NIST Advanced Manufacturing Series
100-64

The U.S. Plastics Recycling Economy

Current State, Challenges, and Opportunities

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National Institute of Standards and Technology policy is to report values in International System of Units (SI). This manuscript, however, summarizes the work of numerous reports that are external to NIST, and in which values were not reported in SI units. For clarity and accuracy, those reported values are shown here in the original non-SI units.

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Abstract

This report builds upon NIST AMS 100-48 (Thomas 2022), which broadly examined the economics of increased circularity in the economy, focusing on the processes, forces, and decision making that result in an unsustainable economy. This report further discusses the current state of plastics recycling, manufacturing, usage, and waste handling in the United States. It discusses and compares state level recycling programs along with national recycling programs in other countries, particularly those with high plastic recycling rates. The report also examines the potential for chemical recycling to address the plastics recycling problem. Finally, it identifies and discusses the stakeholders in the plastic recycling economy, including their incentives, barriers, and challenges to increasing recycling or recycled content use.

Keywords

Manufacturing; Plastics; Recycling; Sustainability; Environmental Impact; Economics

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Executive Summary

This report examines U.S. plastic recycling along with identifying means for increasing the plastics recycling rate. Presented below is a summary of findings regarding recycling that are made throughout the report. The first category describes the needs for increasing recycling in the U.S. while the sections afterward characterize the U.S. in terms of plastic recycling stakeholder challenges and incentives. Citations and further discussion are found in the text of the report.

- **Needs for Increased Recycling**
    - Given that packaging is a major use for plastics (44.8 % from Table 2.1), there is a need to find solutions for recycling the types of plastic used for this application, which might include adopting different types of plastic for this usage.
    - There are many plastic types that cannot be recycled together, resulting in limited availability for plastic recycling. Creating higher volume streams with few contaminants is a critical component of plastics recycling. Thus, there is a need for more uniform plastic products and packaging (i.e., “plastic simplification”) and/or low-cost methods for separating contaminants and additives to decrease costs through economies of scale.
        - To create more uniform plastic products, there is a need to understand the substitutability of different plastic types and plastic additives, including the costs of producing different variations.
    - There is a need for a method to differentiate recyclable products and/or those products made from recycled materials. Aside from regulations, taxes, subsidies, or a substantial increase in primary material costs, it will likely be difficult to increase plastic recycling rates without the ability to differentiate products. This might be achieved with a standard metric such as an index or score, which allows consumers to reliably select more circular products and allow producers to benefit from either producing recyclable products or using recycled materials.
    - Extended producer responsibility programs along with similar efforts (e.g., bottle deposit laws) appear effective in increasing recycling; however, the most effective and efficient design of such a program is unclear. Additionally, there is likely a need for standards to support such policies as well as material-related standards and standards to track plastic materials. A better understanding is needed regarding the specifics of these programs, needs for success, and their effectiveness.
    - Chemical recycling is often viewed as an alternative to disposing of plastic in a landfill, particularly for plastics that are difficult to recycle mechanically. In some instances, it might be a high performing option environmentally while in other situations a different option might perform better. There is a need to better understand the environmental impact and economics of chemical recycling, as there are many unknowns and conflicting information.

    - One means for increasing incentives for chemical recycling as an option might be through mass balance accounting (MBA); however, the effects of such an effort are not fully understood.
        - There is a need to understand the willingness-to-pay for products that make recycled content claims under MBA.
    - There is a need to understand the market effect on mechanical recycling when incentives for chemical recycling are increased through MBA and other methods, as mechanical recycling is generally considered to have fewer/lower environmental impacts and is to some extent a competitor with chemical recycling. There are several data challenges and a need to improve/maintain data on plastics manufacturing, its supply chain, plastic recycling, and related environmental impacts.
- **Plastic Usage and Manufacturing Value Added in the U.S.**
    - In 2020, U.S. plastics manufacturing value added was $131.4 billion, as seen Table 2.2.
        - Total shipments (revenue) were $284.4 billion, as seen Table 2.2.
        - Direct and indirect value added with imports is estimated as $313.9 billion, as seen in Table 2.4.
    - The U.S. produced approximately 55 megatons of plastic in 2019 (Milbrandt et al. 2022). Meanwhile, 37.7 megatons of plastic were landfilled in the same year (Milbrandt et al. 2022). The plastics that were landfilled are estimated to have a market value between approximately $4.5 billion and $9.9 billion (Milbrandt et al. 2022).
    - Packaging is the largest use of plastics with 44.8 % of plastic being used for this purpose, as seen in Table 2.1. The second largest use is for buildings and construction (18.8 %), as seen in the same table, followed by other uses (13.2 %) and consumer/institutional products (11.9 %).
- **Environmental Benefits of Recycling**
    - U.S. plastic and synthetic rubber manufacturing is responsible for 4.2 % of the U.S. economy’s environmental impact (see Table 3.6), measured as a weighted 12-factor value that is estimated using environmentally extended input-output analysis. Because this is an estimate of plastic manufacturing’s environmental impact, it excludes the impacts from usage and end-of-life processing (e.g., microplastics in the ocean).
        - Currently, reducing the environmental impact of plastic production is one of the major benefits of recycling with an additional benefit of preserving resources for future generations.
        - Increased plastic recycling in the U.S. is unlikely to significantly reduce ocean plastics or other plastic pollution due to the source of these pollutants and the circumstances of how they occur.

            - It is estimated that 99.75 % of ocean plastics are released by non-U.S. countries (Our World in Data 2021); however, some plastics are sold by or exported from the U.S. to these countries for recycling.
            - It is estimated that between 11 % and 50 % of mismanaged plastics in the U.S. (i.e., it does not get recycled, incinerated, or placed in a landfill) were originally collected for recycling (Law et al. 2020). Note that the wide range is due to both uncertainty in the total mismanaged plastics and the mismanaged plastics collected for recycling.
            - A large portion of plastic pollution originates from primary microplastics such as textile particles lost during laundering, tire dust from wear and tear, and eroding road markings (Boucher and Friot 2017), which are not affected by current recycling efforts.
            - In 2010, plastic waste, paring, and scrap exports were the equivalent of 90.9 % of plastic collected for recycling and nearly all (> 90 %) went to Asian countries, as seen in Figure 3.2. By 2022, exports had decreased by 78.7 %.
                - Many Asian countries have high rates of mismanaged plastic (i.e., it does not get recycled, incinerated, or placed in a landfill). For instance, 25 % of China's plastic waste is estimated to be mismanaged with 60 % mismanaged in Thailand, 74 % in the Philippines, and 64 % in Vietnam (Law et al. 2020).
                - By 2022, Canada was the top destination with 33.0 % of U.S. exported plastic collected for recycling being shipped there (Table 3.2).
                - In 2022, approximately 50.4 % or more of U.S. exported plastic that was collected for recycling still went to regions with high levels of mismanaged waste (Table 3.2).
    - Despite its environmental impact, plastic often has a lower carbon footprint than other materials used for the same purpose (Edwards and Fry 2011; Chaffee and Yaros 2014); thus, there are likely to be trade-offs when considering an alternative material.

- **U.S. plastic recycling activity**
    - In 2018, 8.7 % of plastics were recycled in the U.S.,15.8 % incinerated with energy recovery, and 75.6 % sent to landfill (U.S. Environmental Protection Agency 2021).
        - U.S. landfills, the primary destination for waste plastic, are required to have liners and collect/treat leachates, to prevent contamination of the

environment; however, there is a limited understanding of the microplastics that remain in treated leachate or manage to escape to the environment. Data on municipal wastewater treatment, which is similar to methods used for treatment of landfill leachate, suggests more than 90 % of microplastics can be removed (World Health Organization 2019).

  - Plastic is recycled largely using mechanical means.
  - Contamination in the waste plastic, such as mixed plastics, food, and other debris, presents challenges for all plastic recycling.
  - Polyethylene terephthalate (PET) (e.g., soda bottles) and high-density polyethylene (HDPE) (e.g., non-carbonated beverage bottles) plastic have the highest recycle rates at 18.2 % and 9.4 %, respectively (see Table 2.1). The lowest rates, such as those for polypropylene (PP) (e.g., straws, cups, and containers) and polystyrene (PS) (e.g., to go containers, hot cups, and utensils) plastics, are less than 1 % (see Table 2.1).
  - For PET bottles, an estimated 27 % of the collected materials are lost – 13 % occurring at the sorting facility and 14 % at the processor facility (Eunomia 2021). HDPE bottles, PP plastic, rigid plastics (resin codes #3-#7), and PET other rigid plastics have losses of 28 %, 41 %, 44 %, and 68 % respectively facility (Eunomia 2021). Most of the losses occur at the sorting facility.

- **Collection and Sorting**
  - Collection costs for general recycling programs often exceed $300 per ton for operating trucks, collection containers, crews, and maintenance in addition to processing fees that range around $100 per ton (Appel et al. 2024).
  - The material price or sale price of plastic waste material is often lower than the cost of collecting and processing.
  - Access to recycling collection is a challenge for plastics recycling.
    - Only 53 % of the U.S. population has automatic enrollment to curbside recycling (Marshall 2017).
    - 85 % of single-family households have access to recycling (curb-side or drop-off) (Marshall 2017).
    - Multifamily household access to a recycling program is only 37 % (Marshall 2017).
  - Individual and community understanding of recycling is a challenge for plastic recycling.
    - Only 60 % of individuals understand that food does not go in the recycling bin (Marshall 2017).
    - Approximately 50 % of individuals believe plastic bags can go in the recycling bin despite it being rare that recyclers can accept such materials and it can damage sorting equipment (Marshall 2017).

- **Mechanical recycling**
  - Mechanical recycling is, typically, seen as the most beneficial means for recycling plastics, as it tends to have a lower environmental impact.
  - Typically, due to degradation of quality, plastic can be recycled two to three times using mechanical recycling, the most prominent method of plastic recycling used (Vogt et al. 2021; Sedaghat 2018).
  - In many instances, mechanically recycled plastics tend to be more expensive to use when compared to the primary alternative.
  - Producing plastic resins using mechanical recycling is a relatively small industry with lower-than-average net income, which includes profit.
    - Custom compounding of purchased resins (NAICS 325991), which includes reformulating plastics resins from recycled plastics products, had an estimated value added of $2.4 billion and shipments of $9.3 billion in 2020, as seen in Table 2.5
    - Net income as a percent of shipments was 7.4 % for NAICS 325991, which is 26.7 % lower than the primary resin counterpart (i.e., NAICS 325211 and 325212) and 56.5 % lower than that for the manufacturing industry in 2020, as seen in Table 2.5.
- **Chemical recycling**
  - Chemical recycling is, typically, seen as a secondary option or supplement to mechanical recycling, as the technology is more advanced, capital-intensive, and tends to have higher environmental impacts.
    - Currently, due to its environmental performance, chemical recycling is often seen as a method to be used after exhausting all other recycling methods, including mechanical recycling, design for recycling, and reusing.
  - Chemical recycling has been discussed as a partial solution to increasing plastic recycling.
    - Existing steam crackers that are used to make plastic can only produce plastic using feedstocks with small portions sourced from recycled materials.
      - Demand may vary for products made with partially recycled material compared to that for a product sourced from fully recycled material.
      - MBA may provide an increase in demand, but there is limited understanding on the effect it has on willingness to pay.
  - Currently, chemical recycling represents very little of the total plastic recycled (i.e., near zero percent); therefore, it has not been thoroughly demonstrated to be economically viable.

        - As of September 2023, there were 11 chemical recycling facilities constructed in the U.S., as seen in Table 3.5 (Bell 2023).
            - Although a number of these facilities are pilot programs or demonstrations and there is additional research being conducted in this area, many of the technologies for chemical recycling have been around for decades (Bell 2023).
            - Of the eleven facilities, seven have the stated purpose of producing materials that can potentially be used to produce plastic products (Bell 2023). Of these, four have an operating status that is either considered partial/intermittent or is piloting/demonstrating (Bell 2023). There is one facility that has an unknown operating status and two facilities that are considered operating (Bell 2023).
        - Pyrolysis, which is a well-established technique that generates pyrolysis oil, is often seen as the best option for chemical recycling of plastics (Davidson et al 2021).
            - The 2020 global pyrolysis oil market was estimated to be $302.1 million (Transparency Market Research 2022). For context, the global oil market in 2022 was $6.6 trillion, which is more than 21 000 times larger (IBIS World 2023).
            - Pyrolysis oil is in many ways similar to that of conventional diesel. Although it could be used for generating plastics, currently the primary application is fuel oil in heavy industry (Doing 2021).
            - Pyrolysis oil has a higher level of contaminants than fossil-based feedstocks for steam crackers, which are used to make plastic. With existing steam crackers, it is estimated that pyrolysis oil can only make up approximately 2 % to 5 % of the oil being processed.
    - Terminology for chemical recycling and what is meant by these terms varies significantly, making it difficult to research and communicate accurately about this technology (RPA Europe 2021).
    - Some costs and benefits of chemical recycling are described in the details of the report. Some aspects of this technology may be in the early stages of development and, unfortunately, there is a lack of transparency regarding chemical recycling processes and their outputs.
        - The environmental impacts of chemical recycling are unclear. Some research suggests there are very few benefits while other research suggests the opposite. Moreover, there is polarized disagreement on the prospects of chemical recycling.
- **Programs with high rates of recycling/collection**

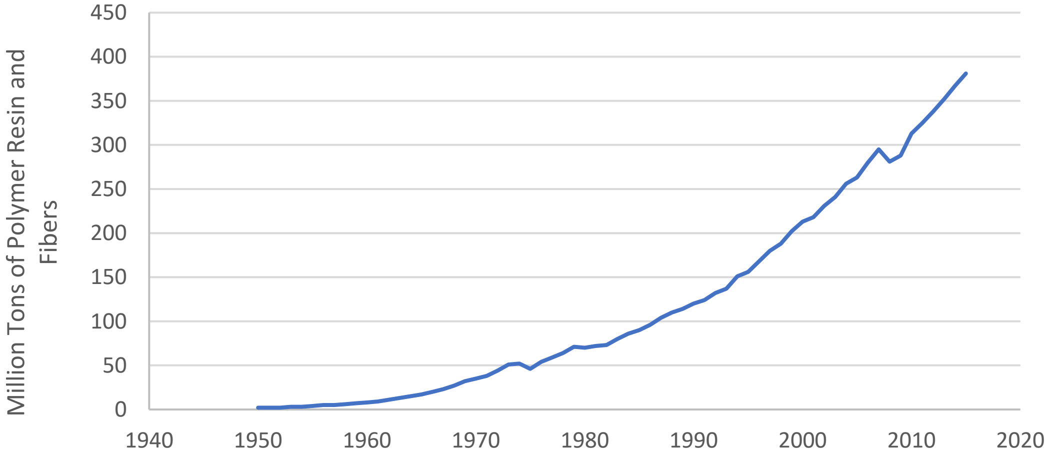
  - Recycling rates vary significantly from country to country, state to state, and even within a state.
  - U.S. States with bottle deposit return systems tend to have higher recycling rates, as seen in Table 4.1. States with higher recycling collection rates tend to have bottle deposit laws.
  - States with higher recycling rates tend to have recycling collection legislation that reward recycling collection, require/enforce recycling collection, and/or ban certain types of plastic (Table 4.1).
  - Successful recycling tends to happen when it is financially viable, technically feasible, and environmentally beneficial. Currently, this includes homogeneous high-value, pure (i.e., low-contamination) streams with many being affected by the price of oil (Merrington 2017).
    - Due to the many types of plastic and the additives, there are many small streams, which reduces economies of scale (Chen 2021).
    - Unfortunately, only a limited number of plastics present a “value generating” or profitable opportunity. For instance, Gao (2020) identified that approximately 20 % of plastic collection efforts met a threshold 15 % return on investment or higher for recycling . Another 50 % had positive returns but did not meet the 15 % threshold. The last 30 % had negative returns.
  - Countries with higher recycling rates tend to have recycling legislation that reward recycling, require/enforce recycling, connect the costs/responsibilities of recycling to manufacturers (often referred to as extended producer responsibility), and/or ban certain plastic products.
    - Bottle deposit systems in the U.S., which tend to be associated with higher levels of recycling, might in some instances be considered a narrow example of extended producer responsibility.
    - Further investigation is needed to understand the different designs for existing extended producer responsibility programs and additional research is needed to understand the effects of these designs.
- **Plastic Recycling Economy Stakeholders Challenges and Incentives**
  - End Users (e.g., consumers)
    - End users have limited information on the recyclability or recycled content of a given plastic product. Increasing information/knowledge can result in incentivizing circular plastics.
      - End user willingness-to-pay (WTP) for recyclable materials could potentially impact the number/types of plastics produced along with the additives, which has been identified as a major challenge for the success of plastics recycling.

        - End user WTP for products with recycled content can create an incentive for producers to use recyclable materials to make new products.
    - As mentioned previously, some end users have limited access to plastics recycling programs and/or have limited knowledge regarding what is recyclable.
- Plastic Waste Collectors and Sorters
    - As mentioned previously, costs often exceed revenue for plastic waste collection and sorting.
    - 64 % of material recycling facilities are privately owned (National Waste and Recycling Association 2018); thus, making a profit is critical for the survival of these facilities.
- Resin (from plastic waste) Manufacturers
    - Producers of recycled plastic material potentially compete with primary materials, which are affected by the price of inputs such as oil and/or natural gas.
    - Data suggests that producing plastic material from recycled waste tends to be less profitable than using primary material and is less profitable than the average manufacturing establishment.
- Plastic Product Manufacturers
    - Contamination can prevent recycled plastic from being used for some applications.
    - Producing plastics from recycled material is often more expensive than using primary material and introduces supply risks.
- Communities and Society
    - Communities tend to bear the effects of plastic pollution and the results of consuming diminishing resources such as the materials for making plastic.

1. Introduction

1.1. Background

Plastic is often thought of as unnatural; however, polymers are abundant in nature (Freinke 2011). In fact, a material called cellulose or celluloid made from cotton, developed in 1863 by a journeyman named John Wesley Hyatt, was the first plastic. Although it did not work well for its original intent (i.e., billiard balls) it worked well for making combs, and by the 1940's plastic was being mass produced for making numerous products. Although the earliest plastics were made from cellulose, today plastics are primarily made from the refining of oil and natural gas (often referred to as "virgin" plastics). The properties of plastic make it exceedingly useful due to its range of properties (e.g., formable, malleable, quick-setting, affordable). In the last 50 years, the adoption and use of plastics has increased significantly worldwide, as seen in Figure 1.1, with polymer production nearing 400 million tons in 2020 (Geyer et al. 2017; Ritchie and Roser 2018).



Data Source: Geyer et al. 2017; Ritchie and Roser 2018

Figure 1.1: Global Plastic Production (million tons)

With mass production comes a massive amount of waste. Plastics manufacturing, including synthetic rubber, represents approximately 4.2 % of U.S. environmental impact[1,2] from economic activity and 1.4 % of GDP. Additionally, plastic waste was 12.2 % of municipal solid waste in the U.S. in 2018, which is the third largest category behind paper/paperboard and food (U.S. Environmental Protection Agency 2021). Unfortunately, many plastics end up in the ocean or littered across the landscape. In addition to plastic products, there are microplastics (small pieces of plastic that are less than 5 mm in length [U.S. National Oceanic and Atmospheric Administration 2023]) that

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[1] The methods used for calculating environmental impact are found in Appendix A.

[2] Calculated using NIST's Manufacturing Cost Guide for 2019 for NAICS 325211, 325212, 326110, 326120, 326130, 326140, 326150, 326160, 326190, and 326220 along with the default settings for weighting.

are released into the environment. Plastics that end up in a landfill or the environment represent a limited resource that is removed from the value chain. Despite the implementation of systems that collect, process, and reuse materials to create new products (referred to as recycling programs throughout the remainder of this document) across the U.S., only a small percent (8.7 % [U.S. Environmental Protection Agency 2021]) of plastics gets recycled or collected for recycling, which is similar to the estimated global rate of 9 % (Geyer et al. 2017). Increasing the amount of plastic that is recycled will first require understanding the challenges and barriers that prevent it throughout the supply chain. Given the current low recycling rate, there are opportunities to drastically increase recycling and the use of recycled content in new plastic products over the next several decades. Beers et al (2022) states that, "If properly supported and expanded, by 2050, nearly 60 % of plastics production could be sourced from complementary mechanical and chemical recycling routes globally and the new materials could generate $2 billion to $4 billion of earnings annually. The only way to transform the system and reach these goals is through rapid and diversified expansion of a range of technologies.”

However, adoption and expansion of these technologies will require addressing numerous major current challenges including (Beers et al. 2022):

- significantly increasing the ability to collect and sort the necessary feedstock supply (quantities and quality)
- balancing trade-offs in energy consumption and environmental impacts between the various alternative paths to increase plastic recycling
- scalability of the various technologies
- market size and competition with alternative materials and pathways
- wide range of attributes of resulting products
- quality and available quantities of qualifying recovered feedstock streams (e.g., material supply)

These issues, among others, must be resolved for significant improvements in plastics recycling and to increase the use of recycled content.

1.2. Scope

Plastics recycling takes plastic waste (i.e., plastic that is disposed of at the end of its use) and incorporates it as an input into new products. This report examines the current state of U.S. plastics recycling, benefits of recycling, and potential means for increasing recycling. The authors acknowledge that reduction of plastic use, substitution with alternatives to primary (i.e., virgin) plastics (e.g., bioplastics), increase of plastic product useful life, and increasing plastic reuse are vital to reducing plastic waste, but each are considered outside the scope of this study. Additionally, aspects of plastic waste that are generally considered outside of scope for this document include incineration and microplastics. As an alternative to landfills, plastic waste is often incinerated for energy recovery. Some refer to incineration as recycling; however, for the purposes of this report energy recovery through incineration is not included as recycling and, therefore, is beyond the scope of this report. Microplastics are often discussed together with recycling with the reduction of microplastics implied as a benefit of recycling. Microplastics include primary microplastics which are released as small plastic particles and secondary microplastics which result from the breaking down of larger plastics (Boucher and Friot 2017). Primary microplastics are estimated to represent 15 % to 31 % of microplastics in the ocean while secondary microplastics are between 69 % and 81 % (European Parliament 2018); however, it is important to note that coastal aquifer patterns of contamination are different than inland patterns (Dey et al. 2023) and inland patterns may vary between countries due to variations in handling of plastic material. Sources for primary microplastics in the ocean include synthetic textile particles often lost during laundering (35 %); tire dust often created from abrasion during use (28 %); city dust from spills, weathering, and abrasion (24 %); road markings (7 %); marine coatings (3.7 %); personal care products (2 %); and lost plastic pellets (0.3 %) (Boucher and Friot 2017). Plastics degrade slowly, often over thousands of years (Chamas 2020), making these plastics a persistent challenge. However, given the sources of microplastic leakage to the environment, recycling is unlikely to contribute significantly to solving the challenge of primary microplastics and, therefore, is largely outside the scope of this report.

As discussed later in the report, secondary microplastics and many ocean plastics are the result of mismanaged waste (i.e., it does not get recycled, incinerated, or placed in a landfill) that, in some instances, originates from plastic collected for recycling. Preventing these plastics from being released into the environment requires a focus on proper handling of plastic waste, whether through recycling or landfilling. Additionally, the U.S. directly accounts for only 0.25 % of ocean plastics (Our World in Data 2021). For the purpose of this report, the reduction of both microplastics and ocean plastics is seen primarily as a handling/mishandling issue and not considered a benefit of increasing U.S. recycling; therefore, these pollutants are largely beyond the scope of the report.

1.3. Approach

This report builds upon National Institute of Standards and Technology (NIST) Advanced Manufacturing Series (AMS) 100-48 (Thomas 2022), which examined the economics of increased circularity in the economy, focusing on the processes, forces, and decision making that result in an unsustainable economy. It further sought to identify cost effective solutions to alter these decisions. The unsustainable economy (i.e., an economy that expends limited effort to preserve resources) is, typically, a result of decisions made by individuals and firms from their stakeholder perspective. It develops primarily from a misalignment of incentives where those that bear the costs of increased sustainability do not receive commensurate benefits. Successful solutions to this problem will tend to alter the economy that align individual or business interests to that of society. Alternatively, successful solutions might mitigate negative outcomes. Four means of achieving sustainability were identified in the report: increasing product longevity, reusing/repairing products, reducing material and energy use, and recycling.

This report builds upon NIST AMS 100-48 by discussing the current state of plastics manufacturing, usage, and waste handling in the United States. It further discusses and compares state level plastics recycling programs along with national recycling programs in other countries, particularly those with high plastic recycling rates. The report examines the potential for chemical recycling to address the plastic waste recycling problem. Finally, this report summarizes the stakeholders in the plastic recycling economy, including incentives, barriers, and challenges to increasing recycling or recycled content use, and future research opportunities.

Different organizations might measure or define "recycling" differently. Unfortunately, the differences are not always clear. In some instances, this report combines estimates to provide broader perspectives; however, caution is recommended when comparing observations across different datasets. Generally, recycling estimates should be seen as approximations, as there are numerous challenges, including inconsistencies in data collection across states and/or countries. For instance, Eurostat (2023), which provides recycling estimates in Europe where recycling tends to be higher, but member states collect the data and are free to decide on the data collection methods. Further, metadata on their recycling estimates did not explicitly define whether the estimates were materials collected or material turned into new products. For plastic packaging waste, Eurostat states that:

> "The weight of recovered or recycled packaging waste shall be the input of packaging waste to an effective recovery or recycling process. If the output of a sorting plant is sent to effective recycling or recovery processes without significant losses, it is acceptable to consider this output to be the weight of recovered or recycled packaging waste."

This suggests that, at least packaging waste, is measured as being the material entering a recycling facility (i.e., not a recovery or sorting facility). However, recycling facilities may further sort materials and discard some portion, such as due to contamination. Other sources of information provide even less information. Estimating precise recycling rates is beyond the scope of this report, as is investigating the precise methods of data collection. Rather, this report relies on others' estimates to make comparisons and draw limited conclusions. Further, this report tends to maintain the language used by the data source. In places where there is confidence that estimates represent plastic that was completely turned into new products, the term "recycled" is used. If there is further sorting or discarding occurring after data for an estimate is collected, then the term "collected" is used. In those situations where it was not entirely clear, the term "recycle/collected" is used.

2. Plastic Usage and Production

There are three basic aspects for the plastics economy: 1) production of plastics, 2) usage of plastics, and 3) disposal of plastics. Production activities include not only plastic manufacturers, but also their suppliers. These industry stakeholders make the final decisions about how plastics are manufactured, what their form will be, and their chemical composition. The user, however, plays just as important of a role and, in many ways, maintains just as much power in determining the final product; however, their role is indirect. Together producers and users are the key determinants of the plastics economy. If the product does not suit the user's purpose, the product is likely to fail in the marketplace. Moreover, it is important to characterize both the production of plastics and their usage, as this will provide a basic understanding of the plastic recycling economy. Section 2.1 discusses how plastics are used. Section 2.2 discusses the plastic manufacturing industry and its share of GDP. These sections are followed by discussing the supply chains for primary (i.e., virgin) plastic (Section 2.3) and recycled plastic (Section 2.4).

2.1. Plastic Usage and Disposal

As estimated by a McKinsey report (Gao, 2020), North America accounted for 18 % of 2018 global plastic consumption while Asia accounted for 46 %.[3] Plastics are produced for many different purposes and there are many different types of plastics. As shown in Table 2.1, packaging (44.8 %) is the largest application for plastics followed by building and construction (18.8 %). As shown in the table, global polypropylene (PP) production represents the largest proportion of resin production with packaging representing the bulk of that production. Low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) represent the second largest proportion of resin production. For these plastics, packaging is also the largest application.

The third largest type of plastic is high density polyethylene (HDPE) followed by polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polystyrene (PS). For three of these five, packaging is the largest use category. PVC and PUR are the exceptions, where PVC's largest application is building and construction while PUR is used in other applications. Thus, packaging is not just the largest application overall, it also the largest for multiple plastic types. Finding solutions for making packaging recyclable or reducing packaging is likely a key element for sustainable plastics. While Table 2.1 provides a characterization of the mass of plastic produced and its application, the following sections characterize the value of the plastics produced in the U.S.

Plastic waste trends closely follow production except for in construction. For instance, packaging accounts for 46.7 % of plastic waste with production slightly less at 44.8 %. Building and construction account for 18.8 % of production while it only accounts for 4.3 % of the waste. This is likely due to the longer lifespan of buildings compared to other types of goods combined with their recent adoption and use in buildings.

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[3] Note that the metric used is not specified; however, it is believed to be by mass.

Table 2.1: Share of Polymer Resin Production According to Polymer Type and Industrial use Sector, 2002-2014

🟩 Low Values

🟥 High Values

	LDPE, LLDPE (e.g., trash bags, squeeze bottles, flexible films)	**HDPE** (e.g., non-carbonated beverage containers, grocery bags, household cleaner bottles)	**PP** (e.g., straws, cups, ketchup bottles, yogurt containers)	**PS** (e.g., to-go containers, hot cups, utensils, foam packing, trays)	**PVC** (e.g., pipes, windows, synthetic leather)	**PET** (e.g., carbonated beverage bottles, water bottles, heatable food trays)	**PUR**	**Other**	**PP&A Fibers**	**Additives**	**Total (Global)**	**Waste Generation (Mt) (Global 2015)**
Plastic types	4	2	5	6	3	1		**7**				
Transportation	0.1%	0.8%	2.6%	0.0%	0.3%	0.0%	1.6%	1.4%			6.7%	5.6%
Packaging	13.5%	9.3%	8.2%	2.3%	0.9%	10.1%	0.2%	0.1%			44.8%	46.7%
Building and Construction	1.1%	3.3%	1.2%	2.2%	8.1%	0.0%	2.4%	0.5%			18.8%	4.3%
Electrical/Electronic	0.5%	0.2%	0.9%	0.6%	0.4%	0.0%	0.4%	1.0%			3.8%	4.3%
Consumer and Institutional Products	2.9%	1.7%	3.8%	1.8%	0.6%	0.0%	1.0%	0.2%			11.9%	12.3%
Industrial Machinery	0.2%	0.1%	0.2%	0.0%	0.0%	0.0%	0.3%	0.0%			0.8%	0.3%
Other	1.7%	0.9%	4.2%	0.7%	1.4%	0.0%	2.5%	1.7%			13.2%	12.6%
Textiles	Not broken out separately											13.9%
Total (Global)	20.0%	16.3%	21.0%	7.6%	11.8%	10.1%	8.2%	4.9%			100.0%	
Waste (Mt) (Global 2015)	18.9%	13.2%	18.2%	5.6%	5.0%	10.6%	5.3%	3.6%	13.9%	5.6%		100.0%
U.S. Recycle Rate 2017	4.2%	9.4%	0.6%	0.4%	-	18.2%		-				

NOTE: A grey box means the value is unknown or not broken out separately.
NOTE: The percentages that are not indicated as “Mt” are believed to be by mass; however, the source does not specify the unit.
Sources: Geyer (2017), Merrington (2017), Drahl (2020)

2.2. Plastic Industry’s Share of GDP

Domestic U.S. economic data tends to be classified using North American Industry Classification System (NAICS) codes. It is the standard used by Federal statistical agencies classifying business establishments in the U.S. NAICS has several major categories each with subcategories. The lowest level of detail is the two-digit NAICS, which has approximately 20 categories. Greater detail is provided by using additional digits; thus, three digits provides more detail than the two digit and the four digit provides more detail than the three-digit. The maximum is six digits, as might be illustrated for automobile manufacturing (NAICS 336111) and light truck and utility manufacturing (NAICS 336112). Sometimes a two, three, four, or five-digit code is followed by zeros, which do not represent categories. They are null or place holders. For example, the code 336000 represents NAICS 336.

The total value added is the best measure available for estimating the value an industry contributes to the economy. Value added is equal to the value of shipments (i.e., revenue) less the cost of materials, supplies, containers, fuel, purchased electricity, and contract work. It is adjusted by the addition of value added by merchandising operations plus the net change in finished goods and work-in-process goods. Value added avoids the duplication caused from the use of products of some establishments as materials. This report uses data from two sources to estimate the value added of plastics manufacturing to the U.S. economy: Bureau of Economic Analysis (BEA) and Annual Survey of Manufactures (ASM). The value-added estimates from the BEA and the ASM are developed using different methodologies. The BEA calculates value added as “gross output (sales or receipts and other operating income, plus inventory change) less intermediate inputs (consumption of goods and services purchased from other industries or imported)” (Horowitz and Planting 2006). ASM’s calculation of value added includes purchases from other industries such as mining and construction that BEA’s does not include.

According to the ASM, plastics and synthetic rubber manufacturing (NAICS 325211, 325212, 326110-326190) accounted for $131.4 billion in value added or 0.6 % of U.S. GDP (see Table 2.2 and Figure 2.1). The BEA provides the primary estimate for U.S. GDP, which is the sum of value added for all industries. Using the BEA definition applied to ASM data, value added for plastics and synthetic rubber manufacturing (NAICS 325211, 325212, 326110-326190) accounted for $95.8 billion or 0.4 % of GDP. Using World Input Output Data, rubber and plastic manufacturing represented 0.6 % of 2014 global GDP with 16.5 % of production being in the U.S. (University of Groningen 2016).

U.S. plastics and synthetic rubber manufacturing are broken into 14 NAICS codes, as seen in Table 2.3. The largest in terms of value added is NAICS 326199, which includes a variety of plastics manufacturing. The second largest is NAICS 325211, which is the production of plastic material and resin. It is important to note that some of the NAICS

Table 2.2: U.S. Plastics and Synthetic Rubber Manufacturing Supply Chain, 2020 (NAICS 325211, 325212, 326110-326190)

	Plastics		Total Manufacturing
	($Billions 2020)	As a Percent of Plastic Shipments	As a Percent of Manufacturing Shipments
I. Services, Computer Hardware, Software, and Other Expenditures			
a. Communication Services	0.3	0.1%	0.1%
b. Computer Hardware, Software, and Other Equipment	0.5	0.2%	0.2%
c. Professional, Technical, and Data Services	1.5	0.5%	0.7%
d. Other Expenditures	14.9	5.2%	4.7%
e. TOTAL	**17.1**	**6.0%**	**5.6%**
II. Refuse Removal Expenditures	**0.9**	**0.3%**	**0.3%**
III. Machinery, Structures, and Compensation Expenditures			
a. Payroll, Benefits, and Employment	51.9	18.3%	15.5%
b. Capital Expenditures: Structures (including rental)	4.1	1.4%	1.1%
c. Capital Expenditures: Machinery/Equipment (including rental)	10.8	3.8%	2.5%
d. TOTAL	**66.8**	**23.5%**	**19.1%**
IV. Suppliers of Materials Expenditures			
a. Materials, Parts, Containers, Packaging, etc… Used	138.6	48.7%	50.6%
b. Contract Work and Resales	7.0	2.5%	2.9%
c. Purchased Fuels and Electricity	6.6	2.3%	1.5%
d. TOTAL	**152.1**	**53.5%**	**55.0%**
V. Maintenance and Repair Expenditures	**3.6**	**1.3%**	**1.0%**
VI. Shipments			
a. Expenditures I.e + II + III.d + IV.d+V	240.4	84.5%	80.9%
b. Net Inventories Shipped	0.1	0.0%	-1.2%
c. Depreciation	9.1	3.2%	3.2%
d. Net Income	34.7	12.2%	17.0%
E. TOTAL	**284.4**	**100.0%**	**100.0%**
VII. Value Added estimates			
a. Value added calculated VI.E-VI.b-VI.A+III.a	95.8	33.7%	35.8%
b. ASM Value added	131.4	46.2%	45.9%

Data Source: Census Bureau 2021

codes feed into others. For instance, the NAICS 325211 likely provides material to other industries such as NAICS 326122, which produces plastic pipes. Shipments or revenue (see Table 2.3) can be seen as representing both the value from the industry being examined along with its purchases ($284.4 billion) while value added represents the industry’s contribution to value ($131.4 billion).

