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Research Article

Method to Develop Potential Business Cases of Plastic Recycling from Urban Areas: A Case Study on Nonhousehold End-Use Plastic Film Waste in Belgium

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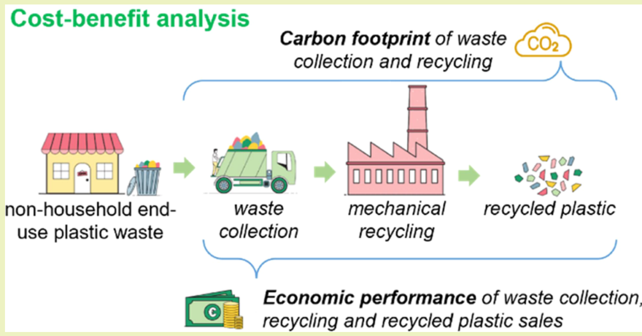
ABSTRACT: Waste management of nonhousehold end-use plastic waste receives considerably less attention compared to household waste. This article develops and applies a cost-benefit analysis model to develop potential business cases for selective collection and mechanical recycling scenarios of nonhousehold end-use plastic film waste from urban areas considering the City of Ghent in Belgium and 12 municipalities nearby as a case study. Three different collection frequencies (weekly, fortnightly, and monthly) and two different mechanical recycling plant layouts (basic and advanced configuration) are considered. Data on waste quantity, composition, and economic parameters are collected from real sampling from urban areas combined with information from the literature. In the most favorable scenarios, results show that the annual costs of collecting and recycling are estimated to be in the range of €635 to €1,445/tonne output, depending on the collection frequencies and plant configurations. Mechanical recycling yields 48−77% regranulates, depending on the plant configuration and feedstock quality. Scale is essential for plastic recycling plant development; a positive net economic balance (ranging from €5 to €537/tonne output) is achieved when at least 10 500 tonnes/year of waste is collected (fortnightly or monthly) and processed. The recycling systems become economically more effective as the processing capacity increases. It is imperative to maintain high feedstock quality as recycling systems become economically less favorable when the residue content in the collected plastic film waste exceeds 30−35%. A greenhouse gas emission calculation indicates that minimizing residue and promoting high-quality feedstock from collected waste are the key to increasing the carbon footprint savings of recycling.



KEYWORDS: *business cases, cost-benefit analysis, nonhousehold end-use plastic film waste, urban areas, carbon footprint*

INTRODUCTION

Europe is the world's second-largest plastic producer, with an estimated 57.9 million tonnes (Mt) of plastic production in 2019.[1] It is estimated that 29.1 Mt of plastic waste was generated in 2019, of which 32% (i.e., 9.4 Mt) was sent to recycling facilities and 68% (i.e., 19.7 Mt) was landfilled and incinerated. This resulted in an estimated 4.0 Mt of recycled plastic (as regranulate) production, which equals a recycling rate of around 15% in 2019.[1−3] Out of 29.1 Mt of waste generated, it is estimated that the packaging sector accounted for 61% (i.e., approximately 17.8 Mt) of the total waste generated.[4] Hestin et al.[5] estimate that 52% (equals around 9 Mt) of the plastic packaging waste in Europe is *nonhousehold end-use plastic waste*—a terminology introduced by Kleinhans et al.,[6] sometimes also called commercial and industrial (C&I) waste. Nonhousehold end-use plastic waste is generated by "end-users" from commercial activities (e.g., wholesales, retail stores, restaurants, coffee shops, cafés, etc.), industrial activities (e.g., manufacture, mining, construction, etc.), and institutional facilities (e.g., schools, offices, etc.). Much of this plastic waste is generated in urban areas such as cities or provinces.[6,7]

Typically, nonhousehold end-use plastic waste is not subjected to public waste management-related legislation.[6] Without such binding regulations, the private market has sent a considerable amount of nonhousehold end-use plastic waste to landfills, incineration, or export outside Europe.[8] A study by Kleinhans et al.[9] indicates that a significant amount of nonhousehold end-use plastic waste is still thrown away in

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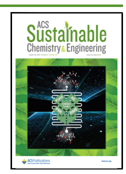

residual bins because of the absence of selective collection systems or economic incentives to recycle their waste.

