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QUANTIFYING HIGH DENSITY POLYETHYLENE FLOWS IN THE UNITED STATES USING MATERIAL FLOW ANALYSIS

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ABSTRACT

A Circular Economy (CE) aims to reduce natural resource consumption, waste generation, and related detrimental environmental, social, and economic impacts by retaining valuable materials in the economy as long as possible. This research focuses on the implementation of CE for High-density polyethylene (HDPE) plastics. Recycled HDPE retains desirable properties such as high durability, flexibility, and corrosion resistance leading to a high demand for recycled HDPE by piping and other building and construction industries. Unfortunately, most HDPE comprising products are mismanaged at their end-of-use (EoU) resulting in significant HDPE stocks being incinerated, landfilled, or disposed of in water bodies. This mismanagement of EoU HDPE products contributes to the plastics waste crisis, leads to deleterious environmental and human health impacts, and further reinforces an unsustainable linear economy model. Therefore, improved plastic waste collection mechanisms are needed to keep the different plastic polymer waste streams segregated and to enable the implementation of efficient recovery processes, particularly for recyclable plastics such as HDPE. A challenge in developing end-of-use infrastructure for HDPE recovery is the knowledge gap related to the systematic accounting of HDPE flows.

Material Flow Analysis (MFA) provides the means to track the stocks and flows of a resource within a defined system. This paper investigates HDPE flows in the United States (US) economy and presents two static MFA models for the years 2015 and 2019. The HDPE recycling rates were found to be at 7.4% and 10.1% in the US in 2015 and 2019, respectively. Based on the available data, EoU packaging and container goods are identified as the primary source for recycled HDPE. Our analysis also revealed discrepancies in historical data about HDPE flow across different industry sectors and life-cycle stages. To overcome limitations associated with data unavailability, HDPE flows for the MFA models were computed based on assumptions discussed in the paper. The availability of more granular data, which includes HDPE flows through industry sectors and sub-sectors, would lead to a more thorough MFA. By providing the static MFA models of HDPE flows and stocks in 2015 and 2019 in the US economy, and identifying specific data collection needs, this investigation takes the first step towards a comprehensive characterization of HDPE flows in the US. Quantifying and characterizing HDPE flows is an important component of anticipating the availability of secondary HDPE feedstocks, scaling up recovery infrastructure adequately, and contributing to our overall understanding of the current and future secondary HDPE market dynamics.

Keywords: High-density polyethylene, Circular Economy, Material Flow Analysis, Waste management

NOMENCLATURE

CE	Circular Economy
HDPE	High-density Polyethylene
MFA	Material Flow Analysis

1. INTRODUCTION

Global plastic consumption is expected to reach 485 million tons by 2030, up from 348 million tons since 2017 [1]. The

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current rate of plastic consumption is unsustainable. Most plastics are made from steadily declining petroleum reserves (a very small fraction is biobased plastics). Plastics are easy to fabricate and mold into complex geometries, and the steadily improving manufacturing process efficiencies have made plastics widely accessible at low costs. This has in turn resulted in increased demand. Their many benefits make them an indispensable part of our daily lives.

Unfortunately, the end-of-use (EoU) management of plastics does not match the growth in demand and the subsequent use and disposal rates of plastics into our environment. Currently more than 90% of EoU plastics are landfilled (or disposed into oceans) causing air, water, and soil contamination and subsequently detrimental human health impacts [2, 3]. Fostering a Circular Economy (CE) model for plastics production, consumption, and waste-management has been advocated for as a potential solution to this challenge [4]. A Circular Economy (CE) model aims to reduce natural resource consumption, waste generation, and related detrimental environmental, social, and economic impacts by retaining valuable materials in the economy as long as possible [5]. However, the lack of effective EoU plastics collection and sorting infrastructure results in the commingling of different plastic waste streams and hinders the processing and recovery of EoU plastics in high demand such as High-density polyethylene (HDPE) [6].

High-density polyethylene (HDPE) is among the most widely used plastics and is used across a variety of durable and non-durable applications [7]. HDPE is a thermoplastic resin that is inexpensive, possesses high durability and is easy to process. HDPE is also lightweight and more inert than Low-density and Medium-density polyethylene (LDPE and MDPE) making it resistant to chemicals during use. HDPE has a desirable mechanical strength for applications in the packaging, building and construction, and consumer and institutional sectors [3, 8]. It has been estimated that the global HDPE waste management market was at 32 million tons in 2018 and is expected to grow to 36.2 million tons by 2024 [9]. Besides just poor infrastructure, other challenges are associated with recovery of plastics. Recycling plastics generally results in material degradation which essentially translates to a loss in material value. Another concern is chemical contamination, which can prevent the recovery of EoU plastics into food-grade packaging. Processes that help maintain the intrinsic material properties and thus, maintain material value are needed to incentivize the recovery of plastics [3]. Readers interested in a detailed techno-economic and environmental impact analysis of current and emerging plastic recycling technologies are encouraged to refer to Uekert et al. (2023) [10].

