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Changing the World's Energy Future

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Material Flow Analysis and LCA of Polyethylene Terephthalate (PET) and Polyolefin Plastics Supply Chains in the United States.

Utkarsh S. Chaudhari [a*], Anne T. Johnson [b], Barbara K. Reck [c], Robert M Handler [a], Vicki S. Thompson [d], Damon S. Hartley [e], Wendy Young [f], David Watkins [g], David Shonnard [a]

[a] Department of Chemical Engineering, Michigan Technological University, 1400 Townsend Drive, Houghton, Michigan 49931, USA.

[b] Resource Recycling Systems, 416 Longshore Drive, Ann Arbor, Michigan 48105, USA.

[c] Center for Industrial Ecology, School of the Environment, Yale University, New Haven, Connecticut 06511, USA.

[d] Biological & Chemical Science & Engineering Department, Idaho National Laboratory, Idaho Falls, Idaho 83415, USA.

[e] Operations Research and Analysis, Idaho National Laboratory, Idaho Falls, Idaho 83415, USA.

[f] Chemstations Inc., 11000 Richmond Avenue Suite 580, Houston, Texas 77042, USA.

[g] Department of Civil, Environmental, and Geospatial Engineering, Michigan Technological University, 1400 Townsend drive, Houghton, Michigan 49931, USA.

[*] Corresponding author: uschaudh@mtu.edu.

ABSTRACT

Plastics are useful and beneficial materials that contribute to an improved quality of life, yet generate significant solid wastes, emissions, and consume significant energy resources. Systems analysis is incomplete on current linear production systems of plastics supply chains and their associated processes. Our study combines material flow and life cycle assessment datasets of Polyethylene Terephthalate (PET) and the main polyolefin polymers in the U.S., comprising over 70% of plastics flows. This study estimates the total greenhouse gas (GHG) emissions and energy consumption of these supply chains, including transportation and end-of-life processes, lacking in prior studies. We calculate annual GHG emissions and energy consumption of these plastic supply chains to be 101 MMT CO_2-eq and 3,248 PJ in 2019, respectively. The GHG emissions of these supply chains represented 1.5% of the total U.S. emissions and 5% of the total U.S. industry related GHG emissions. The total energy consumption of these supply chains represented 3.1% of the total U.S. energy consumption in 2019. Transportation of PET and polyolefin plastic materials contributes 5% and 2% to the total supply chain GHG emissions and energy consumption, respectively. This baseline study provides a benchmark and enables a comparison to future circular production systems for plastics in the U.S

KEYWORDS: Plastics supply chain, Systems analysis, Material flow analysis, Life cycle assessment, Greenhouse gas emissions, Energy consumption, Linear-to-circular economy, Plastic waste

INTRODUCTION

Plastic materials offer various advantages and are preferred over other materials due to low cost, lightweight, durability, and chemical resistance. Plastic used in packaging was shown to have lower environmental impacts and energy consumption compared to alternative materials such as glass, and metal, mainly due to the light weight of plastic packaging[1]. The 2019 U.S. plastics industry created more than one million jobs and generated $432 billion in product shipments. In the United States, the plastics industry operated 15,746 establishments with 81% (12,816) being associated with plastic manufacturing[2]. The U.S. plastics recycling industry has an economic impact of $6 billion and creates about 30,000 direct and indirect jobs[3].

However, the current production and consumption patterns of plastic supply chains follow a linear economy model ("take-make-use-dispose") that has led to a number of challenges, including depletion of limited natural resources and mismanagement of valuable materials at end-of-life (EOL)[4]. The current linear economy model poses a threat to global warming and climate change[5] and impedes progress towards meeting several of the 17 main Sustainable Development Goals (SDGs) developed by United Nations[6], particularly SDG 12 (Responsible Consumption and Production), 13 (Climate Action), and 14 (Life below Water). To facilitate sustainability, it is essential to understand the material flows in plastic supply chains as well as their environmental and energy impacts.

More than 175 nations and 1000 plus organizations are working towards ending global plastic waste problem[7, 8] and have recognized that a transition toward a circular economy is desired[9]. Chemical recycling technologies (also known as advanced recycling technologies) are thought to be an important part of the solution to implement a circular economy by creating high-quality virgin-grade recycled plastic resins. However, the sustainability and required changes for transitioning from linear-to-circular economy are not well understood. To completely understand the sustainability of future circular plastic supply chains, we must first take a closer look at the current (baseline) plastic supply chains and estimate the baseline environmental and energy impacts.

Only a few peer-reviewed studies published in scholarly journals have conducted systems analyses of plastics supply chains. At the global scale, a study by Zheng and Suh reported the "cradle-to-end of life" greenhouse gas (GHG) emissions of all plastics produced along with their conversion and EOL processes (base year 2015)[10]. Their study reported total annual GHG emissions of 1,781 million metric tons (MMT) of CO_2-eq with 61% contributed by resin production, 30% by conversion and 9% by EOL processes. Another two studies reported "cradle-to-end of life" GHG emissions in China, with one study focused on polyvinyl chloride (PVC), polypropylene (PP), and polyethylene (PE) plastics (base year 2020)[11] and another study on polystyrene (PS), acrylonitrile-butadiene-styrene (ABS), and PVC plastics (year 2007-2017)[12]. In Europe, the GHG emissions of the plastic supply chains were found to be 208 MMTCO_2-eq in 2018[13]. However, all of the above-mentioned studies lack transportation-related impacts and information on end-use markets for recycled resins in different applications is missing. Only one study reported the GHG emissions and total energy demand of all plastics consumed in the U.S[14], but was limited only to resin production and conversion processes, excluding the EOL processes and transportation related impacts.