2.3. Primary Plastic Manufacturing Supply Chain

According to Bryce (2021), primary plastic is largely made from crude oil, natural gas, and to some extent coal and bio-based materials. For example, crude oil is heated in a

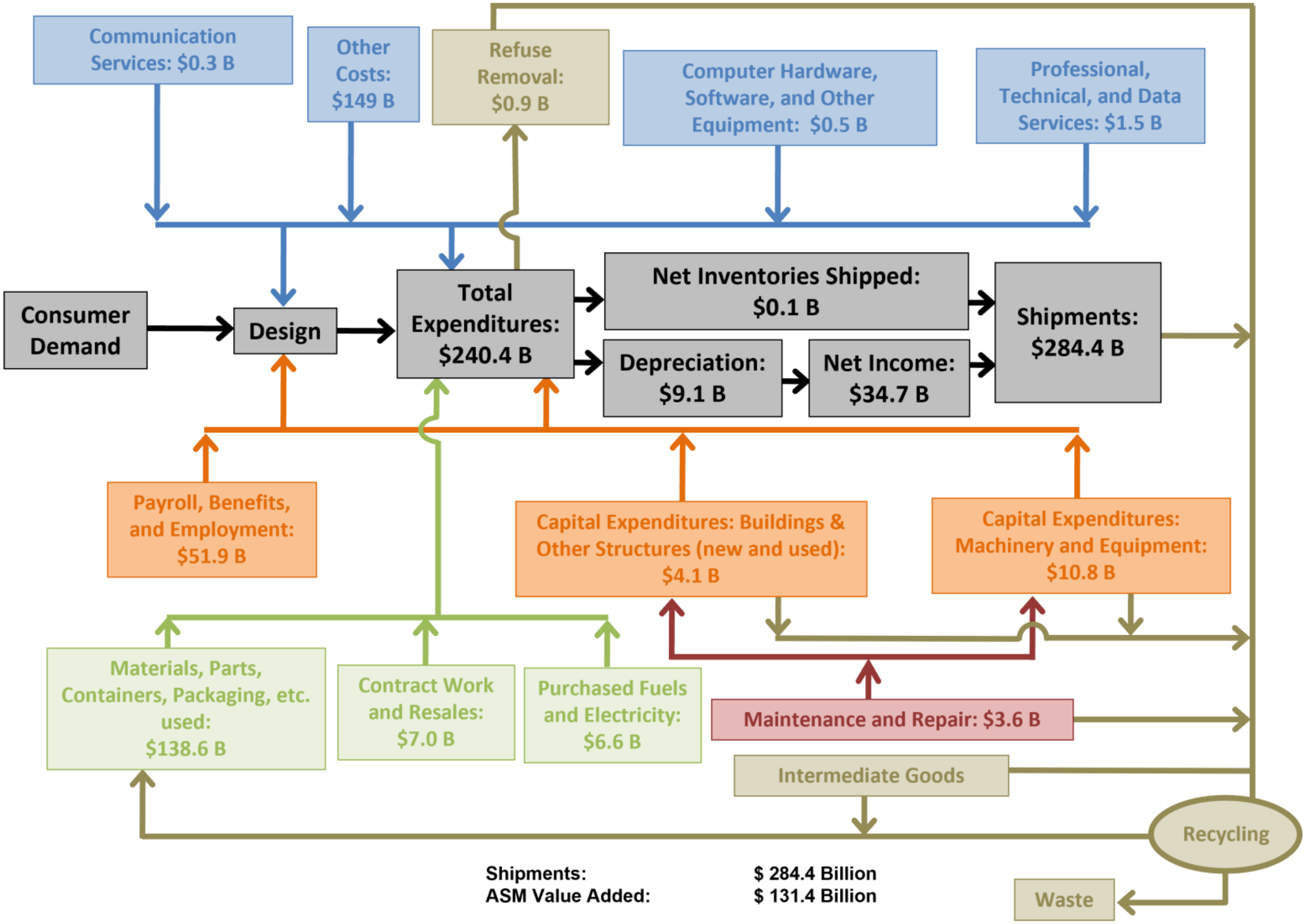


Figure 2.1: U.S. Plastics and Synthetic Rubber Manufacturing Supply Chain, 2020 (NAICS 325211, 325212, 326110-326190)
NOTE: Colored categories are defined in Table 2.2; Data Source: Census Bureau 2021

Table 2.3: U.S. Plastics and Synthetic Rubber Manufacturing Value Added by NAICS, 2020

2017 NAICS code	Meaning of NAICS code	Sales, value of shipments, or revenue ($Billion)	Value added ($Billion)
325211	Plastics material and resin manufacturing	76.2	28.7
325212	Synthetic rubber manufacturing	6.6	2.9
326111	Plastics bag and pouch manufacturing	12.9	6.0
326112	Plastics packaging film and sheet (including laminated) manufacturing	13.6	5.7
326113	Unlaminated plastics film and sheet (except packaging) manufacturing	13.2	5.5
326121	Unlaminated plastics profile shape manufacturing	8.3	5.7
326122	Plastics pipe and pipe fitting manufacturing	11.2	5.0
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	3.9	2.0
326140	Polystyrene foam product manufacturing	9.0	3.9
326150	Urethane and other foam product (except polystyrene) manufacturing	11.2	5.7
326160	Plastics bottle manufacturing	12.1	5.6
326191	Plastics plumbing fixture manufacturing	4.9	2.8
326199	All other plastics product manufacturing	96.1	48.9
326220	Rubber and plastics hoses and belting manufacturing	5.1	2.9
TOTAL		284.4	131.4

Source: Data Source: Census Bureau 2021

furnace and then through distillation different compounds are separated with one being naphtha, a component used to make plastic. To make plastic, this material needs to be broken down into a raw hydrocarbon state (i.e., chemical production). Figure 2.2 provides example flow diagrams for production of PET (a) and HDPE (b) (Kim et al 2023). The resulting materials are then put through polymerization, which produces repeating chains called polymers. For example, HDPE is produced using ethylene that are the result of “steam cracking,” which applies high heat and pressure to crude oil or natural gas in a zero-oxygen environment. With natural gas, ethane is separated from methane and then sent to a cracker (Frazier 2017). The resulting material can then be strung together in long chains (Frazier 2017). Inputs to PET involve similar processes, using one or a combination of Purified Terephthalic Acid (PTA) and ethylene, which is also typically generated from fossil fuels.

To understand the plastics manufacturing supply chain, Table 2.2 and Figure 2.1 breakdown the shipments (i.e., revenue) of plastic manufacturing into its different components, including supply chain components, using data from the ASM. One component, expenditures, is represented by sections I through IV in Table 2.2. These are summed in Section VI.a. Shipments can be further broken into three other components: net inventories shipped, depreciation, and net income. Value added would typically be shipments less expenditures less net inventories shipped plus payroll, benefits, and employment. Materials, parts, and containers (III.a) is a large component. The values as seen as a percent of shipments is not dramatically different from the entire manufacturing industry, which is shown in the last column of Table 2.2. However, payroll, benefits, and employment expenditures are 2.8 percentage points higher for plastics. Additionally, the sum of expenditures (i.e., I through VI) is higher than for total manufacturing with net income, which includes profits, being a lower percentage. More than half of the revenue received (i.e., shipments) from plastic and synthetic rubber manufacturers goes to suppliers of materials (i.e., category IV), demonstrating the importance of their role. Capital expenditures are also higher than total manufacturing, demonstrating that there is a higher level of investment in structures and machinery needed for plastics manufacturing than for the average manufacturer.

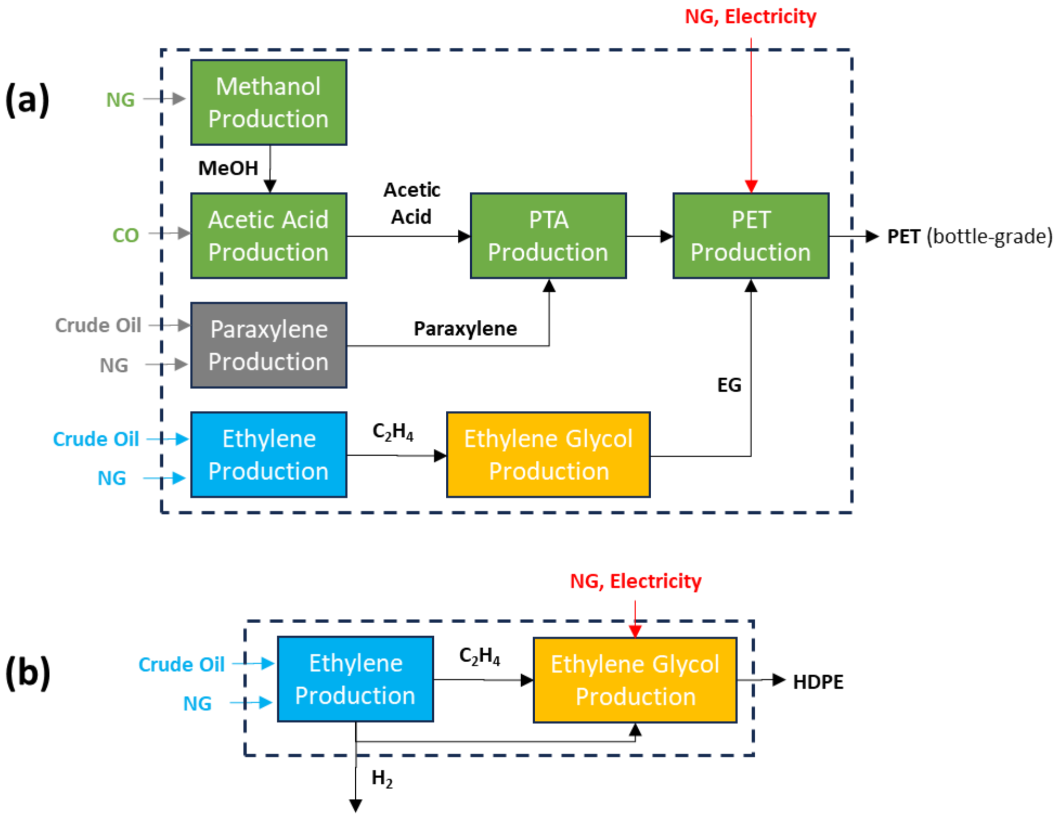


Figure 2.2: Flow Diagram of plastic resin production for (a) PET and (b) HDPE (Kim et al 2023)

Another method of examining the plastics manufacturing supply chain is to use economic input-output analysis. Table 2.4 presents the results of input-output analysis using NIST's Manufacturing Cost Guide (MCG) (Thomas 2020), which is based on BEA's economic input-output tables. It examines U.S. manufacturing of plastics and synthetic rubber and

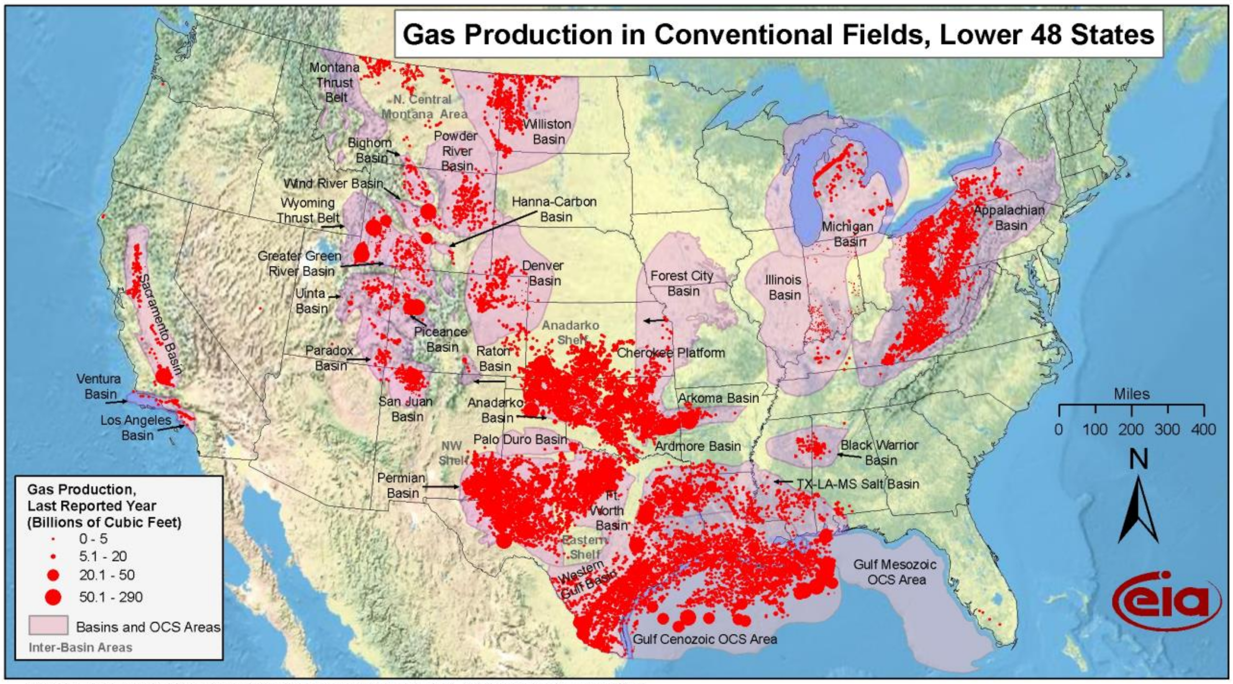
Table 2.4: Plastic and Synthetic Rubber Supply Chain (NAICS 325211, 325212, 326110-326190)

Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)
326190	Other plastics product manufacturing	29 589.4	8 048.7	37 638.1
325211	Plastics material and resin manufacturing	18 570.0	11 837.2	30 407.2
324110	Petroleum refineries	5 577.6	13 425.6	19 003.2
325110	Petrochemical manufacturing	14 620.7	3 591.6	18 212.3
211000	Oil and gas extraction	16 553.9	1 564.6	18 118.6
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	12 024.5	4 502.1	16 526.6
325190	Other basic organic chemical manufacturing	8 852.1	3 453.3	12 305.4
424A00	Other nondurable goods merchant wholesalers	9 764.4	229.2	9 993.6
326120	Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing	5 886.7	1 618.1	7 504.7
3252A0	Synthetic rubber and artificial and synthetic fibers and filaments manufacturing	4 639.0	2 311.5	6 950.5
221100	Electric power generation, transmission, and distribution	6 135.6	473.7	6 609.4
550000	Management of companies and enterprises	6 227.1	215.6	6 442.7
326160	Plastics bottle manufacturing	3 499.5	1 753.1	5 252.6
326150	Urethane and other foam product (except polystyrene) manufacturing	2 652.1	1 305.9	3 958.0
325180	Other Basic Inorganic Chemical Manufacturing	2 953.3	712.2	3 665.5
326140	Polystyrene foam product manufacturing	2 445.6	858.2	3 303.7
531ORE	Other real estate	3 184.0	93.6	3 277.7
484000	Truck transportation	2 899.7	143.4	3 043.1
423A00	Other durable goods merchant wholesalers	2 513.2	76.5	2 589.6
52A000	Monetary authorities and depository credit intermediation	2 506.5	35.8	2 542.3
482000	Rail transportation	2 228.6	233.4	2 461.9
424700	Petroleum and petroleum products	2 412.3	30.8	2 443.1
1111B0	Grain farming	1 617.0	548.0	2 165.0
561700	Services to buildings and dwellings	1 798.5	125.5	1 924.0
533000	Lessors of nonfinancial intangible assets	1 897.8	23.4	1 921.3
541300	Architectural, engineering, and related services	1 833.3	81.7	1 915.0
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	1 487.7	346.4	1 834.1
561300	Employment services	1 775.1	17.6	1 792.7
3259A0	All other chemical product and preparation manufacturing	1 178.2	521.5	1 699.7
541100	Legal services	1 642.7	19.9	1 662.6
	Other	66 976.4	9 756.1	76 732.5
	Total	245 942.7	67 954.1	313 896.8

Calculated using NIST’s Manufacturing Cost Guide (Thomas 2020).
Note: Supply chain items are shown in black while greyed out industries represent the industries being the focus in this report (i.e., plastic and synthetic rubber manufacturing)

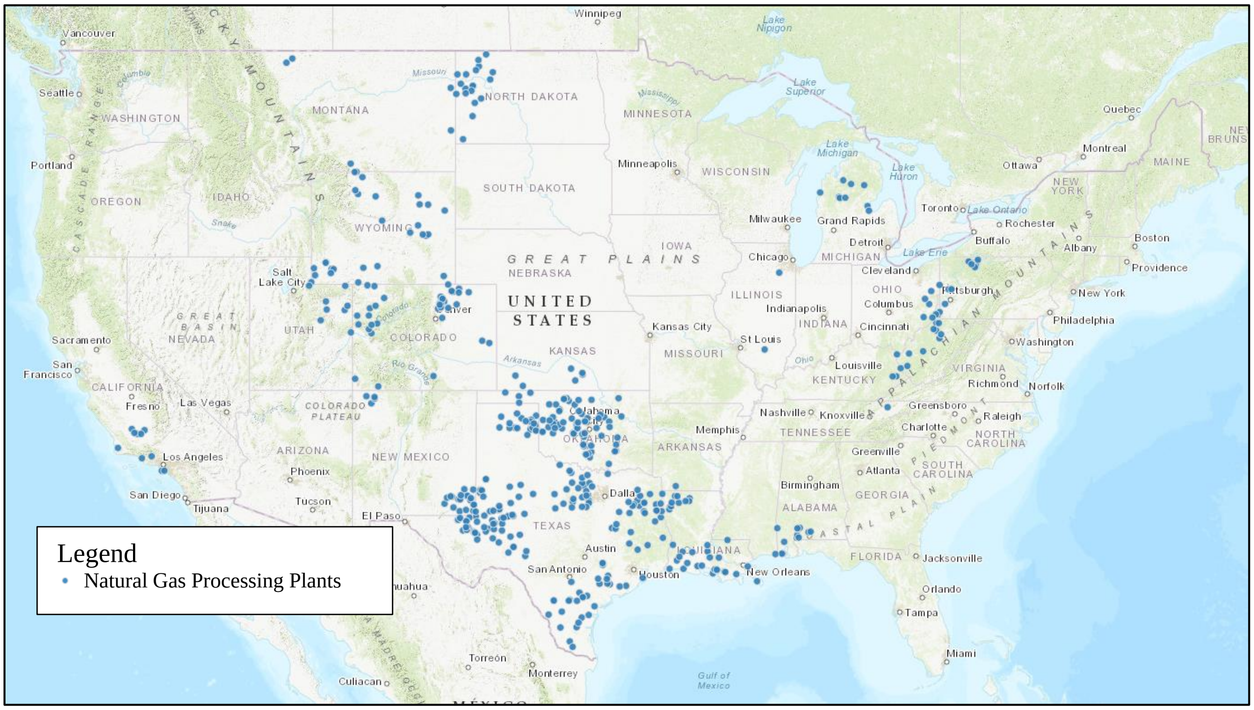
shows the top 30 supply chain components, including the industries being examined which are shown in grey. These are out of approximately 381 industries. The largest supply chain component (measured as the total of estimated imports and value added), excluding the industries being examined, is petroleum refineries followed by petrochemical manufacturing and oil/gas extraction. The top three supply chain items (NAICS 324110, 325110, and 21100), excluding the industries being examined (i.e., those greyed out), are petroleum and petrochemical related and represent 17.6 % of the total direct and indirect value added, including imports. If direct plastic manufacturing is excluded, the share of the supply chain for these NAICS codes increases to 27.6 %. The cost of these inputs is likely to have significant influence on the cost of plastics, as discussed later in this report. Other items to note include wholesalers, which represent 3.2 % of total direct and indirect value added, including imports. Wholesalers often store products and connect producers with users. Another cost item to note is that of rail and truck transportation, which represents 1.8 % of the direct and indirect value added, including imports. The importance of these items is that they have significant influence on the prices of primary plastic and possibly the prices for recycled plastic as well. Unfortunately, these values are for all plastic manufacturing and there is not input-output data specific to recycled plastic; however, the supply chain for all plastics provides some insight for recycled plastics. The cost effectiveness of plastic recycling depends to some extent on the costs of recycled plastic compared to primary plastic; thus, reducing costs can make recycled plastic more competitive.

According to the U.S. Energy Information Administration (2023a), in the U.S. natural gas is the primary feedstock for making plastics; however, “the… Energy Information Administration (EIA) is unable to determine the specific amounts or origin of the feedstocks that are actually used to manufacture plastics in the United States” (U.S. Energy Information Administration 2023a). This is due to the high flexibility in the feedstocks that are used (U.S. Energy Information Administration 2023a). As illustrated in Figure 2.3, U.S. gas production is generally concentrated to particular areas of the country (called basins) and natural gas processing plants are concentrated in or near these basins, as illustrated in Figure 2.4. In the U.S., there were 478 natural gas processing plants as of October 2020. The 129 operating petroleum refineries in the U.S. as of January 1, 2023 (U.S. Energy Information Administration 2023b) are more distributed throughout the U.S., as seen in Figure 2.5. However, there are only 35 steam crackers in the U.S. used to create ethylene, as illustrated in Figure 2.6, the steam crackers are centralized along the Gulf Coast of the U.S. Plastics resin manufacturing is more dispersed throughout the U.S. (see Figure 2.7), requiring the transportation of these chemicals to the plastic resin production facilities. Recall that transportation costs are among the top costs for plastics manufacturing, accounting for 1.8 % of direct and indirect value added. Similarly, the potential primary end markets for plastics are likely to correlate with population densities.



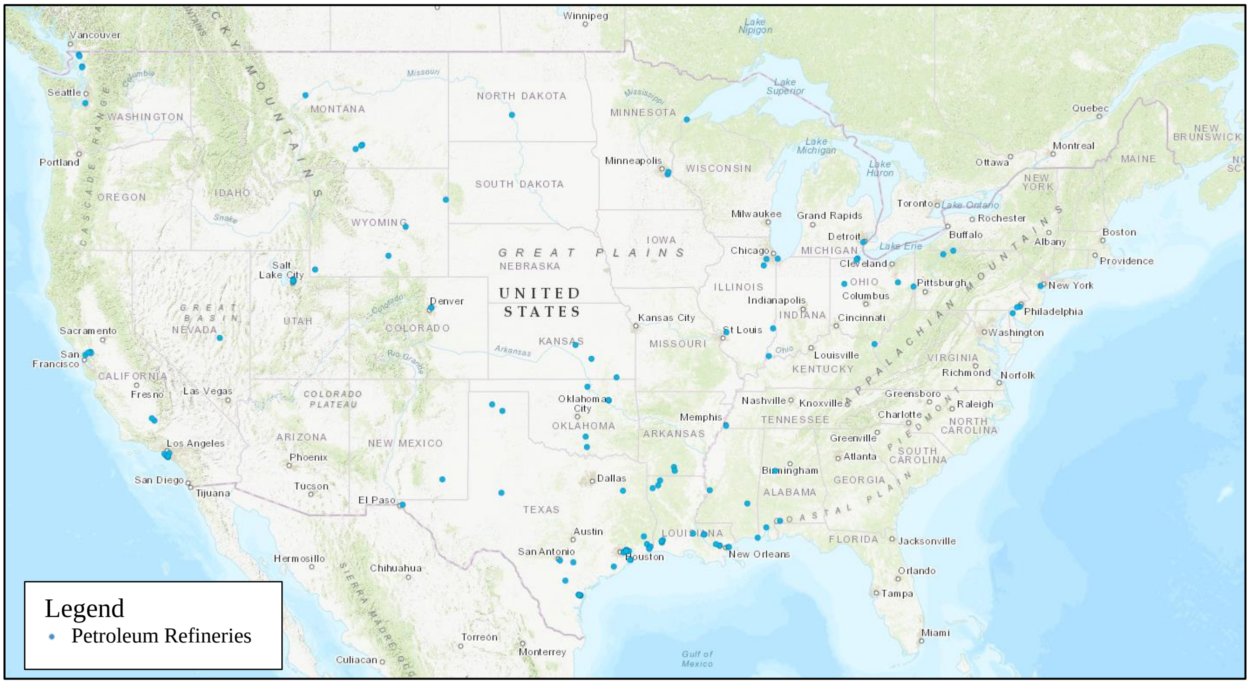
Source: Energy Information Administration based on data from HPDI, IN Geological Survey, USGS
Updated: April 8, 2009

Figure 2.3: U.S. Gas Production in Conventional Fields



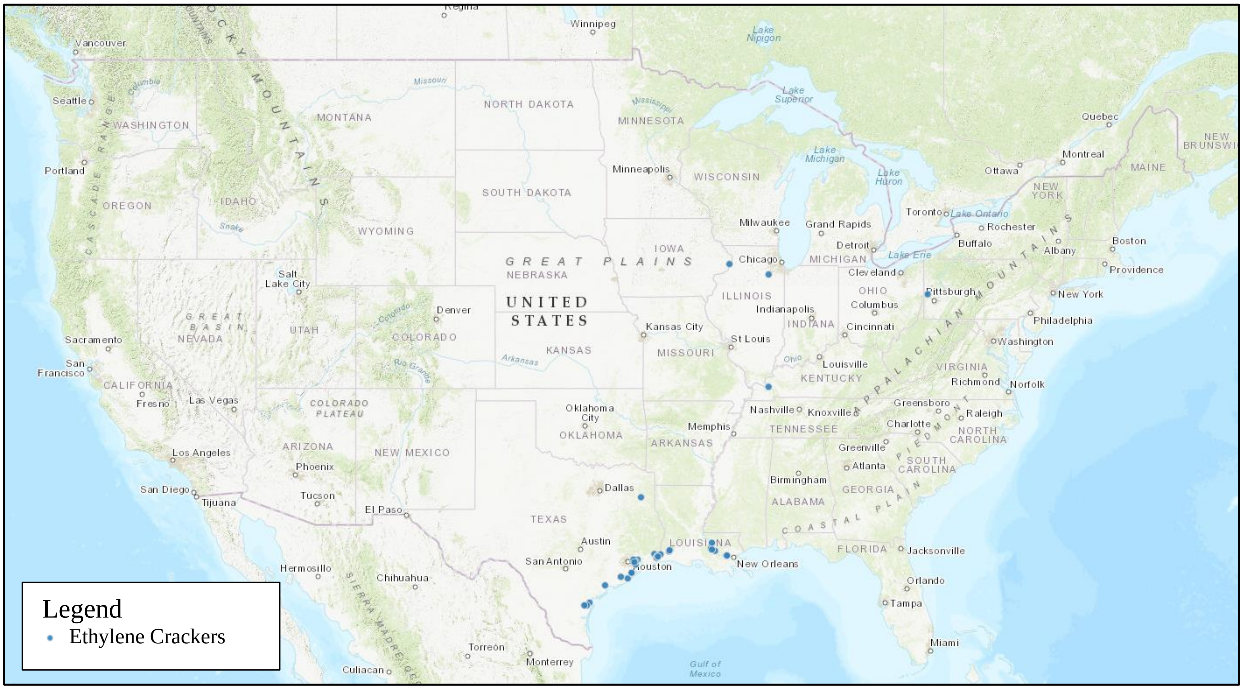
Source: U.S. Energy Information Administration. 2020a

Figure 2.4: Natural Gas Processing Plants



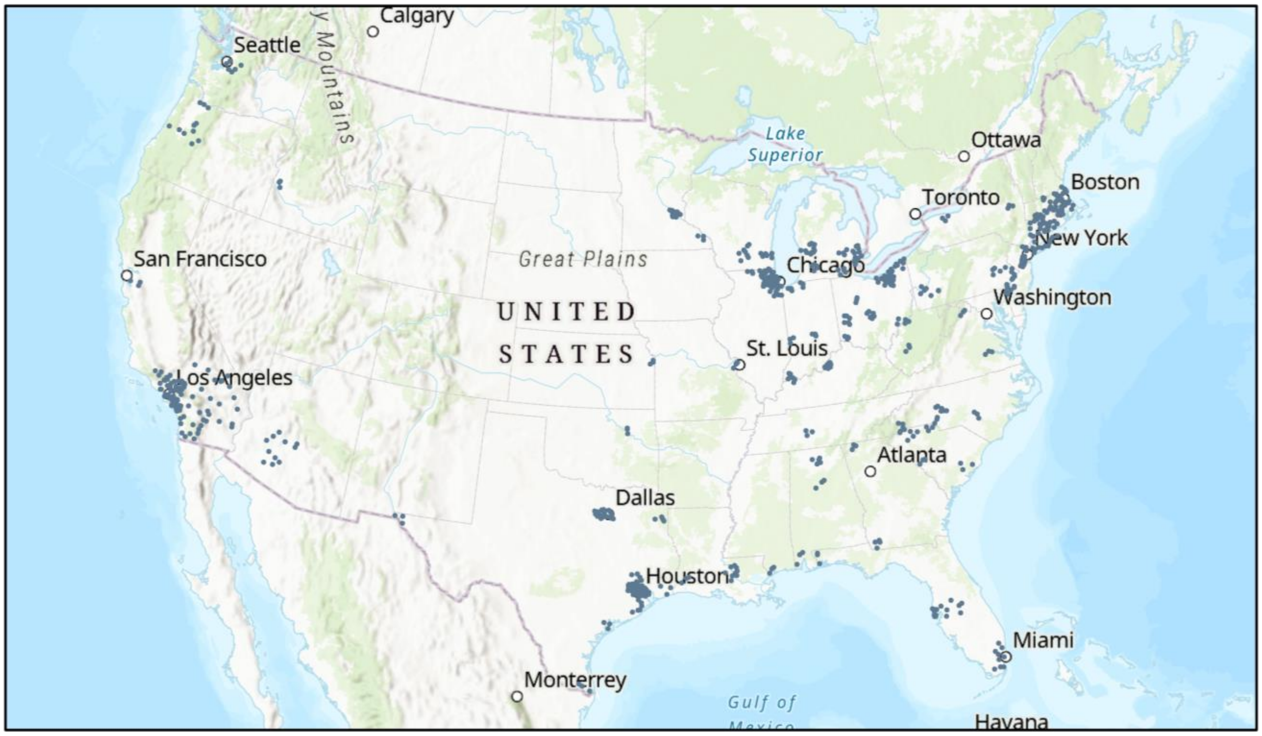
Source: U.S. Energy Information Administration. 2020b

Figure 2.5: Petroleum Refineries



Source: U.S. Energy Information Administration. 2020c

Figure 2.6: Ethylene Crackers

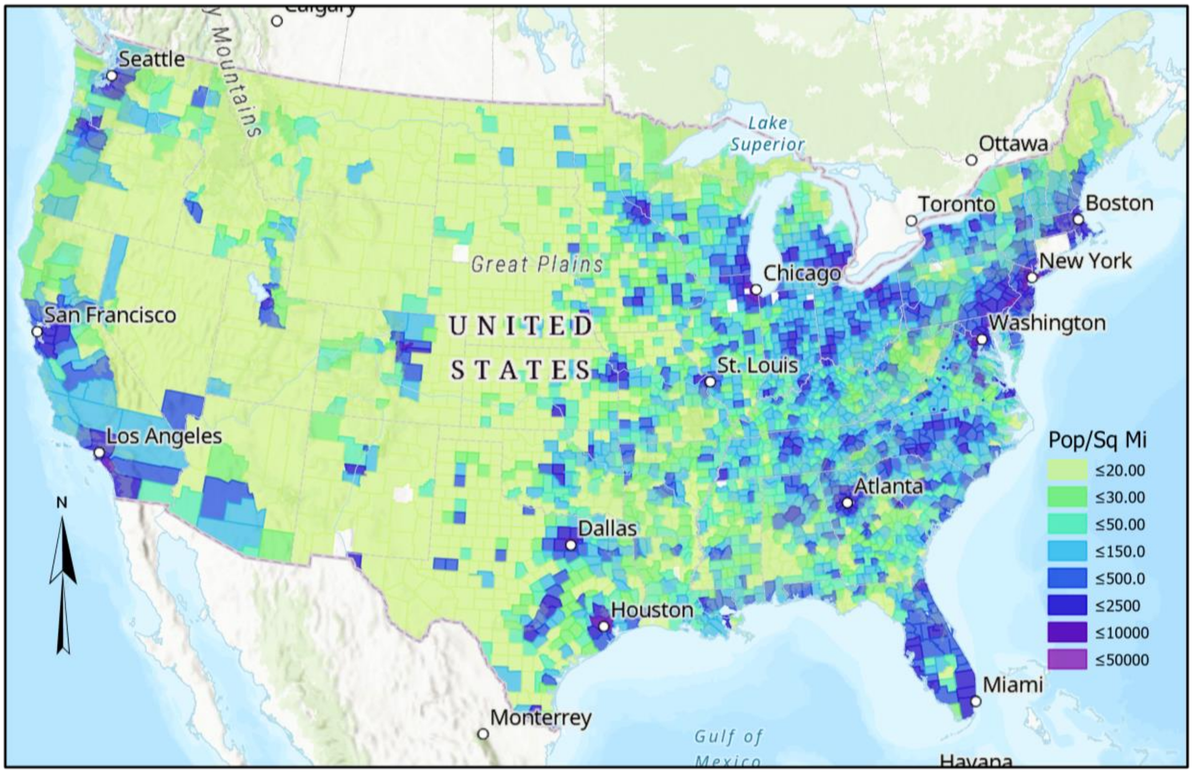


Data Source: U.S. Census Bureau (2023d)
Note: Locations are accurate to the county level.