Interestingly, the secondary HDPE market does not conform to the above stated dynamics. The demand for recycled HDPE remains strong, so much so, that at times when the cost of recycled-HDPE (r-HDPE) is greater than virgin-HDPE (v-HDPE) [11]. This demand for r-HDPE is fueled primarily by the building and construction industry. The durability of r-HDPE for the construction of drainage pipes, siding, decks, and outdoor furniture has driven up demand for r-HDPE, which in turn has resulted in complex market dynamics that makes it difficult to anticipate quantity available and also the associated price. While the overall recycling rate of HDPE remained close to 10% in 2019, it should be noted that the recycling rate of HDPE containers and bottles is approximately 27-30% [12, 13]. It is anticipated that the demand for r-HDPE for the use in non-durable products such as those mentioned above will continue to increase. Not only will increased recycling HDPE capacities reduce our dependence on fossil based energy and water use, but it is also a means of diverting waste-HDPE away from landfills, water bodies and minimizing unregulated combustion or incineration [14, 15]. Understanding past, current, and future HDPE material flows can help engineers, practitioners, and policy makers develop effective mechanisms to mitigate HDPE waste.

This paper provides a starting point in analyzing the HDPE market from a systems perspective by characterizing past HDPE flows across the US. Using material flow analysis (MFA), this paper presents two static models that illustrate HDPE flows from the production stage through their EoU and disposal or recovery stages for 2015 and 2019. This historical perspective on HDPE flows aims to identify and estimate missing data related to HDPE flows across the life cycle stages of the different industries that use HDPE. Thus, the main contributions of this work are to:

1. Provide a mechanism via MFAs to track historical physical HDPE flows and identify missing and uncertain HDPE flows.
2. Enable greater accuracy in predicting future HDPE flows by identifying discrepancies in historical data.
3. Provide estimates for uncertain/ missing HDPE flows where possible.
4. Provide insights regarding changes in HDPE production, consumption, and waste management characteristics in the recent past.

This paper is structured as follows: Section 2 provides an overview of MFA and its suitability to the current analysis via a literature review. The methods, data collected (with sources), and assumptions made to develop the MFA model are presented in Section 3. The results and analysis are provided in Section 4 and followed by a summary of the key findings in Section 5.

2. BACKGROUND: MATERIAL FLOW ANALYSIS

Material Flow Analysis (MFA) is a systematic approach to investigate the stocks and flows of a material within a defined system boundary [16]. Defining the system boundary includes specifying the time-frame and geographical area of interest in the investigation. The material of interest in an MFA can be a specific substance or a type of product or merchandise.

In an MFA model, the system being investigated is modeled using *processes*, *stocks*, and *flows* whose definitions are provided below (based on ref. [16]):

- A *process* is defined as the transformation, transportation, or storage of the material of interest.
- A *stock* in an MFA model is defined as a reservoir of the material of interest and is associated with a specific process.