Our study addresses the above-mentioned research gaps, providing a complete system perspective, including all relevant processes. In our work, we have conducted a systems analysis on the complete plastics supply chain for the United States, by combining material flow analysis (MFA) datasets with life cycle assessment (LCA) datasets for polyethylene terephthalate (PET) and polyolefin plastics such as high-density polyethylene (HDPE), liner low-density polyethylene (LLDPE), low-density polyethylene (LDPE), and PP. Together, these plastic types cover 71% of the U.S. plastic production[15] and represent about 79% of the total plastic waste found in the U.S.[16]. The purpose of this analysis is to establish baseline GHG emissions and energy consumption of the complete PET and polyolefin plastics supply chains in the U.S. This baseline assessment provides a benchmark to compare against scenarios for circular economy of plastics that may be realized in the future. The objectives for this research are to:

1. Establish current baseline annual material flows of PET and polyolefin plastics supply chains in the U.S.
2. Identify the main processes involved in the current (baseline) PET and polyolefin plastics supply chains in the U.S. with a "cradle-to-end of life" scope.
3. Calculate the total current annual GHG emissions and energy consumption of PET and polyolefin plastics supply chains in the U.S.
4. Identify the main data gaps in the material and life cycle datasets for PET and polyolefin plastics.
5. Interpret systems analysis results and discuss the main challenges and opportunities to create a circular economy in PET and polyolefin plastics supply chains in the U.S.

METHODS

The main processes involved in the PET and polyolefin plastics supply chains are shown in the Section 1 of the Supporting Information – 1 (SI-1) document (see Figure S1). It shows "cradle-to-end of life" processes starting from production of virgin resins, then to semi-manufacturing processes, followed by plastics product manufacturing and end-use sectors, until the end-of-life processes (landfill, incineration, recycling, leakage), including intermediary transportation steps. Semi-manufacturing processes include a broad range of processes (more than 600 processes) including, but not limited to, extrusion, blow molding, injection molding etc[17]. As chemical recycling technologies are still in the early developing stages, the total amount of plastic waste recycled by such technologies remains negligible. Therefore, recycling of waste plastics by chemical recycling technologies was not considered as a part of this supply chain study. However, the reader is referred to a recent study[18] integrating chemical and mechanical recycling into plastics supply chains for further details on systems analysis of a future circular economy of plastics scenario. Refer to Section 1 of SI-1 document for more information on Figure S1.

Material Flow Datasets

The main source of material flow data on virgin resin production for polyolefins (HDPE, LDPE/LLDPE, PP) and their use in different semi-manufacturing processes (2019) was based on the ACC resin review report (published in 2020)[19]. However, the ACC report does not provide separate data for PET resin. The total U.S. virgin PET production capacity in 2019 was approximately 5.080 MMT (confidential industry source). Due to lack of data for virgin PET resin production, we assumed an average production capacity utilization rate of 89% based on polyolefin plastics from the ACC report, yielding 4.521 MMT PET/year, shown in Figure 1. The import and export data for virgin resins and semi-manufactured products was based on the U.S. International Trade Commission (USITC) 2019 database[20] and can be found in Supporting Information – 2 document (SI-2; Excel File, 'Trade' Tab). The net change to the in-use stocks was calculated by taking the difference between mass flows in and out of the 'Product Manufacturing & End-Use Sectors' box. Sample calculations are shown in the Section 1 of the SI-1 word document and actual values are shown in the SI-2 Excel document.

The most recent (2018, published in 2020) and a complete U.S. nation-wide dataset for the EOL management of plastics was based on the U.S. EPA report[16]. The EPA has not yet published the data for 2019, which was supposed to be published in 2021. We limited our study to the most recent datasets available prior to global pandemic (COVID-19) to avoid any disruptions caused in the overall plastics supply chains. The U.S. EPA reports, Stina Recycling, and Association of Plastics Recyclers (APR), National Association for PET Container Resources (NAPCOR) reports[21-25] cover only the post-consumer waste. To the best of our knowledge, no source of data is available for pre-consumer industrial plastic waste generation; however, this material mostly gets re-used in the process itself because it is relatively clean and high quality material (includes single plastic edges, parts, trimmings etc.)[26].

Plastic leakage into the environment itself is another complex and a huge system due to multiple sources and sinks of plastic material. Different plastic leakage studies have different estimates due to different system boundaries and to the best of our knowledge, there are no U.S. plastic resin-specific leakage data in the literature; all of the plastic leakage studies discuss in general about all plastics[27-29]. Additionally, the contribution of high-income countries such as U.S. to the plastic leakage is minimal due to well established recycling infrastructure, compared to lower and upper middle countries[27]. Some studies report plastic leakage in the U.S. ranging from 1.13 to 2.24 MMT/year[28]. Considering the limitations mentioned just above, the Section 1 of the SI-1 word document contains information on how we estimated the PET and polyolefin plastic leakage in our study.

LCA Datasets

The "cradle-to-gate" GHG emission and energy demand factors for virgin resin production and mechanical recycling were obtained from Franklin Associates LCA reports[30-36], whereas those for semi-manufacturing processes were "gate-to-gate" based on the Ecoinvent 3.3 database from the LCA software SimaPro v9.0. To calculate total GHG emissions, we utilized GHG emission factors (kg CO_2-eq), which are estimated using Intergovernmental Panel on Climate Change (IPCC) 2013 Global Warming Potential (GWP) over 100-year timeframe life cycle impact assessment method. To calculate energy consumption, we utilized energy demand factors (MJ), which are estimated using Cumulative Energy Demand (CED) life cycle impact assessment method. The electricity used inside each of the semi-manufacturing processes ecoprofile was updated based on the 2020 U.S. average electricity grid mix[37] (see Section 2 of SI-1 document for the distribution of electricity grid mix). For the category of "other conversion processes", we took an average of all conversion processes as shown in SI-2 document ('Semi-Manufacturing Processes' tab). The GHG emission and energy demand factors for landfilling and incineration with energy recovery, including collection and transportation steps, were obtained from the U.S.