Figure 2.7: Approximate Location of Resin Manufacturers (NAICS 3252), 2021

2.4. Supply Chain for Manufacturing Plastics from Recycled Material

The supply chain for recycled content-based plastics starts with plastic consumers and flows through plastics waste collection, sorting, and recycling. Plastic consumers are spread out across the entire U.S. (i.e., decentralized) with varying population densities (Figure 2.8), and thus the availability of plastic waste is highly correlated with population. For a given community, plastic waste must be collected from decentralized locations (i.e., every home and business) and aggregated at a centralized location for sorting. Waste collection is accomplished through recycling programs that vary significantly across areas of the country and even across neighboring communities. Approximately 93 % of surveyed respondents in North America believe recycling is moderately to extremely important (World Economic Forum 2022). However, this survey also revealed that 30 % indicate that a lack of programs or services kept them from recycling more with 28 % indicating inconvenience was an inhibitor as well. Additionally, only an estimated 53 % of the U.S. population has automatic enrollment to curbside recycling; that is, 53 % have a recycling service that doesn't require opting in or subscribing (Marshall 2017). Of these, only 44 % were served with a wheeled cart (Marshall 2017) (typically 0.242 m^3 (64 gal) or greater) while most others use small bins (typically 0.068 m^3 (18 gal)), which limits the amount of material that can be collected. As illustrated in Figure 2.9, a wheeled cart allows for a larger amount of recycling material.

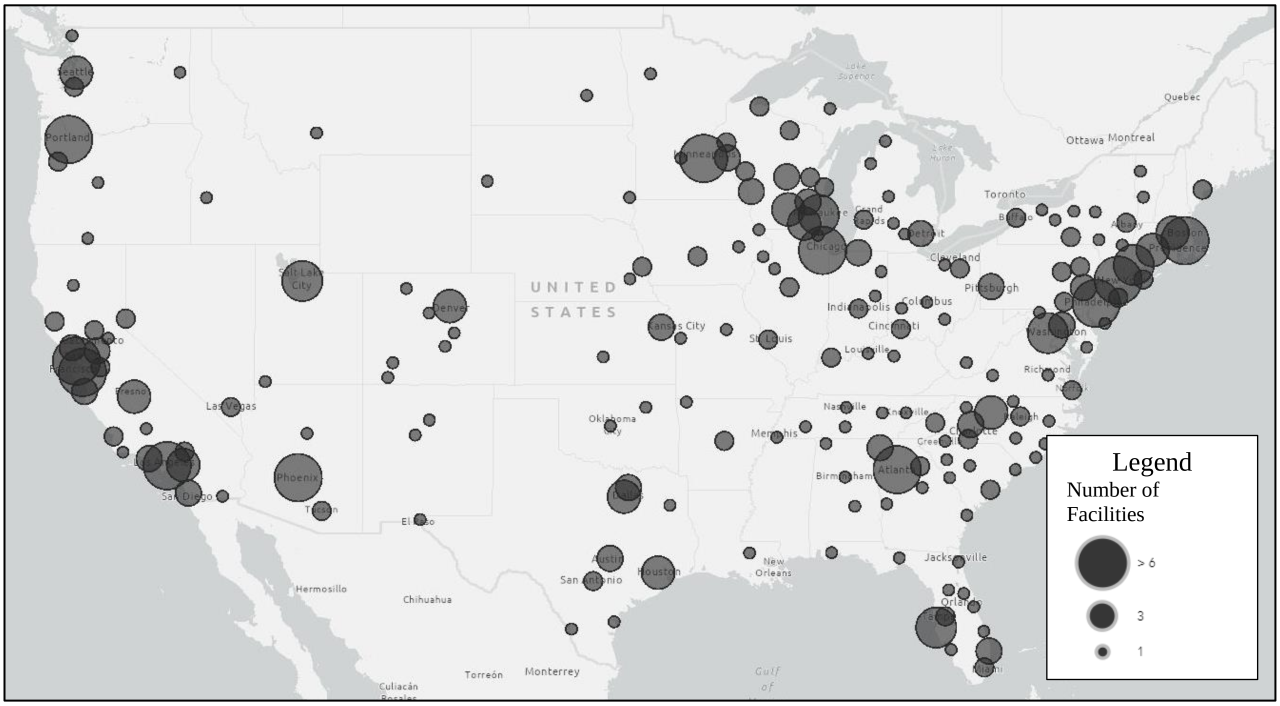


Population Data source: U.S. Census Bureau (2023e)

Figure 2.8: Population Density

Figure 2.9: Illustration of Non-Wheeled Cart / Bin (Left) and Wheeled Cart (Right)

Plastics collected for recycling are sorted at a material recovery facility (MRF). In the U.S., there are an estimated 990 MRFs (i.e., NAICS 562920) with a total of $5.9 billion in revenue (i.e., value of shipments), according to 2017 Annual Business Survey data (U.S. Census Bureau 2023c). Figure 2.10 shows the availability of an MRF for a given location varies across the Contiguous U.S., with some states having 0 (e.g., Wyoming), 1 (e.g., Idaho), or 2 (e.g., Oklahoma). Alaska and Hawaii face additional transportation challenges given their isolated locations. This lack of accessibility to MRFs makes it more difficult for many communities to provide recycling programs. Additionally, the type of plastic waste that is accepted varies by



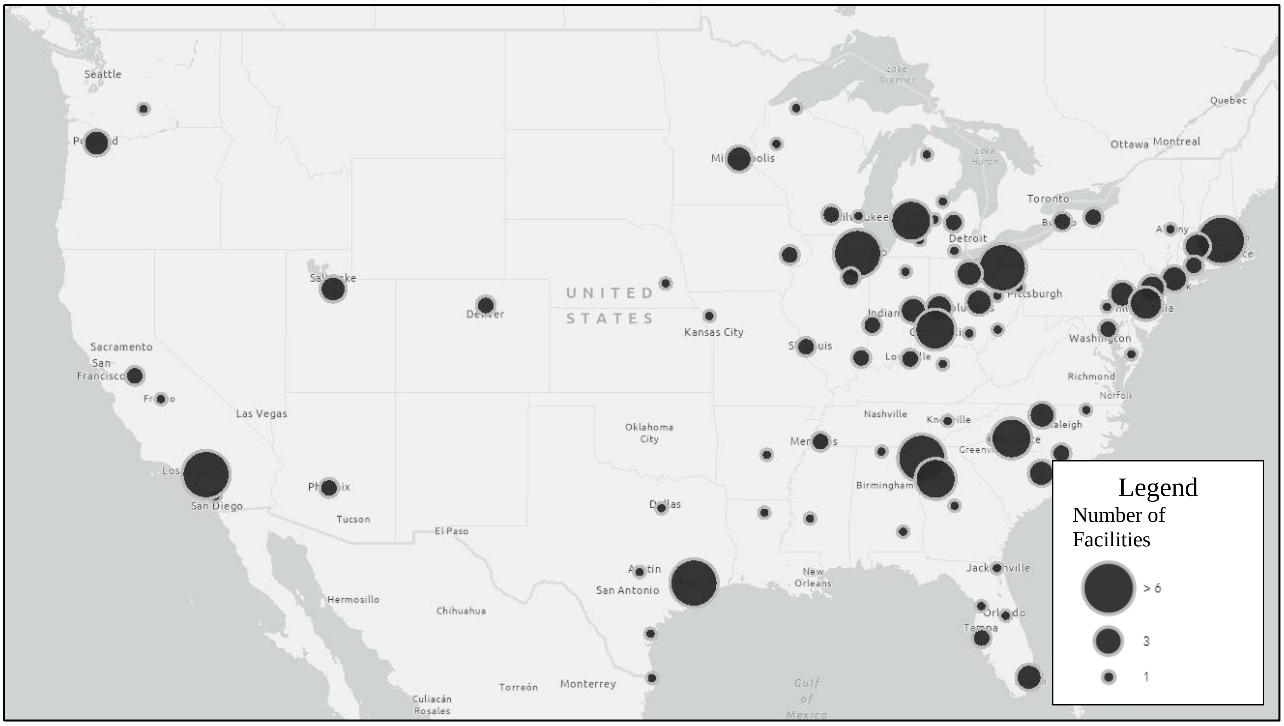
Source: U.S. Environmental Protection Agency 2023b

Figure 2.10: Material Recovery Facilities (MRFs)

MRF and community program, adding another layer of complexity of the plastics recycling supply chain. This is discussed further in Section 5.2.2.

Typically, after sorting at an MRF, plastic materials are then sent to a plastic recycling facility; however, it is important to note that some collected plastics are exported (see Section 3.1.1 for more details). Mechanical recycling is the primary method used for recovering plastics and includes six steps: collection, sorting by plastic type, washing, shredding, separating by quality/class, and finally extruding/compounding, which turns the shredded plastic into pellets that can be used by manufacturers (RTS 2020). The chemical composition of the material is largely unaltered.

In the U.S., there are an estimated 196 mechanical plastic recycling facilities (less than 20 % of the number of MRFs), as illustrated in Figure 2.11, with varying range of acceptance of plastic types. As shown in the map, there tends to be more plastic recycling facilities on the east portion of the U.S. and near the coasts, where large populations are located. As with MRFs, the availability of plastic recycling facilities limits opportunities in some areas of the country from having plastic recycling programs. Many states in the western portion of the country have zero plastic recycling facilities (Figure 2.11), and the need for transporting plastic waste long distances is cost and resource prohibitive.



Source: U.S. Environmental Protection Agency 2023b

Figure 2.11: Plastic Recycling Facilities

Some insight into the costs and supply chain of mechanical recyclers can be found by examining the supply chain data from the Annual Survey of Manufactures for NAICS 325991, which is described as, “establishments primarily engaged in (1) custom mixing and blending [of] plastics resins made elsewhere or (2) reformulating plastics resins from recycled plastics products.” The data for this industry is presented in Table 2.5, which is directly comparable to the data in Table 2.2. Also shown is the data for plastic material, resin, and synthetic rubber manufacturing (NAICS 325211 and 325212), which includes primary plastic resins. It is important to note that neither category in Table 2.5 is strictly primary or recycled plastic, but rather it is likely that they are more prevalently primary or recycled plastic. Comparing the percentages reveals that net income, which includes profit, as a percent of shipments is 26.7 % lower for the recycled resin category, suggesting that it may be less profitable than primary production. When compared to that for all U.S. manufacturing (see Table 2.2), it is 56.5 % lower, suggesting it is much less profitable than the average manufacturing activity as of 2020. Payroll, benefits, and employment accounts for a larger proportion of recycled resin shipments than primary as does materials, parts, containers, and packaging. Increasing productivity and decreasing material costs might result in recycled plastic being more cost competitive and more profitable, resulting in an increase in plastic being recycled.

Additional insight into resin production from recycled material can be gained through data from the Department of Energy (DOE) Industrial Assessment Center (IAC) program. It is a publicly available database of 148 000 recommendations for 20 000 facilities, as of October 2021. The data is the result of DOE technical assessments of facilities conducted by university engineering students and staff from 26 IACs made up of 31 universities (Industrial Assessment Center 2021; U.S. Department of Energy 2011). Each observation in the IAC database is a recommendation for an investment. It includes an Assessment Recommendation Code (ARC), the cost to implement the recommendation, estimated annual savings, year, whether the recommendation was implemented, and some characteristics of the establishment including sales, various energy expenditures, and number of employees. For the IAC to conduct an assessment, a facility must generally have the following: gross annual sales of $100 million or less, consume energy at a cost between $100 000 and $2.5 million annually, employ no more than 500 people, and have no technical staff whose primary duty is energy analysis (U.S. Department of Energy 2011). These requirements suggest that the facilities being examined are likely to have a relatively higher level of low-cost, high-return investment possibilities, as these establishments have higher costs (i.e., energy costs) and fewer resources to identify potential investments.

The net present value with a 10-year study period was used to examine the returns of possible cost savings from the IAC recommendations for NAICS 325991, which includes recycled resin manufacturing. Only 17 firms were examined within this NAICS code, which included a total of 154 recommendations; thus, the data mostly provides anecdotal evidence. NPV is calculated by summing cash inflows and subtracting cash outflows for each year and adjusting it, using a discount rate, to a common time period, which we will call time zero (Thomas 2017). Table 2.6 presents the net present value summed by the ARC recommendation codes, which can provide insight into opportunities for advancing efficiency in the production of resin from recycled plastic. The largest category in Table 2.6 is *Direct Productivity Enhancements - Labor Optimization - Automation* followed by *Energy Management – Motor Systems – Air compressors*. The large size of these suggests that there might be similar opportunities (i.e., automation and energy cost reduction) at other facilities. Other areas that seem promising are in lighting, heat recovery, and ventilation. The 10-year net present value of the recommendations for each facility as a percent of sales ranged between 0.1 % and 33.4 %. Thus, some of the facilities had a large opportunity for reducing costs relative to their size while others had fewer opportunities. Approximately 73.9 % of establishments in this NAICS code (3235991) in the U.S. have fewer than 50 employees. Only two establishments in the IAC data had fewer than 50 employees and between them the total NPV as a percent of sales was 8.8 % while those with 50 employees or more had an NPV equivalent of 1.3 % of sales. That is, despite being the majority of the industry, small firms represented only 11.7 % of those who sought out and received advice from the IAC program and their savings relative to their size were 4.5 times larger. Both the disproportionally small representation of small firms and the higher level of returns suggests the possibility of there being significant opportunities for increasing efficiency and productivity. However, it is important to note that two establishments is too few to draw a solid conclusion.

Table 2.5: Supply Chain for Recycled Resin and Primary Resin Compared

	Includes Recycled Resin		**Includes Primary Resin**	
	Custom compounding of purchased resins (NAICS 325991)		**Plastic material, resin, and synthetic rubber manufacturing (NAICS 325211, 325212)**	
	($Billions 2020)	**As a Percent of Shipments**	**($Billions 2020)**	**As a Percent of Shipments**
I. Services, Computer Hardware, Software, and Other Expenditures				
a. Communication Services	0.01	0.1%	0.0	0.0%
b. Computer Hardware, Software, and Other Equipment	0.02	0.2%	0.1	0.2%
c. Professional, Technical, and Data Services	0.06	0.6%	0.4	0.4%
d. Other Expenditures	0.38	4.0%	3.8	4.6%
e. TOTAL	**0.46**	**4.9%**	**4.4**	**5.3%**
II. Refuse Removal Expenditures	**0.02**	**0.2%**	**0.4**	**0.5%**
III. Machinery, Structures, and Compensation Expenditures				
a. Payroll, Benefits, and Employment	1.44	15.4%	9.3	11.2%
b. Capital Expenditures: Structures (including rental)	0.16	1.7%	1.1	1.3%
c. Capital Expenditures: Machinery/Equipment (including rental)	0.22	2.4%	4.2	5.1%
d. TOTAL	**1.82**	**19.6%**	**14.6**	**17.6%**
IV. Suppliers of Materials Expenditures				
a. Materials, Parts, Containers, Packaging, etc… Used	5.60	60.0%	46.2	55.8%
b. Contract Work and Resales	0.20	2.1%	1.6	2.0%
c. Purchased Fuels and Electricity	0.14	1.5%	2.8	3.4%
d. TOTAL	**5.94**	**63.7%**	**50.6**	**61.1%**
V. Maintenance and Repair Expenditures	**0.09**	**0.9%**	**1.3**	**1.6%**
VI. Shipments				
a. Expenditures I.e + II + III.d + IV.d+V	8.33	89.3%	71.3	86.1%
b. Net Inventories Shipped	0.01	0.1%	0.5	0.6%
c. Depreciation	0.30	3.2%	2.6	3.2%
d. Net Income	0.69	7.4%	8.4	10.1%
E. TOTAL	**9.33**	**100.0%**	**82.8**	**100.0%**
VII. Value Added estimates				
a. Value added calculated VI.E-VI.b-VI.A+III.a	2.43	26.0%	20.3	24.5%
b. ASM Value added	3.34	35.8%	31.5	38.1%

Data Source: Census Bureau 2021

Table 2.6: Sum of 10-Year NPV Calculated from IAC Data at the 3 Digit ARC Code (NAICS 325991)

ARC Code and Description	Sum of NPV
44400: Direct Productivity Enhancements - Labor Optimization - AUTOMATION	2 687 089
24200: Energy Management - Motor Systems - AIR COMPRESSORS	1 020 128
27100: Energy Management - Building and Grounds - LIGHTING	1 001 377
22400: Energy Management - Thermal Systems - HEAT RECOVERY	989 922
27300: Energy Management - Building and Grounds - VENTILATION	810 036
21300: Energy Management - Combustion Systems - FUEL SWITCHING	770 089
46200: Direct Productivity Enhancements - Reduction of Downtime - QUICK CHANGE	757 165
41200: Direct Productivity Enhancements - Manufacturing Enhancements - DEFECT REDUCTION	689 176
24100: Energy Management - Motor Systems - MOTORS	605 909
33100: Waste Minimization / Pollution Prevention - Post Generation Treatment / Minimization - GENERAL	541 095
26100: Energy Management - Operations - MAINTENANCE	454 477
27200: Energy Management - Building and Grounds - SPACE CONDITIONING	428 921
22500: Energy Management - Thermal Systems - HEAT CONTAINMENT	386 814
35200: Waste Minimization / Pollution Prevention - Recycling - SOLID WASTE	292 178
26200: Energy Management - Operations - EQUIPMENT CONTROL	280 582
23500: Energy Management - Electrical Power - TRANSMISSION	246 492
23200: Energy Management - Electrical Power - POWER FACTOR	226 108
42100: Direct Productivity Enhancements - Purchasing - RAW MATERIALS	152 049
45100: Direct Productivity Enhancements - Space Utilization - FLOOR LAYOUT	92 619
34100: Waste Minimization / Pollution Prevention - Water Use - GENERAL	90 773
22200: Energy Management - Thermal Systems - HEATING	76 018
22600: Energy Management - Thermal Systems - COOLING	63 232
24300: Energy Management - Motor Systems - OTHER EQUIPMENT	60 648
35300: Waste Minimization / Pollution Prevention - Recycling - OTHER MATERIALS	55 321
21200: Energy Management - Combustion Systems - BOILERS	40 346
44200: Direct Productivity Enhancements - Labor Optimization - PRACTICES / PROCEDURES	38 016
23100: Energy Management - Electrical Power - DEMAND MANAGEMENT	37 045
28100: Energy Management - Ancillary Costs - ADMINISTRATIVE	32 004
44300: Direct Productivity Enhancements - Labor Optimization - TRAINING	25 222
27400: Energy Management - Building and Grounds - BUILDING ENVELOPE	24 808
41100: Direct Productivity Enhancements - Manufacturing Enhancements - BOTTLENECK REDUCTION	15 238
22100: Energy Management - Thermal Systems - STEAM	923

Note: The description includes the one digit ARC code followed by the two digit and three digit code description each separated with a hyphen.

3. Current State of Plastic Recycling in the U.S.

Although the EPA released a National Recycling Strategy, the U.S. has not implemented a cohesive national recycling program (U.S. Environmental Protection Agency 2024). Rather each state and/or local jurisdiction has its own policies and approaches as was highlighted by the variation in community recycling programs discussed in Section 2.4. There are three primary streams for plastic waste: landfilling/disposal, recycling, and incineration (Vogt et al. 2021). Plastic accounted for 12.2 % of municipal solid waste in the U.S. in 2018 (U.S. Environmental Protection Agency 2021), by weight, and a mere 8.7 % of plastics are recycled/collected in the U.S. with 15.8 % being combusted with energy recovery and 75.6 % being landfilled (U.S. Environmental Protection Agency 2021). PET, which is best known for being used for beverage bottles, has the highest recycle/collection rate in the U.S. at 18.2 % (see Table 2.1). The lack of plastic recycling is not just a U.S. problem, but a global issue as well. It is estimated that as of 2015, globally 9 % of all plastics ever produced were recycled/collected, 12 % were incinerated, and 79 % were disposed of in landfills (Geyer et al. 2017). According to Gao (2020), globally in 2018 it is estimated that 16 % of plastics were mechanically recycled, 25 % were incinerated, 40 % were disposed of in landfills, and 19 % are unmanaged (Gao, 2020). The following sections discuss the methods used to recycle plastics (Section 3.1), including mechanical recycling (Section 3.1.1) and chemical recycling (Section 3.1.2), as well as the impact that recycling might have on sustainability (Section 3.2).

3.1. Plastic Recycling Methods

Recycled plastic tends to have a lower carbon footprint than primary material. For instance, an examination of PET, HDPE, and PP showed that recycling had a lower carbon footprint than primary material (Association of Plastic Recyclers 2020). For PET, recycled plastic had 40.8 % of the carbon dioxide equivalent compared to primary plastic. Unfortunately, plastic recycling faces several challenges. For instance, contamination is a concern that can affect performance, appearance, and have health consequences when used in food containers (Selke 2001). Often recycled material is mixed with primary material for performance purposes (Selke 2001) and depending on the method for recycling, there are some limitations on how many times a plastic can be recycled – typically only 2 to 3 times mechanically – due to degradation each time (Vogt et al. 2021; Sedaghat 2018). Thus, 100 % circularity, in the sense that plastic is regenerated into new products indefinitely, is not feasible with the more prevalent recycling processes (i.e., mechanical recycling). However, this could change with advancements in some forms of chemical recycling. Below is a discussion on the two primary methods of recycling: mechanical recycling and chemical recycling.

3.1.1. Mechanical Recycling

Plastics is primarily recycled through mechanical means. As stated in Section 2.4, there are six primary steps when plastic gets recycled using this method: collection, sorting by plastic type, washing, shredding, separating by quality/class, and finally extruding/compounding, which turns the shredded plastic into pellets that can be used by manufacturers (RTS 2020). In this process, the plastic chemical composition is largely left intact. Many consumers may imagine that their soda bottle is recycled over-and-over again in a circular flow; however, when a plastic is recycled, it is often recycled for a different use that has lower performance requirements, as recycled plastic typically degrades. For instance, PET soft drink bottles, which have the highest recycling/collection rate (see Table 2.1) are often recycled into carpet or non-food bottles, as the process for making it suitable as a soda bottle can be expensive (Selke 2001). HDPE bottles, which are often used for non-carbonated beverage containers, are often recycled into drainage pipes, containers, pallets, and lumber (Selke 2001).

In addition to the limitations on recycling, there are about 60 popular plastic types with more than 300 different types in total, and they cannot all be recycled together – some cannot be recycled at all. There are about seven major categories of plastic and, potentially, many small streams with a low volume (Chen 2021). Frequently, plastics labeled with the same resin identification number cannot necessarily be recycled together. Plastics also contain plasticizers, flame retardants, heat stabilizers, fillers and other additives, which limit the ability to recycle the materials into certain products with specific applications, such as food or biomedical packaging (Gu et al. 2017; Geyer et al. 2017). Figure 3.1 traces the 2018 U.S. plastic waste stream from the type of plastic to disposal/recycling destination. Note that some assumptions and calculations, as discussed below the figure, were necessary to estimate these flows. Approximately 15 % of all plastics are collected. However, nearly half of that collected is not recycled into new products. Some plastics collected for recycling are lost in sorting (approximately 34 % of collected materials) and processing (approximately 13 %). There are also losses due to mismanagement, which is more difficult to estimate, but approximated at 2.1 % of all plastics discarded or recycled. As a result, the amount estimated to be recycled in this figure is approximately 52 % of those collected or 8 % of all U.S. plastics. Note that this is slightly different than the estimate of 8.7 % from EPA due to methods and data sources. The estimated amount recycled in 2018 from the EPA is 6180 million lbs (2803.2 thousand metric tons) while Figure 3.1 puts it at 2811.1 thousand metric tons. The sum of plastic discarded and plastic collected is approximately 10 % higher in Figure 3.1 than provided by the EPA.

Historically, a significant portion of plastic waste in the U.S. was exported. For instance, in 2010 “plastic waste, paring, and scrap” exports were the equivalent to 90.9 % of recycled/collected plastic, as seen in Figure 3.2. It is likely that much of this was originally collected for the purpose of recycling. Most of these exports were to Asian countries (see Table 3.1), which tend to have high rates of mishandling plastic (Law et al. 2020). Thus, there is a high likelihood that some portion of these plastics contributed to polluting the environment (both land and seas). U.S. exports of plastic waste have decreased considerably since 2010 (see Table 3.1) largely driven by China’s National Sword Policy (Vedantam et al. 2022), as the 2023 exports were down 79.0 % of the 2010 amount. As of 2018 (the latest data for total recycled plastics from the EPA), exports were the equivalent of 38.5 % of recycled plastic versus 90.9 % in 2010 (see Figure 3.2 and Figure 3.3). The primary destination of U.S. plastics, however, was still landfills followed by combustion for energy recovery (not shown). Moreover, there has been a downward trend in total plastic waste being exported from the U.S. Additionally, the top destination for exported plastic waste has shifted to Canada (35.8 %) and Mexico (17.6 %) (see Table 3.1); however, 50.4 % of the exports listed in Table 3.2, which shows exports by plastic type, remain countries

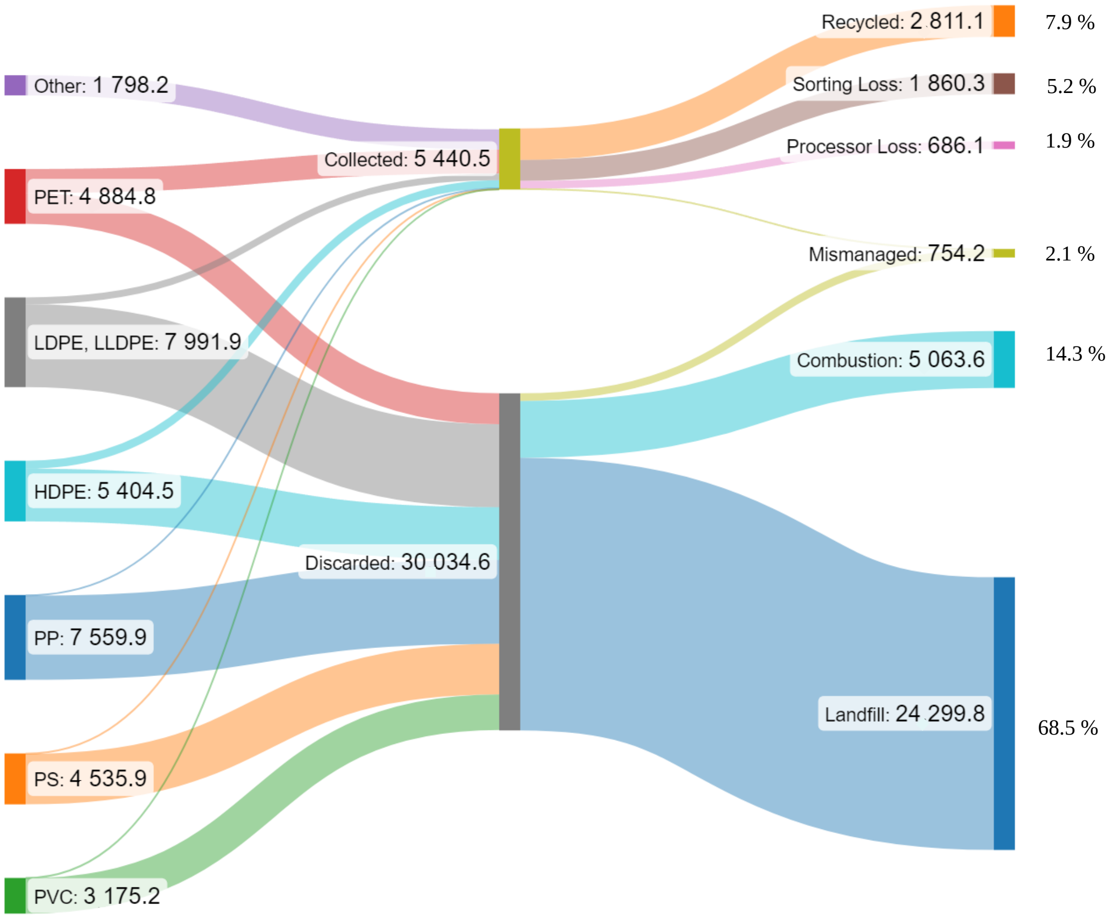


Figure 3.1: Approximated U.S. Plastic Waste Stream (2018), Thousands of Metric Tons

Data Sources: Belliveau and Lester 2004; Drahl 2020; Law et al. 2020; Eunomia 2021; U.S. Environmental Protection Agency 2021; Tiseo 2023: Alexander 2023; Smith et al 2022
Notes: Sorting and processing loss rates were taken from Eunomia (2021) and matched with estimates of material recycled by plastic type from Tiseo (2023). The amount of material recycled from Tiseo (2023) combined with the loss rates from Eunomia (2021) were used to calculate the amount collected. The amount of material recycled from Tiseo (2023) combined with the recycle rates provided in Drahl (2020) were used to calculate the amount of material both recycled and discarded with discarded material calculated by subtracting the amount recycled. PVC recycle rates are from Alexander (2023) and the amount recycled is from Belliveau and Lester (2004). Landfill and combustion rates were estimated from data in U.S. Environmental Protection Agency (2021) and applied to the estimate of discarded materials. A lower bound estimate of 2.33 %, estimated using data from U.S. Environmental Protection Agency (2021) and Law et al. (2020). Using the same sources, a lower bound estimate of 11 % was used to estimate mismanaged plastics that were collected for recycling. Some numbers break PET bottles and PET other apart. For calculation purposes, it was estimated that 41 % of PET collected was bottles, estimated using data from Smith et al (2022). For comparison, the EPA estimate for plastic landfilled is 53 940 million pounds, for combustion it is 11 240 million pounds, and recycled is 6180 million pounds; moreover, there is less than 1 % difference between the EPA and the values above.

estimated to have high rates of mismanagement, as estimated in Law et al. (2020). Table 3.2 also shows that a large portion of exported plastics are ethylene polymers with other plastics being the largest category. Many countries are importing plastic waste for its economic value, as plastic recycling can be profitable, especially if there are a lack of regulations (European Environmental Agency 2019). Additionally, low labor costs can also contribute to profitability.

Table 3.1: 2010 and 2023 U.S. Exports of Waste, Paring, and Scrap of plastic, by Destination

	2010			2023				
	Pounds (millions)	Percent of Exports	Rank	Pounds (millions)	Percent of Exports	Rank	% Change	2016 Percent waste mismanaged
China	2076.8	45.8 %	1	3.8	0.4 %	20	-99.8 %	25
China, Hong Kong SAR	1607.3	35.4 %	2	7.1	0.7 %	15	-99.6 %	25 (China)
Canada	308.6	6.8 %	3	340.5	35.8 %	1	10.3 %	NA
India	227.8	5.0 %	4	100.9	10.6 %	3	-55.7 %	79
Indonesia	90.7	2.0 %	5	39.1	4.1 %	6	-56.9 %	61
Mexico	48.8	1.1 %	6	168.0	17.6 %	2	244.0 %	23
Viet Nam	35.7	0.8 %	7	44.5	4.7 %	5	24.7 %	64
Malaysia	32.4	0.7 %	8	75.9	8.0 %	4	134.1 %	20
Other Asia, nes	22.5	0.5 %	9	11.5	1.2 %	13	-48.7 %	NA
Rep. of Korea	19.7	0.4 %	10	3.4	0.4 %	21	-83.0 %	NA
Rest of World	66.0	1.5 %		157.4	16.5 %		138.6 %	NA
TOTAL	4536.3	100.0 %		952.0	100.0 %		-79.0 %	

Data Source: UN Comtrade 2022 and Law et al. 2020
NA: Not available

Figure 3.2: Flow Diagram of U.S. Plastic Waste with Export Destinations, 2010

Data Source: UN Comtrade 2022

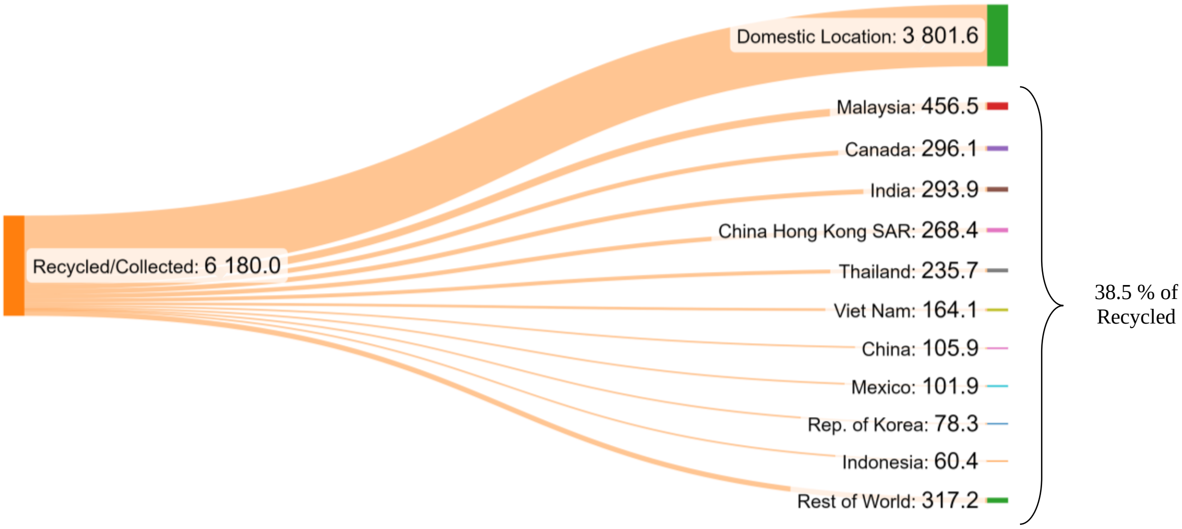


Figure 3.3: Flow Diagram of U.S. Plastic Waste with Export Destinations, 2018 (millions of pounds)

NOTES: Data take from Figure 3.1 and from UN Comtrade 2022

Table 3.2: Destination of U.S. Exported Waste, Parings, and Scrap Plastics, 2022 (Percent of Total)

	Waste, Paring, Scrap, of Plastic				
	Polymers Of Ethylene	Polymers Of Styrene	Polymers Chloride	Other Plastics	TOTAL
Canada	7.6 %	1.9 %	0.6 %	22.9 %	33.0 %
Mexico	2.7 %	0.4 %	1.9 %	14.4 %	19.5 %
India	9.3 %	0.0 %	0.1 %	0.7 %	10.1 %
Malaysia	5.8 %	0.0 %	0.2 %	2.0 %	8.0 %
Indonesia	4.5 %	0.0 %	0.0 %	0.1 %	4.7 %
Viet Nam	2.3 %	0.0 %	0.0 %	1.0 %	3.4 %
Germany	0.1 %	0.0 %	0.0 %	2.8 %	2.9 %
Türkiye	1.0 %	0.2 %	0.2 %	1.2 %	2.5 %
El Salvador	2.0 %	0.0 %	0.0 %	0.3 %	2.3 %
Pakistan	1.0 %	0.0 %	0.0 %	0.5 %	1.5 %
Spain	0.3 %	0.3 %	0.5 %	0.3 %	1.4 %
China, Hong Kong SAR	0.3 %	0.1 %	0.0 %	0.8 %	1.2 %
Rest of World	4.7 %	0.6 %	0.3 %	3.2 %	8.8 %
TOTAL	41.6 %	3.5 %	3.9 %	50.3 %	100.0 %

Source: UN Comtrade 2022

3.1.2. Chemical Recycling

A relatively new development is the broader interest in chemical recycling. Future developments in chemical recycling might allow materials to be recycled many more times than mechanical recycling allows, accept higher levels of contamination, and be able to recycle some mixed plastics; however, some of the processes may be newer or not to a scale of production that allows for a full understanding of the costs and environmental impacts. Currently, the EPA does not include chemical recycling in its estimate of the amount of plastic that is recycled (Kaufman 2022) and, under the Clean Air Act, two methods for chemical recycling, pyrolysis and gasification, are classified as waste combustion (Quinn 2022); however, that may change with the development of new technologies and potential shifting of policies at the state and federal levels of government. For instance, a number of states have reclassified these activities as manufacturing (Hogue 2022). It is important to note, however, that many of the basic processes for chemical recycling are not new. For instance, one of the most common options recognized for chemical recycling is pyrolysis, which has a patent dating back to 1877 and it was adopted for waste recycling in the 1950s (PEC 2023). Most plastic recycling methods can be grouped into four categories (Schwarz et al. 2021):

- Primary Recycling: Materials are recycled to produce products with the same properties as the original.
- Secondary Recycling: Materials are reused but with lower quality and often used for lower value products.
- Tertiary Recycling: Plastic is used to create chemicals and/or feedstock. Typically, polymers are not kept intact.
- Quaternary Recycling: The energy in plastic is recovered through incineration to produce heat or electricity.