However, data and studies regarding the flows and recycling potential of nonhousehold end-use plastic waste remain scarce.[5,10,11] One study by Jacobs et al.[8] indicates that more than half of the nonhousehold end-use plastic waste is shipped to countries outside Europe (e.g., Malaysia or Vietnam). This finding aligns with data reported from analysis in the Belgian market, which suggests that a substantial quantity of C&I packaging waste is shipped to countries outside Europe.[12] The waste management practices of the shipped waste at their final destinations are poorly documented, but it is stated that there are concerns related to environmental impact and sustainability.[13] Unlicensed waste management operators in these countries treat plastic waste with improper operating conditions (e.g., obsolete recycling infrastructure and inadequate personal protective equipment). Other possible waste treatments in these countries are illegal dumping, unsanitary landfill, or open burning.[14−17] Thus, for this reason, in 2021, Valipac started a program that allows tracing of the collected and sorted Belgian nonhousehold end-use plastic waste to their final (recycling) destination via external editors to ensure proof of legal and operational complaints.

Currently, few economic incentives for nonhousehold end-use plastic waste exist for recycling in Europe, which results in low recycling capacities.[18−20] One of the key drivers for a considerable amount of plastic waste export is thus cheaper export tariffs compared to those of domestic waste treatment. Nevertheless, from the waste management perspective, recycling nonhousehold end-use plastic waste also has enormous potential to improve regranulate production, increase recycling rate targets, and play a crucial role in the circular economy of plastic in Europe.[6,21]

Nonhousehold end-use plastic waste seems to be "forgotten" as a separate category in waste statistical databases and reports.[6,22,23] Yet, it is an important stream for achieving recycling targets in certain regions, as indicated by Hestin et al.[5] Next to quantity, there is limited information on the waste composition of nonhousehold end-use plastic packaging waste in Europe. However, Hestin et al.[5] estimate that 58% is film (e.g., shrink films, stretch films, refuse sacks, etc.), while the remaining 42% is rigid (e.g., bottles, tubes, trays, etc.). This finding aligns with the study by Bracken[24] and OECD,[22] which indicate that the plastic film is the most prevalent type of C&I waste in the United States and Australia, respectively. Within the nonhousehold end-use plastic film waste, polyethylene (PE) is estimated to be the largest fraction (i.e., 83%), followed by polypropylene (PP) (i.e., 16%) and poly(ethylene terephthalate) (PET) (i.e., 1%). Moreover, it is estimated that the nonhousehold end-use rigid plastic waste consists of 64% high-density polyethylene (HDPE), 19% PP, and 16% PET.[5,25] Some studies indicate that nonhousehold end-use plastic waste tends to have less contamination and impurities than household plastic waste.[5,22,25,26] Horodytska et al.[27] show that the nonhousehold end-use plastic film waste has better feedstock quality for mechanical recycling because the waste stream has a relatively homogeneous composition.

Currently, the business cases of selective collection and recycling of nonhousehold end-use plastic waste from urban areas are done by commercial or voluntary agreements between the waste producers and waste management companies. For example, waste producers and operators in the construction sector can come to an agreement to selectively "pick" only certain high-value waste items, such as windows and doors, for recycling.[28,29] In the agriculture sector in many European countries, waste management is done voluntarily (and agreed upon) between farmers and recyclers. The recyclers usually collect the waste through "a bring" or "a pickup" system, depending on the waste quantity.[30−32] Usually, businesses are encouraged by local governments and extended producer responsibility (EPR) organizations to (voluntarily) sort their waste by material types (e.g., plastic, paper, cardboard, etc.). In some cases, rewards are given to businesses, such as in Belgium, where authorized waste operators collect the waste for recycling, and in return, waste producers receive a one-time premium incentive of €150 (starter incentive) and a recycling incentive of €30/tonne of plastic packaging waste.[12] Recently, significant progress in nonhousehold end-use plastic waste treatment has been made in the Flanders region-Belgium by the ratification of VLAREMA regulations in 2021 (i.e., Flemish regulations concerning the sustainable management of material cycles and waste). In article 8 of VLAREMA, companies are obliged to perform a source separation of up to 24 waste categories, including plastic waste.[33] In compliance with the regulations, companies must establish a partnership with authorized waste collectors, and a compliance certificate will be given by local (regional) authorities (i.e., OVAM, the public waste agency of Flanders responsible for developing environmental policies and reinforcements).[34,35]