EPA WARM reports[38, 39]. The waste plastic material is considered to have no upstream burdens[35]. The impacts of transportation from virgin resin production to semi-manufacturing processes and then on to final goods manufacturer, as well as from reclaimer to semi-manufacturing processes, were determined as shown in the section 2 of the SI-1 document and 'Transportation' Tab of the SI-2 document. The LCA data for mechanically recycled LDPE/LLDPE resin was not found in the published literature, and this lack of data is also recognized by the U.S. EPA WARM reports[38, 39]. Therefore, we calculated an average of the available GHG emission and energy demand factors for HDPE and PP based on Franklin Associates LCA report[35] and applied it to the LDPE/LLDPE resin. The total U.S. GHG emissions and energy consumption includes the impacts associated with all the materials that are processed in the U.S. Thus, the GHG emissions and energy consumption associated with exported materials are included in the total U.S. GHG emissions and energy consumption, as these exported materials are processed in the U.S. We assumed no environmental or energy burdens associated with imported resins and products; however, all of the processes involving this imported material are counted towards the U.S. GHG emissions and energy consumption. For example, we included the impacts of imported virgin resin processed in the semi-manufacturing processes. Also, we didn't estimate the GHG emissions and energy consumption from 'Product Manufacturing and End-Use' stage because it is infeasible to assign a multitude of product-specific emissions and energy consumption specific to a resin material[13, 14], as these impacts are attributable to product and not the resin material. Also, there is no transformation of resin material in final product manufacturing. The transformation of material is already accounted for in our analysis, which happens during semi-manufacturing processes. We provide a tabulated summary of all sources of material and LCA datasets for each supply chain stage for all plastic types in the SI-2 document, 'Virgin Resin Production' tab, 'Semi-Manufacturing Processes' tab, 'Landfills & WTE' tab, 'Collection, Sorting, Baling' tab, 'Mechanically Recycled Resins' tab, and 'Transportation' tab of the Excel file. The LCA calculations for GHG emissions and energy consumption are shown in SI-2 document, 'PET' tab, 'HDPE' tab, 'PP' tab, and 'LDPE/LLDPE' tab, organized by supply chain stage. These results were obtained by multiplying the U.S. annual material flows by the appropriate process life cycle emission factors or energy consumption factors (see Section 2 of the SI-1 document for the calculations).

RESULTS AND DISCUSSION

Baseline Material Flow System of PET and Polyolefin Plastics in the U.S.

The U.S. baseline material flows of PET and polyolefin plastics through different supply chain processes are shown in Figure 1. The legend shown on the left bottom side of Figure 1 shows different color for each type of plastic resin. In 2019, 87% of the PET and polyolefin virgin resin production was dominated by polyolefin plastics with the highest share by LDPE/LLDPE (36%, 12.693 MMT), followed in order by HDPE (29%, 10.045 MMT), PP (22%, 7.648 MMT)[19] and the remaining 13% (4.521 MMT) by PET resin. The U.S. is a net exporter of virgin polyolefin resins and a net importer of PET resin. About 48% of PET and polyolefin plastic resins, including recycled resins, were processed via extrusion processes, 13% by injection stretch blow molding (ISBM), 10% by injection molding, 8% by blow molding, and 21% by other conversion processes. The category 'Others' among semi-manufacturing processes are not well defined in the available data sources due to a wide range of processes (greater than 600 [17]). The recycled content is defined as the ratio of recycled resins to total (virgin + recycled) resins processed by semi-manufacturing processes [15]. The recycled content of PET and polyolefin plastic supply chains in the U.S. was only 4%. The recycled content, by resin type, was the highest for PET (12.9%) followed by HDPE (3.8%), LDPE/LLDPE (1.2%), and PP (0.3%). Overall, the U.S. was a net importer of semi-finished PET and polyolefin plastic products in 2019, with a majority of the imports associated with PET and PP plastics. The net change to the existing in-use stocks for PET and polyolefin plastic supply chains resulted in an addition of a minimum 5.079 MMT of PET and polyolefin materials. The individual in-use stock values for PET, HDPE, LDPE/LLDPE, and PP supply chains were found to be 1.363 MMT, 1.818 MMT, 2.747 MMT and -0.848 MMT, respectively. The negative in-use stock number for PP supply chain represents a net "release" from the existing PP material stock, whereas the positive for other supply chains represents a net "addition" to the existing material stock. The total PET and polyolefin plastic leakage was found to be 1.36 MMT.