Some chemical recycling methods fit into primary recycling (e.g., solvent-based) while others fit into tertiary recycling (e.g., pyrolysis or gasification).

Chemical recycling of plastics, which has also been referred to as advanced recycling, molecular recycling, or feedstock recycling, uses solvents, heat, biological processes and/or enzymes among other methods to break down plastic waste into their chemical building blocks (i.e., molecules). The different terms for chemical recycling are sometimes used synonymously and sometimes they refer to different meanings (Davidson et al. 2021). Biological recycling, which uses enzymes, is often referenced as a chemical recycling process or as a third category along with chemical and mechanical recycling (GAO 2022). Among these three, biological recycling is considered the least mature (GAO 2022). A review of the literature by RPA Europe (2021) shows that the term “chemical recycling” of plastic is often used to refer to turning used plastic into material for producing new plastic products and, in some cases, turning used plastic into material for incineration to produce energy. Thus, there are inconsistencies in the terms used for chemical recycling. This report is primarily interested in, and thus will focus on, turning used plastic into material for producing new plastic products.

There are four main processes for chemical recycling: chemical depolymerization, pyrolysis, gasification, and solvent-based recycling, the last of which is not considered by some to be chemical recycling (RPA Europe 2021). Each method needs to be evaluated to understand its sustainability. There are thermal and chemical means for decomposing polymers. Pyrolysis and gasification use thermal heat while chemical depolymerization, also known as chemolysis, uses chemical agents to break down polymers into monomers and oligomers (RPA Europe 2021). A review of life-cycle assessment literature by Davidson et al (2021) suggests that “pyrolysis is often highlighted as the best chemical recycling method,” but they acknowledge that this may be a biased conclusion as there is better data on this technology. Other approaches (e.g., gasification, depolymerization and hydrocracking) likely need to be investigated further to confirm such a conclusion.

The report by RPA Europe (2021) prepared for the European Chemicals Agency comes to a series of conclusions regarding chemical recycling. Three of the six conclusions are that:

- “The lack of clarity in chemical recycling terminology leads to confusing conclusions on the potential role of chemical recycling in the circular economy.”
- “Chemical recycling technologies differ in their potential to contribute to the circularity of plastics.”
- “Analysis of research literature has shown fragmented knowledge about the fate of substances of concern in various chemical recycling processes.”

There is also polarized disagreement on the prospects of chemical recycling (RPA Europe 2021). Discussions with experts reveal that despite transparency being important, currently there is a general lack of it regarding chemical recycling processes and their outputs (RPA Europe 2021). One expert commented that there is a “lack of transparency in the whole system” from chemical inputs to waste and output (RPA Europe 2021). Another expert comments that the “process uses huge amounts of energy and then creates a waste stream. Is it somehow sustainable?” (RPA Europe 2021). Solis and Silveira (2020) identify that generally higher temperatures result in higher purity, but that comes at a cost in terms of energy and its related environmental impacts. Moreover, the costs and benefits of chemical recycling are in the details, which are either not known or not yet transparent.

The limited data and limited number of full-scale operations are insufficient to support conclusions about the economic feasibility of chemical recycling (Solis and Silveira 2020). Solis and Silveira (2020) assess the technology readiness level (TRL) for eight chemical recycling technologies (see Table 3.3) and identify three as being at the higher readiness level: conventional pyrolysis, catalytic cracking, and conventional gasification. However, even these technologies do not have enough data to make conclusions about their economic feasibility. There are several companies that are developing chemical recycling technology; however, many are in the early stages of commercialization, which can result in high per unit capital costs (Peng et al. 2022). Moreover, the economic and environmental viability of chemical recycling of plastic at large scales is yet to be determined. A survey of literature in Nikiema and Asiedu (2022) estimates the investment cost for processing one ton per day of material using mechanical recycling as being between $2000 and $10 000 while that of chemical recycling was estimated at

$857 000 using pyrolysis and $385 000 using gasification; however, these costs may change as the technology for chemical recycling matures. In terms of environmental performance, mechanical recycling tends to outperform chemical recycling, including solvent-based recycling (Schwarz et al. 2021; Meys et al. 2020; Klotz et al. 2024).

Table 3.3: Technology Readiness Level (TRL) for Eight Chemical Recycling Technologies

Technology	TRL
Conventional Pyrolysis	9
Catalytic Cracking (adding a catalyst to the cracking process)	9
Conventional Gasification	9
Plasma Gasification	8
Hydrocracking (adding hydrogen to cracking process)	7
Plasma Pyrolysis	4
Microwave Assisted Pyrolysis	4
Pyrolysis with in-line Reforming	4

TRL 8-9: Large company, in development/in commercial operation
TRL 8-9: Small/medium company, successfully sold/in commercial operation
TRL 4-7: Small/medium company, in development
TRL 1-5: R&D centre/university

Source: Solis and Silveira 2020

Solis and Silveira (2020) along with others conclude that chemical recycling is only one part of the solution for plastic recovery or is a supplement to other approaches such as mechanical recycling. One expert notes that “chemical recycling applies to those products, plastics, polymers, which cannot be recycled mechanically” (RPA Europe 2021); however, there are some questions regarding the benefits of chemical recycling. Uekert et al. (2023) suggests that economic and environmental metrics for the pyrolysis and gasification methods they examined were 10 to 100 times higher than using primary material due to low yields and high energy costs. That is, pyrolysis and gasification were shown to perform both less economical and less environmentally friendly when compared to primary plastic. Table 3.4 shows some of these results, with mechanical recycling having a minimum selling price (MSP) significantly lower than both primary material and chemical recycling across the plastic types considered with the TRL of chemical recycling still not ready for commercial deployment (TRL range between 3 and 7). Note that they used six different environmental metrics for their analysis, including E-factor (i.e., waste generation), energy use, greenhouse gas (GHG) emissions, land use, toxicity, and water use (not reported here). The low yield estimates from chemical recycling also brings up questions about the ability to repeatedly recycle plastic.

Table 3.4: Minimum Selling Price and TRL for Recycling Technologies (Uekert 2023)

	Plastic Type	Primary	Mechanical Recycling		Chemical Recycling		
				Dissolution	Enzymatic Hydrolysis	Glycolysis	Methanoloysis
Minimum Selling Price	HDPE	$0.79	$0.63	$1.10	-	-	-
	LDPE	$0.81	$0.46	$0.73	-	-	-
	PP	$0.86	$0.38	$0.74	-	-	-
	PET	$1.19	$0.54	$0.87	$2.01	$0.96	$1.05
TRL		9	9	3	4	5	7

Gracida-Alvarez et al. (2023) show that chemical recycling of HDPE and LDPE can result in a 23 % and 18 % decrease in GHG emissions when compared to crude oil-derived LDPE and HDPE, respectively. Some organizations have raised concerns regarding the existing examinations of chemical recycling (Zero Waste Europe 2020) and there are numerous reasons why various studies may differ in their results; however, delving into the specifics of these is beyond the scope of this report. One conclusion that might be made, though, is that the details seem to make a significant difference in the outcome and more authoritative research is needed.

Experts note that, although chemical recycling might be able to handle mixed plastics and higher levels of contamination, sorting is often still necessary and the ability to deal with contamination has limitations. The implication is that other methods (e.g., reuse; repair; product simplification – reducing complexity to lower costs, impacts, and risk; design for recycling; and mechanical recycling) should be exhausted before considering chemical recycling. Such an approach would ensure that waste plastics are not competing with the same high volume and quality feedstocks required and used for mechanical recycling. Experts also noted that design for recycling is important (RPA Europe 2021). A McKinsey and Company report estimates that by 2030, chemical recycling (referred to as advanced recycling in the report) could account for 31 % or more of the polymer demand by mass at 20 % year-over-year growth (Peng 2022). It is important to note that this could be an optimistic view, as the percentage of recycled material being chemically recycled in 2020 is estimated by the same report as being at zero or near zero. Additionally, this estimate implies global plastic recycling will grow from supplying 7 % of polymer demand to between 14 % and 21 %, a significant level of growth in less than a decade. The McKinsey report also estimates that this level of growth would require $40 billion in capital investment.

The scaling up of chemical recycling capability has just begun. As of September 2023, there were 11 chemical recycling facilities constructed in the U.S. as provided in Table 3.5 (Bell 2023). Although a number of these facilities are pilot or demonstrations and there is additional research being conducted in this area, many of the technologies for chemical recycling have been around for decades (Bell 2023). Of the eleven facilities, seven have the stated purpose of producing materials that can potentially be used to produce plastic products. Of these, four have an operating status that is either considered partial/intermittent or is piloting/demonstrating. There is one facility that has an unknown operating status and two facilities that are considered operating. The ExxonMobil plant in Baytown, TX, which is one of the two in full operating

Table 3.5: Current U.S. Chemical Recycling Facilities

Company	**Location**	**Process**	**Feedstock**	**Capacity (tons/yr)**	**Processed Material**	**Output**	**Stated Purpose of Output**	**Status**
Regenyx	Tigard, OR	Pyrolysis	Mixed plastic and polystyrene	3650	4400 tons from 2004 to July 2021	Oil, naphtha, styrene monomer	Fuels, recycled content polystyrene	Pilot / demonstration
Fulcrum Sierra BioFuels	McCarran, NV	Gasification and Fischer-Tropsch	Municipal solid waste	219 000	Unknown	Synthetic crude oil	Aviation fuel	Operating
Brightmark Energy	Ashley, IN	Pyrolysis	Mixed plastic waste, possibly including household electronic and/or medical waste	100 000	2000 tons over 4 years	Diesel fuel, naphtha blends, wax	Transportation fuels and chemical raw materials	Partially or intermittently operating
PureCycle	Ironton, OH	Solvent-based purification	Waste polypropylene	66 430 tons/year (estimated)	Unknown	Polypropylene resin	Recycled polypropylene plastic	Partially or intermittently operating
Alterra Energy Plastic Recycling Facility	Akron, OH	Pyrolysis	Mixed plastic waste, possibly including household electronic and/or medical waste	21 000 tons/year	Unknown	Pyrolysis oil	Fuel of plastic feedstock	Pilot / demonstration
Prima America	Northumberland, NH	Pyrolysis	Mixed non-cholorinated plastic waste	Unknown	Unknown	Sytnetic diesel	Fuel	Pilot

Company	**Location**	**Process**	**Feedstock**	**Capacity (tons/yr)**	**Processed Material**	**Output**	**Stated Purpose of Output**	**Status**
Eastman	Kingsport, TN	Gasification and solvolysis	Gasification: Mixed waste plastic, Solvolysis: #1 PET	Gasification: 25 000 tons/year, Solvolysis: 110 000 tons/year	Unknown	Gasification: Synthesis gas, Solvolysis: Monomers	Chemicals, recycled content plastics, and synthetic fibers	Plastic gasification: Operating, Solvolysis: Under construction with processing startup at 10 % capacity
New Hope Energy	Tyler, TX	Pyrolysis	Plastic (not PVC) and paper waste	18 250 tons/year	Unknown	Synthetic crude, pyrolysis oil, chemical feedstocks, plastic feedstocks	Fuels, chemicals, plsatics production, asphalt	Unknown
ExxonMobil	Baytown, TX	Pyrolysis	Mixed plastic waste, including synthetic turf	40 000 tons/year	Unknown	Resin pellets	Plastic products	Operating
Nexus Circular	Atlanta, GA	Pyrolysis	HDPE, LDPE, Polypropylene, and polystyrene	18 250	4000 tons as of January 2023	Pyrolysis oil	Feedstock for plastic products	Partially or intermittently operating
Braven Environmental	Zebulon, NC	Pyrolysis	Mixed plastic waste	12 000 tons/year	Unknown	Pyrolysis oil	Fuel	Operating

status, is part of a larger petrochemical facility. There is no publicly available information on the amount of plastic waste being processed or how much resin has been produced. The other facility is the Eastman gasification facility in Kingsport, TN. As these facilities become operational and increase their scales of production, more information should be available on a feasibility of large-scale chemical recycling to provide one option to increase plastic recycling rates while not competing with mechanical recycling for the high-volume, high-quality plastic waste feedstocks. More research is needed in assessing the dynamics between mechanical recycling and chemical recycling as well as any economic, environmental, and societal trade-offs and synergies resulting of recycled content, both from mechanical recycling and chemical recycling compared to primary input content.

3.1.2.1. Pyrolysis

The pyrolysis of waste plastic is considered a tertiary recycling process (Schwarz et al. 2021) and involves five basic steps (Beston 2023):

- Pretreatment: waste plastic is shredded and dried to remove moisture.
- Pyrolysis: the dried material is heated in a reactor to between 300º and 800º Celsius where it undergoes thermal decomposition in the absence of oxygen.
- Condensation: the material passes through a condensation system that cools the gases and condenses them into liquids.
- Filtration: remaining gases are filtered to remove fine particulates and impurities.
- Material Collection: the materials, which include pyrolysis oil or bio-oil, gases, and some solid residues, are collected.

Pyrolysis is most often identified as an option for chemical recycling; however, frequently it is not considered suitable for all plastic types. It is generally considered suitable for LDPE, LLDPE, PP, PS, and ABS, which is categorized under plastic #7 (Beston 2023). PVC is considered less suitable due to the releases of toxins that occur during decomposition as is PET, as it does not yield oil during decomposition and releases oxygen, which poses a safety hazard (Beston 2023). The primary product of pyrolysis is liquid oil (90 % by weight), which has properties (viscosity, density, flash point, cloud point, and energy content) similar to that of conventional diesel (Maqsood et al. 2021). After additional processing, materials could include, but may not be limited to, the following (Yadav 2022): Naphtha, Benzene, Toluene, Xylenes, Ethane, Ethylene, Propylene, Propane, Butane, Butene, and Aromatics. Some of these materials can be used in making plastic (Dai et al 2021; Kabeyi and Oludolapo 2023), and thus the end product could be a replacement for primary resin production.

The 2020 global pyrolysis oil market (i.e., revenue for oil made from pyrolysis) was estimated to be $302.1 million (Transparency Market Research 2022). For context, the global oil market in 2022 was $6.6 trillion, which is more than 21 000 times larger (IBIS World 2023). Currently, the primary application of pyrolysis oil is fuel oil in heavy industry (Doing 2021). There is a wide range of quality in pyrolysis oil and the contaminants determine the potential for recycling it into plastics (Kusenberg et al 2022). Steam crackers, which would typically be used in the process of converting pyrolysis oil to plastic, rely on a stable and predictable feedstock quality (Kusenberg et al 2022). Having higher levels of contaminants, pyrolysis oil feedstock is significantly different than, and thus not a perfect substitute for, fossil-based feedstocks and is not acceptable for industrial steam crackers (Kusenberg et al 2022; Erkmen et al 2023). At current levels of production, contaminants are diluted by mixing pyrolysis oil with fossil-based feedstocks, making it possible for them to be processed. One estimate is that the pyrolysis oil can make up approximately 2 % to 5 % of the oil being processed in a typical cracker (Tangri 2024) while another study placed a likely scenario as being 5 % (Argonne 2023; Gracida-Alverez et al 2023). Thus contaminate removal strategies will need to be improved to increase the share of pyrolysis oil that can be included in plastic production.

3.1.2.2. Gasification

Gasification is considered a tertiary recycling process (Schwarz et al. 2021) and involves reacting an agent such as steam, oxygen, and air with plastic waste, at temperatures between 500 ºC to 1300º C (Saibea et al 2020). This typically produces synthesis gas or syngas (Saibea et al 2020), as opposed to the primary product of pyrolysis which is liquid oil. It is important to note that gasification can also include pyrolysis (Shah et al 2023). There are other types of materials that are gasified (e.g., coal and biomass); however, some of the properties of waste plastic make it difficult to use traditional gasification technologies (Shah et al 2023). Syngas is typically a mixture of carbon monoxide and hydrogen that can be used as a substitute for natural gas or as feedstock for producing other chemicals (Brems et al. 2013). The primary use of syngas is in the production of fuels such as diesel and methanol (Capodaglio and Bolognesi 2019). Although a pilot program in Alberta, Canada was announced in 2022 between NOVA Chemicals Corporation and Enerken Inc to produce plastics from syngas (NOVA Chemicals 2022), there seem to be limited examples of this type of activity. The 2019 global syngas market was estimated to be $43.6 billion (Allied Market Research 2021); however, syngas feedstock can include coal and biomass. Thus, much of the value may not originate with plastic waste.

3.1.2.3. Solvent-Based Recycling of Plastic

Solvent-based recycling, which is often not considered to be chemical recycling, dissolves waste plastic in solvents to remove impurities and then polymers can be recovered through precipitation (Zhao et al. 2018). At least for some instances, this process can be considered primary recycling. A major challenge for this process is that plastic waste often includes mixed polymers; thus, separation is an issue (Zhao et al. 2018). Additionally, solvents and impurities can diminish the quality of the final product (Zhao et al. 2018). A report by Grand View Research (2023) estimated the global solvent-based plastic recycling market to be $599.75 million in 2021. Additionally, some companies are claiming to be using this technology; thus, it does appear that solvent-based recycling is being applied to some extent.

One study, by Saleem et al. (2023), examined the environmental impacts of the chemical recycling of PET and PP plastics using xylene solvents. Their analysis showed that the recovery of the xylene was a significant factor. They analyzed two scenarios: 1) 90 % recovery of xylene and 2) 100 % recovery. For context, B/R instruments estimates a 95 % recovery rate for xylene solvent recycling (B/R Instruments 2019). In the first scenario, for four factors (energy, photochemical oxidant formation, fossil depletion, and ozone depletion) xylene recycling of PET and PP performed better than using primary materials; however, marine eutrophication, human toxicity, terrestrial acidification, and climate change were worse. For all eight factors examined, scenario 2 performed better than using primary materials, including a 22.6 % reduction in climate change measured in kg CO_2 equivalent. Further reductions are possible with the adoption of renewable energy.

3.2. Recycling's Impact on Sustainability

An implicit goal of recycling is to increase sustainability, in part through decreasing environmental impacts. Section 3.2.1 discusses the reduction of impacts from primary plastic production through recycling. Section 3.2.2 discusses the pollutant effects of plastic and Section 3.2.3 discusses the effects of plastics being disposed of in landfills, specifically the potential leachate that can pollute the environment.

3.2.1. Reducing Impacts of Primary Material Production

U.S. plastics manufacturing activity (cradle to gate analysis for NAICS 325211, 326110-326190) is estimated to be 3.6 % of the overall U.S. economy's environmental impact or 4.2 % when including synthetic rubber (see Table 3.6). This is measured using twelve weighted impact factors in an environmentally extended input-output analysis conducted by NIST's Manufacturing Cost Guide using the default weights in the tool (Thomas 2022). A breakdown of different components considered in the estimate is presented in Table 3.8. Each item is weighted to generate the weighted impact. Additional details on the methodology are discussed in Appendix A.

The cradle-to-gate impact of plastics manufacturing for GWP is 2.7 % of total annual U.S. GHG emissions. These results are consistent in magnitude in Ritchie (2023), where the global life cycle of plastics, including production, conversion, and end of life, were estimated to be responsible for 3.3 % of global GHG emissions. This was estimated using OECD (2022a) estimates of emissions from plastic along with utilizing Jones et al. (2023) to estimate total emissions. Karali, et al (2024) estimates global impacts of primary plastic production to be 5.3% using a process-based (i.e., bottom-up) approach, with each step of the production process representing a significant portion of the GHG emissions:

- Extraction and/or mining – 20 %
- Hydrocarbon refining and processing – 16 %
- Other chemical production – 13 %
- Monomer production – 26 %
- Polymerization – 8 %
- Product shaping – 17 %

Although a global study, it is reasonable to infer that U.S. production would have similar distribution of GHG emissions associated with each stage of the supply chain.

To put the environmental impact of plastic manufacturing into context, primary metal manufacturing (NAICS 331-332) is estimated to be 4.8 % of U.S. impacts from economic activities. Discrete tech products (NAICS 333-336), which includes the usage of some plastics, is 6.9 % of U.S. impacts from economic activities. Table 3.6 also provides other key industry sectors for additional context. It is also important to note that environmental impacts downstream from plastic manufacturing, for instance those from a machine assembling a dashboard at an automobile manufacturing plant, are not included in the U.S. estimates for plastics and synthetic rubber.

Reducing environmental impacts of production and preserving resources is among the major benefits of plastic recycling, particularly if mechanical recycling remains the primary means used. It is estimated that if all plastics were recycled, it would result in a 25 % decrease in carbon equivalent emissions for global plastic production as estimated by Zheng and Suh (2019). For illustrative purposes, a 25 % decrease in the environmental impact of plastic production in the U.S. (NAICS 325211, 326110-326190) equates to 0.9 % of the U.S. economy's environmental impact (see Table 3.6) and 1.1 % when including synthetic rubber (NAICS 32511). According to a report by the Association of Plastics Recyclers (2020), PET resin has 40.8 % of the carbon dioxide equivalent of that of primary resin. Recycled HDPE resin has 29.6 % and PP has 28.8 % of the carbon dioxide equivalents of primary resin.

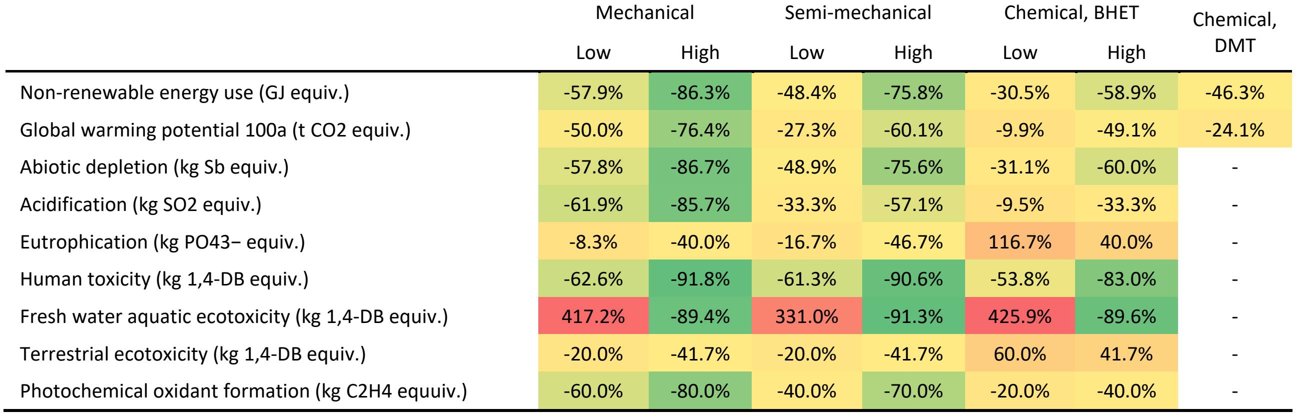
An examination of PET bottle recycling by Shen et al. (2010) shows a decrease between 8.3 % to 91.8 % in eight of the nine environmental impact factors considered, across three estimation methods examined, for mechanical and semi-mechanical recycling (see Table 3.7). The only impact category that shows any potential increase is for freshwater aquatic ecotoxicity (-91.3 % to +417.2 %). Chemical recycling has more trade-offs in environmental impacts than mechanical recycling. For the six categories that realize reductions for chemical recycling, those reductions are smaller than mechanical recycling. Two categories may realize increases or decreases, freshwater aquatic ecotoxicity and terrestrial ecotoxicity, and eutrophication realizes increases across all estimation methods, implying at least one trade-off in environmental impacts. As stated previously, plastic can only be recycled mechanically a limited number of times; thus, one can expect that it will still be discarded through some means. One potential exception would be through the development of chemical recycling once mechanical recycling is infeasible.

Table 3.6: Environmental Impact along with Direct and Indirect Value Added, Select Industries

Industry Description and NAICS Code	Environmental Impact as Percent of Total Economy Impact	Direct and Indirect (i.e., Supply Chain) Value Added ($million 2019)	Direct and Indirect Value Added as Percent of GDP	Environmental Impact per Billion Dollars of Value Added
Food, Beverage, and Tabacco Products (NAICS 311-312)	29.4 %	868.6	4.9 %	33.9
Food (NAICS 311)	28.8 %	806.8	4.5 %	35.7
Beverages and Tabacco (NAICS 312)	2.5 %	182.8	1.0 %	13.8
Discrete Products (NAICS 313-323, 327-332, 337-339)	14.2 %	1069.9	6.0 %	13.2
Textiles, Apparel, and Leather (NAICS 313-316)	0.9 %	63.6	0.4 %	14.1
Paper Manufacturing and Printing (NAICS 322-323)	3.9 %	210.9	1.2 %	18.5
Primary Metal and Fabricated Metal Product Manufacturing (NAICS 331-332)	4.8 %	481.1	2.7 %	9.9
Primary Metal Manufacturing (NAICS 331)	3.6 %	233.8	1.3 %	15.5
Fabricated Metal Product Manufacturing (NAICS 332)	2.5 %	333.6	1.9 %	7.5
Discrete Tech Products (NAICS 333-336)	6.9 %	1355.9	7.6 %	5.1
Process Products (NAICS 324-326)	35.6 %	1611.5	9.1 %	22.1
Petroleum and Coal Products (NAICS 3251)	30.7 %	1101.8	6.2 %	27.9
Plastic, Tires, and Rubber (NAICS 325211, 325212, 32522, 326)	4.9 %	285.1	1.6 %	17.3
Plastic and Select Rubber (NAICS 325211, 325212, 32522, 326110-326190, 326220)	4.3 %	251.0	1.4 %	17.1
Plastic and Synthetic Rubber (NAICS 325211, 325212, 326110-326190)	4.2 %	245.9	1.4 %	17.2
Plastic (NAICS 325211, 326110-326190)	3.5 %	224.5	1.3 %	15.5

Calculated using NIST's Manufacturing Cost Guide (Thomas 2020).
NOTE: These estimates are for the production of goods and are not a life cycle analysis. That is, it is what is frequently referred to as cradle to gate.

Table 3.7: Estimates of Environmental Impact (Percent Change from Primary Material)



	Mechanical		Semi-mechanical		Chemical, BHET		Chemical, DMT
	Low	High	Low	High	Low	High	
Non-renewable energy use (GJ equiv.)	-57.9%	-86.3%	-48.4%	-75.8%	-30.5%	-58.9%	-46.3%
Global warming potential 100a (t CO2 equiv.)	-50.0%	-76.4%	-27.3%	-60.1%	-9.9%	-49.1%	-24.1%
Abiotic depletion (kg Sb equiv.)	-57.8%	-86.7%	-48.9%	-75.6%	-31.1%	-60.0%	-
Acidification (kg SO2 equiv.)	-61.9%	-85.7%	-33.3%	-57.1%	-9.5%	-33.3%	-
Eutrophication (kg PO43− equiv.)	-8.3%	-40.0%	-16.7%	-46.7%	116.7%	40.0%	-
Human toxicity (kg 1,4-DB equiv.)	-62.6%	-91.8%	-61.3%	-90.6%	-53.8%	-83.0%	-
Fresh water aquatic ecotoxicity (kg 1,4-DB equiv.)	417.2%	-89.4%	331.0%	-91.3%	425.9%	-89.6%	-
Terrestrial ecotoxicity (kg 1,4-DB equiv.)	-20.0%	-41.7%	-20.0%	-41.7%	60.0%	41.7%	-
Photochemical oxidant formation (kg C2H4 equuiv.)	-60.0%	-80.0%	-40.0%	-70.0%	-20.0%	-40.0%	-

Source: Shen et al. 2010
NOTE: Shen et al. (2010) uses three methods ("cut-off" approach, the "waste valuation" approach and the "system expansion" approach) for mechanical, semi-mechanical, and chemical recycling. Shown above are the low and high estimates from these three approaches.

3.2.2. Reducing Plastic as a Pollutant

Typically, plastic does not biodegrade or does not biodegrade in any reasonable amount of time and plastic debris collects in landfills, waterways, and other locations (Geyer 2017). It is important to note that despite its environmental impact, plastic often has a lower carbon footprint than other materials used for the same purpose (Edwards and Fry 2011; Chaffee and Yaros 2014); thus, there are likely to be trade-offs when considering an alternative material.

In considering investments in recycling, it is important to identify the goals that are being pursued, as other solutions might be more effective and/or more economical. For instance, recycling is often discussed hand-in-hand with plastics in the ocean. Recycling can reduce this problem by reusing waste plastic for producing new products; however, some materials collected for recycling are mismanaged, resulting in a potential increase in ocean plastics. Recall that Figure 3.1 estimated 2.1 % of plastics were mismanaged in the U.S. Domestic recycling programs could be significantly increasing the ocean plastic problem, as it is estimated that between 11 % and 50 % of mismanaged U.S. plastics were originally collected for recycling (Law et al. 2020). Thus, a trade-off where reducing plastic going to a landfill by increasing collection for recycling could lead to an increase in mismanaged plastic that ends up in the ocean or other waterways.

Table 3.8: Environmental Impact of Plastics Manufacturing (NAICS 325211, 326110-326190) as a Percent of the U.S. Economy's Environmental Impact, by TRACI Impact Factor

Items to be measured	Units	Percent of U.S. Total	Base Weights
Base weighting	*Weighted Impact*	*3.6 %*	-
Global Warming	kg CO2 eq	2.7 %	0.03
Acidification	H+ moles eq	3.6 %	0.06
HH Criteria Air	kg PM10 eq	2.4 %	0.07
Eutrophication	kg N eq	3.3 %	0.30
Ozone Depletion Air	kg CFC-11 eq	6.7 %	0.05
Smog Air	kg O3 eq	2.9 %	0.09
ecotox	CTUe	3.7 %	0.08
HH_can	CTUHcan	9.9 %	0.02
HH_noncan	CTUHnoncan	3.3 %	0.04
Primary Energy Consumption	thousand BTU	4.7 %	0.10
Land Use	acre	2.3 %	0.06
Water Consumption	kg	2.5 %	0.08

Data Source: UN Comtrade 2022 and Law et al. 2020
NA: Not available

Data Source: UN Comtrade 2022 and Law et al. 2020
NA: Not available

It is important to note that mismanaged plastic waste in the U.S. is a low percentage of the total (see Figure 3.1); however, it ends up being a large mass due to the size of the U.S. population and the per capita plastic waste generated (Law et al. 2020). In 2018, this percentage equated to approximately 754.2 thousand metric tons, as seen in Figure 3.1. Exported waste plastic as a percent of recycled/collected plastic was 38.5 % in 2018 (see Figure 3.3). As of 2023, approximately 30.1 % of U.S. exported waste plastic is still exported to Asia (Table 3.1), a major contributor to ocean plastic. For instance, 25 % of China's plastic waste is estimated to be mismanaged. Other Asian countries often have as high or higher rates (e.g., 60 % in Thailand, 74 % in the Philippines, 64 % in Vietnam) (Law et al. 2020). Another 17.6 % of U.S. plastic waste is exported to Mexico, which also has a high mismanagement rate at 23 % (Law et al. 2020).

Improved handling of waste materials along with policies regarding the trade and export of waste may have a large impact in reducing U.S. plastic environmental impact. The U.S. is not a major direct contributor to ocean plastic, as it accounts for 0.25 % of the plastics in the ocean (Our World in Data 2021); however, it is likely higher when considering the indirect contributions such as those collected for recycling and shipped to Asia. The environmental impact of landfilling plastic is likely lower than it being mismanaged and entering the ocean. Thus, to reduce its contribution to ocean plastics, the U.S. could advance its management of plastics collected for recycling.