In the context of nonhousehold end-use plastic, urban areas are important because of high business densities.[36,37] This makes urban areas crucial to improve the material utilization efficiency of a region(s) and become a source of concentrated secondary resources that can be recycled into valuable materials.[38,39] Extra costs and environmental footprint arise from the conservation of raw materials in urban areas, for example, caused by selective waste collection and recycling.[40,41] Studies from Boskovic et al.[42] and Marques et al.[43] indicate that costs associated with selective collection can account for up to half of the costs of the recycling system. Thus, properly estimating collection costs is crucial in assessing the business case development of nonhousehold end-use plastic waste recycling. The estimation of selective collection costs can be improved by understanding key parameters such as waste quantity and composition from the urban areas, number of collection points, vehicle capacity, and collection frequencies.[42]

Furthermore, the literature suggests that recycling nonhousehold end-use plastic waste is still scattered, less organized, and driven mainly by initiatives between waste producers and waste management companies.[28−32] As a result, the recycling rates of nonhousehold end-use plastic waste are relatively low and are estimated to be around 20−30%.[5,6] Yet, from the environmental perspective, mechanical recycling of the nonhousehold end-use plastic film still outperforms incineration with energy recovery.[27,44]

Therefore, this study develops and applies a method to develop (or predict) potential business cases of selective collection and mechanical recycling of nonhousehold end-use plastic waste from urban areas, focusing on the largest plastic film fraction, as indicated by Hestin et al.[5] The City of Ghent and its 12 neighboring municipalities in Belgium are selected as the case study. The potential business cases of different selective collection and recycling scenarios are predicted by building a cost-benefit analysis (CBA) model. Granular logistic

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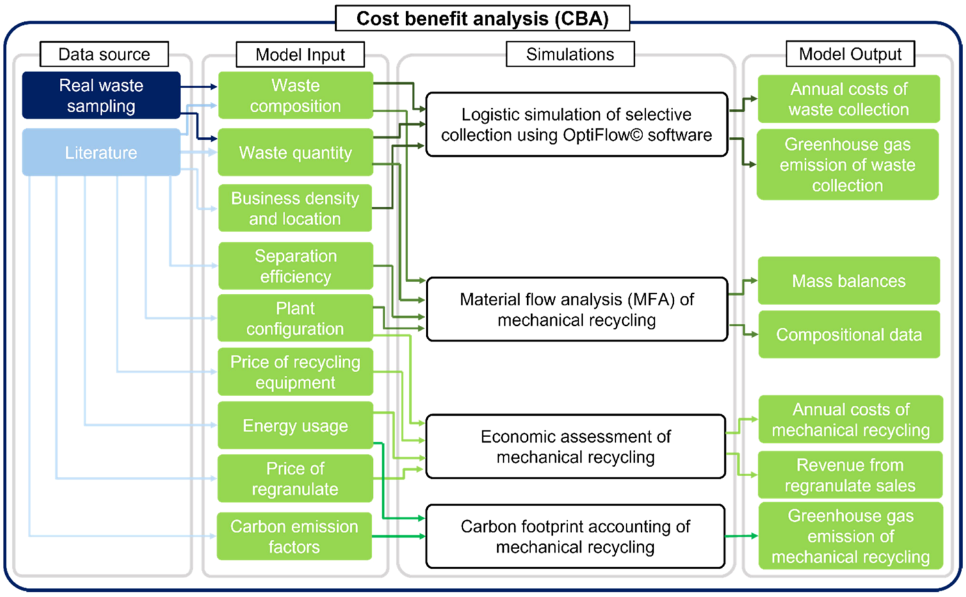