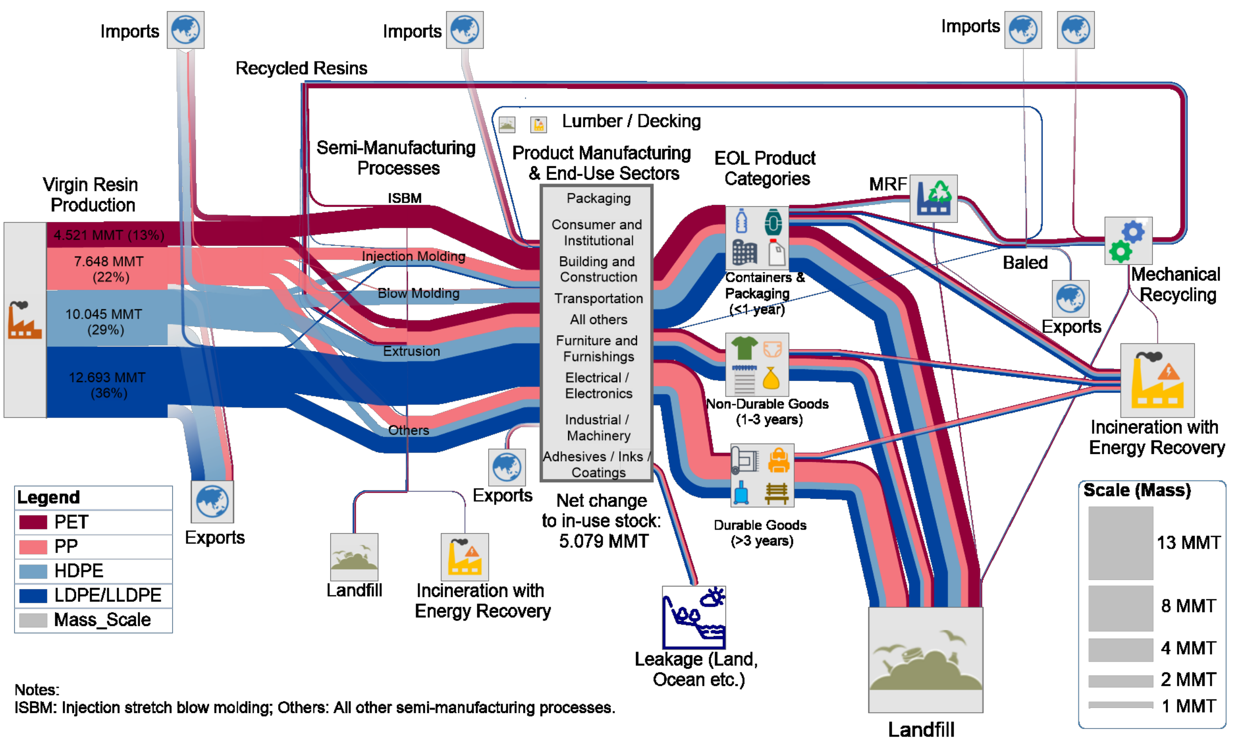

Figure 1. Baseline material flow system for PET and polyolefin plastics in the U.S. (2019). Note: The width of the arrow is directly proportional to the magnitude of the material flows. The trade flows (import and export) are shown with color gradient starting from light shade ("source") to dark shade ("destination") representing the direction of flow of material.

MMT: million metric tons; MRF: material recovery facility

In the U.S., a total of 32.4 MMT/year of plastic waste was generated, according to U.S. EPA data[16], though it is worth mentioning that another study using a "bottom-up" approach, determine a number above 40 MMT/year[40]. Of this 32.4 MMT/year, about 41% (13.2 MMT) of total plastic waste generated was found in the 'containers and packaging' EOL product category, followed by 'durable goods' (38%, 12.4 MMT) and 'non-durable goods' (21%, 6.8 MMT) categories. The share of PET and polyolefin plastic waste in the total U.S. plastic waste generated was 79% (25.7 MMT), with most of it dominated by LDPE/LLDPE (24%, 7.8 MMT) followed by PP (23%, 7.4 MMT), HDPE (18%, 5.7 MMT), and PET (15%, 4.8 MMT). Of this total PET and polyolefin plastic waste generated, only 7% (1.8 MMT) was collected for sorting and mechanical recycling and the rest was managed by landfills (77%, 19.7 MMT) and incineration facilities (16%, 4.2 MMT). The rates of collection for sorting were the highest for PET (19%, 0.9 MMT) followed by HDPE (9%, 0.5 MMT), LDPE/LLDPE (4%, 0.3 MMT) and PP (1%, 0.045 MMT). As the U.S. EPA does not include agricultural waste in their data, other reports provide an estimate of generation of agricultural film (0.055 MMT) in the U.S.[21, 24]. The end-use markets for mechanically recycled PET (0.79 MMT) were mainly found in the production of fibers (41%), food contact (28%), and non-food contact (7%) bottles, and the rest in film, sheets, and other applications such as strapping (24%)[25]. Mechanically recycled HDPE (0.3 MMT) found its applications mainly in production of non-food contact bottles (37.4%), pipes (33.2%), lumber / decking (8%), lawn/garden products (7.4%), automotive applications (7.1%), film/sheet applications (3.2%), and crates / baskets / pallets /other applications (3.6%)[41, 42]. There is limited information available on end-use markets for mechanically recycled PP and the actual PP reclamation capacity. However, it is known that mechanically recycled PP finds its applications in crates / baskets / pallets, other injection molded items, and automotive applications[22-24]. Most of the post-consumer baled PE films find markets in lumber and decking (46%) and the remainder in film/sheet (34%), injection molding (12%), or other applications (8%)[21]. The individual material flow system diagrams, by resin type, are shown in Section 3 of SI-1 document (Figure S2 to Figure S5) and the data is shown in SI-2 document as explained in the Methods section.

GHG Emissions of PET and Polyolefin Plastics Supply Chains in the U.S.

Total GHG emissions of the U.S. baseline PET and polyolefin plastics supply chains are presented in Figure 2. The total GHG emissions of these supply chains were found to be 100.6 MMT CO_2-eq/year. This represents ~1.5% of the total U.S. GHG emissions (6,600 MMT CO_2-eq/year, not including net land use change emissions) and 5% of the total U.S. industry-related GHG emissions (1,965 MMT CO_2-eq, including electricity-consumption emissions) in 2019[43]. The upstream processes (pre-consumer) such as virgin resin production (58%, 58.4 MMT CO_2-eq/year) and semi-manufacturing processes (29.3%, 29.5 MMT CO_2-eq/year) dominated the total GHG emissions. The contribution of EOL processes (downstream or post-consumer) to the total GHG emissions were small, only 7.7% (7.8 MMT CO_2-eq/year). The large magnitude of plastics materials transported in these supply chains created GHG emissions of 5% (5 MMT CO_2-eq/year) of the total supply chain GHG emissions.