Increased preferences for recycling by consumers have been suggested through unit-based pricing of waste (Yamaguchi et al. 2016), increased uniformity of recyclable product materials

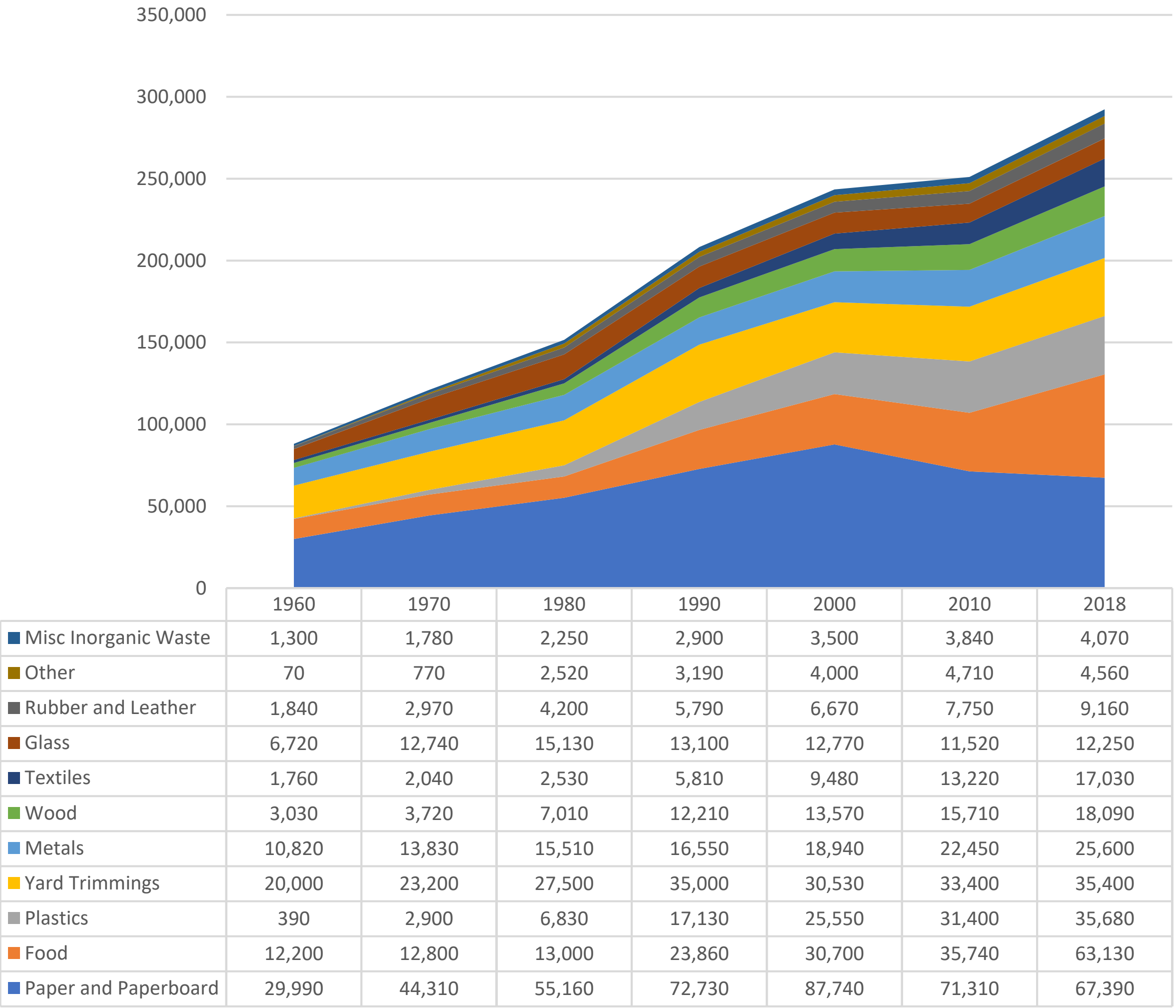
(Park et al. 2018), and greater consumer awareness of recyclability (Klaiman et al. 2016; Orset et al. 2017), which could increase the amount of recyclable materials collected from households.

3.2.3. Landfill Leachate

As mentioned previously, an estimated 75.6 % of U.S. plastic waste is disposed of in landfills (U.S. Environmental Protection Agency 2021) and accounted for 35 680 tons or 12 % of municipal solid waste in 2018, making it the third largest source behind food and paper/paperboard (see Figure 3.4). This is substantially different than in 1960 where plastic was the second smallest material waste stream. Since a large majority of plastics are deposited at these facilities, it is important to consider their environmental impacts. According to the U.S. Environmental Protection Agency (2023a), U.S. federal regulations address the following aspects of municipal solid waste landfills:

- “Location restrictions—ensure that landfills are built in suitable geological areas away from faults, wetlands, flood plains or other restricted areas.
- Composite liner requirements—include a flexible membrane (i.e., geo-membrane) overlaying two feet of compacted clay soil lining the bottom and sides of the landfill. They are used to protect groundwater and the underlying soil from leachate releases.
- Leachate collection and removal systems—sit on top of the composite liner and removes leachate from the landfill for treatment and disposal.
- Operating practices—include compacting and covering waste frequently with several inches of soil.
- Groundwater monitoring requirements—requires testing groundwater wells to determine whether waste materials have escaped from the landfill.
- Closure and post-closure care requirements—include covering landfills and providing long-term care of closed landfills
- Corrective action provisions—control and clean up landfill releases and achieves groundwater protection standards
- Financial assurance—provides funding for environmental protection during and after landfill closure.”

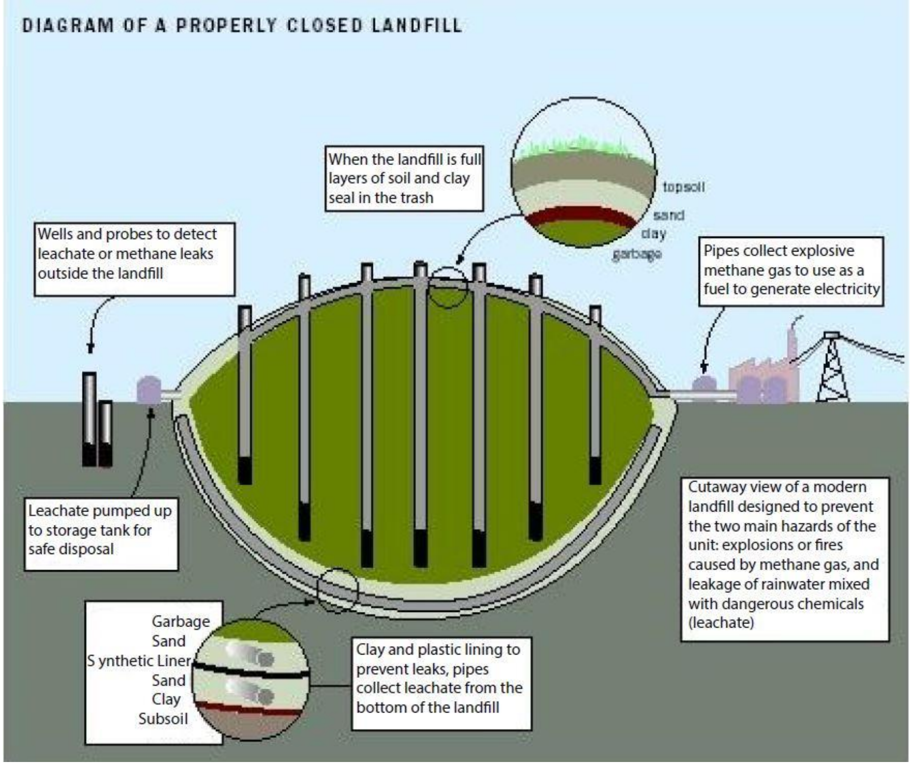
Although landfills are required to have liners, there are leachates (contaminated liquids) that could runoff and pollute local environments. As mentioned above, landfills are required to have collection and removal systems in place along with treatment. In 2016, Silva et al. (2021) published the first study addressing microplastics’ levels in landfill leachates. Only a few other studies on this issue have been conducted since that publication (Silva et al. 2021); thus, in total there are only a few studies that consider microplastics in landfill leachate (He et al 2019). These studies do show that there are microplastics in the leachate from landfills. In the U.S., landfills collect and treat leachates, as illustrated in Figure 3.4; however, given the limited knowledge on landfill microplastics in leachates, it is unclear to what extent microplastics remain in treated leachate. Methods for leachate treatment borrow from technologies used to treat municipal wastewater (Samuels 2018), which is considered effective at removing particles of similar size and characteristics with data suggesting that more than 90 % of microplastics can be removed (World Health Organization 2019). Advanced treatment is capable of removing even smaller particles (World Health Organization 2019). Moreover, current literature does not attribute or discuss landfills in the U.S. as contributing significantly to microplastics in the environment, but these contaminants are not well understood. Possible solutions for addressing potential microplastics in leachate, assuming it is a significant issue, is to deposit less plastics in landfills by recycling or using less plastic. Another solution might be to develop or implement treatment methods that remove microplastics from leachate.



	1960	1970	1980	1990	2000	2010	2018
■ Misc Inorganic Waste	1,300	1,780	2,250	2,900	3,500	3,840	4,070
■ Other	70	770	2,520	3,190	4,000	4,710	4,560
■ Rubber and Leather	1,840	2,970	4,200	5,790	6,670	7,750	9,160
■ Glass	6,720	12,740	15,130	13,100	12,770	11,520	12,250
■ Textiles	1,760	2,040	2,530	5,810	9,480	13,220	17,030
■ Wood	3,030	3,720	7,010	12,210	13,570	15,710	18,090
■ Metals	10,820	13,830	15,510	16,550	18,940	22,450	25,600
■ Yard Trimmings	20,000	23,200	27,500	35,000	30,530	33,400	35,400
■ Plastics	390	2,900	6,830	17,130	25,550	31,400	35,680
■ Food	12,200	12,800	13,000	23,860	30,700	35,740	63,130
■ Paper and Paperboard	29,990	44,310	55,160	72,730	87,740	71,310	67,390

Source: U.S. Environmental Protection Agency. (2022). "National Overview: Facts and Figures on Materials, Wastes and Recycling." https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Figure 3.4: Municipal Solid Waste by Material (Tons)

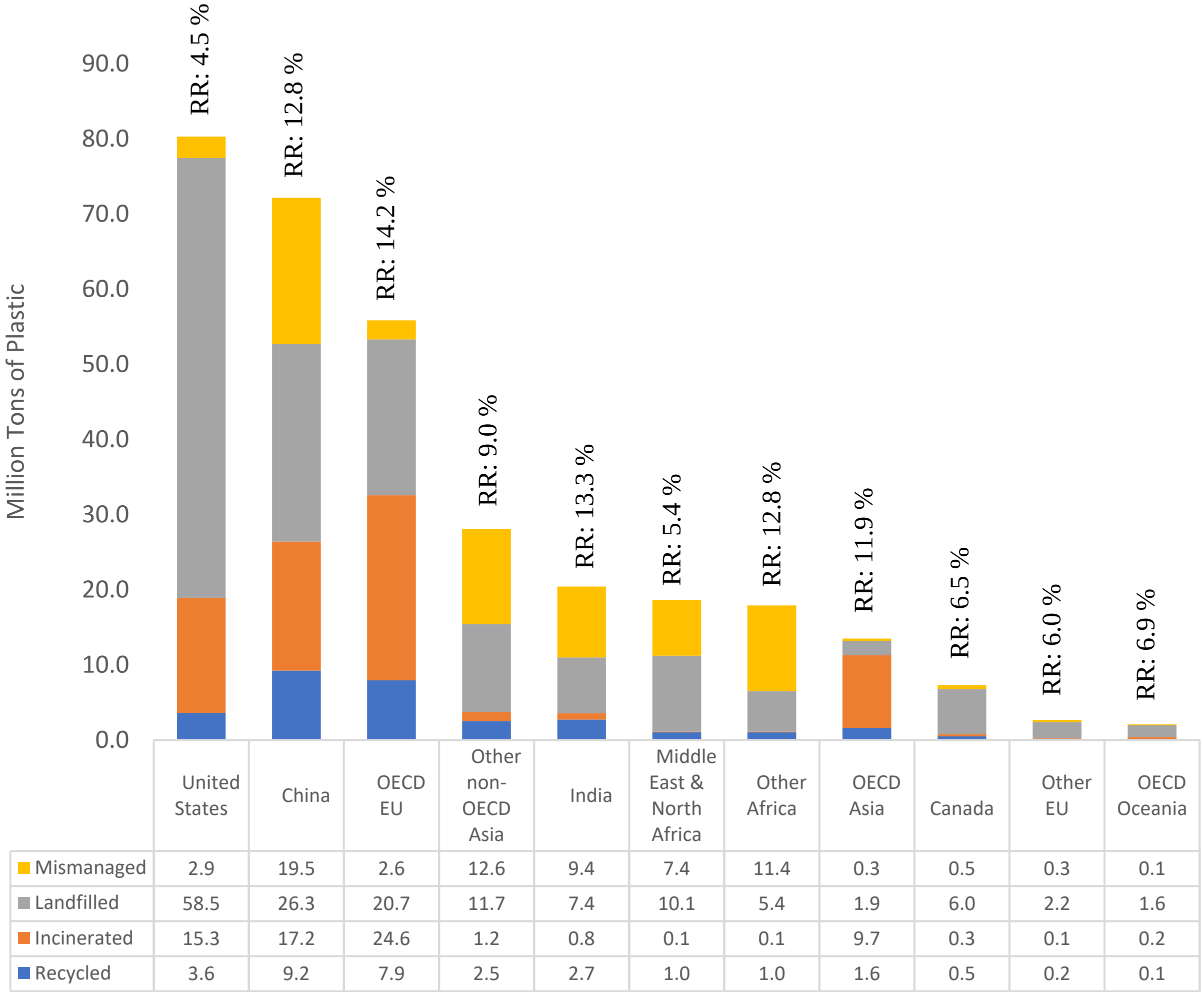


Source: U.S. Environmental Protection Agency (2023)

Figure 3.5: Cross-Section of a Municipal Solid Waste Landfill

4. Characteristics of Successful Recycling/Collection Programs

Even though the EPA has published a national recycling strategy (U.S. Environmental Protection Agency 2024), the U.S. has not implemented a national recycling program for plastics; however, there are many state and local level programs. Additionally, many countries around the world have successful recycling programs. This chapter discusses various recycling programs, both domestically and internationally, to identify the characteristics of high-performing efforts. According to OECD estimates, the U.S. appears to have a high amount of plastic waste with a lower recycling/collection rate, as seen in Figure 4.1. China and EU countries in the OECD tend to have higher rates of recycling/collection. The U.S. has a low rate of mismanagement at 3.6 % compared to China (27.0 %), OECD EU (4.6 %), India (46.2 %), and others (rates not shown).



	United States	China	OECD EU	Other non-OECD Asia	India	Middle East & North Africa	Other Africa	OECD Asia	Canada	Other EU	OECD Oceania
🟨 Mismanaged	2.9	19.5	2.6	12.6	9.4	7.4	11.4	0.3	0.5	0.3	0.1
⬜ Landfilled	58.5	26.3	20.7	11.7	7.4	10.1	5.4	1.9	6.0	2.2	1.6
🟧 Incinerated	15.3	17.2	24.6	1.2	0.8	0.1	0.1	9.7	0.3	0.1	0.2
🟦 Recycled	3.6	9.2	7.9	2.5	2.7	1.0	1.0	1.6	0.5	0.2	0.1

RR = Plastics Recycle Rate
Source: OECD 2022b

Figure 4.1: Estimated Plastic Waste Volumes by End-of-Life Fate, 2019

Romano et al. (2019) show that waste management performance, frequently measured as waste production, recycling, and/or cost efficiency, is affected by demographics, socio-economics, geography, methods of collection, and government policy. They further show that zero waste policies affect recycling. Eunomia (2017) identifies the following as being characteristics of high-performance recycling/collection:

- "Comprehensive schemes to enable people to recycle (e.g., Mandatory separate collection of dry materials and biowaste)
- Clear performance targets and policy objectives (e.g., recycling targets, requirements to separate certain materials from residual waste - supported by measures such as landfill bans)
- Funding for recycling, (e.g., government funding, Extended Producer Responsibility schemes)
- Financial and behavioral incentives to directly and indirectly encourage citizens to recycle (e.g., taxes on residual waste treatment and disposal, restrictions on residual waste bins, differential 'Pay As You Throw' and Deposit Refund Schemes)"

There is also a tendency for the cost of disposing of products in a landfill to affect the rate of recycling/collection (Eunomia 2021). Accessibility to recycling facilities tends to increase recycling rates as well (Abbott et al 2011).

Successful recycling/collection programs take different forms; however, as discussed below, a common characteristic includes regulations or policies implemented by governing bodies that have either a penalty for not recycling or rewards that support recycling. Penalties might include fines for not recycling or decreased funding if a local jurisdiction fails to recycle. Rewards might include tax incentives or bottle deposits, where a portion of the price of a product is refunded when the plastic material is returned.

4.1. U.S. State Level Recycling/Collection

There are many factors that might influence recycling/collection, as discussed above. Table 4.1 provides some characteristics of state recycling activities, including the recycle rate of rigid plastics and PET bottles, along with some demographic information: population density, education, and per capita income. As discussed above, it is possible that socioeconomics might affect recycling rates. Those with higher income have more resources to dedicate to recycling and education can increase the knowledge about recycling. Population density places pressure on scarce resources while reducing the cost per unit to collect those resources, making recycling more advantageous. Research has also supported the effect of socioeconomics. For instance, Romano et al. (2019) suggest that population density and income positively affect recycling.

It is important to note the difference between the recycling rate and collection rate. Of the portion of materials collected, only a portion are successfully recycled into new materials. There are several reasons why some materials collected are not recycled, including contamination and the limitations of machinery for sorting. For PET bottles, an estimated 27 % of the collected materials are lost – 13 % occurring at the sorting facility and 14 % at the processor facility

(Eunomia 2021). Sorting losses “are a result of material missed by sorting equipment or manual pickers, or collected material not being of sufficient quality to be marketed” (Eunomia 2021). The source of processor losses “include moisture, dirt, labels, coatings, caps and glues” (Eunomia 2021). HDPE bottles, PP plastic, rigid plastics (#3-#7), and PET other rigid plastics have losses of 28 %, 41 %, 44 %, and 68 % respectively (Eunomia 2021). Most of the losses occur at the sorting facility.

For the state level data in Table 4.1, the recycle/collection rate of rigid plastics has a positive correlation coefficient with population density, education attainment (measured as the percent of the population aged 25 and over that have a bachelor’s degree or higher), and per capita income. The average population density of the top 20 % of states (i.e., top ten states) by rigid plastics recycling/collection rate has a population density of 215 people per km^2 while the bottom 20 % has a population density of 35 people per km^2. In the top 20 %, 22.9 % of those aged 25 and older have a bachelor’s degree or higher while in the bottom 20 % the rate is 17.3 %. Income is also higher in the top 20 % at $71 963 per capita compared to $54 008 per capita. This anecdotal evidence suggests the possibility that places in the U.S. that have higher rigid plastic recycling/collection tend to have higher population density, higher education levels, and higher income; however, population density and income do not positively correlate in the European Union when using the recycle/collection rates in Table 4.3, which is discussed below. It is important to note that several European countries have per capita GDP much lower than in the U.S., which may partially explain this issue. For instance, in the U.S., Mississippi has the lowest 2022 per capita income at $46 248 per capita. In the European Union, 18 of the 27 countries have a lower GDP per capita (USD equivalent), with eight being less than half that of Mississippi’s. It is possible that at lower incomes, low value materials become more important, as it might be relatively more advantageous to recover them. Additionally, cultural differences, differences in the cost of inputs for plastic production, and other socioeconomic factors could drive different behaviors in both consumption and recycling/collection.

It is important to note that population density and income tend to correlate with each other, and the relationships with recycling may include confounding effects from other factors. There is a great deal of literature exploring these and other relationships with recycling. For this report, it is important to note that there are likely strategies that tend to be successful in increasing recycling at many different locations; however, successful recycling is influenced by characteristics of a population and there is the possibility that a successful strategy in one area might not be as successful in another area. Customized guidance to each location may be needed. Examining state, local, and foreign recycling practices/policies can provide insight, but caution needs to be taken in drawing conclusions.

An examination of the fifty U.S. states shown in Table 4.1 shows that policies and regulations tend to result in higher recycling/collection rates. Data may be needed to drive results as well. The states with higher rates of rigid plastics recycling/collection tend to have policies and legislation in place related to recycling along with good data tracking. High recycling/collection rates are also associated with bottle deposit laws. As one moves down the list to lower

Table 4.1: Plastic Recycling, Related Governing, and Population Characteristics, by State (sorted by Rigid Plastics Recycling)

State	Rigid Plastics (total)	PET Bottles	Data quality and availability	Recycling Related Legislation Identified	bottle deposit law	Population Density (people per km^2)	Percent of those Aged 25 or Higher with Bachelors Degree or Higher	Per Capita Income ($)
MAINE	57 %	78 %	Fair	Electronics recycling bill, bans on single-use plastic bags and polystyrene food containers, bottle deposit law	Yes	17.1	22 %	59 463
MICHIGAN	39 %	57 %	Good	Prohibits some items from landfills, bottle deposit law, programs for recycling electronics and scrap tires, grants for local recycling programs	Yes	68.7	19 %	56 813
VERMONT	37 %	51 %	Good	Ban on curbside recyclables being disposed of in trash, trash charge based on volume/weight, recyclables banned from landfills, bottle deposit law	Yes	26.9	26 %	63 206
CONNECTICUT	33 %	47 %	Good	bottle deposit law	Yes	287.5	23 %	84 972
NEW YORK	32 %	54 %	Good	Product stewardship programs for electronics and batteries, bottle deposit law	Yes	165.5	22 %	78 089
MARYLAND	31 %	30 %	Good	Mandated 30%-35% recycling rate with penalties for failing to meet it	No	245.6	22 %	70 730
CALIFORNIA	30 %	57 %	Good	bottle deposit law, fees for material sent to landfill, infrastructure development	Yes	98.0	22 %	77 339
MASSACHUSETTS	28 %	38 %	Good	Municipal and micro grants for reuse, some recyclable are banned from landfills, bottle deposit law	Yes	348.0	25 %	84 945
RHODE ISLAND	28 %	36 %	Good	Mandated recycling targets	No	409.8	21 %	65 377

NEW JERSEY	27 %	22 %	Fair	Counties required to have a 50% municipal waste stream recycling rate, tax for landfill disposal, ban on a variety of single use products	No	487.6	26 %	78 700
HAWAII	26 %	44 %	Good	bottle deposit law	Yes	87.5	22 %	61 175
OREGON	26 %	69 %	Good	Select cities are required to provide recycling, bottle deposit law	Yes	17.0	22 %	62 767
NEW HAMPSHIRE	25 %	29 %	Limited		No	59.4	25 %	74 663
PENNSYLVANIA	21 %	14 %	Fair		No	112.2	21 %	65 167
WASHINGTON	21 %	28 %	Good		No	44.7	24 %	75 698
WISCONSIN	21 %	24 %	Fair	Requires access to recycling program	No	42.0	22 %	61 210
IOWA	18 %	30 %	Fair	bottle deposit law	Yes	22.0	21 %	58 905
INDIANA	17 %	16 %	Fair	Grants to develop recycling market	No	73.1	19 %	57 930
ARIZONA	14 %	15 %	Fair		No	24.3	20 %	56 667
KANSAS	14 %	16 %	Limited		No	13.9	22 %	60 152
MINNESOTA	14 %	25 %	Good	Select counties required to have 35% recycle rate, commercial businesses required to recycle 3 types of materials	No	27.7	26 %	68 010
MISSOURI	13 %	9 %	Fair		No	34.6	20 %	56 551
NEBRASKA	13 %	14 %	Fair		No	9.8	22 %	63 321
SOUTH DAKOTA	13 %	16 %	Limited		No	4.5	22 %	65 806
DELAWARE	12 %	9 %	Good		No	196.1	21 %	61 387
NORTH DAKOTA	12 %	15 %	Limited		No	4.4	22 %	66 184
UTAH	12 %	14 %	Limited		No	15.3	24 %	57 925
IDAHO	11 %	13 %	Limited		No	8.6	20 %	54 537
ILLINOIS	11 %	12 %	Fair		No	89.1	22 %	68 822
NEVADA	11 %	16 %	Fair	Required to provide recycling to households in some areas	No	10.9	18 %	61 282
MONTANA	10 %	12 %	Limited		No	2.9	22 %	57 719
TEXAS	10 %	11 %	Fair		No	43.1	21 %	61 985
WYOMING	10 %	12 %	Limited		No	2.3	19 %	71 342
COLORADO	9 %	8 %	Good		No	21.5	27 %	74 167
GEORGIA	9 %	9 %	Good		No	71.7	21 %	57 129
OHIO	9 %	11 %	Good		No	111.5	19 %	57 880

VIRGINIA	9 %	10 %	Good	Recently passed credits and tax incentives for recyclers	No	84.4	24 %	68 211
FLORIDA	8 %	7 %	Good		No	155.0	21 %	63 597
NEW MEXICO	8 %	10 %	Limited		No	6.8	16 %	51 500
NORTH CAROLINA	8 %	8 %	Fair		No	82.9	22 %	57 416
ARKANSAS	7 %	5 %	Fair		No	22.4	16 %	51 787
KENTUCKY	7 %	8 %	Fair		No	44.1	16 %	52 109
OKLAHOMA	7 %	7 %	Limited		No	22.3	18 %	54 998
ALABAMA	5 %	6 %	Limited		No	38.3	17 %	50 637
LOUISIANA	5 %	4 %	Limited	Tax credit for purchasing new recycling equipment	No	41.6	17 %	54 622
MISSISSIPPI	4 %	4 %	Limited		No	24.4	15 %	46 248
SOUTH CAROLINA	4 %	2 %	Fair		No	65.7	20 %	53 320
TENNESSEE	4 %	3 %	Limited		No	64.7	19 %	58 279
WEST VIRGINIA	2 %	3 %	Fair		No	28.8	14 %	49 169
ALASKA	1 %	1 %	Limited		No	0.5	21 %	68 919

* Common containers and packaging materials

** Data quality and availability is from Eunomia (2021). The core requirements for the data assessment was tonnage data that was no more than three years old; covered single-family, multi-family, and commercial sources of material; and whether the data was sufficiently granular enough to quantify the different common containers and packaging materials.

Source: Eunomia 2021, U.S. Department of Commerce and U.S. Census Bureau 2023b, U.S. Census Bureau 2021, St. Louis Federal Reserve 2023 recycling/collection rates in Table 4.1, there are fewer and fewer with recycling legislation (e.g., bottle deposits programs) and data becomes fair or limited. Eunomia (2021) also suggests that landfill fees also affect recycling. Eunomia (2021) concludes that "deposit return systems are critical for high performance and the policy is most effective when curbside recycling and deposits work together." Seven of the top ten states by rigid plastics recycling/collection have a bottle deposit system while none of the states in the bottom ten have one.

The U.S. Federal Trade Commission (FTC) Green Guides state that claiming an item is recyclable requires that recycling/collection facilities are available to a majority (at least 60 %) of U.S. residents and the product is used in the manufacture of a new item (FTC 2024). For plastics, only certain types of PET and HDPE plastic met this definition (FTC 2024). In 2021, the U.S. had an estimated 1383 MRFs (NAICS 562920), which equates to 4.2 facilities per million inhabitants (U.S. Census Bureau 2023a). This might be compared to the European Union, which in 2018 had an estimated 33 341 recovery facilities or 74.7 facilities per million inhabitants. Unfortunately, the differences between these are not clear, as there could be differences in the definition of what is included as a MRF and its capacity, what is defined as recycling facilities, or other factors.

4.2. Non-U.S. Recycling Programs

In 2020, the European Union generated 19.0 billion kg (41.9 billion lbs) of plastic waste with an estimated 8.1 billion kg (17.9 billion lbs) being recycled/collected and 1.1 billion kg (2.4 billion lbs) of that being recycled/collected was exported (Eurostat 2023). Other estimates for the European Union put the plastics recycling/collection rate at 32.5 % (European Parliament 2023).

The European Union has a focus on waste prevention, recycling, and reuse (European Council 1997); however, not all European countries are in the European Union. A number of European countries are touted as having successful recycling/collection programs; however, a large amount of the plastic material that is collected is exported with limited knowledge about its fate (Bishop et al. 2020). For instance, 46 % of separated PE was exported with an estimated 3 % of that ending up in the ocean (Bishop et al. 2020). In 2019, Europe generated an estimated 29.1 Mt of plastic waste with 9.4 Mt (33 %) being sent to recycling/collection facilities and only 4 Mt being effectively recycled (Lase et al. 2023). There are also some missing plastics that go unaccounted.

Eunomia (2017) conducted a study to compare national recycling rates of all materials. This required some adjustments to official estimates, as each country has slightly different items included in recycling. For instance, some might include construction and demolition wastes and/or recycling losses. After adjustments to create comparable recycling estimates, Eunomia (2017) estimates that Germany has the highest recycling rate at 56.1 % (see Table 4.2) followed by Austria (53.8 %) and South Korea (53.7 %). Note that the adjusted value is only available for the countries with the top recycling rates. The U.S. unadjusted value was 34.6 %. Section 4.2.1.1 through Section 4.2.1.5 discuss recycling in the top five countries listed in Table 4.2.

Eurostat (2023) provides estimates of plastic waste generated, population, plastic waste recycled, and plastic waste exported. Table 4.3 uses Eurostat data to estimate plastic waste per capita, plastic recycled/collected as a percent of total plastic waste, and plastic waste exported as a percent of recycled plastic. Note that some countries have a percent exported that is greater than 100 %, which may be due to a large amount of imports. Waste exported is shown, but it is often unclear what happens to exported plastic waste. Hungary, Bulgaria, and Lithuania each report high levels of plastic being recycled, with total waste plastic exported as a percent of total recycled plastic being 2.4 %, 1.1 %, and 7.8 % respectively. Recall that the 2018 U.S. exports of plastic as a percent of that recycled is 38.5 %.

As previously mentioned, population density and education attainment are two readily measurable factors that might influence recycling. The U.S. population density is 36 people/km^2 (World Bank 2023) and has a per capita GDP of $70 248.6. The discussions below include the 2020 population density and the 2021 per capita income.

Table 4.2: Adjusted Recycle Rate (Top 10 Countries), Estimated by Eunomia

Country	Recycling Rate (Percent)	Adjusted MSW Recycling Rate (Percent)
Germany	66.1	56.1
Austria	55.9	53.8
South Korea	59.0	53.7
Wales	63.8	52.2
Switzerland	52.7	49.7
Italy	52.6	49.7
Belgium	53.5	49.4
Netherlands	56.6	46.3
Slovenia	53.9	45.8
Singapore	61.0	34.0
United States	34.6	-

Source: Eunomia 2017

4.2.1. Top 5 Countries with High Recycling/Collection Rates of All Materials

To further explore various approaches to plastic recycling, the following sections discuss the practices and policies of the top 5 countries with high recycling/collection rates, as identified in Table 4.2

4.2.1.1. Germany

Western Germany’s 1972 Waste Disposal Act, which has evolved into the current Waste Management Act, is the primary guiding law for recycling in Germany (Office of Global Education 2019). After the reunification of East and West Germany in the late 1980’s and early 1990’s, it began to be the guide for east Germany as well. Prior to reunification, importing raw materials into east Germany was prohibitively expensive, which resulted in higher levels of reusing and recycling of materials (Office of Global Education 2019). Germany's recycling program has also been influenced by public constraints on landfill capacity and packaging accounts for 50 % of municipal waste by volume (Patel 2000). Germany has a high population density, which may have influenced land use policies.

Table 4.3: European Union Plastic Recycling Rates, By Country (2020)

Country	Plastic Waste Generated (Thousands kg)	Plastic Waste per Capita (kg)	Plastic Recycled/Collected as a Percent of Plastic Waste	Total Waste Plastic Exported as a Percent of Total Recycled/Collected Plastic
Hungary	159 808	16.4	91.4 %	2.4 %
Bulgaria	367 487	52.9	82.4 %	1.1 %
Lithuania	110 399	39.5	81.6 %	7.8 %
Netherlands	642 780	36.9	72.4 %	40.9 %
Romania	304 857	15.8	72.3 %	5.9 %
Germany	3 097 163	37.2	70.3 %	25.1 %
Slovenia	67 282	32.1	65.2 %	281.3 %
Spain	876 807	18.5	64.8 %	10.5 %
Estonia	43 142	32.5	57.6 %	11.6 %
Slovakia	199 211	36.5	57.6 %	6.8 %
Czechia	556 682	52.1	55.0 %	3.9 %
Latvia	112 421	58.9	52.9 %	7.6 %
Denmark	139 833	24.0	51.2 %	12.2 %
Austria	399 084	44.8	48.2 %	6.9 %
Poland	2 238 779	59.0	41.7 %	7.1 %
Luxembourg	31 317	50.0	39.0 %	0.0 %
Portugal	447 175	43.4	37.0 %	7.3 %
Greece	172 216	16.1	36.9 %	27.5 %
Croatia	126 223	31.1	34.0 %	29.3 %
Belgium	994 896	86.3	33.2 %	98.5 %
Malta	8 802	17.1	33.2 %	44.0 %
Finland	132 105	23.9	31.2 %	26.9 %
Italy	4 848 441	81.3	29.0 %	4.8 %
Sweden	342 506	33.2	13.6 %	26.1 %
Cyprus	17 174	19.3	11.3 %	173.7 %
France	2 399 602	35.6	11.3 %	11.8 %
Ireland	197 614	39.8	-	-
European Union	19 030 000	42.5	42.6 %	19.6 %

NOTE: Eurostat states that, "The Member States are free to decide on the data collection methods. The general options are: surveys, administrative sources, statistical estimations or some combination of methods."
Source: Eurostat 2023

It is important to consider the metric used for measuring the percent of material recycled. For instance, official statistics show a plastics recycling rate in Germany of 48.8 % (Wecker 2018); however, this is the amount of material collected. Not all collected material is recycled. Some plastics cannot be recycled due to additives embedded in the materials. Additionally, plastic degrades after being recycled and eventually is not usable. When considering other factors, the German recycle rate for plastics is estimated to be about 38 % (Wecker 2018).

Recycling policies/regulations: Yes
Population density: 238 people/km^2 (World Bank 2023a)
Economy: $51 203.6 per capita GDP (World Bank 2023b)

4.2.1.2. Austria

Austria has a producer responsibility model, which shifts the financial burden of designing, financing, and managing recycling programs to manufacturers (Walker 2023). Recycling is also paid for through municipal taxes. Austria has a blanket ban on certain types of waste going to the landfill and bans plastic bags.

Recycling policies/regulations: Yes
Population density: 108 people/km^2 (World Bank 2023a)
Economy: $53 637.7 per capita GDP (World Bank 2023b)

4.2.1.3. South Korea

South Korea has strict policies on recycling, where food, garbage, recyclables, and bulky items are separated. There are penalties for non-compliance and rewards for reporting violators. Similar to other successful recycling programs, South Korea has a producer responsibility model, where some of the burden and responsibility of recycling is shifted to the producer. South Korea has a very high population density, which may be a factor in recycling policy preferences and effectiveness.

Recycling policies/regulations: Yes
Population density: 531 people/km^2 (World Bank 2023a)
Economy: $34 997.8 per capita GDP (World Bank 2023b)

4.2.1.4. Wales

Wales has statutory recycling targets for local governments. This has resulted in household recycling rates increasing from 5.2 % in 1998-1999 to 60.7 % in 2018-2019 (Welsh Government 2020). Additionally, Wales has provided funding for recycling services, charges for bags, and banned many single-use plastics (Welsh Government 2020).

Recycling policies/regulations: Yes
Population density: 277 people/km^2 (United Kingdom) (World Bank 2023a)

Economy: $ 46 510.3 per capita GDP (United Kingdom) (World Bank 2023b)

4.2.1.5. Switzerland

Switzerland bans the landfilling of combustible materials, biodegradable municipal waste, and has taken steps to expand incineration capacity (Herczeg 2013). Materials are required to be separated, is supervised by local authorities, and failure to comply can result in fines (Shehu 2021).

Recycling policies/regulations: Yes
Population density: 219 people/km^2 (World Bank 2023a)
Economy: $ 91 991.6 per capita GDP (World Bank 2023b)

4.2.2. Top 5 European Union Countries with High Plastic Recycling/Collection Rates

In addition to discussing the top countries overall in Section 4.2.1, the sections below explore the policies and practices of the top 5 European countries in terms of plastic recycling/collection, as presented in Table 4.3.

