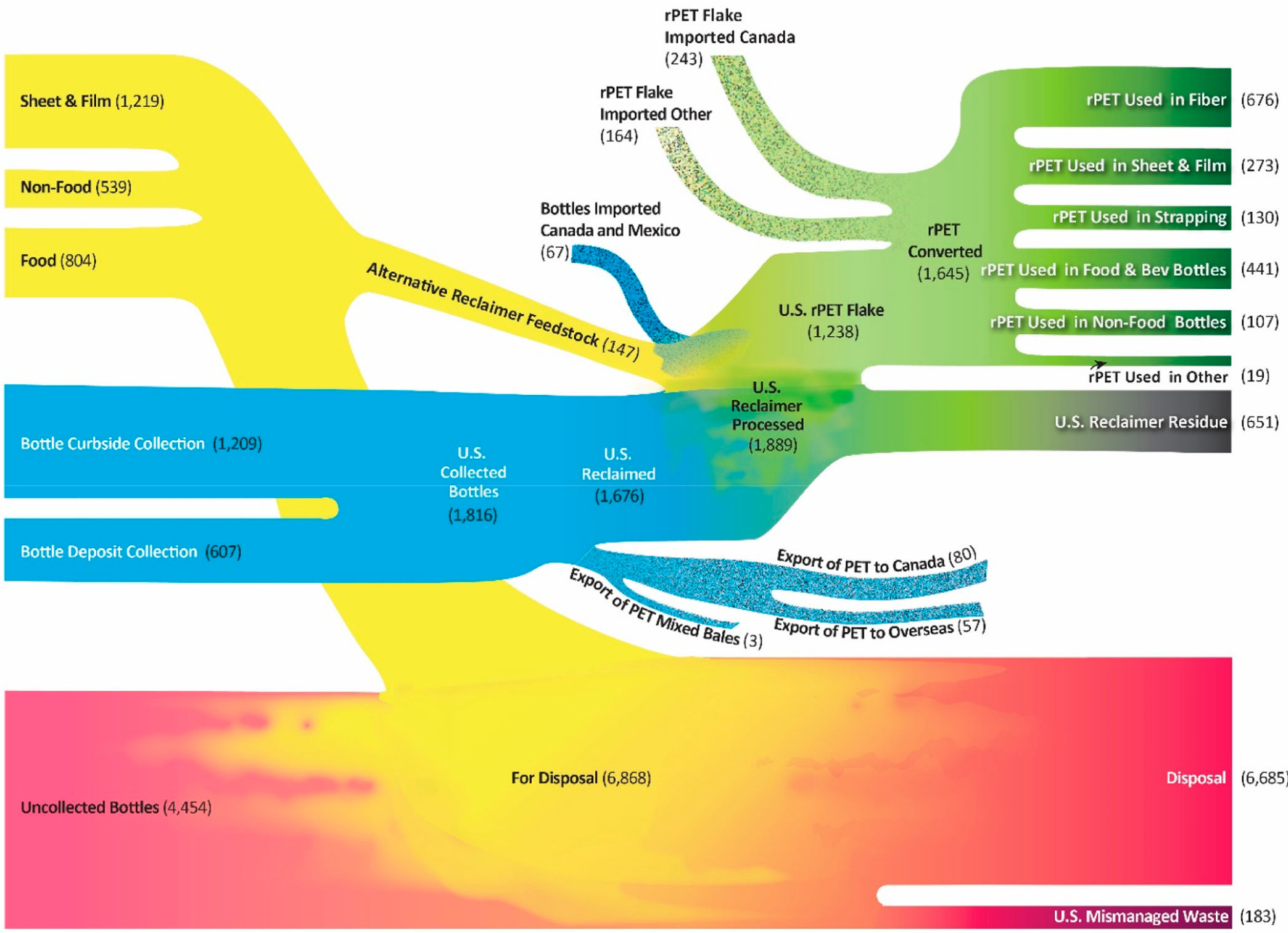

Figure 2.

U.S. flows of PET in million lb, adapted from NAPCOR.[31] Yellow represents nonbottle "thermoform" PET resin, blue represents collected bottle PET resin, and light red represents uncollected bottles. Green represents rPET converted into products, while dark red represents disposal and mismanaged waste. The gray U.S. reclaimer residue represents unknown stream exiting reclaimer processes.

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Table 1.

U.S. Material Recovery Facility Average Inbound Materials, Consisting of Recyclables and Contamination

MRF inbound material	percent of total collected (%)	amount	
recyclables	83.1	(million lb)	(metric tons)
residential mixed paper	33.3	7 800	3 538 000
mixed glass containers	17.7	4 154	1 884000
corrugated cardboard	11.1	2 613	1 185 000
PET bottles	5.2	1 209	548 000
other plastics (#3–7)	3.7	858	389 000
steel cans	2.6	605	274 000
bulky rigid plastics	2.5	585	265 000
aluminum cans	2.0	468	212 000
colored HDPE bottles	1.7	390	177 000
non-bottle PET	1.2	273	124 000
natural HDPE bottles	1.1	254	115 000
aluminum foil	0.7	156	71 000
carton food and beverage containers	0.7	156	71 000
contamination	16.9		
other unacceptable materials	6.0	1 407	638 000
other plastics (#3–7)	3.5	821	372 000
other unacceptable paper	2.7	633	287 000
food, liquids, and yard debris	2.6	610	277 000
plastic film	2.0	469	213 000
polystyrene foam	0.07	16	7 000

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Table 2.

Resources Used and Environmental Releases Per Metric Ton of Each Feed for Material Recovery Facilities and Reclaimers

resource use or release	units	MRF	reclaimers
electricity	kWh/ton of feed	13.7	251.7
diesel use	L/ton of feed	0.75	0.75
baling wire	kg/ton of feed	1.559	
natural gas	scm/ton of feed	0.516	0.051
sodium hydroxide	ton/ton of feed		0.0047
water use	ton/ton of feed		0.188
wastewater	L/ton of feed	0.631	188
diesel storage emissions	kg/ton of feed	2.3×10^{-6}	2.5×10^{-6}
greenhouse gases	kg CO_2 equiv./ton of feed	8.58	103.7
additional emissions	see the Supporting Information		

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Table 3.

Compositions of PET Bottles and Bales

	content of PET bottles	content of PET bales
PET bale		100.0%
other materials in PET bales		4.2%
PET items in PET bales		95.8%
dirt and moisture	6.4%	6.1%
PET	81.4%	78.0%
PE	7.5%	7.2%
PP	3.4%	3.3%
EVA	0.9%	0.9%[a]
paper	0.4%	0.4%[a]
halogens	303 ppm	
metals	512 ppm	
food contact regulated metals	25 ppm	

[a]Some percentages remain the same between table columns due to rounding.