Figure 1. Granular cost-benefit analysis (CBA) model methodology (inputs, simulations, and outputs) in developing business cases for selective collection and mechanical recycling of nonhousehold end-use plastic film waste, including greenhouse gas emission inputs, simulations, and outputs.

simulations, modeling the process flows within mechanical recycling facilities, and quantifying the economics and greenhouse gas (GHG) emission of the entire process are considered in the CBA. The logistic simulations are done in OptiFlow software[45] based on the input from waste operators. The material flows and economic modeling is developed by following the material flow analysis (MFA) and techno-economic assessment (TEA) modeling approach.[46−49] Finally, the GHG emission (in kg CO_2-equiv) is quantified by following the life cycle assessment (LCA) modeling approach.[50−52]

MATERIALS AND METHODS

Overall Modeling Approach. An overview of the business case development using cost-benefit analysis (CBA) modeling of selective collection and recycling of nonhousehold end-use plastic film waste is presented in Figure 1. Two data sources are used in this study: (i) primary data collected from real waste sampling combined with (ii) literature and databases (Figure 1).[46,53,54] Two waste sampling campaigns were conducted for (i) estimation of film waste quantity and (ii) waste compositional analysis. Next, the annual costs of different selective collection schemes from urban areas (weekly, fortnightly, or monthly collection frequencies) are estimated using OptiFlow Route Optimization software.[45] The annual costs of mechanical recycling of nonhousehold end-use plastic film are estimated by combined material flow analysis (MFA) in the recycling plant and economic assessment, as suggested by Larrain et al.,[47] Hernández et al.,[48] and Bashirgonbadi et al.[46] The required inputs for the MFA model are waste quantity and composition, recycling plant configuration, and separation efficiency of equipment used in the recycling plant. Later, the MFA results and data on capital investment and utility consumption are used as the basis for the economic assessment. Furthermore, a sensitivity analysis is carried out to see how residue content in the collected waste (in %) impacts the economic balance of mechanical recycling of nonhousehold end-use plastic film. Lastly, the GHG emission associated with collecting and recycling nonhousehold end-use plastic film waste from urban areas in this study is estimated and compared with the baseline scenario (i.e., virgin PE granulate production with incineration as EoL treatment).

Description of the System Boundary and Baseline Scenarios. This study considers the urban areas of Ghent and its 12 neighboring municipalities in Belgium as a case study (system boundary). The City of Ghent (postcode: 9000−9070) is located in the Flemish Region of Belgium that covers an area of approximately 156 km^2 with a total of 261 483 inhabitants,[55] which equals a population density of 1655 inhabitants/km^2. This study also includes the effect of processing scale (in tonnes/year waste processed) on recycling operations. For this purpose, 12 neighboring municipalities within approximately 10 km (radius) of Ghent are considered, from which the nonhousehold end-use plastic film waste can be collected and processed at the recycling plant hub in Ghent. These municipalities are Sint-Martens-Latem (postcode: 9830), Melle (postcode: 9090), Zelzate (postcode: 9060), Wetteren (postcode: 9230), Merelbeke (postcode: 9820), De Pinte (postcode: 9840), Lokeren (postcode: 9160), Deinze (postcode: 9800), Nazareth (postcode: 9810), Lochristi (postcode: 9080), Evergem (postcode: 9940), and Eeklo (postcode: 9900).

Six NACE sectors (standardized classification for economic activities in Europe[56]) are selected in this study. NACE A: *agriculture, forestry, and fishing*; NACE B: *mining and quarrying*; NACE C: *manufacturing;* NACE D: *electricity, gas, steam, and air conditioning supply;* NACE F: *construction*; and NACE G: *wholesale and retail trade, repair of motor vehicles and motorcycles*. These sectors are selected because they are Europe's biggest nonhousehold end-use plastic producers.[6,56] NACE sector E: *water supply, sewage, waste management and remediation*; NACE sector G 46.77: *wholesale of waste and scrap*; and NACE C.20−22: *manufacture of chemical, pharmaceutical, rubber, and plastic products* are excluded from this study because these sectors do not fall under the definition of "nonhousehold end-use plastic waste". The exclusion of these sectors also prevents double counting on estimating the total waste generation (e.g., from NACE G 46.77) from the considered urban areas in this study.[6]