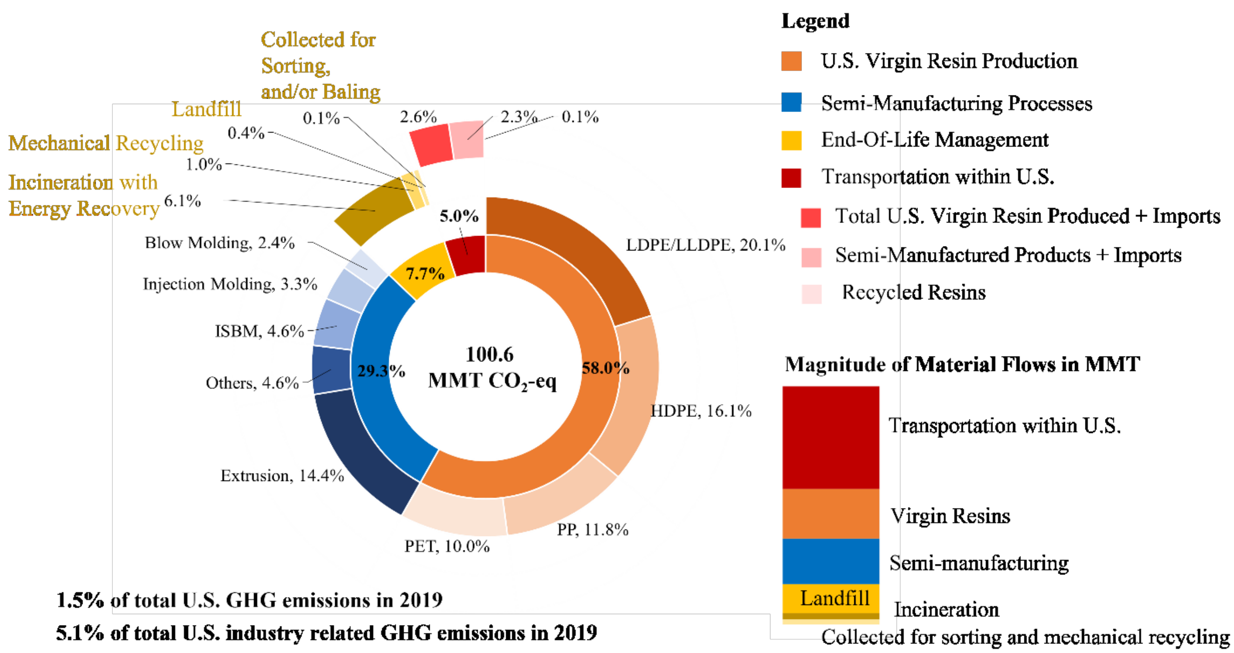

Figure 2. Total GHG emissions of PET and polyolefin plastics supply chains (2019).

The polyolefin plastics dominated the GHG emissions of virgin resin production with 48% of total GHG emissions, with the highest contribution by LDPE/LLDPE (20.1%, 20.25 MMT CO_2-eq/year), HDPE (16.1%, 16.17 MMT CO_2-eq/year), and PP (11.8%, 11.85 MMT CO_2-eq) consistent with their respective material flows. The GHG emission of virgin PET resin production was 10% of the total GHG emissions of the supply chains. Among the semi-manufacturing processes, extrusion processes had the highest contribution to the total GHG emissions with a share of 14.4%, which includes film, sheet, pipe, and fiber extrusion. This is followed by other conversion processes, ISBM, injection molding, and blow molding processes.

The EOL GHG emissions were dominated by incineration (6.1%, 6.2 MMT CO_2-eq/year) followed by mechanical recycling (1%, 1.04 MMT CO_2-eq/year), landfilling (0.4%, 0.45 MMT CO_2-eq/year), and collection for sorting and or/baling (0.1%, 0.12 MMT CO_2-eq/year). Despite the higher magnitude of plastic material flows to landfills (Figure 1), the GHG emissions from landfilling plastic wastes are low because they do not contain biodegradable carbon. Thus, it only includes GHG emissions associated with collection and transportation of plastic waste to the landfill facility and landfill operating equipment[39]. However, in our previous systems analysis model for PET bottles, we showed that landfilling plastics leads to sourcing of more fossil-derived virgin plastics, which results in higher GHG emissions[18]. Among the EOL processes, incineration with energy recovery contributed the most to GHG emissions even after accounting for avoided emissions due to displaced electricity, which could be due to low electrical conversion efficiency of incinerator (17.8%)[39]. The total GHG emissions distribution of individual material flow system diagrams are shown in Section 4 of SI-1 document (Figure S6 to Figure S9).

Total Energy Consumption of PET and Polyolefin Plastics Supply Chains in the U.S.

The total energy consumption of PET and polyolefin plastic supply chains in the U.S. is presented in Figure 3. The total energy consumed by PET and polyolefin plastic supply chains was 3,335.5 PJ (excluding energy savings due to incineration with energy recovery) and 3,248.2 PJ (including energy savings due to incineration with energy recovery). The total energy consumption of PET and polyolefin plastics (3,248.2 PJ) represents 3.1 % of the total U.S. energy consumption (100.2 Quads [44] or 105,716.6 PJ) in 2019. Most of the total energy is accounted for by upstream processes with the highest contribution by virgin resin production (78.4%, 2,546.3 PJ), followed by semi-manufacturing processes (21.4%, 696.5 PJ). The total energy consumed due to transport of plastics within the U.S. was about 2.1% (66.8 PJ). Of the total energy consumed during production of virgin resins (2,546.3 PJ), 66.6% is associated with material feedstock energy and 33.4% is the actual process and fuel energy used for production of resins. The downstream processes had comparatively lower energy consumption than upstream processes. The energy impacts associated with mechanical recycling (0.5%, 17.7 PJ) were the highest followed by landfilling (0.2%, 6.3 PJ) and collection for sorting and/or baling (0.1%, 1.8 PJ). The negative sign represents energy savings of 2.7% (-87.2 PJ) for EOL management by incineration with energy recovery, despite contributing the highest to GHG emissions (see Figure 2) at EOL. The total energy consumption distribution of individual material flow system diagrams is shown in Section 5 of SI-1 document (Figure S10 to Figure S13).