4.2.2.1. Hungary

Hungary has regulations in place regarding packaging and collecting packaging, including a ban on single-use plastics and oxo-degradable plastic, which are plastics that due to oxidation fragment into the environment (Petrányi et al 2023). Hungary has also implemented a producer responsibility scheme with rules that ensure the producer bears financial responsibility for waste management. The country has levies in place for packaging and other plastic products.

Recycling policies/regulations: Yes
Population density: 107 people/km^2 (World Bank 2023a)
Economy: $ 18 7281.1 per capita GDP (World Bank 2023b)

4.2.2.2. Bulgaria

Bulgaria has a relatively low population density and per capita income and its recycled/collected plastic as a percent of plastic waste generated is 82.4 % (see Table 4.3), making it the second highest in the European Union. The country has adopted extended responsibility measures that include the acceptance of returned products and waste remaining after the use of a product, the financial responsibility for waste management, and obligation to provide information on the extent to which a product can be reused and recycled (Sirleshtov et al. 2021). Producers are also responsible for the separate collection of packaging waste. Some plastics incur a fee such as for some types of plastic shopping bags (Sirleshtov et al. 2021). Regulations require no less than 60 % of the weight of packaging waste be recovered or incinerated for energy recovery (Sirleshtov et al. 2021).

Recycling policies/regulations: Yes

Population density: 64 people/km^2 (World Bank 2023a)
Economy: $ 12 221.5 per capita GDP (World Bank 2023b)

4.2.2.3. Lithuania

Lithuania's recycled/collected plastic as a percent of plastic waste is 81.6 % (see Table 4.3). It has a bottle deposit system in place and has a ban on certain types of plastic bags (European Environmental Agency 2021). It also has a tax on certain types of plastic packaging (Vitkuniene 2022). These actions have resulted in a relatively high plastics recycling/collection rate. It is interesting to note that Lithuania has a relatively low population density and low income per capita.

Recycling policies/regulations: Yes
Population density: 45 people/km^2 (World Bank 2023a)
Economy: $ 23 723.3 per capita GDP (World Bank 2023b)

4.2.2.4. Netherlands

With recycled/collected plastic as a percent of plastic waste generated being 72.4 % (see Table 4.3), the Netherlands has bans on certain types of single-use plastics (Donk 2021). Producers and importers are responsible for the costs of cleaning up, transporting, and processing certain types of litter (Donk 2021). Producers are also financially responsible for environmental awareness programs (Donk 2021). Single-use plastics are required to have markings indicating their environmental impact if thrown away (Donk 2021). Producers and importers are required to ensure at least 90 % of certain plastics are collected separate from other waste (Donk 2021). The Netherlands also has a deposit bottle scheme in place (Donk 2021).

Recycling policies/regulations: Yes
Population density: 518 people/km^2 (World Bank 2023a)
Economy: $ 57 767.9 per capita GDP (World Bank 2023b)

4.2.2.5. Romania

Romania has banned certain types of plastic bags, has taxes on yet other types of plastic bags, and some municipalities have banned certain single-use plastics for various applications (Radu and Dulamea 2021). Romania also has an extended producer responsibility scheme where producers are financially responsible for the collection and sorting of various packaging waste (Radu and Dulamea 2021). It is interesting to note that despite relatively low population density and per capita GDP, Romania has a high plastics recycling/collection rate with recycled/collected plastic as a percent of plastic waste generated being 72.3 % (see Table 4.3).

Recycling policies/regulations: Yes
Population density: 84 people/km^2 (World Bank 2023a)
Economy: $ 14 858.2 per capita GDP (World Bank 2023b)

5. Plastics Recycling Economy

Section 2 and Section 3 discussed the production of plastics and the current state of plastics recycling in the U.S. with Section 4 discussing successful recycling/collection programs in the U.S. and other counties. This section focuses on the economics of plastics manufacturing and recycling processing. Successful material recycling tends to happen when it is financially viable, technically feasible, and environmentally safe. Currently, the economic viability exists primarily for homogeneous high-value, low-contamination streams, and is affected by the price of oil (Merrington 2017). Plastics recycling is often broken into post-industrial recycling and post-consumer recycling. Post-industrial recycling includes recycling waste material generated from the manufacturing process. Many companies engage in this type of recycling, which is often more profitable for recyclers and more efficient for producers because it uses concentrated quantities of uniform material that is largely uncontaminated. Post-consumer recycling is the recycling of waste material from consumers. Successful recycling of post-consumer plastics is currently focused on plastics that are available in high volumes, easily identified, and of high-value resin type. Thus, a significant volume of plastics is not recycled and end up in landfills.

A result of the complexities of recycling is that the cost for using recycled plastic material for some applications may be higher than primary material. In some cases, the cost of using recycled plastic is estimated to be slightly more expensive (see Table 5.3), but it can be twice as high as primary material (Staub 2021). In 2020, U.S. plastics manufacturing value added was $131.4 billion or 0.6 % of GDP and total shipments were $284.4 billion, as seen in Table 2.2. This industry produced approximately 55 megatons of plastic in 2019. Meanwhile, as seen in Table 5.1, 37.7 megatons of plastic were landfilled in 2019. These plastics are estimated to have an approximated recycling market value between $4.5 billion to $9.9 billion (3.5 % to 7.7 % of plastics manufacturing value add).

Table 5.1: Market Value of Landfilled Plastics

Plastic Material	2019 Landfilled (kt)	2019 Average Market Price ($/ton)	Average Market Value ($million)
PET	4554	294	1339
HDPE	6448	126-705	812-4546
PP	7202	244	1757
LDPE/LLPE	13 290	29-131	385-1741
PVC	614	100-700	61-430
PS/EPS	2815	44	124
Other	2796	n/a	n/a
TOTAL	37 719		4478-9937

Source: Milbrandt et al. 2022

The relative costs to manufacturers to use recycled plastics instead of primary plastic can vary significantly from case to case. A report prepared by RRS estimates that the marginal cost of incorporating post-consumer recycled plastic into a selection of products was between $0.05/kg and $0.24/kg with the primary drivers for cost being the application, resin type, and whether the final product will be in contact with food (RRS 2021). As a result, the business case for using post-consumer recycled plastics varies. For instance, Gao (2020) identified that approximately 20 % of plastic collection efforts met a threshold 15 % return on investment or higher for recycling (Gao 2020). Another 50 % had positive returns but did not meet the 15 % threshold. The remaining 30 % had negative returns.

It is important to note that just because a plastic is collected for recycling, does not mean it is recycled, as the plastic needs to be recyclable as well as have a customer for that recycled material. Some collection efforts for recycling result in plastics being landfilled. One challenge is the dispersed nature of plastic waste. To recycle plastic, it must be recollected, separated, concentrated, and decontaminated, which is currently a costly and labor-intensive process.

Another challenge is that recyclers state there are no (or limited) markets for plastics #3-#7 (PVC, LDPE, LLDPE, PP, PS, and other) and non-bottle plastics #1-#2 (PET and HDPE), resulting in them often being discarded, stored, or incinerated (Hocevar 2020). In some instances, recyclers pay for collected plastics waste to be hauled away to landfills. What is required is a shift in the incentives throughout the plastics recycling economy to drive supply and demand throughout the supply chain loop.

Thomas (2022) identified three primary needs for increasing plastics recycling. First, there is a need to aggregate streams to increase collection volume and economies of scale. This might include reducing the number of plastic types (i.e., “plastic simplification”), standards for additives use and tracking in plastic, and understanding the economics of individual plastic streams. Second, there is a need for standards or technologies for a low cost means for separating post-consumer plastic types and preventing/removing contaminants. Finally, the most notable need is to be able to differentiate product brands and models by both recycled content and/or recyclability. This might be achieved with a standard metric such as an index or score, which allows consumers to reliably select more circular products, both in terms of recycled content and/or recyclability, and allow producers to benefit from producing more circular products (more recycled content and recyclable materials). This need is the most notable because it can create incentives for stakeholders to internalize the negative externalities and, thus, potentially address the other two identified needs. Aside from regulations, taxes, subsidies, or a substantial increase in primary material costs, it will likely be difficult to increase plastic recycling rates without the ability to differentiate products by recycled content / recyclability and increase consumer demand for such products.

5.1. Stakeholder Economics in Plastics Recycling

This section discusses the stakeholder’s perspectives in the plastic recycling economy with a focus on important incentives and/or disincentives impacting plastic recycling. As illustrated in the stakeholder map in Figure 5.1, the production of primary plastic begins with the extraction of oil and gas while plastic recycling activities start occurring in the manufacturing process and occur through numerous stakeholders. Using symbols, Figure 5.1 associates each stakeholder with one or more of the following:

- negative externalities - ☁
- profit or savings - 💵
- compensation to employees - 👥
- utility (or value) gained from using plastics - 🎢

Manufacturers and material extractors are associated with the negative externalities for producing plastic. Users gain utility from using plastic and the community or society bears the cost of negative externalities.

Section 5.2 through Section 5.6 are based on the following stakeholders with a focus on non-durable (e.g., single-use) plastic goods:

- End users
- Plastic Waste Collectors and Sorters
- Manufacturers
    - Plastic Resin Manufacturers
    - Plastic Product Manufacturers
- Communities and Society

These stakeholders play prominent roles in determining whether plastic materials are recycled, through both decisions related to recycled content and recyclability. The end users decide their willingness to purchase or pay more (or less) for a product with recycled/recyclable material relative to products using primary material. End users also decide whether to recycle their waste plastics; thus, they are both a customer and supplier. Plastic waste collectors and sorters determine the extent of the collection infrastructure, what waste plastic materials they accept and sell, and their methods for collection and sorting, which influences the quantity, purity, and price of recycled plastic. Collectors and sorters get their supply of waste plastic from end users and determine supply of those waste plastics to manufacturers. The manufacturers of recycled plastic resin decide what price they are willing to pay for waste plastic from the collectors and sorters. Resin manufacturers also sell resins to plastic product manufacturers. Recycled resin manufacturers might compete with primary resin manufacturers (directly or indirectly), which can cause the prices to be highly correlated. Recycled plastic faces the additional challenge that their product often cannot be used for all purposes or require additional costs. Plastic product manufacturers decide what products to manufacture and how to manufacture those products, including what inputs to use in manufacturing (e.g., recycled plastic resin and additives included) that impact both the recycled content and the recyclability of the product. Finally, the communities and society are the ones that are impacted by the negative externalities of plastic manufacturing and disposal and implement policies than can impact incentives throughout the plastics recycling ecosystem.

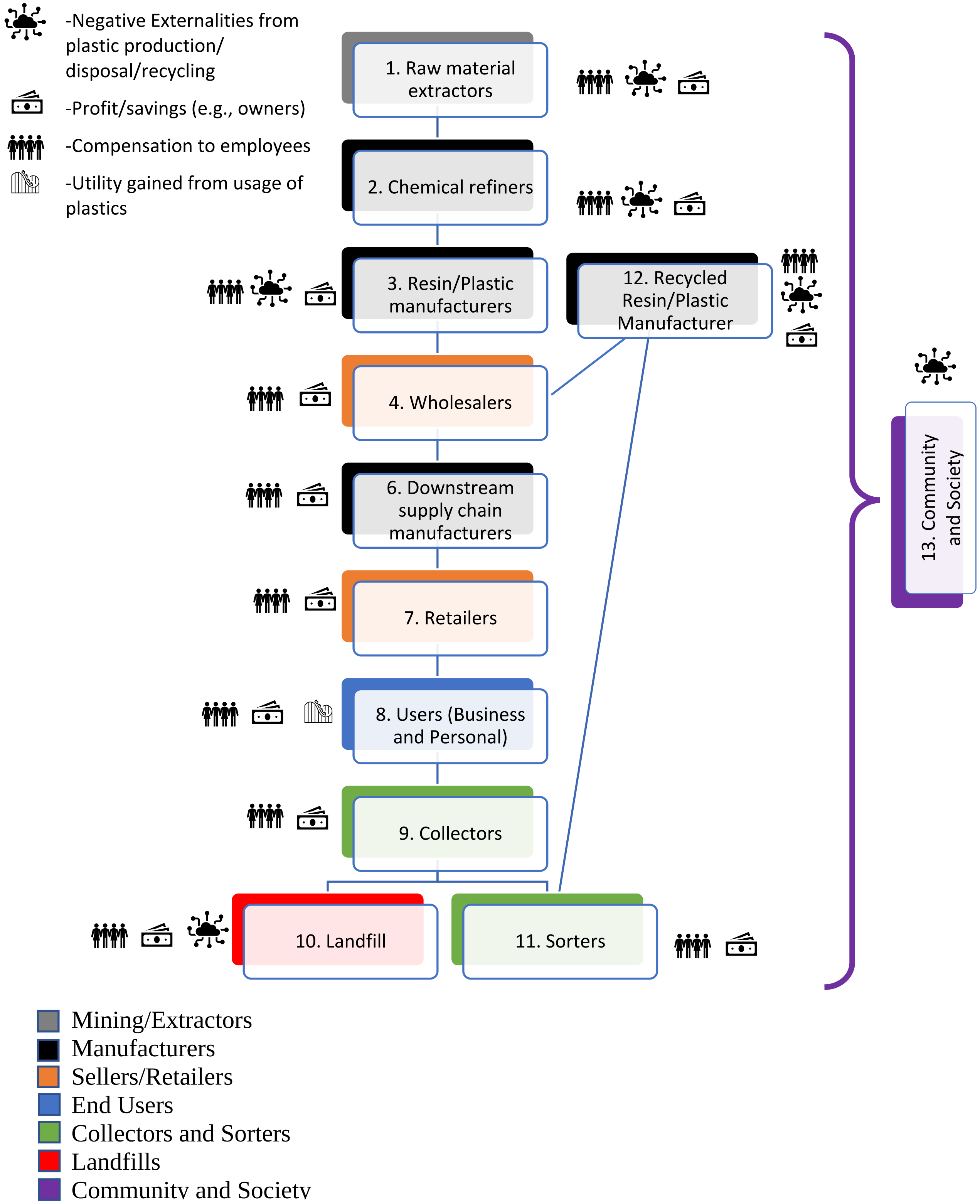


Figure 5.1 Stakeholders Related to Plastics Recycling

Because it is currently the primary method used, the focus of the stakeholder discussion is from the aspect of mechanical recycling; however, some chemical recycling topics are discussed. Mining and extraction along with sellers and retailers are not discussed, as their effect on recycling is typically considered limited.

It is important to note that in the U.S., businesses are primarily operated by private entities to generate income/profit and may not have the incentives to consider the non-regulated impacts of their products on society and the environment. Thus, there is often a trade-off between sustainability/recycling (societal benefits) and financial gain for a business unless incentives exist for internalizing these externalities in the private sector. That is, the business case for sustainability/recycling is important. Many of the investments that businesses make in sustainability/recycling are likely driven by shifts in input supply and costs (e.g., relative price of primary versus recycled inputs), product demand (e.g., differentiation or brand loyalty), or reacting to government policy (e.g., regulation or incentives). Thus, it is critical to consider the financial incentives for businesses when trying to increase plastic recycling. In a competitive market, a profit seeking firm produces (i.e., supplies) more goods as the market price increases. A supply curve (combination of quantity supplied at each price) is represented by the blue line labeled *S1* in Figure 5.2.

Similarly, consumers make decisions to maximize their well-being (i.e., utility) through a combination (i.e., "basket") of product consumption. A consumer's incentives are based on optimizing their consumption using their personal marginal utility and marginal costs of

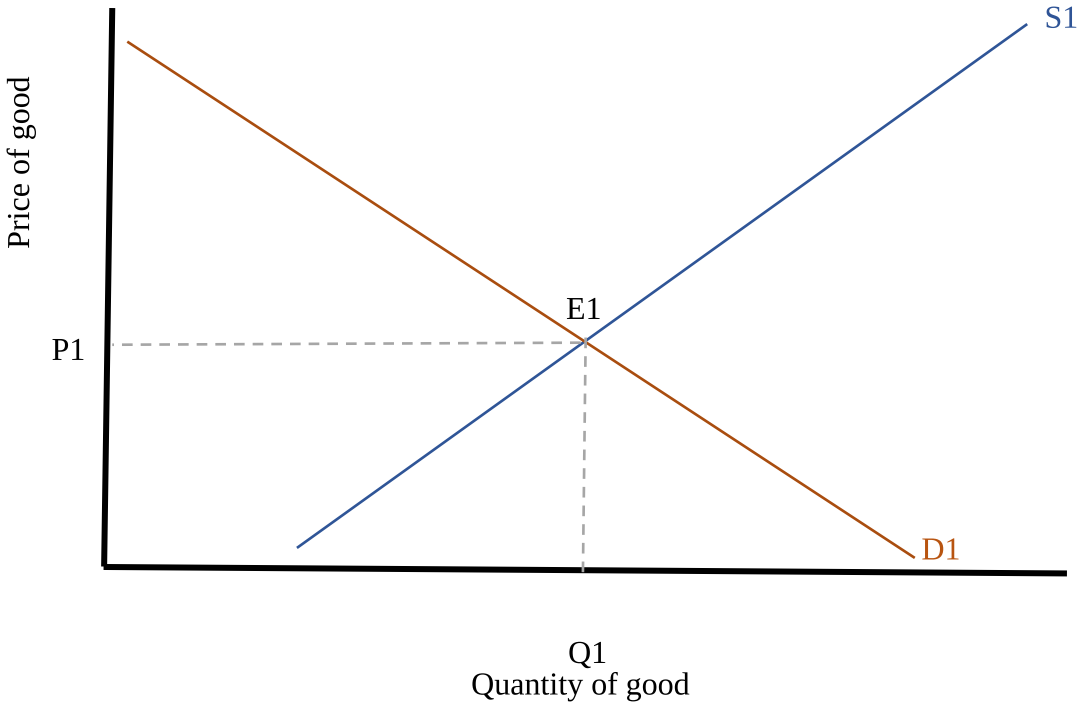


Figure 5.2: Illustrative Supply Curve (S1), Demand Curve (D1), and Equilibrium (E1) Quantity (Q1) and Price (P1) for a Competitive Market

each good in the basket. Generally, consumers are willing to purchase (i.e., demand) more of a good as price decreases. A demand curve (combination of quantity demanded at each price) is represented as the red line labeled *D1* in Figure 5.2. The intersection of these two lines is the market clearing (i.e., equilibrium) price (*P1*) and quantity (*Q1*), labeled as *E1*.

Many factors can impact the supply and demand curves for a given good. For example, if all (most) producers experience higher input costs to manufacturing, this results in a leftward shift in the supply curve represented as line *S2* in Figure 5.3. Assuming the same demand curve, the shift in the supply curve leads to a new equilibrium (*E2*) with a higher price (*P2*) and a lower quantity demanded (*Q2*).

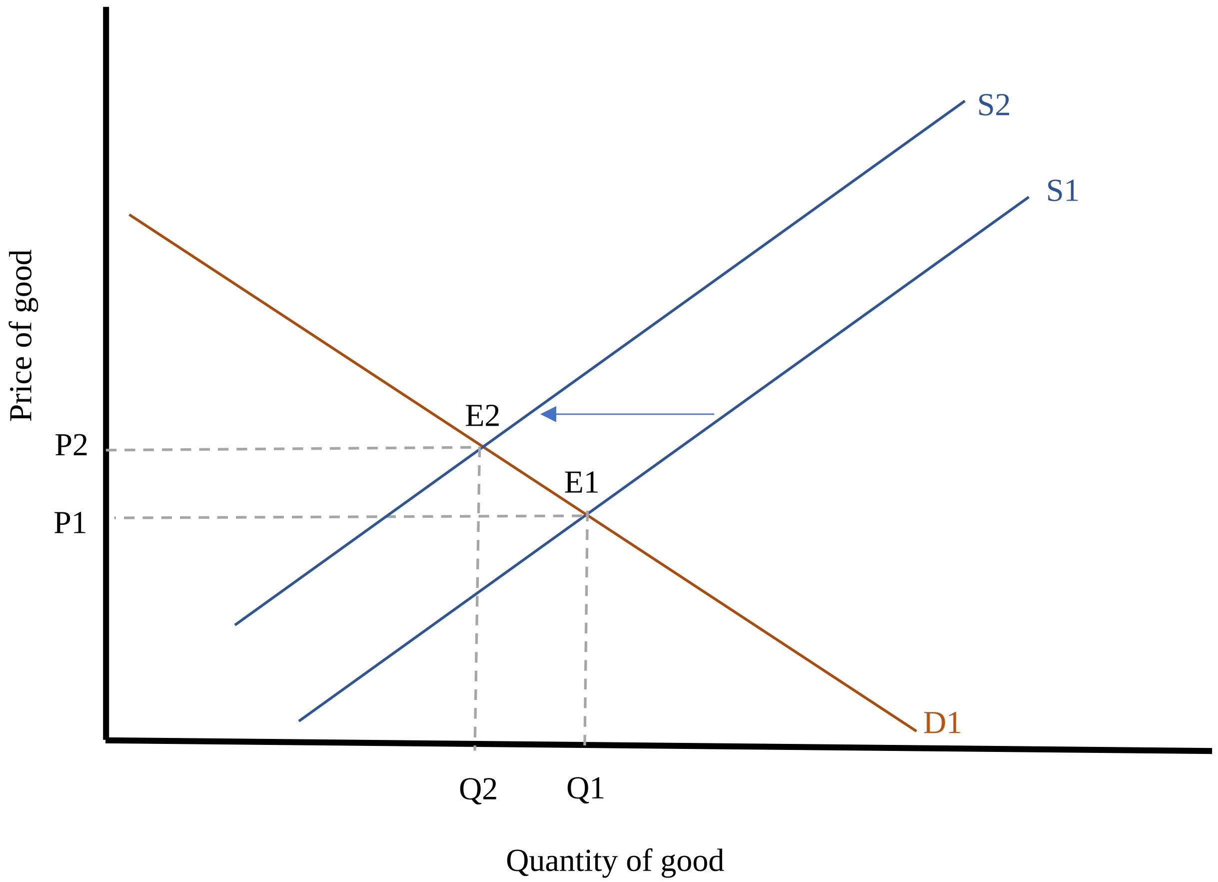


Figure 5.3: Illustrative Shift in Supply Curve

Similarly, a shift in the demand curve can be caused by a change in the utility consumers get from a product (e.g., if consumers preferred goods with recycled content), resulting in the consumer willing to pay a higher price for the same quantity of the product. This (rightward) shift is represented by line *D2* in Figure 5.4. Assuming the same supply curve, the shift in the demand curve leads to a new equilibrium (*E3*) with a higher price (*P3*) and a higher quantity supplied (*Q3*).

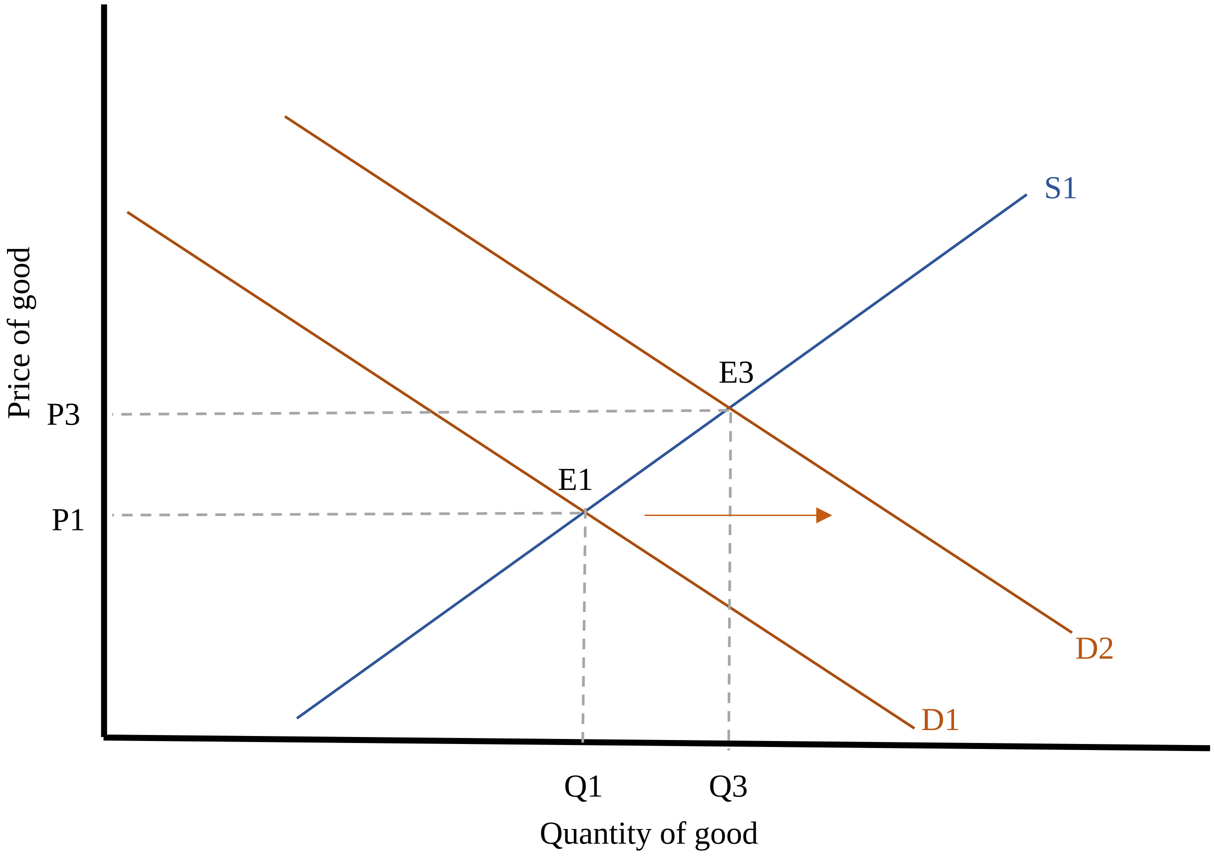


Figure 5.4: Illustrative Shift in Demand Curve

In this example, the change in the product inputs to increase recycled or recyclable content shifts both the supply and demand curves, thus leading to a new equilibrium. The resulting equilibrium price and quantity will depend on the relative size of the shifts, but it is known that the new equilibrium price will be higher in this example because both shifts apply upward pressure on the market price. Note that this example is illustrative and the impacts on supply and demand from increasing recycled content/recyclability may vary depending on the product of interest, application, and structure of input costs and consumer preferences.

5.2. End Users

Plastic product end users, including consumers and businesses, play two roles: demand of plastic products and the supply of recyclable plastic material. Section 5.2.1 and Section 5.2.2 discuss the demand for plastics and factors for recycling behavior, respectively.

5.2.1. Demand for Plastic Products

Plastics are used for many products, as they provide several benefits. According to Andrady and Neal (2009), “plastics deliver unparalleled design versatility over a wide range of operating temperatures. They have a high strength-to-weight ratio, stiffness and toughness, ductility, corrosion resistance, bio-inertness, high thermal/electrical insulation, non-toxicity and outstanding durability at a relatively low lifetime cost compared with competing materials; hence plastics are very resource efficient.” These benefits make plastics appealing to both producers and consumers. To reduce environmental impacts, society might consider alternative solutions; however, it is critical to examine these alternatives to determine whether they truly are beneficial. Some evidence suggests some consumers are willing to adopt different solutions. For instance, an estimated 57 % of North Americans surveyed indicated that they were willing to choose new products with reusable packaging (World Economic Forum 2022).

As previously discussed, the market for a good is determined by its supply and demand, which are functions of the costs and benefits of a product, including the utility (i.e., well-being) of the product; however, not all costs are necessarily included in the decision-making process. Some costs may be realized by third parties to the purchase/sale (i.e., negative externalities such as plastic waste), creating a non-optimal amount of consumption for society—e.g., when producers and users of plastic products do not bear the cost of the environmental impact for producing and discarding the goods. The equilibrium quantity is greater than if negative externalities were internalized in the market, with more primary plastics produced and sold. The points in the supply chain where these tend to occur are labeled in Figure 5.1 with ☁. This situation skews the production/consumption of plastics such that it is not the most efficient outcome for society, as the true cost is not incorporated into the equilibrium price in Figure 5.3.

Some consumers are altruistically willing to pay higher prices to reduce negative externalities (i.e., internalizing at least some of the negative externalities), which increases (or creates) the demand for recycled/recyclable plastic. However, there are challenges for consumers in successfully and correctly internalizing the negative externalities from environmental impacts. In some instances, unintended consequences might lead to different negative externalities. An example of these issues might be found in the effort to reduce the use of plastic straws. In reducing plastic straw use, many restaurants adopted paper straws; however, there are trade-offs for this conversion, including the environmental impact during production, GHG emissions during decomposition, challenges in recycling paper straws, and chemicals embodied in paper and plastic materials (Hirschlag 2023).

The challenges for a consumer in reducing externalities is that they have limited information about how a product is produced and what materials were used. Frequently, producers are not required and/or not able to provide this information. Additionally, there are many types of environmental impacts, many of which are difficult to quantify. A product could have a higher impact in one negative externality category and lower in another category compared to a competing product. There are also disputes on how to evaluate these types of trade-offs. Finally, there are minimal standards or guidance resources that consumers can use to compare products and select those with lower negative externalities. Moreover, the good intentions of consumers by themselves may not be enough to reduce negative externalities to reach an efficient outcome. Consumers need better information related to circularity and environmental performance to make better decisions.

5.2.1.1 Consumer Preferences for Circular Products

Circular products include, but are not limited to, those that are made with recycled materials and/or materials that can be recycled (i.e., made from primary materials, but can be recycled) and include products that are reused (refurbished or offered as second-hand). Previous research has explored the factors that drive a consumer's willingness to pay (WTP) for circular (recycled) goods and whether they are willing to pay as much or more (a price premium) than non-circular alternatives. Given these products may cost more to produce, a positive WTP would suggest there may be a viable market for such products under current consumer preferences. (The WTP literature has primarily focused on individual consumers and not businesses as purchasers of inputs.)

Research into organic and sustainable products demonstrate positive WTP over similar products without such attributes (e.g., Kystrallis et al., 2005; Sogari et al., 2016). Consumers have expressed preferences towards goods that are associated with positive human health (e.g., organic) and fair animal treatment (e.g., free range chickens) over sustainable products, which are typically described in terms of environmental impact (Gatti et al., 2022). In the case of circular products, much of the research is focused on the drivers of WTP, but in comparison to less-circular products, the overall WTP, as a premium, is mixed. Park et al. (2018) and Orset et al. (2017) found positive WTP for more circular drink bottles over less circular ones. However, Pretner et al. (2021) found a lower WTP for more circular clothing (hoodies), made from recycled materials. Also, other factors affect the attitudes towards these products, including a consumer's own environmental preferences (Polyportis et al., 2022; Pretner et al., 2021, Testa et al., 2022), perceived ability to make a positive impact through purchase choices (Hein, 2022), perceived quality (Hamzaoui-Essouossi and Linton, 2022), and contamination concerns (Polyportis et al., 2022; Magnier et al., 2019).

Environmental attitudes can positively affect WTP, but they also have been shown to negatively influence WTP for recycled plastic products, particularly for consumers who view any plastic consumption as a negative (Testa et al., 2022). In the case of quality, the use of warranties can lessen those concerns (Hamzaoui-Essouossi and Linton, 2022). For contamination concern, consumers tend to have lower preferences for goods where contamination may pose a health risk or induce a feeling of discomfort from using products that have been previously used (Cao and Xu, 2023), particularly if they are used in close contact with the user's skin or to package food or health products, even if the material has been processed and manufactured into another application (Magnier et al., 2019).

Messaging, labeling, labeling content, certification, certification structure, and certifying entity all have been shown to play a role in influencing consumer preferences for organic, sustainable, and circular products. Messaging about the benefits of product attributes, the presence of a label identifying the attribute (e.g., Gatti et al., no date), the amount of content provided on the label (e.g., Atkinson and Rosenthal, 2014), perceived certification strength (verification; e.g., Darnall et al, 2016; Darnall et al, 2017), and a recognizable name or perceived unbiasedness of the certifying entity (e.g., third party) play positive roles (e.g., Van Loo et al., 2011; Nie et al., 2022), in general, but these vary based on the product and consumer attitudes.

Less has been explored in how consumers perceive differences between those recycled products that are not recyclable and those made of primary sources that are recyclable. Additionally, much of the literature is based on consumer purchase intent—e.g., they are asked about a hypothetical situation and are not making an actual transaction. (In cases of organic (e.g., meat, produce) and sustainable products (e.g., timber, palm oil, coffee), market data do exist.) Responses are not subject to budget constraints and choice could potentially change when selecting on the bundle of goods limited by a budget. A known limitation within the literature is presence of social desirability bias (e.g., Klaiman et al. 2016) or the "intention-behavior gap" (Polyportis et al. 2022) by respondents surveyed about products generally viewed as environmentally friendly, where respondents are more likely to answer positively about such attributes, but in some instances when market transaction data exist, or the studies have specifically attempted to control for such bias, the unbiased or actual WTP is lower.

5.2.2. End User Recycling

Successful recycling by consumers and businesses requires access to a recycling program and understanding what plastic is recyclable. This is a cost that is, in some ways, incorporated into the supply curve for recycled plastics. Much of this cost is born by communities and consumers. As mentioned previously, only 53 % of the U.S. population has automatic enrollment to curbside recycling collection and of these, only 44 % were served with the larger wheeled cart instead of a small bin that must be carried to the curb (Marshall 2017). Additionally, 82 % had single stream recycling (i.e., comingled materials collection). Those with automatic enrollment plus wheeled cart-based collection and single-stream collection had higher levels of recyclable material collected per household (Marshall 2017). Additionally, 85 % of single-family households have access to recycling collection (curbside or drop-off locations), but multifamily access is only 37 % with an overall access rate of 73 % (Appel et al., 2024). As shown in Table 5.2, the

Table 5.2: Percent of U.S. Population with Access to Plastics Recycling, by Type of Plastic Recycled (2021)

Plastic Type		Accepted (Explicitly or Implicitly)
1	PET Beverage Bottles (with deposit)	88
1	PET Bottles, Jugs, and Jars (without deposit)	87
1	PET Clamsells, Tubs and Trays	54
1	PET Cups	52
2	HDPE Bottles, Jugs, and Jars	87
4	LDPE Bottles, Jugs, and Jars	70
4	LDPE and LLDPE Containers	57
5	PP Bottles, Jugs, and Jars	72
5	PP Tubs and other Containers	59
6	Rigid PS Containers	45

Data Source: Sustainable Packaging Coalition 2022.