The four baseline scenarios considered in this study (in Table 1) consist of two waste compositions (high and low feedstock quality), three waste collection frequencies (weekly, fortnightly, and monthly), and two recycling plant layouts (basic and advanced recycling plants), which are elaborated in the following sections. Moreover, in each scenario (S1−S4, Table 1), the processing capacity (i.e., mass input to the recycling plant, in tonnes/year) is varied from 2500 to 20 500 tonnes/year (i.e., maximum processing capacity, in tonnes/year[47]). This approach is taken to investigate how (i) waste composition (i.e., feedstock quality), (ii) selective collection frequencies, and (iii)

Table 1. Summary of Nonhousehold End-use Plastic Film Waste Recycling Scenarios Considered in This Study[a]

scenarios	collection frequencies	waste input composition	recycling plant configuration	processing scale (in tonnes/year)
S1	weekly, fortnightly, and monthly	higher quality	basic recycling plant	2500−20 500
S2	weekly, fortnightly, and monthly	lower quality	basic recycling plant	2500−20 500
S3	weekly, fortnightly, and monthly	higher quality	advanced recycling plant	2500−20 500
S4	weekly, fortnightly, and monthly	lower quality	advanced recycling plant	2500−20 500

[a]Three collection scenarios (weekly, fortnightly, and monthly) are included in each recycling scenario (S1−S4).

recycling processing capacity affect the overall economic balance and viability of the whole recycling chain.

Estimation of Nonhousehold End-Use Plastic Film Waste Quantity and Composition. *Waste Quantity Estimation.* Table 2 provides key examples of the data set used to estimate the quantity of nonhousehold end-use plastic film. The waste quantity is estimated based on real waste sampling in 2018 done by Valipac (i.e., Green Dots company in Belgium responsible for managing C&I waste) in Ghent−Belgium, from 3470 companies within NACE sector A−G. The data collection from waste sampling provides us with the total waste quantity per NACE sector (in tonnes) from several companies. For example, in Table 2, 58 and 400 tonnes of nonhousehold end-use plastic film waste were collected from NACE sector G.45 and NACE sector G.46 during the sampling campaign, respectively. A total of 58 and 400 tonnes of plastic film waste were collected from 261 to 564 companies within NACE sectors G.45 and G.46, respectively. Therefore, the (average) quantities of the nonhousehold end-use plastic film generated per company within NACE sector G.45 and NACE sector G.46 are estimated to be 0.22 and 0.71 tonnes/year.company, respectively. These estimates are calculated by dividing the weight of nonhousehold end-use plastic film waste collected (in tonnes) by the total number of companies that participated in the sampling campaign in 2018, as shown in Table 2.

The next step is estimating the total nonhousehold end-use plastic film waste generation per NACE sector in the whole selected region. This is done by combining (and extrapolating) the data set built from waste sampling in 2018 and Orbis databases.[54] The extrapolation is done by multiplying the (average) waste generated per company with the total active companies listed in the Orbis database[54] (Table 2) within Belgian postal codes 9000−9940. For example, it is estimated that one company within NACE sector G.45 generates 0.22 tonnes of plastic film waste annually, while there are 484 companies within the same NACE sector in Ghent (Postal code: 9000−9070). Therefore, the amount of nonhousehold end-use plastic film waste generated from NACE sector G.45 from urban areas Ghent is estimated to be 107 tonnes/year (i.e., 0.22 tonnes × 484 companies), as shown in Table 2. The complete data set on waste quantity can be found in the Supporting Information (SI), Tables SI1 and SI2. Moreover, it is important to note that we discounted the total active company listed in Orbis databases[54] by 20%. This assumption is made because we observe that some of the offices are empty buildings that generate no plastic waste. Lastly, a similar approach is used to estimate the total nonhousehold end-use plastic film waste generated in the 12 neighboring municipalities. More information on waste quantity from the 12 selected municipalities can be found in SI-Section 3.