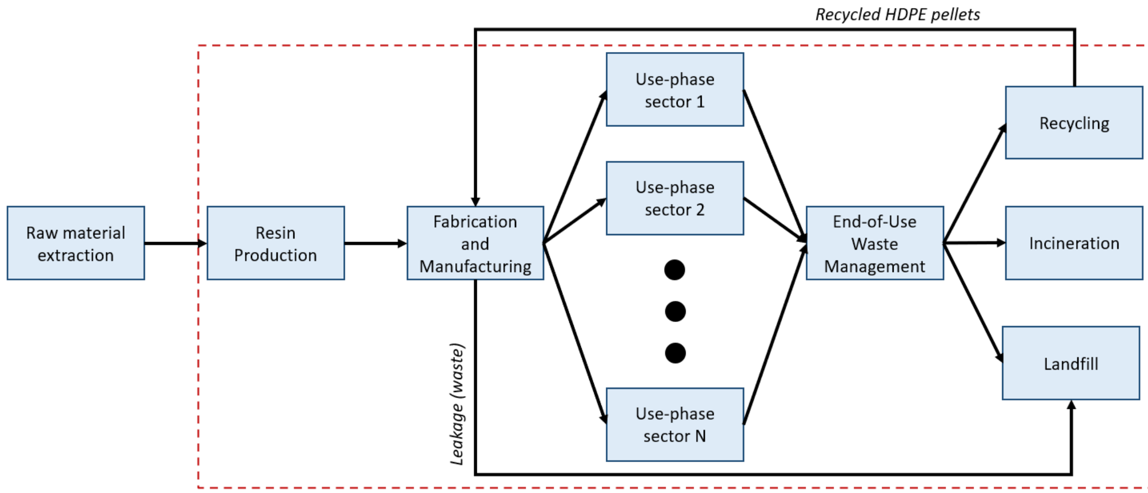

FIGURE 1: THE LIFECYCLE OF HDPE PLASTICS. THE DASHED OUTLINE REPRESENTS THE PROCESSES CONSIDERED WITHIN THE SYSTEM BOUNDARY FOR THE MFA CONDUCTED IN THIS WORK.

- *Flows of materials* connect processes within an MFA model. Flows entering and leaving the defined system boundary are called *imports* and *exports*, respectively.

MFA models must conform to the law of conservation of mass: the sum of inputs into a process must equal the sum of all outputs from a process and changes in stocks (see Eq. 1, where subscript p represents a process).

$$\sum Inputs_p = \Delta Stock_p + \sum Outputs_p \tag{1}$$

MFA is a central industrial ecology methodology, which enhances our understanding of material use, losses, recovery efficiencies, and other parameters associated with tracking resources within a given system through the use of Sankey diagrams and quantitative descriptors. Conducting an MFA includes analyzing a clearly defined system via the detailed description of each flow in the system and also via the quantification of each flow within the given system [17]. MFA has therefore been applied to a wide variety of commodities including products such as Lithium-ion batteries and other electronics [18, 19]. It has also been used to track individual materials such as rare earth elements [20–22]. Further, MFA has been recognized as a decision-support tool for waste management systems. According to the review by Allesch and Brunner (2015), MFAs are useful in evaluating the performance of current waste management systems, comparing different waste management systems, collecting and providing the required information for further evaluation using methods like Life Cycle Assessment (LCA), and scenario analyses to improve waste management systems [23]. Recent research has applied MFA to investigate plastic production, consumption, and waste management practices.

Millette et al. (2019) used MFA to characterize plastic flows in Trinidad and Tobago during 2016 and identified promising opportunities for CE implementation [24]. They reported that 48% of plastic waste landfilled in Trinidad and Tobago came from packaging for imported products. Di et al. (2015) presented an MFA model of seven plastic polymers in the US during 2015 [7]. They reported that more than 88% of total plastics were consumed in packaging and containers, consumer and institutional products, and building and construction products. They also reported a very low rate of overall plastics recycling at approximately 6.2% and that 77% of plastic waste was landfilled in 2015. Heller et al. (2020) also reported that less than 8% of total plastics reaching end of life was recycled in the US in 2017 [25].

Antonopoulos et al. (2021) used MFA to investigate post-consumer plastic packaging waste collection, sorting, and recycling in the European Union in 2017 [26]. They reported that the recycling rate for post-consumer plastic packaging waste in the European Union was at 14% without accounting for the waste exported for recycling (and 25% when accounting for recycling exports). They also estimated a potential plastic packaging waste recycling rate of 49% with the utilization of best practices and available technology. Chaudhari et al. (2022) used a combination of MFA and LCA to estimate the total greenhouse gas emissions and energy consumption of Polyethylene Terephthalate and Polyolefin plastics supply chains [27].

This paper builds on previous research in this area and specifically investigates the production, consumption, and end-of-use management of HDPE plastics because of its high potential for recoverability as discussed in Section 1. In addition, this paper also presents the comparison of two MFA models for HDPE plastics in the US economy during 2015 and 2019. By comparison of the HDPE MFA models in these two years, this paper provides insights regarding changes in the HDPE market in the recent past.

3. METHODS

The MFA models presented in this study were prepared using the STAN software [28]. This section provides the details of the MFA system boundary, data sources and estimation procedures used to quantify HDPE flows and stocks.