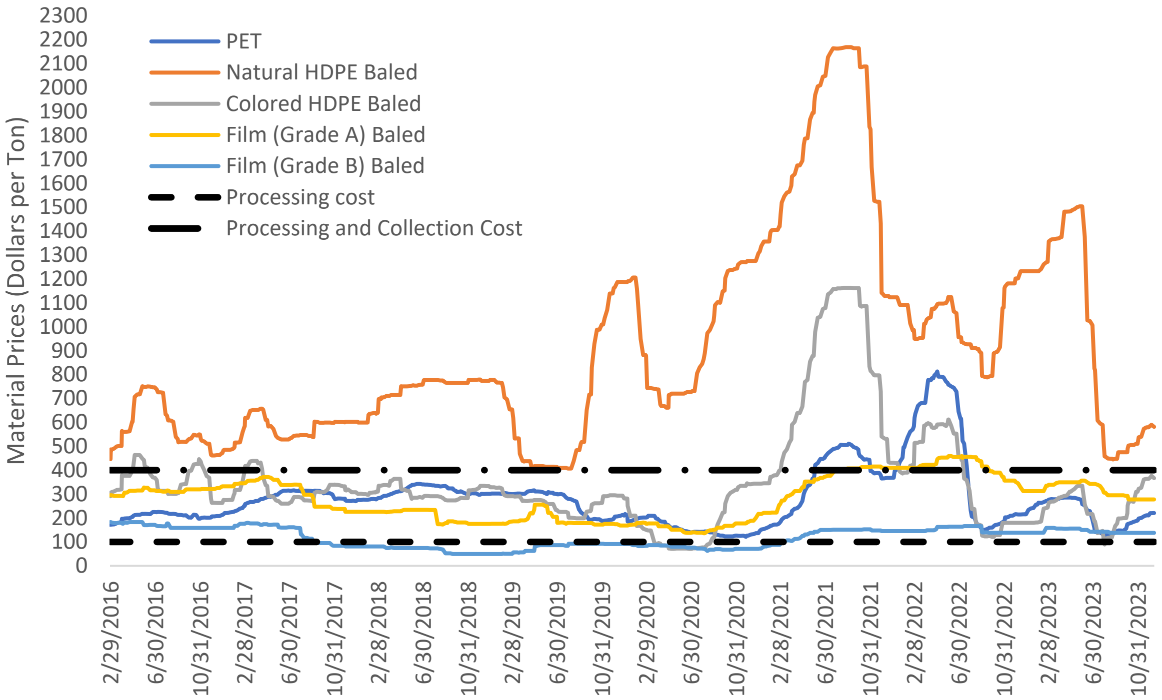
accessibility to recycling collection programs for each plastic type varies. Note that some post-consumer plastics cannot currently be recycled through the MSW system and, thus, are never collected (e.g., PVC).

Acquiring knowledge about recycling is a cost for communities and individuals. Currently, only 60 % of individuals know that food does not go in the recycling bin and 50 % believe plastic bags can go in the recycling bin despite it being rare that recyclers can accept such materials and it can damage sorting equipment (Appel et al., 2024). Additionally, recycling poses some additional costs for consumers and businesses, as it requires time and resources, including time spent understanding what can be recycled, along with square footage for storing recyclable materials. For some, there can be additional costs such as transporting the materials to drop-off locations or subscribing to a recycling service. These costs could result in constraining the supply of recycled plastic, increasing material costs and the risk of losing access to materials. Increasing access to curbside recycling collection programs would reduce the costs to end users for recycling plastic. Additionally, technological advancements that make it easier for end users to determine what plastic waste is recyclable, such as improved labeling, would lead to better sorting and fewer contaminants for plastic recycling.

5.3. Plastic Waste Collectors and Sorters

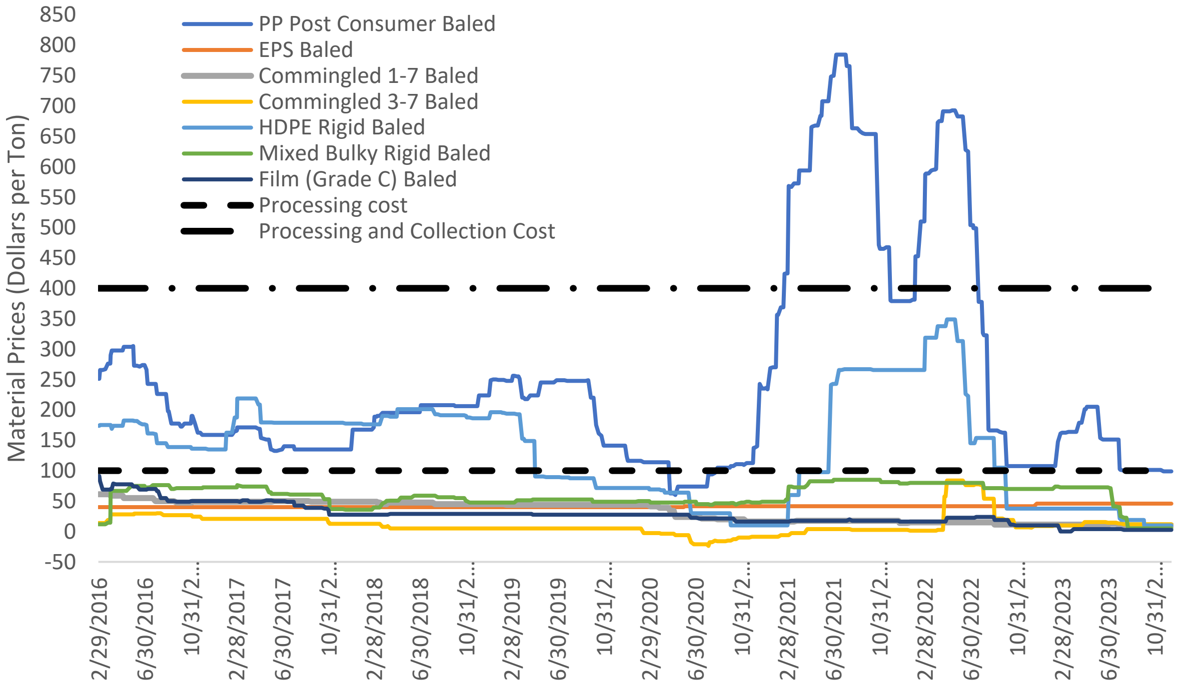
As mentioned previously, currently only a limited number of plastics present a “value generating” or profitable opportunity. Recall that Gao (2020) estimated that approximately 20 % of plastic collection efforts met a threshold 15 % return on investment or higher for recycling, 50 % had positive returns but did not meet the 15 % threshold, and 30 % had negative returns.

Collection costs for general recycling collection programs have been estimated to often exceed \$300 per ton for operating trucks, collection containers, crews, and maintenance in addition to processing fees that range around \$100 per ton (Appel et al. 2024). Most privately-owned MRFs charge a processing fee to community recycling programs (Appel et al. 2024). As seen in Figure 5.5 and Figure 5.6, the material price or sale price of plastic materials is often lower than this estimated cost of collecting and processing (i.e., \$100 + \$300 = \$400 per ton), suggesting that sorting/collecting costs may often exceed the revenue from sales. It is often even below the processing cost alone. Only natural HDPE was above the cost of both processing and collection, as of December 15, 2023. Four plastics are priced higher than the processing cost alone and the remaining six are less than the processing cost. As illustrated in Figure 5.7, prices can fluctuate from region to region, but tend to correlate. Although 64 % of MRFs are privately owned (National Waste and Recycling Association 2018), the cost of processing and market price of plastics makes it difficult for the private sector to recycle materials without additional financial incentives. Plastic waste collectors and sorters need innovations that can increase the volume of high-quality waste plastic, whether that is advancements in collection and sorting technologies (e.g., smart collection bins [Huh et al. 2021], optical [RRS 2020]and robotic [Gibson 2020] sorting equipment, and secondary MRFs that provide more extensive sorting [Hood-Morley 2020]) or product simplification and transparency (e.g., chemical tracers, digital watermarks, shrink sleeve labels) that decreases the complexity and uncertainty in the plastic waste stream.



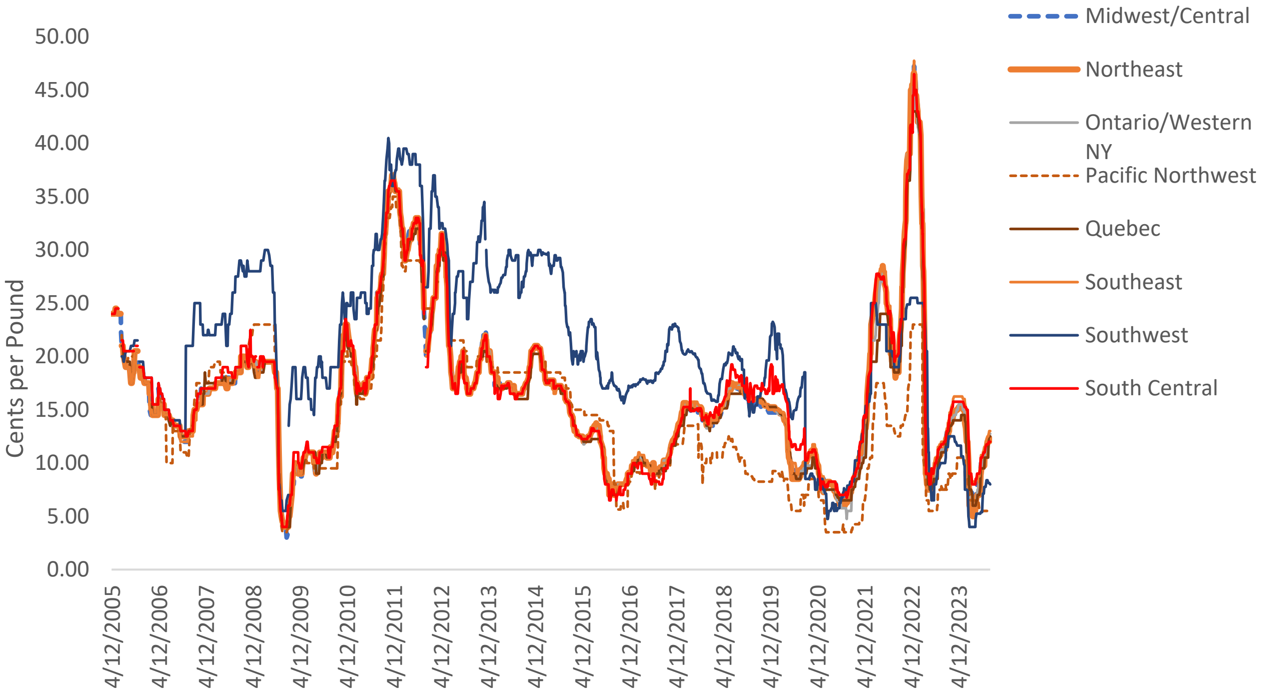
NOTE: Those shown above were $100 or higher as of December 15, 2023
Data Source: Recycling Markets (2024)

Figure 5.5: Recycled Plastic Material Prices (National Average), Higher Priced



NOTE: Those shown above were less than $100 as of December 15, 2023
Data Source: Recycling Markets (2024)

Figure 5.6: Recycled Plastic Material Prices (National Average), Lower Priced



Data Source: Recycling Markets (2024)

Figure 5.7: PET Median Weekly Prices, by Region

5.4. Resin (from plastic waste) Manufacturers

Once plastic materials are sorted, they are taken or sold to a recycler, who typically uses mechanical means to produce plastic resin. Mechanical recyclers typically purchase plastic waste materials from sorting facilities at market prices, which were illustrated in Figure 5.5 and Figure 5.6. Mechanical recyclers may compete (directly or indirectly) with primary plastic resin manufacturers when selling their products; however, the prices of resin from recycled plastic is not necessarily directly comparable to that of resin from primary plastic, as recycled plastic typically has higher levels of contaminants, restricting its use for some applications and creating higher costs relative to primary resin for other applications. For instance, Table 5.3 shows the costs for HDPE post-consumer resin compared to primary resin (Resource Recycling 2019). Three of the four post-consumer resins are more expensive than the primary material. Additionally, the supply of recycled plastic is more variable, creating uncertainty in supply quality and availability.

The prices for a selection of common recycled resin types are shown in Table 5.4 and range between $180 per ton and $2120 per ton (Plastic News 2024). Note that the price to purchase recycled resins are often lower than that for similar primary materials; however, as mentioned above, this is not an apples-to-apples comparison due to contamination and other factors for recycled plastic. However, for some applications, such as those that have lower material requirements, using plastic sourced from recycled material may be more cost effective. Thus, the cost effectiveness of using plastic from recycled material depends on the application.

Table 5.3: HDPE Plastic Resin Price per Pound

	Post-Consumer Resin				Primary
	PCR: Color HDPE (color sorted)	PCR: Color HDPE	PCR: Natural HPDE	PCR: Natural HPDE (food grade)	Primary HDPE (Spot price)
Cost to source bales or primary pellets	$0.25	$0.20	$0.20	$0.25	
Handling and transport	$0.16	$0.16	$0.16	$0.16	
Processing and yield loss	$0.14	$0.14	$0.22	$0.22	$0.51
Total	$0.55	$0.50	$0.58	$0.63	$0.51

Data Source: Resource Recycling. (2019).

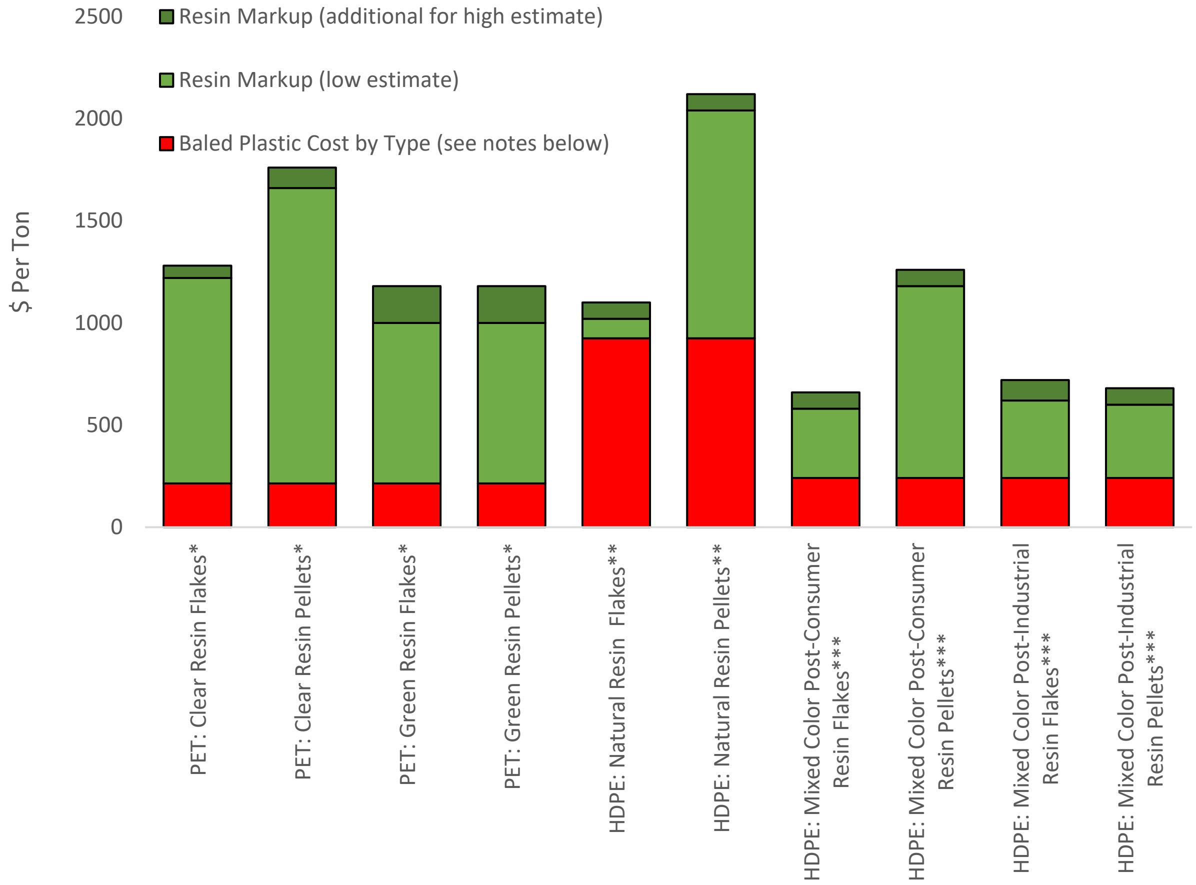
Table 5.4: Recycled Resin Prices ($ per ton), February 5, 2024

	Recycled Plastic		Primary Plastic	
Plastic Type	Low Price	High Price	Low Price	High Price
PET	1000	1760	1380	1720
HDPE	580	2120	1200	1660
LDPE	340	1560	1340	1600
PP	600	760	1260	2180
PVC	500	620	1310	2080
PS	180	1180	2780	3940
PC	1660	1940	-	-
LLDPE	740	780	1140	1780
ABS	1260	1780	2100	3540

Note: See expanded version in Appendix B.
Source: Plastics News (2024)

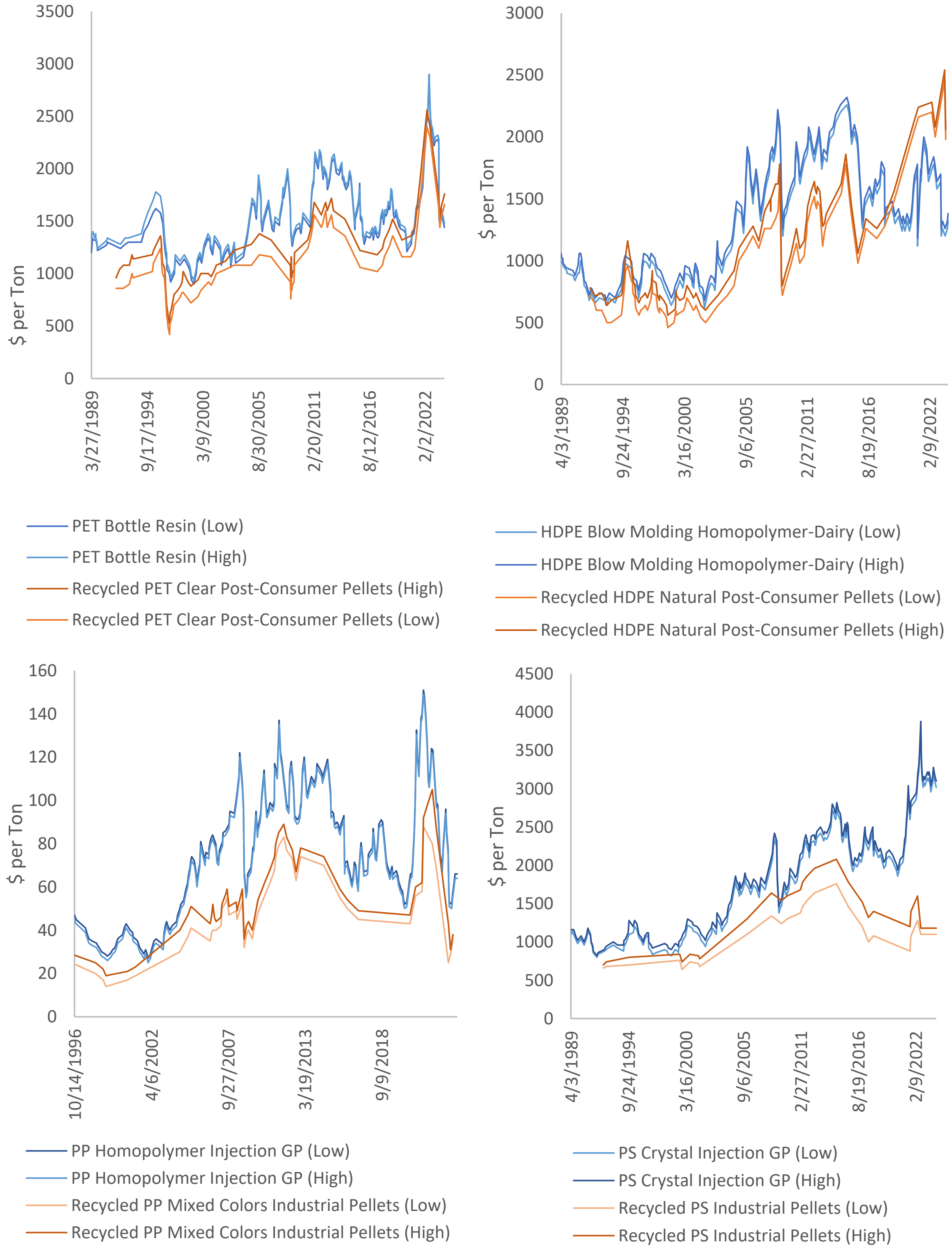
To examine the costs and revenues of recycled resin manufacturers, Figure 5.8 matches baled plastic waste by plastic type with selected plastic resin prices; however, the waste plastic data is at a broader level than the primary resin data. Therefore, it only provides general insights into the relative prices. The green portions of the graph represent the estimated revenue that might exceed the cost of the baled plastic. The other costs, such as processing costs, and any profit would need to come from this portion. Recall from Figure 2.5 that the net income, which is similar to profit, as a percent of shipments for the industry that includes recycled resin manufacturing (NAICS 325991) was lower than that for primary resin and for that of total manufacturing. Also recall that 89.3 % of shipments (i.e., revenue) went toward expenditures. Resin prices seem to be heavily influenced by either market prices of primary plastics or a third factor that affects both primary and recycled plastics (e.g., oil prices), as the prices of primary and recycled plastic tend to correlate (see Figure 5.9). It is important to note that the interval of the collection of observations for the data in Figure 5.9 is intermittent and there are more observations for primary plastic than recycled. Despite the data issues, the correlations are apparent in the graphs. Additionally, as illustrated in Figure 5.10, primary plastic prices tend to follow the patterns of oil and gas prices. Thus, recycled plastic prices may fluctuate independent of the costs of producing them, making profitability difficult. This situation may be exacerbated by oil subsidies in various countries. The linkage between oil prices, primary plastic, and recycled plastic has also been examined more formally such as by Gu et al (2020).

Plastic resin manufacturers that use recycled content need improvements in supply of recycled inputs and higher demand and prices for recycled content in end-use plastic products. As for plastic waste collectors and sorters, input costs could be reduced through greater volumes and certainty in availability of high-quality plastic waste as well as better transparency in waste plastic formulation. Recycled plastic resin demand can be increased through increases in consumer demand for recycled content in end-use products.



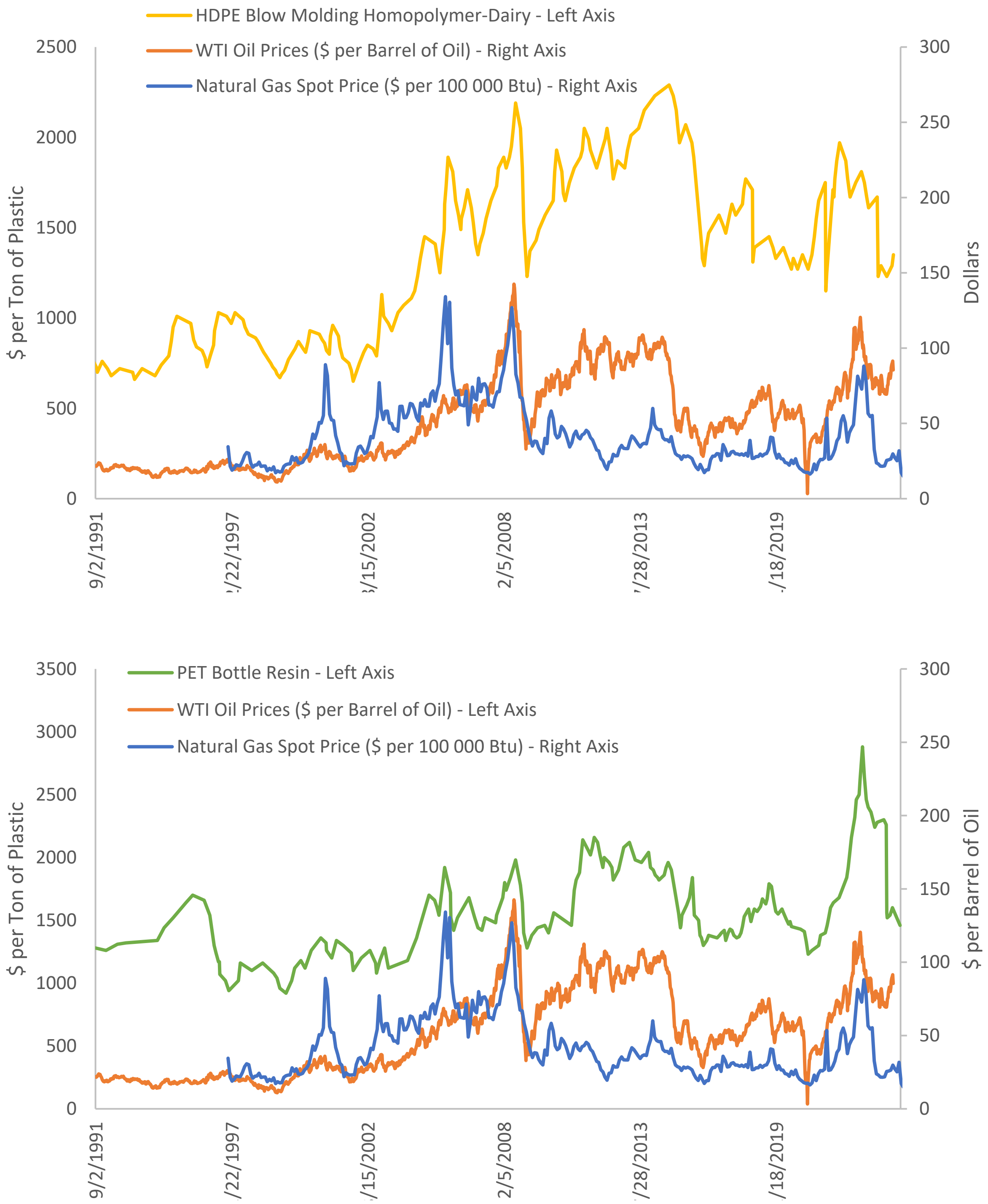
NOTE: Resin Prices are for February 5th, 2024
* Baled plastic cost is the 2023 average of all types of PET
** Baled plastic cost is the 2023 average of natural HDPE
*** Baled plastic cost is the 2023 average of mixed color HDPE
Data sources: Plastics News (2024) and Recycling Markets (2024)

Figure 5.8: Recycled Resin Prices for Select Plastic Types (National Averages)



Data sources: Plastics News (2024) and Recycling Markets (2024)

Figure 5.9: Select Primary and Recycled Plastic Resin Prices (National Average)



Data Source: Recycling Markets (2024), U.S. Energy Information Administration (2023c), U.S. Energy Information Administration (2023d)
Note: Recycled plastics is the average of the high and low values

Figure 5.10: Select Plastic Prices (National Average), Oil Prices (Cushing WTI Spot Price), and Natural Gas Prices (Henry Hub Spot Price)

5.5. Plastic Product Manufacturers

Plastic product manufacturers choose what products to produce (e.g., end-product characteristics) and how to produce those products (e.g., input selection). Input selection includes whether to include recycled resin in the product in place of primary resin. End-product characteristics are met using plastic additives that not only impact the performance of the product during use (e.g., durability), but also the end of use options (e.g., recyclability). Considerations for manufacturer decisions on recycle content and recyclability of their end-use products are discussed below.

5.5.1. Recycled Content

A product manufacturer's decision whether to purchase and use recycled input material is based on a combination of relative impacts on profitability, including input and manufacturing costs, supply chain risks, and revenue implications. As previously discussed, recycled plastic resin may have additional limitations, costs, or risks associated with its use in place of primary resin. Recycled resin may be less expensive, but with lower quality compared to primary material, limiting its use for some applications. Using recycled material may require additional costs for some applications due to the need to remove contaminants. Additionally, the supply of recycled plastics resin is currently limited and has greater availability uncertainty, making it riskier to use recycled resin for manufacturing.

In the cases where additional costs or risks exist, the manufacturer will require additional revenue from their products to maintain the same level of risk-adjusted profitability. This requires the ability to differentiate their product to create a higher consumer's WTP relative to a primary plastic-based product. Creating a higher WTP requires the consumer (1) to be able to accurately identify different characteristics between two products and (2) place a positive value on those characteristics. The latter was discussed in Section 5.2.1.1, which acknowledges that the WTP varies from product to product (e.g., plastic packaging versus durable plastic goods) and consumer to consumer (e.g., environmental preferences).

To differentiate a product, manufacturers need to be able to make legally binding claims of product characteristics (e.g., recycled content) that are clearly interpretable and trusted by consumers. Thus, there must be accepted rules for tracking manufacturing inputs from recycled content to validate such claims. Given the small amounts of mechanically recycled plastic, it is possible that the recycled content is mixed with primary plastic inputs (resin or input to resin production) during the manufacturing process, making it difficult to track which products the recycled content resides and in what quantities.

Determining the amount of recycled content in a product could be difficult due to the nature of plastic manufacturing. A single facility typically manufactures multiple products using many of the same inputs, such as plastic resin. For mechanically recycled plastic resin, physically tracking the amount of recycled content may be difficult if the same resin batch is used to manufacture different products because the recycled plastic resin may get mixed with primary resin. Similarly, chemical recycling leads to inputs for the plastic resin manufacturing process that could be identical to the primary counterpart, making it nearly impossible to track the recycled input through the manufacturing product.

Such claims require an accepted chain of custody (CoC) approach. CoC is used to create transparency and trust through a supply chain regarding properties of products that are difficult or impossible to distinguish (e.g., amount of recycled content) compared to their alternative product. There are five CoC models, with different strengths and weaknesses, that can be considered for plastic product claims. Beers et al. (2022) defines each as (taken from ISO (2020)):

- **Identity preserved** - inputs originate from a single source and the product is kept physically separated and its characteristics are maintained throughout the supply chain (e.g., specific product from a specific farm)
- **Segregated** - aggregation of products of identical origin or produced according to the same standards (e.g., certified organic food)
- **Controlled blend** - products with a set of specified characteristics are mixed according to certain criteria with products without those characteristics (e.g., single batch of a product)
- **Mass balance** - products with specified characteristics are mixed with products without all of the same characteristics, resulting in a claim on a part of the output, proportional to the input (e.g., Fair Trade tea, cocoa, or sugar)
- **Book and claim** – a fully administrative model applied when there is not a physical connection between the certified supply and the final product (e.g., solar renewable electricity credits)

For additional details on different CoC models, see Beers et al (2022) and ISO (2020).

Several factors about the nature and current state of plastic manufacturing limits the potential CoC models that can realistically be successfully implemented. First, the amount of recycled plastic content (inputs or resin) available is small relative to total plastic demand. Second, recycled plastic resin or inputs to the plastic resin manufacturing process of the same quality as those made from primary inputs are indistinguishable once they have been mixed, making it difficult to trace recycled resin from input to end-product. Third, a variety of plastic products with different input ratios are manufactured within the same facility using the same input stock, each of which has a potentially different value to using recycled content. The current lack of economies of scale makes it difficult to make identity preserved or segregated CoC models feasible. The difficulty in tracking inputs through the manufacturing process makes the controlled blend model difficult to implement. Given the non-uniformity of plastic products, the book and claim model does not appear applicable because, unlike electricity where units are equivalent (i.e., 1 kWh = 1 kWh), one unit of one plastic is not equivalent to another if the input formula is not identical. What remains as a feasible option for the current plastics sector is the mass balance model, which per Beers et al. (2022), mass balance accounting, or MBA, “is best suited when the volumes or values of goods or materials from desired sources are too low to be shipped, stored, or processed separately or the technical process does not allow for differentiation.” Beers et al. (2022) also provides an excellent summary of how MBA can be applied to recycled plastic resin use in plastics manufacturing:

> “MBA allows for integration of feedstock from recycled plastic sources along with conventional fossil feedstock. To account for recycling, credits are produced when recycled raw materials are consumed and based on the mass entering the system. Credits are then decoupled during the production process (e.g.,

> undergoing steam cracking) and reassigned to physical materials and applied to outgoing products. Credits are managed using a digital inventory, and conversion factors are used to reflect actual operating yields, losses, and bills of materials. As a result, credits can be based on different units depending on the material and process (e.g., mass, energy, or greenhouse gas (GHG) equivalents)."

MBA rules can be designed to change over time, providing more flexible implementation initially by allowing the use of recycled content credits to be applied to those products that show the greatest consumer WTP to start to encourage more use of recycled plastics, and then becoming increasingly restrictive over time as the market for recycled plastic grows and matures. This same flexibility creates concerns about how to initially apply the approach, including the rules on system boundary (e.g., end-product, geographical), units to use for the credits (e.g., mass, energy value), connectivity/traceability (e.g., trace molecules through manufacturing), allocation (e.g., proportional versus non-proportional), accounting period (e.g., continuous, one-year), and recycled content to allow (post-consumer, post-industrial), which could determine consumer trust in and acceptance of such claims (Beers et al 2022).

Figure 5.11 shows an example of how MBA can be applied to a facility that is using both recycled plastic resin (A – yellow) and primary plastic resin (B – red) to produce three unique products C, D, and E. There are three potential allocation methods considered (discussed from left to right), including assumptions on recycled inputs lost in the manufacturing process (loss adjustments). First, there is equal allocation of recycled content where every product manufactured is allocated the same percentage of recycled content. Second, there is free allocation of recycled content and loss adjustments (represented by *) applied to products without the recycled content claim. Third, there is free allocation of recycled content with loss adjustments applied to products without the recycled content claim. Depending on which approach is selected, the resulting product claims would be significantly different. In reality, the end location of the recycled plastic resin is unknown and the free allocation methods may be viewed by some consumers as "greenwashing." Thus, consideration must be placed on the allocation rules, whether it is free allocation, equal allocation, or some allocation combination (including loss adjustments) as well as what aggregation level (e.g., batch, facility, or multi-facility) and timescale to specify the allocation to get buy-in from consumers. The same approach and concerns can be applied to chemically recycled and primary inputs to the plastic resin manufacturing process.

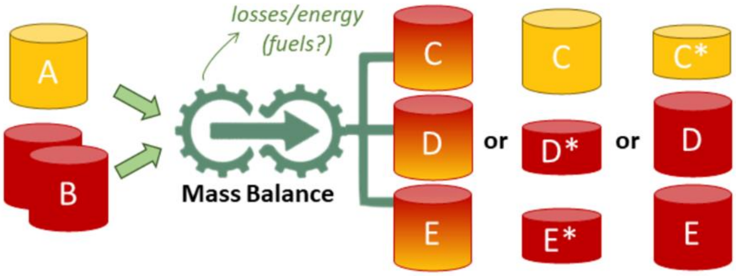


Figure 5.11: Mass Balancing Chain of Custody Model (Beers et al. 2022)

Given the potential complexities of an MBA model, it is important to ensure consumer acceptance of the MBA approach implemented and resulting certifications. Consumer trust in and use of certifications could, in turn, incentivize manufacturer use of recycled plastics and increase the viable market for plastics with recycled content. Thus, consumers need to understand and trust the certification process. There are already numerous certification and standards that apply MBA to plastics, including ISCC Plus, Standard for Advanced Products, Ecoloop, REDcert2, UL 2809, Recycled Material Standard (Beers et al 2022). Although some groups continue to have concerns regarding the MBA approach (Zero Waste Europe 2021) that will need to be addressed to ensure wide acceptance. There is a clear need for more research to understand consumer and consumer protection group perspectives on MBA to ensure acceptance.