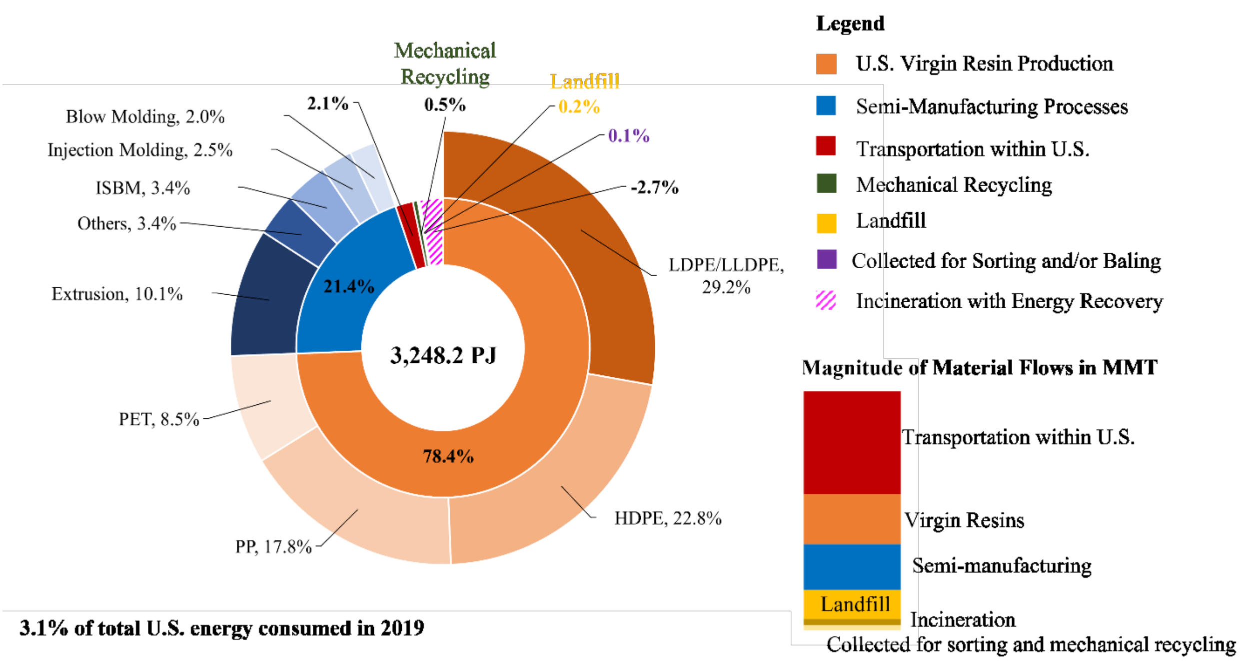

Figure 3. Energy consumption of PET and polyolefin plastics supply chains (2019).

The GHG emissions and energy consumption of the complete supply chains for individual plastic resin type are shown in Figure 4. The LDPE/LLDPE supply chain had the highest GHG emissions (29.4 MMT CO_2-eq) and energy consumption (1,072.8 PJ), followed by HDPE (25.1 MMT CO_2-eq, 890.3 PJ), PP (23.3 MMT CO_2-eq, 763.6 PJ), and PET (22.9 MMT CO_2-eq, 521.9 PJ). Resin production dominates GHG emissions and energy consumption for all plastic types, mainly due to extraction of non-renewable petrochemical feedstocks and production of raw materials to produce final resin. The impacts of semi-manufacturing processes for PET and PP are considerably higher than that of LDPE/LLDPE and HDPE due to the higher emission and energy consumption factor of fiber extrusion process. The EOL GHG emissions ranged between 7-8% of total emissions for these resins. The energy recovered due to incineration was the highest for the LDPE/LLDPE, PP, HDPE, and PET supply chains aligning with respect to their incineration rates. Transportation GHG emissions are between 4-6% of total emissions for these resins, and energy demand ranges between about 2-3% of total energy consumption.

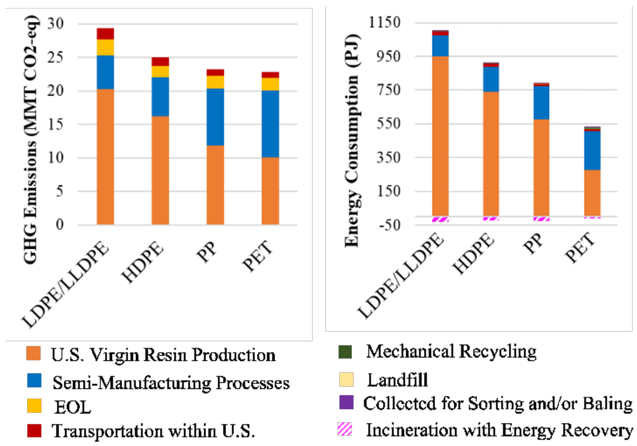

Figure 4. GHG emissions and energy consumption of supply chains by plastic type.

DISCUSSION

This section provides additional interpretations of results shown in Figures 1-4 and information regarding the geographic distribution of major plastic supply chain infrastructure, organized by upstream and downstream processes. As part of a baseline analysis and thinking ahead to a circular economy, knowing these locations are helpful in deciding the optimum locations of chemical recycling facilities and for ensuring a stable supply of PET and polyolefin feedstocks with minimum cost and environmental impacts.

Upstream Processes

The production of virgin resin includes the use of non-renewable petrochemical feedstocks such as natural gas, crude oil, or coal. As a result of technological improvements (such as horizontal drilling), the U.S. steam crackers rely mainly on the natural gas-sourced feedstocks for production of plastics[45-47]. Only one plastics manufacturer, based in Tennessee, produces plastic resins from a coal gasification process[48]. Other regions, such as in Europe and China, rely mainly on naphtha and coal, respectively, for production of plastics[49]. Another main reason for high plastics production in the U.S. is that the fossil fuel and plastics production are highly integrated together[46, 48]. Most of the U.S. ethylene crackers are located in the South region of the U.S.[50] with 20 in located in the state of Texas, 10 in Louisiana, 1 in Kentucky, and the remainder in the Midwest region (1 in Illinois, and 1 in Iowa). All of these facilities are operated by 18 companies in total, with a few having joint ventures with other companies. The PET resin manufacturers (11 facilities, 4-5 manufacturers) are mainly located in the southeast region of the U.S with most of them located in the states of South Carolina and North Carolina[51]. With growing awareness about reducing carbon footprint and shifting towards circular economy, many virgin resin producers are now collaborating with advanced recycling companies and investing in scaling of advanced recycling technologies, such as pyrolysis[52]. See Section 6.1 of the SI-1 document for more information on the geographical distribution of PET and polyolefin plastics convertors.