3.1 MFA system boundary and processes

The MFA models in this study consider HDPE stocks, flows, and processes in the US economy in 2015 and 2019. Based on a review of relevant literature [7, 27], the life cycle processes of HDPE considered within the system boundary for the MFA models in this research are (a) HDPE resin production, (b) fabrication and manufacturing, (c) distribution and use, and (d) EoU waste management (see Fig. 1). Three waste management strategies are identified for plastic waste by the US Environmental Protection Agency (EPA) [29, 30]: (a) recycling, (b) incineration (combustion for energy), and (c) disposal through landfills.

The use-phase HDPE products are classified into three groups based on their lifetime: (a) Packaging and containers (with a lifetime of < 1 year), (b) durable goods (with a lifetime of > 3 years), and (c) non-durable goods (with a lifetime of 1 – 3 years) based on refs. [7, 29, 30]. Packaging and container products include bottles, jars, other plastic containers, bags, sacks, and wraps. Non-durable products are primarily comprised of consumer and institutional goods such as plates, cups, and trash bags. Durable products containing HDPE span a variety of use-phase sectors including building and construction, industrial and transportation, electrical and electronics, and furniture.

3.2 HDPE flow data and estimations

The required data for the 2015 HDPE MFA model was obtained from Di et al.'s (2021) publication on the US plastic flows [7], and the US EPA report on material generation and management of Municipal Solid Waste (MSW) in 2015 [29]. According to EPA, MSW includes (but is not limited to) packaging, food, grass clippings, sofas, computers, tires and refrigerators collected from homes, schools, hospitals, and businesses [31]. The required data for the 2019 HDPE was obtained from Chaudhuri et al.'s (2022) investigation of US plastics supply chain [27], and Milbrandt et al.'s (2022) evaluation of US plastic waste in 2019 [12]. Data sources of specific flows are provided in Appendix A. The units used for HDPE flows are kTons (metric, 1 kTon = 1,000,000 kg).

The HDPE flows for different use-phase sectors in the 2019 MFA model were estimated using relevant available data. The 2019 Post-consumer Plastic Recycling Data Dashboard reports approximately 677 KTons of sales of HDPE natural bottle resin in the US in 2019 [13]. Based on the EPA's report on material generation and waste management in 2015 and 2018, natural HDPE bottles account for approximately 20% of the packaging and container products containing HDPE [29, 30]. Assuming that the natural HDPE bottles held the same proportion of HDPE packaging and container products in 2019, a flow of approximately 3384 kTons of HDPE into the use-phase packaging and containers sector was estimated.

Granular data related to the consumption of HDPE for use-phase durable and non-durable products in 2019 was not found. Therefore, the estimation assumed that the proportions of HDPE plastic consumption in different use-phase sectors were similar in 2015 and 2019. The share of HDPE plastics consumed in different use-phase sectors in 2015 was obtained from ref. [7]. This information was used with the HDPE natural bottle resin sales data (discussed above) to estimate the HDPE flows into use-phase sectors such as furniture, and building and construction.

4. RESULTS AND DISCUSSION

The MFA models of HDPE production, use, and EoU management in the US in 2015 and 2019 are shown in Fig. 2 and Fig. 3, respectively. Any flows that were estimated by the authors are colored orange. Flows that are colored red indicate the possibility of discrepancies in the available data.

4.1 HDPE resin production and Manufacturing

Reported HDPE resin production in the US was 8559 kTons and 10045 KTons in 2015 and 2019, respectively [7, 27]. While the resin production increased from 2015 to 2019, the net HDPE resin flow to the manufacturing and fabrication sector after trade were similar: 7643 kTons in 2015 and 7582 kTons in 2019, as shown in the incoming flows into the *fabrication and manufacturing process* in the MFA models presented in Figures 2 and 3.

These results indicate a steady demand for HDPE resin by the US manufacturing and fabrication sector in the recent past. The available data reports that the HDPE waste from fabrication and manufacturing in 2015 was approximately 21.2% of the flow into the sector [7]. The available data for 2019 reported that HDPE waste from the fabrication and manufacturing sector was 0.82% of the HDPE flow into the sector [27]. This is significantly lower than the reported waste in 2015. However, this data was estimated by only considering waste during manufacturing and conversion processes [27]. It is possible that the data for 2019 did not include waste due to factors such as rejection of HDPE resin due to quality control issues.