MBA is seen by many as a critical enabler for chemical recycling of plastics with it being supported by the American Chemistry Council and Association of Plastic Recyclers; however, the literature and discussions on the benefits of MBA for mechanical recycling is limited (RMS 2022). More research is needed in understanding how MBA has been applied to existing markets, best practices and lessons learned from those markets, and implications of applying an MBA approach to recycled content in end-use plastics, both for mechanical recycling and chemical recycling. As was discussed in Section 3.1.2, the dynamics between mechanical recycling and chemical recycling is currently unknown, with the potential for chemical recycling to compete with instead of being a complement to mechanical recycling both for feedstock inputs and to end-use manufacturers desiring recycled content. It is also important to recall that chemical recycling is, typically, proposed as a supplement to mechanical recycling, as it tends to have higher environmental impacts. It can be problematic if chemical recycling supplants or prevents growth in mechanical recycling. Research is needed to understand how implementing the MBA approach will impact this relationship, positively or negatively, to avoid unintended consequences.

5.5.2. Recyclability

Although the focus has been on the use of recycled content, similar manufacturer concerns exist for designing products for recyclability. As has been discussed, not all plastic is recyclable. Also, not all plastic that is recyclable can be recycled through every regional MSW system. Increasing plastic recycling could be accomplished through both increasing the recyclability of plastic waste and the ease of recycling. Both of which require changing manufacturer incentives.

Although resources exist to assist product manufacturers in designing more recyclable products (APR 2024), a product manufacturer’s decision whether to design their product to be recyclable is typically based on a combination of relative impacts on profitability, including input and manufacturing costs, product performance, and revenue implications. As previously discussed, each plastic product is designed to meet a specific purpose that requires different formulations for different products, including different types of additives. Additives provide a range of valued characteristics from formability to durability. As was highlighted previously, plastic simplification is one way to increase the recyclability of plastics, which primarily includes removing additives where possible and providing transparency to those additives when they cannot be removed without impacted product quality. Some additives (e.g., colorants) provide minimal to no additional product performance while others may provide necessary characteristics for the products purpose (e.g., flame retardants).

For a manufacturer to decide to simplify their plastic products, it must determine what additives can be removed, what if any impact that will have on the product quality and performance, and what the impact on profitability will be relative to the status quo product. The ability for the manufacturer to differentiate their product as recyclable or more easily recyclable to ensure the same or higher WTP from the consumer may provide the necessary incentives to encourage more product simplification. As in the case of recycled content, this requires the ability to differentiate their product relative to a primary plastic-based product. Creating a higher WTP requires the consumer (1) to be able to accurately identify different characteristics between in two products and (2) place a positive value on those characteristics. The latter was discussed in Section 5.2.1.1, which acknowledges that the WTP varies from product to product (e.g., plastic packaging versus durable plastic goods) and consumer to consumer (e.g., environmental preferences).

Currently, consumers have limited information on the recyclability of a given plastic product. Better metric(s) and labeling are necessary because consumers find the current “recycling arrow” and numbering system confusing and it does not provide any guidance on what plastic is recyclable (Che 2023). For example, a regionalized recyclability index could provide consumers with a better understanding of whether a plastic is recyclable in their area through their MSW system. It is important to note that consumer WTP for recyclability creates incentives that reach into the earlier part of the supply chain than that of WTP for recycled content in a product, as it affects the types of plastics that are made from primary material. That is, consumer WTP for recyclable materials could potentially impact the number/types of plastics produced along with the additives, which has been identified as a major challenge for the success of plastics recycling. The many types of plastics and their additives results in diminishing economies of scale, making it uneconomical to recycle some plastics.

5.6. Communities and Society

The last set of stakeholders are communities and society. These stakeholders experience the cost burden of negative externalities and bear any aid provided for recycling plastics, including collection and sorting of waste plastics, standards and technology investment, and research into the effect of plastic waste. Many of these investments are meant to shift the supply and demand curves for recycled and primary plastic, as shown in Figure 5.3. For instance, many collection and sorting programs are publicly funded, which lowers the costs of recycling for the private sector and shifts the supply curve in Figure 5.3 to the right for recyclables, including plastic waste. Governments also set policy and regulations on industry that can impact incentives, which were discussed in Section 4.

One significant challenge for setting policy is that much of society has limited information, knowledge, or expertise on plastics manufacturing, consumer willingness to pay, the full effects of plastic waste, measuring environmental impact, the source of plastic waste, and plastic industry economics and business models. As a result, many potentially inefficient solutions might be implemented at a high cost to society, resulting in less plastic being recycled and more environmental impact than might otherwise have occurred. Communities need reliable resources to assist in making policy decisions that impact the plastics recycling economy.

5.7. Stakeholder Needs to Address Challenges

The challenges identified in this study for each stakeholder revolve around making easier and better decisions throughout the plastics supply loop with better, trusted information and/or making it cheaper and more reliable to collect and use recycled / recyclable plastic material. The needs highlighted for each stakeholder are as follows:

- Resin manufacturers need…
    - Lower cost, higher quality, and increased certainty for availability of recycled plastic
- Product manufacturers need…
    - Ability to differentiate their products with recycled and/or recyclable content
    - Greater transparency in what is in plastic resin/products
- End users need…
    - Better, trusted information on recycled content in and recyclability of plastics products
    - Better understanding of and more trusted information on the trade-offs between products
    - More access to and wider acceptance of different plastics in recycling programs
- Plastic waste collectors and sorters need…
    - Increase in the amount and quality of plastic waste that is collected
    - Increase the ability to better sort plastic waste
- Community/society needs…
    - More education and awareness of effective plastic waste reduction and recycling policies
    - Potential associated economic, environmental, and societal trade-offs of those policies

Given the lack of progress in plastic recycling, there is a need for changes to the plastics recycling ecosystem that incentivize (1) the use of more recycled and recyclable plastic, (2) more and easier collection, (3) more and easier sorting, and (4) recycling a wider variety of plastic types. New technologies for sorting and innovation in plastic manufacturing and recycling combined with insights into consumer perspectives and behavior will be needed to make significant improvements to plastic recycling rates.

5.7.1. Differentiated Product Market

Many of the necessary incentive changes can be addressed, at least in part, by creating an acceptable differentiated market for products that are made from recycled content and/or recyclable materials because it will provide the consumer with better information about their purchases, both to create demand for these products and help consumers improve their recycling decisions. Additionally, this will incentivize manufacturers to use more recycled/recyclable content where there is consumer demand. As was discussed in Section 5.2.1, consumer WTP may be higher or lower for recycled content or recyclable products depending on consumer preferences and product application.

Whether creating a differentiated market will encourage more plastic recycling will depend on the relationship between the current market price and the WTP for the primary-based/non-recyclable product (V) and the recycled/recyclable product (R).

Table 5.5 summarizes market opportunities and challenges for the introduction of circular products (e.g., recycled, recyclable, reused) to existing or new markets by comparing (1) consumers' willingness to pay (WTP) for primary-sourced (V) and circular (R) goods with (2) producers' production costs (C) for each, relative to the current (or expected) market price (P).

Three considerations are evaluated given specific market conditions. The first consideration is whether a market would currently exist for a primary-sourced product (i.e., is the price consumers would be willing to pay greater than the production costs?). The second consideration is, regardless of whether a market currently exists, could the introduction of a circular alternative be supported in the market (i.e., do prices exceed production costs?). The third consideration is whether a production cost reduction, in the production of circular goods (e.g., through increased production efficiency), would be needed to create a market for it. Whether a market could support the introduction of a circular good, or if a cost reduction is needed, is dependent on consumer awareness and preferences.

Two consumer information sets are considered—full information and no information—regarding the general awareness of the circular attributes of the product (e.g., if a product is made of recycled content). Full information awareness is further differentiated between consumers who express a positive or negative view of the circular attribute. In the case where consumers prefer the circular product and would be willing to pay a price premium, a fourth consideration is included to identify if a price premium could be captured through product differentiation (i.e., marketing it as a sustainable alternative in an existing market) or product attribution (i.e., marketing it as a sustainable product to develop a new market).

In the case of when consumers have no information about the circularity of a product (e.g., if it is not labeled), the WTP for the circular good is assumed to be the same as the primary-sourced good—they are viewed as indistinguishable products. When consumers are aware of circular attributes of a good, and those are viewed positively (negatively), the WTP for the circular good is assumed higher (lower) than the primary-sourced offering.

Example 1: Preference for Circular Products

In the scenario where a circular alternative is introduced to an existing market ($P>C(V)$), the cost of production of the circular alternative is greater than for the primary-sourced product ($C(R)>C(V)$), and some consumers prefer a sustainable product ($WTP(R)>WTP(V)$), the viability of the circular product depends on the current market price and whether the circular attributes could be marketed, through product differentiation, in a way to elicit a price premium to at least offset the increased production costs or if greater efficiencies could be gained through production changes (e.g., input costs) to reduce production costs.

Example 2: No Preference for Circular Products or No Awareness of Circular Attributes
In the scenario when a circular alternative is introduced to an existing market (P>C(V)), the cost of production of the circular alternative is greater than for the primary-sourced product (C(R)>C(V)), and consumers generally have no preference for sustainable products or they have no awareness regarding the sustainability of a product (WTP(R)=WTP(V)), the viability of the circular product depends the ability of a producer to sell a product with lower per-unit profitability or ability to reduce production costs.

Example 3: Negative Preference for Circular Products
In the scenario when a circular alternative is introduced to an existing market (P>C(V)), the cost of production of the circular alternative is greater than for the primary-sourced product (C(R)>C(V)), and consumers generally prefer a primary-sourced product over a sustainable alternative (WTP(R)<WTP(V)), the viability of the circular product depends on the ability of producers to offer the product at a reduced cost, which might require production costs reductions to offset the price discounts or quality assurances (e.g., warranties) needed to induce consumer purchases.

Example 4: New Markets for Circular Products
The first three examples focused on circular products entering an existing product market. There could be instances where primary-sourced products are too expensive to produce, or the circularity attributes are required to develop new markets. In such cases the market price is not yet defined and it would require a better understanding of consumer WTP and the cost structure to evaluate the market support.

5.7.2. Research Needs for a Differentiated Market

Such a differentiated market requires product claims to be acceptable to society. Manufacturers must be willing to make legally binding claims while consumers must trust those claims to be accurate and verified. Research is needed to better understand (1) consumers' willingness-to-pay (WTP) for recycled content / recyclable products based on product claims, (2) the form in which those product claims should be provided to consumers, and (3) the validation and transparency needs of those claims for consumers to trust and use them for decision-making.

Gaining this insight into consumer WTP can be done through both stated preferences and revealed preferences. Revealed preferences can be obtained from market prices of currently differentiated goods (labels/claims about unique characteristics such as recycled content, recyclability, bio-based content, sustainable materials or processes). Research might focus on determining if the premiums differ by product class (e.g., shoes, single use packaging, flooring) or whether the value is non-linear to the type of claim or amount of recycled content.

Research can also assess the acceptance of how the claims are validated, including those for the recycled content in a product and the recyclability of a product. For example, consumers may view different CoC methods, such as MBA, as acceptable for some products but not others.

Table 5.5: Market opportunities and challenges for circular products by WTP and price

			Consumer						
			Full Information (Negative)		***No Information (Baseline)***		***Full Information (Positive)***		
			P = WTP(V) > WTP (R)		*P = WTP(V) = WTP (R)*		*P = WTP(V) < WTP (R)*		
Producer	**C(V) > C(R)**	Existing Market?	Could Current Market Support?	Cost Reduction Needed?	Could Current Market Support?	Cost Reduction Needed?	Could Current Market Support?	Price Premium Possibility?	Cost Reduction Needed?
	P>C(V)>C(R)	Yes	Maybe	Maybe	Yes	No	Yes	Yes (Differentiation)	No
	C(V)>P>C(R)	No	Maybe	Maybe	Yes	No	Maybe	Yes (Attribution)	No
	C(V)>C(R)>P	No	No	Yes	No	Yes	Maybe	Yes (Attribution)	Maybe
	C(V) = C(R)								
	P>C(V)=C(R)	Yes	Maybe	Maybe	Yes	No	Yes	Yes (Differentiation)	No
	C(V)=C(R)>P	No	No	Yes	No	Yes	Maybe	Yes (Attribution)	Maybe
	C(V) < C(R)								
	P<C(V)<C(R)	No	No	Yes	No	Yes	Maybe	Yes (Attribution)	Maybe
	C(V)<P<C(R)	Yes	No	Yes	No	Yes	Maybe	Yes (Differentiation)	Maybe
	C(V)<C(R)<P	Yes	Maybe	Maybe	Yes	No	Maybe	Yes (Differentiation)	No

P is the market price of a primary-based good, *C(V)* is the production cost of a circular good, *C(R)* is the production cost of a primary-based good, *WTP(V)* is the willingness-to-pay for a primary-based good, and *WTP(R)* is the willingness-to-pay for a circular good.

MBA is used successfully in other industries (e.g., lumber, coffee, sugar, cocoa, and biofuel); however, it needs to be determined if and how it can be applied to plastics recycling, both mechanical and chemical. Implementation of different chain of custody schemes could lead to different recycling rates, but also different environmental impacts (such as GHG emissions) due to several factors including the dynamics between mechanical recycling to chemical recycling, whether that is competition for plastic waste feedstocks or to inputs to end-use product manufacturers. Determining how these quantifiable impacts change under different conditions is a research need.

There is a lack of research that considers both recycled content and recyclability of products. Research could assess how consumers value different combinations of circularity characteristics (e.g., recycled content but not recyclable versus primary content but recyclable) and the outcome of these valuations on the recycling of plastics. Additionally, a metric could be developed to combine the circularity of a product that considers both the inputs (e.g., recycled content) and end-of-life (recyclable). Such a circularity metric could provide a more holistic assessment of the performance of products such as plastics.

6. Summary

This report examined U.S. plastics recycling and methods for increasing the plastics recycling rate in the U.S. In 2020, U.S. plastics manufacturing shipments were $284.4 billion with value added of $131.4 billion. The economic activity is also associated with 12.2 % of municipal solid waste (as of 2018) and 4.2 % of the U.S. economy's environmental impact per analysis using environmentally extended input-output analysis (as of 2020). Currently, 8.7 % of plastics are recycled in the U.S. with 15.8 % being combusted with energy recovery and 75.6 % being landfilled. This low recycling rate provides an opportunity to increase plastic recycling and use of recycled content over upcoming decades to account for 60 % of the source material (Beers et al 2022) and generate significant economic value ($2 billion to $4 billion) while also reducing the environmental impacts and preserving resources for future generations. However, significant improvements are needed throughout the plastic supply loop to accomplish such an aggressive goal.

This study summarizes the current state of the U.S. plastics manufacturing, usage, and waste handling, discusses characteristics that influence the effectiveness of recycling programs, examines the potential for chemical recycling, assesses the incentives, barriers, and challenges facing each stakeholder in the U.S. plastics economy, and provides some future research opportunities to address stakeholder needs. One focus of this study is on single use plastics because packaging accounts for 44.8 % of plastic production and is the largest use category for numerous types of plastic. Additionally, packaging's short product life makes it vital to improve its circularity.

The conventional plastic supply chain is largely centralized, driven by the inputs into the manufacturing process. Primary plastic's primary input material is fossil fuels (crude oil and/or natural gas), accounting for 17.6 % of the plastic and synthetic rubber manufacturing supply chain value added. Oil and gas production only occurs in certain regions of the country, with refining and processing plants being even more concentrated. Even plastic resin manufacturers are primarily located in a few areas of the country.

Conversely, the recycled plastics supply chain is decentralized, with the primary input (plastic waste) spread out across the entire U.S. correlated with population density. The plastic waste must be collected broadly from addresses in the U.S., transported to MRFs for sorting, and then sent to plastic recycling facilities, which are limited in their locations across the country. At which point, the recycled plastic is provided to manufacturers. The decentralized nature of recycled plastic and the range of plastic formulation (60 common plastic types with many, often unknown, additives) and product applications creates logistical and economic barriers that can hinder recycled plastics competitiveness with primary plastic. For example, approximately 15 % of plastic waste is collected, but 7.9 % is recycled due to losses during sorting and processing as well as through mismanagement. Of this 7.9 %, 38.5 % is exported to other countries, some of which is going to countries with high levels of plastic waste mismanagement.

The mechanical recycling process tends to degrade plastic quality, leading to lower quality plastic each time it is recycled. One potential solution is chemical recycling, which uses methods such as solvents, heat, and enzymes to break down waste plastic into their chemical building blocks (i.e., molecules). The relative economic and environmental performance of chemical recycling is still unclear due to limited data or full-scale operations of such facilities. There are conflicting results in the literature on the economic and environmental performance. Some research suggests there are few benefits while other research suggests there are significant benefits when compared to using primary plastic. The most well-established chemical recycling approach is pyrolysis that generates pyrolysis oil that is comparable to conventional diesel fuel. The pyrolysis oil market as a percent of the total oil market is less than 0.01 %; thus, the economic viability of this market for producing plastic products is not well established. Pyrolysis oil has a higher level of contaminants than fossil-based feedstocks for steam crackers and is treated as a contaminant, with expectations that pyrolysis oil can only make up approximately 2 % to 5 % of the oil being processed before impacting product quality. Other chemical recycling processes have varying economic and environmental performance, with research generally finding that chemically recycled plastic often performs better than primary plastic, but worse than mechanically recycled plastic. Although, due to the lack of information and early stage of development of some of these processes, the underlying assumptions selected can have a significant impact on the relative performance. Thus, chemical recycling is best used complementary to mechanical recycling, targeting lower quality plastic waste feedstocks that cannot be mechanically recycled, as one of a suite of solutions needed to significantly increase plastic recycling.

Programs with successful recycling vary by country, state, and region. States with higher recycling rates tend to have bottle deposit laws. They also tend to have recycling legislation that reward recycling, require/enforce recycling, and/or ban certain types of plastic. Likewise, countries with higher recycling rates tend to have recycling legislation that reward recycling, require/enforce recycling, connect the costs/responsibilities of recycling to manufacturers (often referred to as extended producer responsibility), and/or ban certain types of plastic. In the U.S., the bottle deposit systems might be considered an example of extended producer responsibility. The specifics for effective extended producer responsibility programs are not closely examined in this report; however, evidence from the U.S. and Europe suggests that this may be an effective means for increasing recycling rates. There is a need to better understand the success and design of extended producer responsibility. Additional policy mechanisms have been implemented in other countries, particularly in Europe. The design and effectiveness of these programs is only generally discussed in this report. Additional research is needed to understand the ideal design of such programs, particularly as they apply to packaging, which is the largest application for plastic. There is likely a need for standardized materials and end products, data, and tracking for packaging recycling. Currently, the plastics used are numerous with a variety of additives. Cost effective package material recycling may require moving from small streams of plastic to large, aggregated ones with additional incentives created through extended producer responsibility.

Each of the key stakeholders in the plastics recycling economy face challenges to recycling and the use of recycled plastic in new products. Plastic resin manufacturers face challenging economics as well as reliability concerns, both in terms of quality and quantity availability, of using waste plastic as a feedstock. Plastic product manufacturers experience a lack of a reliable, high volume recycled plastic resin as well as difficulty extracting additional willingness-to-pay (WTP) from consumers for those products that use recycled/recyclable content. End users face barriers in both selecting and recycling plastic. Consumers have minimal to no reliable information on the recycled content or the recyclability of those products. Plastic waste collectors and sorters deal with the decentralization and availability uncertainty of the waste plastic feedstock as well as the complexities of the wide range of plastic materials, many of which are not currently recyclable. Communities and society are challenged with a lack of information and understanding of the most effective policies to improve their plastics recycling economy and the trade-offs that can occur from enacting such policies.

Increasing plastic waste recycling will require improvements throughout the plastics recycling economy. Lower cost, higher quality, and increased certainty for availability of recycled plastic would make recycled plastic more appealing to resin manufacturers. Product manufacturers will demand more recycled plastic resins and/or recyclable plastic resins if they have greater transparency in what is in plastic resin they are purchasing as well as an ability to increase their profits through trusted product claims that can differentiate their products with recycled and/or recyclable content. For end users to demand more recycled/recyclable products and increase their recycling of waste plastics, they require better, trusted information on recycled content in and recyclability of plastic products (i.e., product labels with clear metrics), better understanding of and more trusted information on the trade-offs between products, and more access to and wider acceptance of different plastics in recycling programs. To increase the amount of plastic waste recycled, collectors and sorters require an increased volume and quality of plastic waste collected as well as an improved ability to sort plastic waste. Finally, communities/society needs more education and awareness of effective plastic waste reduction, collection, and recycling policies that can be implemented for their circumstances and any potential economic, environmental, and societal trade-offs faced by implementing these policies.

The plastic recycling economy requires advancements in technology and changes to incentives that will lead to (1) increased use of recycled and recyclable plastic, (2) more and easier collection, (3) more and easier sorting, and (4) recycling a wider variety of plastic types. Technological innovations are needed throughout each step in the process, such as plastic formulation simplification and transparency, advanced collection and sorting equipment, and scaling up of chemical recycling technologies. Many of the necessary incentive changes can be addressed, at least in part, by creating a differentiated market for products that are made from recycled content and/or recyclable because it will provide the consumer with better information about their purchases, both to create demand for these products and help consumers improve their recycling decisions. Additionally, this will incentivize manufacturers to use more recycled/recyclable content where there is consumer demand.

Such a differentiated market requires product claims to be acceptable to all stakeholders. Manufacturers must be able to make legally binding claims that consumers can use in decision-making. Research is needed to better understand the consumer’s WTP for recycled content / recyclable products based on product claims, the form in which those product claims should be provided, and the transparency in the validation of those claims such that they are trusted and used for decision-making.

Research is needed to determine consumer WTP for differentiated plastic goods (i.e., recycled content, recyclable content, or both), what form in which consumers prefer the differentiation to be provided (i.e., labeling and metrics), and consumer perspectives on acceptability of the methodology implemented to validate such claims. Mass balance accounting (MBA) has been used in other industries and has been suggested as the appropriate chain of custody (CoC) method to provide the necessary flexibility to encourage transparent claims for the plastics industry, but it is yet to be determined how effective MBA has been under these current implementations (particularly relative to alternative CoC models) and whether customers will accept this approach and internalize such information that is based on the MBA method. Given the need to improve circularity at each step in the supply loop in the plastic recycling economy, it is also necessary to develop metrics that are holistic. Such metrics would need to combine recyclable and recycled content characteristics for a given product into a single circularity metric that consumers can easily understand.

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Appendix A. Economic Input-Output Analysis and Environmental Impact

A discussion on the methods for examining manufacturing costs is presented in NIST AMS 100-18, Thomas (2019), and Thomas and Kandaswamy (2017; Thomas 2018c; Thomas 2019b). The following is drawn from these publications.

Input-Output Analysis for BEA Data: The Manufacturing Cost Guide utilizes input-output analysis, which develops a total requirements matrix that when multiplied by a vector of final demands equals the output needed for production. The total requirements matrix is developed using the methods outlined in Horowitz and Planting (2009):

$$X = W(I - BW)^{-1} * Y \tag{A.1}$$

Where:
$X =$ Vector of output required to produce final demand
$Y =$ Vector of final demand, as defined in the BEA input-output data
$W = (I - \hat{p})D$
$B = U\hat{g}^{-1}$
$I =$ Identity matrix
$D = V\hat{q}^{-1}$
$p =$ "A column vector in which each entry shows the ratio of the value of scrap produced in each industry to the industry's total output."
$U =$ "Intermediate portion of the use matrix in which the column shows for a given industry the amount of each commodity it uses—including noncomparable imports, scrap, and used and secondhand goods. This is a commodity-by-industry matrix."
$V =$ "Make matrix, in which the column shows for a given commodity the amount produced in each industry. This is an industry-by-commodity matrix. V has columns showing only zero entries for noncomparable imports and for scrap."
$g =$ "A column vector in which each entry shows the total amount of each industry's output, including its production of scrap. It is an industry-by-one vector."
$q =$ "A column vector in which each entry shows the total amount of the output of a commodity. It is a commodity-by-one vector."
$\widehat{\ }$ "A symbol that when placed over a vector indicates a square matrix in which the elements of the vector appear on the main diagonal and zeros elsewhere."

In Equation A.1, a total requirements matrix $W(I - BW)^{-1}$ is multiplied by a vector of final demand for commodities Y to estimate the total output X. The total requirements matrix provided by the BEA was used in this analysis. All variables in Equation A.1 have known values in the input-output data. The output X required to produce an alternate level of final demand can be calculated by altering the final demand vector from the actual final demand Y in the input-output data to Y'. For the Manufacturing Cost Guide, Y' has the sum of the final demand and intermediate use for the commodities selected by the user. If the user selects multiple industries, the overlapping intermediate uses are subtracted from Y'.

Environmental Impact Categories: The TRACI 2 impact categories are each an aggregation of multiple emissions converted to a common physical unit. For example, the global warming impact category includes impacts of many pollutants, such as carbon dioxide (CO_2), methane (CH_4), Nitrous Oxide (NO_X), and fluorinated gases, which are converted to their carbon dioxide equivalent (CO_2e) impact and aggregated to estimate the total impact for that impact category. The environmental impacts are measured in terms of the common physical unit per dollar of output. The impact can be calculated by multiplying the output in the input-output analysis by the impact categories. One should note that when examining manufacturing activities, these impacts represent the environmental impact resulting from the production of goods and services within the economy. They do not include impacts due to consumer use and end-of-life waste streams.

Impact Category Weights: Having 12 impact categories makes it difficult to rank industry environmental activity; therefore, the 12 impact categories have been combined into one using the Analytical Hierarchy Process (AHP). AHP is a mathematical method for developing weights using normalized eigenvalues. It involves making pairwise comparisons of competing items. The weights used in this paper were developed for the BEES software and can be seen in Table 6.1 (Lippiatt 2010). This paper uses 12 of the 13 impact categories for which weights were developed. Indoor Air Quality (IAQ) is excluded because it is more applicable to the design of buildings and ventilation systems rather than to manufacturing activities. The weight of IAQ is proportionally allocated to the other 12 categories. The final metric for each industry or industry/commodity combination is the proportion of the total impact from assembly-centric products. The percent of environmental impacts, based on the weights, are calculated using the following equation:

$$
\begin{aligned}
Env_{z,Y'} = {} & \frac{x_{z,Y'} * GWP_z}{\sum_{i=1}^{n} x_{i,Y'} * GWP_i} * 0.30 + \frac{x_{z,Y'} * Acid_z}{\sum_{i=1}^{n} x_{i,Y'} * Acid_i} * 0.03 + \frac{x_{z,Y'} * HHA_z}{\sum_{i=1}^{n} x_{i,Y'} * HHA_i} * 0.09 \\
& + \frac{x_{z,Y'} * Eut_z}{\sum_{i=1}^{n} x_{i,Y'} * Eut_i} * 0.06 + \frac{x_{z,Y'} * OD_z}{\sum_{i=1}^{n} x_{i,Y'} * OD_i} * 0.02 + \frac{x_{z,Y'} * Sm_z}{\sum_{i=1}^{n} x_{i,Y'} * Sm_i} * 0.04 \\
& + \frac{x_{z,Y'} * Eco_z}{\sum_{i=1}^{n} x_{i,Y'} * Eco_i} * 0.07 + \frac{x_{z,Y'} * HHC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHC_i} * 0.08 + \frac{x_{z,Y'} * HHNC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHNC_i} \\
& * 0.05 + \frac{x_{z,Y'} * PE_z}{\sum_{i=1}^{n} x_{i,Y'} * PE_i} * 0.10 + \frac{x_{z,Y'} * LU_z}{\sum_{i=1}^{n} x_{i,Y'} * LU_i} * 0.06 + \frac{x_{z,Y'} * WC_z}{\sum_{i=1}^{n} x_{i,Y'} * WC_i} \\
& * 0.08
\end{aligned}
\tag{A.2}
$$

Where
$Env_{z,Y'}$ = Environmental impact from industry z for final demand Y'
GWP_z = Global warming potential per dollar of output for industry z
$Acid_z$ = Acidification per dollar of output for industry z
HHA_z = Human health –criteria air pollutants – per dollar of output for industry z
Eut_z = Eutrophication per dollar of output for industry z

OD_z = Ozone depletion per dollar of output for industry z
Sm_z = Smog per dollar of output for industry z
Eco_z = Ecotoxicity per dollar of output for industry z
HHC_z = Human health – carcinogens – per dollar of output for industry z
$HHNC_z$ = Human health – non-carcinogen – per dollar of output for industry z
PE_z = Primary energy consumption per dollar of output for industry z
LU_z = Land use per dollar of output for industry z
WC_z = Water consumption per dollar of output for industry z
$x_{z,Y'}$ = Output for industry z with final demand Y'

Table 6.1: Environmental Impact Categories and Weights for Assessing Impact

Items to be measured	Units	Weights
Global Warming Potential	kg CO_2 eq	0.30
Acidification	H^+ moles eq	0.03
Human Health- Criteria Air Pollutants	kg PM_{10} eq	0.09
Eutrophication	kg N eq	0.06
Ozone Depletion	kg CFC-11 eq	0.02
Smog	kg O_3 eq	0.04
Ecotoxicity	CTUe	0.07
Human Health - Carcinogens	CTUHcan	0.08
Human Health – Non- Carcinogens	CTUHnoncan	0.05
Primary Energy Consumption	thousand BTU	0.10
Land Use	acre	0.06
Water Consumption	kg	0.08

Value Added: The total requirements matrix $W(I - BW)^{-1}$ from Equation A.1, which shows the total output required to meet a given level of final demand, is multiplied by final demand in the input-output data to estimate the total output. As mentioned previously, the output required to produce a particular level of final demand can be calculated by altering final demand to Y'. For the Manufacturing Cost Guide, Y' equals the sum of final demand and intermediate uses for those NAICS codes (or ISIC codes) selected by the user. If the user selects multiple industries, the overlapping intermediate uses are subtracted from Y'.

Value added is calculated by assuming the proportion of output needed to produce a commodity is the same proportion of value added, which is consistent with methods proposed by Miller (2009). The proportions calculated using the input-output analysis are then multiplied by the value added:

$$VA_{z,Y',2012} = \frac{x_{z,Y',2012}}{x_{z,2012}} * VA_{z,2012} \tag{A.3}$$

Where

$VA_{z,Y',2012}$ = Value added from industry z with final demand Y' in 2012
$x_{z,2012}$ = Total output for industry z in 2012
$x_{z,Y',2012}$ = Output for industry z with final demand Y' in 2012
$VA_{z,2012}$ = Total value added from industry z in 2012

Imports in the "Supply Chain Analysis – Imports Oriented" option are calculated in a similar fashion, where the proportion of total output used from a particular industry is the same for imports. The ratio is multiplied by the intermediate imports from the BEA import matrix.

Labor: Due to data limitations, the labor data is aggregated to the 3-digit NAICS codes. Employment estimates by industry NAICS code by Standard Occupation Code (SOC) are multiplied by the estimated hours worked per week in each industry. Note that this assumes that all occupations are working the average hours. The product of this is multiplied by the estimate of wages by industry NAICS code by SOC occupation code. The values are then scaled to match the BEA input-output data estimate of compensation. The result is then multiplied by the proportion of the ratio of $x_{z,Y',2012}$ to $x_{z,2012}$, which is consistent with methods proposed in Miller (2009). The result is a matrix of the compensation of labor, categorized by NAICS by SOC, to produce the selected commodities:

$$C_{z,s,Y'} = \frac{x_{z,Y'}}{x_z} * C_{z,s,} * \left(\frac{E_{z,s} * LH_s * W_{z,s}}{\sum_{i=1}^{n} E_{z,i} * LH_s * W_{z,i}} \right) \tag{A.4}$$

Where
$C_{z,s,Y'}$ = Compensation for occupation s in industry z with final demand Y'
$C_{z,s,}$ = Total compensation for occupation s in industry z
x_z = Total output for industry z
$x_{z,Y'}$ = Output for industry z with final demand Y'
$E_{z,s}$ = Employment for industry z and occupation s
LH_s = Labor hours per employee for occupation s
$W_{z,s}$ = Hourly wages per employee for industry z and occupation s

Adjusting for Inflation: Values are adjusted to 2019 using the Consumer Price Index for all cities for all items from the Bureau of Labor Statistics.[4]

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[4] Bureau of Labor Statistics. Consumer Price Index. https://www.bls.gov/cpi/

Appendix B. Expanded Resin Price Data

The table below is an expanded version of Table 5.4: Recycled Resin Prices ($ per ton), February 5, 2024

Plastic Type		Recycled Plastic Low Price	Recycled Plastic High Price	Primary Plastic Low Price	Primary Plastic High Price
PET	Clear Post-Consumer Flake	1220	1280	1380	1720
	Clear Post-Consumer Pellets	1660	1760		
	Green Post-Consumer Flake	1000	1180		
	Green Post-Consumer Pellets	1000	1180		
HDPE	Natural, Post-Consumer Flake	1020	1100	1200	1660
	Natural, Post-Consumer Pellets	2040	2120		
	Mixed Colors Post-Consumer Flake	580	660		
	Mixed Colors Post-Consumer Pellets	1180	1260		
	Mixed Colors Industrial Flake	620	720		
	Mixed Colors Industrial Pellets	600	680		
LDPE	Film Clear Post-Consumer Pellets	1440	1560	1340	1600
	Film Colored Post-Consumer Flake	340	420		
	Film Colored Post-Consumer Pellets	700	780		
PP	Industrial Flake	600	640	1260	2180
	Industrial Pellets	720	760		
PVC	Clear Industrial Flake	500	620	1310	2080
PS	Industrial Flake	880	920	2780	3940
	Industrial Pellets	1100	1180		
	High Heat Crystal Post-Consumer Flake	180	300		
	High Heat Crystal Post-Consumer Pellets	1060	1180		
PC	Clear Industrial Flake	1720	1920	-	-
	Mixed Colors Industrial Flake	1660	1740		
	Mixed Colors Industrial Pellets	1820	1940		
LLDPE	Stretch Film Pellets	740	780	1140	1780
ABS	Mixed Colors Industrial Flake	1660	1780	2100	3540
	Mixed Colors Industrial Pellets	1260	1360		

Source: Plastics News (2024)