Downstream Processes

We targeted the EOL fate of plastics products found in 'Containers & Packaging' category (Figure 1) to generate Figure 5. We did this because only this plastic waste is collected for sorting and further recycling, whereas those in other categories are only landfilled and incinerated. About 93% of the PET material collected for sorting and recycling is originating from bottles and jars, and the remaining 7% from other PET packaging products such as clamshells and trays, with no information available on recycling of PET film applications[16]. Among the HDPE material collected for sorting, 91% is originating from HDPE bottles and containers, and the remaining 9% is from bags, sacks, and wraps[16]. The LDPE/LDPE material found in the bags, sacks, and wraps category is collected for recycling and the remainder goes to landfills and incineration facilities. The PP material collected for sorting is originating mainly from the containers and other packaging materials such as lids, caps, trays, baskets etc. Many studies have been published previously identifying the main challenges and opportunities to promote recovery and recycling of plastics at their EOL[15, 26, 53-60]. For more information on interpretation of material flows, please refer to section 6.2 of the SI-1 document and Figure S14 for complete composition of U.S. plastic waste generation by resin type and EOL product categories.

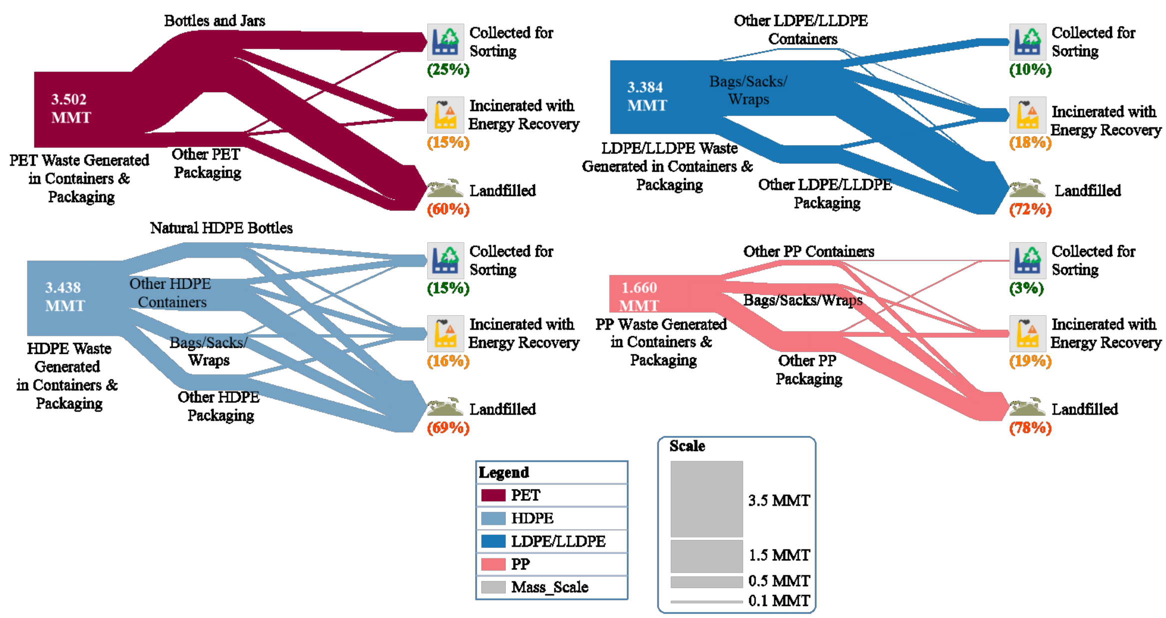

Figure 5. End of life management of PET and polyolefin plastic products found in 'containers and packaging' category, based on [16].

From the discussion above, the current U.S. collection, sorting in MRFs, and recycling processes are mostly suitable and well established for 3D-rigid small plastic containers and packaging products (mainly PET bottles and jars, HDPE natural and colored bottles) as opposed to flexible plastics packaging products such as bags, sacks, and wraps. Most of the PET and polyolefin plastic products (bottles, jars, milk jugs, films etc.) are getting mechanically recycled into non-durable (textile) and durable products (lumber/decking) for which the collection and sorting processes are not well established and thus, ultimately becomes landfilled or incinerated at their EOL. Currently, only PET resin is mechanically recycled into food contact applications. However, on-going research efforts in mechanical recycling of plastics could make it possible to produce high quality or food-grade recycled HDPE, LDPE and PP resins up to a certain level of recycled content[61, 62]. Technological and packaging innovations such as label-free packaging could also help to increase yields of recycled resins and reduce the carbon footprint of these materials[63, 64]. Promoting recovery and recycling of plastics from durable and non-durable products would require a collection system, advanced sorting processes, policies, take back programs, and collaboration with other material supply chains. Chemical recycling technologies could help promote the circular economy and recycling rates of not just packaging materials but also difficult to recycle plastics products such as textiles.