4.2 Comparison of HDPE Consumption and Reported Waste

In terms of HDPE consumption, the packaging and containers sector recorded the highest HDPE use-phase flows, followed by the building and construction sector, and the consumer and institutional sector. In 2015, the reported EoU HDPE waste from packaging and containers goods was 93.7% of the use-phase HDPE flows into the packaging and containers sector from fabrication and manufacturing. In contrast, the 2019 MFA shows that the reported EoU HDPE waste from packaging and containers goods was 196.9% of the use-phase HDPE flows into the packaging and containers sector from fabrication and manufacturing. The reported EoU HDPE waste from durable goods were approximately 76.8% and 69.6% of the use-phase HDPE flow into the sector in 2015 and 2019, respectively. In the case of non-durable goods, the reported EoU HDPE waste from durable goods were approximately 58.5% and 21.6% of the use-phase HDPE flow into this sector in 2015 and 2019, respectively. These flows can be visualized at the *use-phase processes* related to packaging and containers, durable goods, and non-durable goods in the MFA models presented in Figures 2 and 3.

Given that the lifetime of packaging and container goods is less than one year, the HDPE flows into the use-phase and the reported EoU HDPE waste from packaging and container goods are expected to be similar. This is consistent with the results from the 2015 MFA but not with the 2019 MFA. The significantly higher amount of EoU HDPE waste from the packaging and containers sector, compared to the HDPE flow into this use-phase