Waste Compositional Analyses. Two waste compositions in the baseline scenarios (higher or lower quality) as feedstocks to recycling plants are considered in this study (Table 3). Our real waste sampling was performed between December 2021 and February 2022 by GRCT (a waste management company in Belgium), with a total of 34 companies participating. The results of our waste sampling are listed in Table 3. The waste sampling campaign was performed to determine waste compositional data of nonhousehold end-use plastic film covering *Wholesale* (e.g., NACE G.46), *Retail* (e.g., NACE G.47),

Table 3. Waste Compositions Used as an Input for the CBA Model[a]

		composition (in %)		averaged composition (in %)	
waste category	characteristics	waste sampling	Hestin et al.[5]	[b]higher feedstock quality	[b]lower feedstock quality
PE film	transparent	50	79	48	38
	colored	36		35	27
PP film	transparent	3	15	5	4
	colored	3		5	4
other films	(PVC, PET, etc.)	4	1	2	2
residue		[c]5	[c]5	[c]5	[d]25
total		100	100	100	100

[a]The composition used in the model is averaged from the waste sampling campaign conducted in urban areas of Ghent in December 2021−February 2022, combined with data from Hestin et al.[5] A more detailed compositional analysis based on the waste sampling in urban areas of Ghent is available in SI-section 4. [b]The higher feedstock quality corresponds to 5% residue content. The lower feedstock quality corresponds to 25% residue content. In waste compositions, the share of the other waste category (i.e., PE transparent, PP colored, etc.) remains proportionally the same. [c]Residue content (i.e., 5%) is taken from previous studies.[57,58] [d]Residue content (i.e., 25%) is taken from the previous study,[59] while the share of the other waste category (i.e., PE transparent, PP colored, etc.) is maintained.

Table 2. Examples of Datasets from Waste Sampling Conducted in Ghent−Belgium in 2018 and Total Active Companies based on Orbis Database[a,54]

	data set from waste sampling in 2018 done by Valipac			orbis[54]	extrapolation
NACE sectors: codes and names	waste quantity	number of companies	waste generated per company	total active companies	total waste generated
G—wholesale and retail trade; repair of motor vehicles and motorcycles					
G45—wholesale and retail trade and repair of motor vehicles and motorcycles	58	261	0.22	484	107
G46—wholesale trade, except for motor vehicles and motorcycles	400	564	0.71	2128	1508
G47—retail trade, except of motor vehicles and motorcycles	429	1065	0.40	3386	1354

[a]The complete dataset is available in Tables SI1 and SI2. *Units*: waste quantity (*tonne*), waste generated per company (*tonne/year.company*), and total waste generated (*tonne/year.NACE sector*).

Figure 2. Few images of the collected samples from the *Construction* sector (e.g., NACE sector F.41) from urban areas of Ghent, consisting of a transparent PE film (A), colored PE film (B), transparent PP film (C), colored PP film (D), and other plastic films (E). More information on the samples is available in SI-section 4.

Construction (e.g., NACE F.41), *Logistics* (e.g., NACE H.49), and "*other*" sectors (e.g., NACE C.10, NACE C.18, etc.). A few key examples of the collected waste during the waste sampling campaign are provided in Figure 2. More information on the waste samples is available in SI-section 4. Moreover, Table 3 also provides nonhousehold end-use plastic film composition estimated by Hestin et al.[5] Finally, the waste composition of these two studies is averaged and used as an input for the CBA.

The residue content was not determined systematically during waste sampling (e.g., level of moisture and dirt measurement); hence, it is estimated from the literature. The higher feedstock quality is assumed to contain 5% of residue, which is taken from previous studies.[57,58] The lower feedstock quality assumes a higher residue content (i.e., 25%),[59] while the share of the waste composition of the other waste categories is maintained.