Looking at the EOL supply chain infrastructure, there are 367[65] – 532[16] material recovery facilities (MRFs), 1,269[16] - 1,776[40] active landfills and 75[16] – 85[40] municipal solid waste (MSW) incinerators facilities in the U.S. A minimum of 69 PET and polyolefin reclaimers exist in the U.S.[66] with most located in the South and Midwest regions. The U.S. reclamation capacity of PET as of 2020 was 1.141 MMT, with 42% of the capacity in South, 33% in Northeast and 25% in West region of the U.S.[25]. The 2019 U.S. reclamation capacity for film was approximately 0.454 MMT, which is mainly for the clean PE films originating from commercial sources[67]. The U.S. reclamation capacity for HDPE bottles in 2019 was 0.590 MMT[67]. The geographical distribution of EOL processors of PET and polyolefin plastics are summarized in Table S1 (see Section 6.2 of the SI-1 document).

Challenges, Data Gaps and Limitations

Gathering MFA and LCA datasets, by resin type, at each stage of the plastics supply chain is time consuming and not easily found in publicly available literature. There is no single MFA and LCA data repository available for all processes involved in plastics supply chains. The diversity of organizations providing the MFA data challenges the compiling and understanding of the data. Also, no U.S. plastic resin specific leakage data exists in the literature hindering a complete understanding of plastic leakage to the environment. Another limitation is that different sources of datasets have different system boundaries and geographical representation and are published at different times, creating a time lag in data analysis and compilation. A standardized methodology, timeliness, and transparency in reporting such datasets are highly needed[68]. For more details on this section, see Section 7 of the SI-1 document.

Promise and Peril of a Circular Economy for Plastics in the U.S.

Many claims are made that the circular economy is a concept that holds great potential to decouple economic growth from environmental harm[5]. However, a circular economy for plastics may not guarantee a more sustainable supply chain with lower impacts to the environment and beneficial economic and societal outcomes. The sustainability of a future circular economy for plastics in the U.S. will depend on the nature of the plastic material flows, the sources of raw materials for plastics production (whether fossil in origin or from biomass), and the processes that recover and recycle plastic resins at sufficient scale and quality. Mechanical recycling processes are not yet able to achieve true closed-loop plastics recycling[18], but chemical recycling of post-consumer waste plastics hold promise to close material loops. Chemical recycling processes are wide-ranging and can be applied to individual plastic types, separated from #1-7 waste plastics, using dissolution / precipitation technology to recover pure resin, chemical and biochemical catalytic deconstruction for monomer recovery, or thermal conversion with pyrolysis or gasification to produce chemical intermediates, combined with upgrading to new virgin quality plastic resins[18, 69-72].

The ultimate determination of whether these technologies will succeed in advancing a circular economy will be based on the relative benefits they achieve for the economy, the environment, and society at large. Technoeconomic analyses (TEA) are essential for indicating the economic competitiveness. The system boundary for TEA is limited to the waste plastic conversion and upgrading processes themselves, and direct comparisons to market price of fossil-derived plastic resins is a benchmark for success. Important considerations in TEA studies are consistent and standardized analysis approaches, for example by employing a discounted cash flow analysis and commonly-accepted modeling parameters [73, 74]. This allows for useful comparisons among different studies and process technologies.

A key difference between TEA and LCA is the system boundary. LCA must not only include the impacts of the process pathway itself (attributional effects), but also include impacts external to the process pathway (consequential effects). For example, when waste plastics are diverted from incineration with energy recovery, significant greenhouse gas emissions are avoided and these credits are attributed to the products of chemical recycling pathways[75]. In the U.S., landfilling is much more common than in the EU where several countries adopted landfill bans, and incineration with energy recovery is the dominant EOL fate for waste plastics. Emission and impact credits from landfilling are much smaller in comparison to incineration, therefore LCAs for chemical recycling in the U.S. compared to the EU are likely to be more challenged[76]. LCAs of plastics recycling should include GHG emissions and energy consumption along with a broad set of impact categories, such as ecosystem toxicity and human health, resources, water and air quality etc. Particular attention to waste plastics leakage to terrestrial and marine environmental should also be included in LCAs.

Similar to the U.S. baseline systems analysis presented in this study, analyses of future scenarios for a circular economy of plastics should integrate diverse datasets and models, combining MFA, process simulation and optimization, TEA, LCA, transportation logistics, and market dynamics[18, 70, 77], and may also include optimization approaches to interrogate system parameters and trade-offs among indicators of sustainability[18, 78-80].

CONCLUSIONS

Some of the key points identified through our study are highlighted in following list:

- GHG emissions and energy consumption of the complete U.S. PET and polyolefin plastics supply chains in 2019 are 1.5% and 3.1% of annual U.S. totals, respectively.

- Transportation of PET and polyolefin plastic materials, absent in other recent plastics supply chain analyses, contributes 5% and 2% to the total the supply chain GHG emissions and energy consumption.
- The GHG emissions and energy consumption of upstream processes were higher than the downstream processes.
- Current recycling practices are converting short lived products (bottles and films, for example) into long lived products (fibers and lumber decking for example) for which collection and recycling infrastructure is not well established.
- The current U.S. collection, sorting, and recycling infrastructure is well established and suitable for "easy-to-recycle" plastic products such as PET, HDPE bottles and containers.
- The collection infrastructure of plastic films is different than other types of plastics and is mainly collected via commercial sources or at store drop-off centers.
- The design of plastic products at the manufacturing stage plays a crucial role in deciding the fate of plastic products; less complicated and mono-material plastic packaging is needed to move toward a circular economy of plastics.
- The analysis of chemical recycling process technologies should be implemented in tandem with process-level and system-level assessments.
- The role of consumers, access to recycling, appropriate education and knowledge of recycling is essential for increasing recovery and recycling rates.

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SUPPORTING INFORMATION

The Supporting information documents are available free of charge at:

The SI-1 document (word file, DOC) contains additional information on description of conceptual material flow framework, data gaps and limitations, individual material flow system diagrams and their GHG emissions and energy consumption.

The SI-2 document (Excel file, XLSX) contains all material flow and LCA datasets organized by supply chain stage and resin type.

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SYNOPSIS

Estimated baseline greenhouse gas emissions and energy consumption of most significant and complete plastic supply chains in the U.S.

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