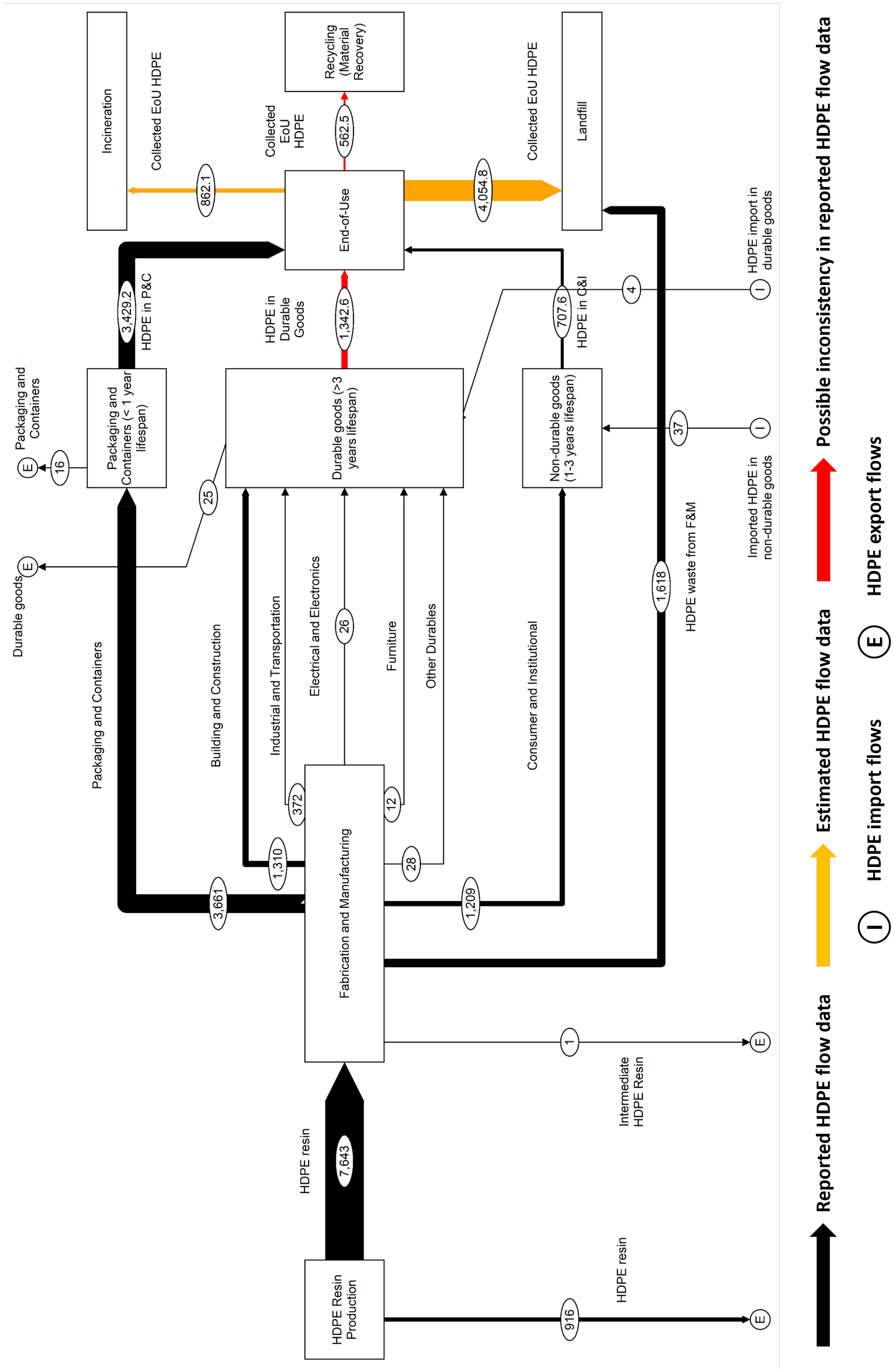

FIGURE 2: THE MFA MODEL OF HDPE PRODUCTION, CONSUMPTION, AND WASTE MANAGEMENT IN THE UNITED STATES IN 2015. ALL HDPE FLOWS ARE INDICATED IN KTONS.

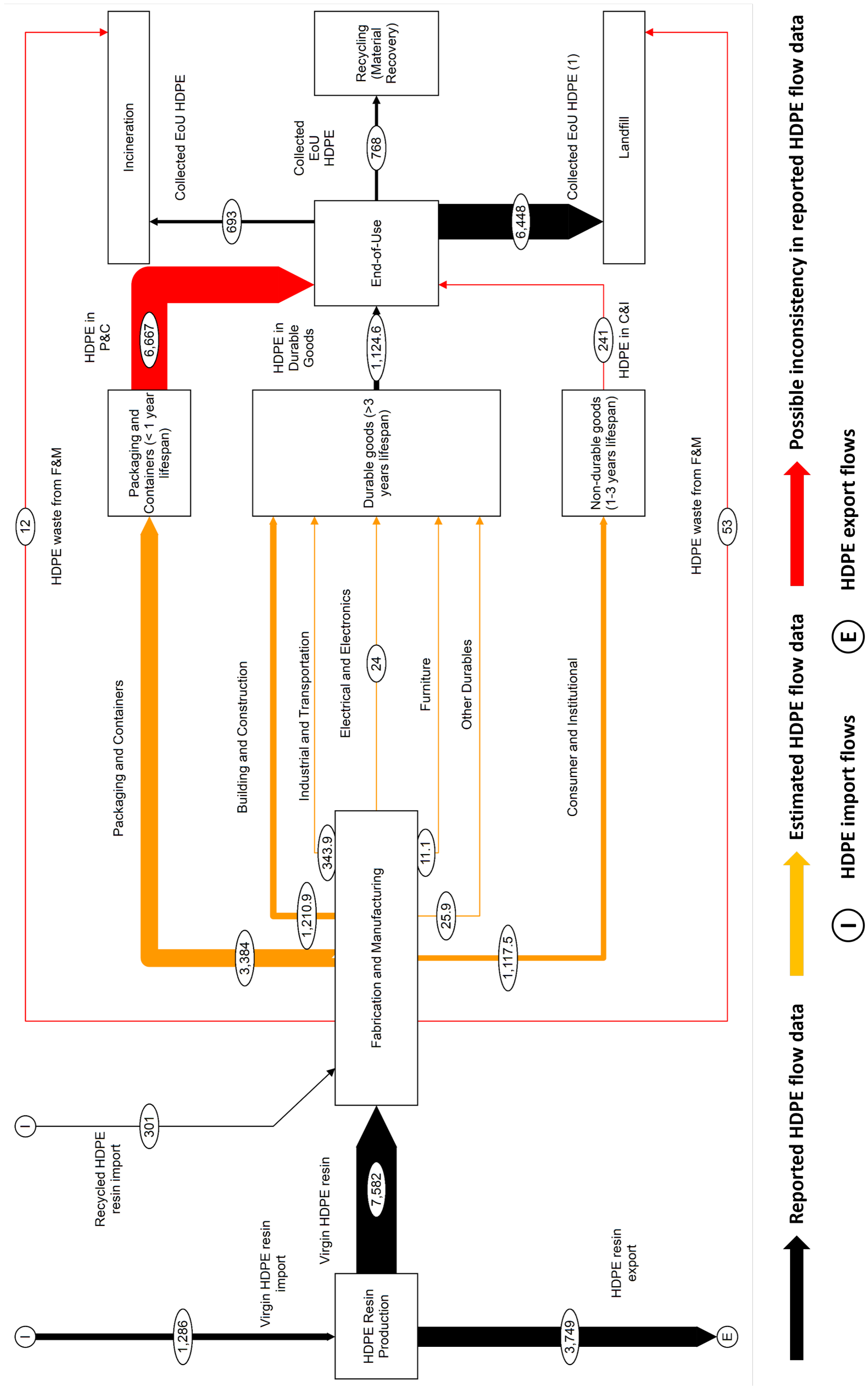

FIGURE 3: THE MFA MODEL OF HDPE PRODUCTION, CONSUMPTION, AND WASTE MANAGEMENT IN THE UNITED STATES IN 2019. ALL HDPE FLOWS ARE INDICATED IN KTONS.

sector from manufacturing and fabrication, could indicate that a large import of packaging and container goods is not accounted for in the available data. A significant change was also observed in the EoU HDPE waste from non-durable goods.

The EoU HDPE waste data for 2015 was obtained from the EPA's report on material generation and waste management [29]. The corresponding EPA report for 2019 is not yet available. The waste management data was collected from the work by Milbrandt et al. (2022) [12]. The 2019 waste management numbers are also compared to the 2018 waste management data released by EPA [30]. The EPA reports 3438.2 kTons of EoU HDPE waste from packaging and container goods in 2018, which is comparable to the 2015 EoU numbers, and the 2015 and 2019 HDPE flows into the packaging and container goods sector from fabrication and manufacturing. Because it is unlikely that the EoU waste generation almost doubled from 2018 to 2019, these results indicate an inconsistency in the data collection approach for HDPE waste (and plastics waste, in general) used by different organizations.

4.3 Reported EoU HDPE Waste Characteristics

The total amount of HDPE wasted reported (from the use-phase) in 2015 is 5479.4 kTons. The breakdown of the EoU HDPE waste in 2015 is as follows: (a) 62.6% from packaging and container goods, (b) 24.5% from durable goods, and (c) 12.9% from non-durable goods. The total amount of reported HDPE waste (from the use-phase) increased in 2019 to 7910 kTons. The breakdown of the reported EoU HDPE waste in 2019 is as follows: (a) 83% from packaging and container goods, (b) 14% from durable goods, and (c) 3% from non-durable goods. These flows can be visualized at the *End-of-Use process* in the MFA models presented in Figures 2 and 3.

The results indicate a 44.4% increase in reported EoU HDPE waste collection from 2015 to 2019. The primary contributors to the increase in total HDPE waste was the packaging and container goods sector. According to the reported data, there was a 94.4% increase in the reported packaging and container waste, a 65.9% decrease in the reported non-durable goods waste, and a 16.2% decrease in the reported durable goods waste.

4.4 EoU HDPE Recycling Characteristics

In 2015, the amount of end-of-use (EoU) HDPE collected for recycling was approximately 7.4% of the net virgin HDPE resin production in the US (accounting for trade). The 2019 MFA shows a slight improvement with 10.1% of the net virgin HDPE resin production in the US (accounting for trade) collected at EoU for recycling. The recycling rate of natural HDPE bottles in 2015 and 2019 were 30.3% and 27.2%, respectively [13]. In 2015, the amount of EoU HDPE collected for recycling from the packaging and containers use-phase sector was approximately 15.4% of the HDPE flow into this use-phase sector. Granular information was not available regarding the breakdown of total recycled HDPE in 2019 by use-phase categories.

The higher recycling rate for HDPE bottles compared to the general HDPE recycling rates indicates a better waste collection, sorting, and recycling infrastructure for bottles. Based on the available data, all of the EoU HDPE collected for recycling in 2015 and 2018 were obtained from packaging and consumer goods [29, 30]. However, based on information on the use of recycled HDPE in the piping industry (obtained through discussions with industry professionals), EoU durable goods are also recycled to provide feedstock for manufacturing drainage pipes [11]. Therefore, it is possible that EoU durable goods are directly recycled through industrial partnerships but not reported in the Municipal Solid Waste data.

4.5 Implications, Limitations, and Future work

This work compared the HDPE MFA models of the US economy in 2015 and 2019. Our analysis indicates a slight improvement in the recycling rate of EoU HDPE and similar consumption of HDPE resin for fabrication and manufacturing within the US. Further, our analysis highlights the current lack of effective data recording mechanisms as an impediment to accurately quantifying and characterizing HDPE flows within the US economy. Based on the MFA models, it is clear that data collection procedures across all the product life cycle stages need to be standardized. Specifically, we identified discrepancies in the collection of plastic waste management data across different organizations. Additionally, it is possible that HDPE waste related to durable goods is being processed for recovery through industrial partnerships and the corresponding data is not included in available waste management reports. The data gathering work for developing the HDPE MFA models also revealed that available plastics consumption and waste management reports are generally classified either by the polymer type or the use-phase sector [9]. However, there is a need to trace specific polymer flows and stocks across different use-phase sectors.

More granular data associated with HDPE leakage in the form of waste at each of the product life cycle phases will enable quantifying and characterizing mismanaged HDPE more accurately. Further, dis-aggregated data associated with sector-wise consumption and EoU waste collection of HDPE-comprising products will enable an accurate quantification and characterization of potentially recoverable HDPE. An accurate quantification of HDPE material demand and consumption will enable stakeholders (e.g., manufacturers, waste management firms, feedstock suppliers) to better forecast supply, demand, and price trends of the primary and secondary HDPE markets. This in turn will allow stakeholders to plan for the future in terms of technological interventions and policy or standards-related interventions (e.g., testing for quality and durability) to create viable secondary HDPE feedstock streams. This is particularly relevant given the strong demand for r-HDPE by the building and construction sector in recent times [11].

The current HDPE MFA models of the US economy were based on historical data and were limited to static analyses. The next phase of research will explore models that enable the forecasting of future HDPE flows and the analysis of different scenarios to enable circularizing these flows via facilitating mechanisms that contribute towards the development of better EoU collection, sorting, and recovery infrastructure as well as identifying other key factors that create a demand for r-HDPE.

5. CONCLUDING REMARKS

This research presented MFA models of HDPE production, consumption, and waste management in the US during 2015 and 2019 using available historical data. The MFA models, presented in this study, provide estimates of HDPE flows that are not reported in currently available data. The comparison of the 2015 and 2019 MFA models indicated that similar quantities of HDPE resin were used for fabrication and manufacturing in the US during these years. The results also indicate a slight improvement in the HDPE recycling rate from 2015 to 2019. This work also identified inconsistencies in recorded data related to EoU HDPE waste collection and management across different organizations and the lack of plastics consumption and waste management data that is specific to both polymer-type (in this case HDPE) and use-phase sector.

This work demonstrates that MFA has the potential to serve as a strategic decision-making tool to enable the implementation of CE principles. Although MFA models are data-intensive, it should be noted that while gathering data on physical flows can be challenging, other data, particularly that related to trade is often less difficult to gather. The current MFA models for HDPE flows across the US economy highlight 1) the need for the collection of data on polymer and use-phase sector-specific plastic consumption, waste collection, and management, and 2) the need for corresponding standards for EoU HDPE collection and management. Understanding HDPE quantities across the economy is a crucial part of developing a strategic plan to circularize the HDPE market, and thus in addressing the ongoing plastics crisis. Gaining an understanding of historical HDPE flows and identifying potential discrepancies may prevent the propagation of errors going forward and help provide more accurate analyses of the HDPE markets for the coming years. The availability of such accurate and granular data will enable the development of secondary HDPE feedstocks.

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APPENDIX A. DATA SOURCES FOR HDPE FLOWS IN MFA MODELS

TABLE 1: DATA SOURCES FOR SPECIFIC HDPE FLOWS USED IN THE MFA MODELS.

HDPE Flow	Data Source
HDPE Resin Production to Fabrication and Manufacturing (2015)	Di et al. (2021) [7]
Export from HDPE Resin Production (2015)	Di et al. (2021) [7]
Fabrication and Manufacturing to HDPE Use-phase Sectors (2015)	Di et al. (2021) [7]
Fabrication and Manufacturing to Landfill (2015)	Di et al. (2021) [7]
Export from Fabrication and Manufacturing (2015)	Di et al. (2021) [7]
Import (and Exports) to (and from) HDPE Use-phase Sectors (2015)	Di et al. (2021) [7]
HDPE Use-phase Sectors to End-of-Use (2015)	EPA (2016) [29]
End-of-Use to Recycling (2015)	EPA (2016) [29]
HDPE Resin Production to Fabrication and Manufacturing (2019)	Chaudhari et al. (2022) [27]
Imports (and Exports) to (and from) HDPE Resin Production (2019)	Chaudhari et al. (2022) [27]
Imports to Fabrication and Manufacturing (2019)	Chaudhari et al. (2022) [27]
Fabrication and Manufacturing to Incineration and Landfill (2019)	Chaudhari et al. (2022) [27]
HDPE Use-phase Sectors to End-of-Use (2019)	Milbrandt et al. (2022) [12]
End-of-Use to Recycling, Incineration, and Landfill (2019)	Milbrandt et al. (2022 [12]