Sensitivity Analyses on Residue Content. Lase et al.[53] show that ±25% of changes in waste composition can affect the recycling performance of household flexible packaging waste treatment. Therefore, in this study, sensitivity is carried out to assess the impact of potential variation on the nonhousehold end-use plastic film waste composition (by means of higher residue content, in %) entering the two recycling plants (i.e., basic and advanced recycling plants). In the sensitivity analysis, the recycling plant capacity of both plants is fixed on the amount of waste collected from the urban areas considered in this study (Ghent and 12 neighboring municipalities in Belgium). The residue content is increased incrementally (5% interval) from 5% up to 50%. At every interval variation, the results of the recycling yield and net economic balance are recorded and discussed.

Logistic Simulation of Nonhousehold End-Use Plastic Film Waste Selective Collection From Urban Areas. A logistic simulation of collecting nonhousehold end-use plastic film waste from urban areas is carried out using OptiFlow Route Optimization software.[45] Three selective collection scenarios are developed: weekly, fortnightly, or monthly waste collection frequencies. It is assumed that the diesel garbage trucks (Euro 6 standard garbage trucks with 40 m^3 capacity) begin the selective collection from the mechanical recycling facility (hub) located in the Port of Ghent−Belgium. Averaged data for loose LDPE films (17 kg/m^3) is used to convert the mass-based data of waste quantity (in tonnes) into volume-based data needed for logistic simulations.[60,61] Moreover, a compaction factor of 10 (estimated value communicated by waste operators) is used in the logistic simulations when the garbage trucks compress the collected plastic film waste.

The garbage trucks collect nonhousehold end-use plastic film waste from companies listed in Tables SI2 and SI3, in which the addresses are collected from Orbis databases.[54] The number of garbage trucks needed for collecting nonhousehold end-use plastic waste depends on the number of companies and collection frequencies per municipality, in which the data points are provided in SI-section 5. It is assumed that the truck's speed is limited to 30 km/h, following the standard

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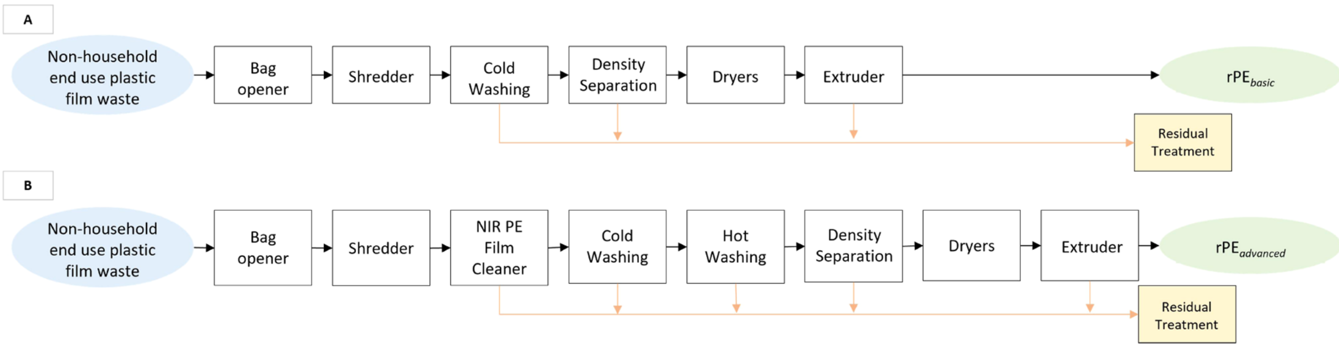

Figure 3. Flow diagram of (A) a basic recycling process and (B) an advanced recycling process considered in this study adapted from previous studies.[47,53]

speed limit in Belgian urban areas.[62] The average service time stop (at each address) is 8 min, and the unloading time at the recycling facility is assumed to be 10 min. Moreover, the truck will make another trip if there is still time available to make another waste collection, assuming that the waste collection is done from 08.00 to 18.00. The estimated waste collection and unloading time are obtained from waste operator input. Finally, the estimated driver cost is €19.5/h with an operational cost (incl. fuel and costs associated with purchasing the truck) to be €0.74/km (on average), which is also based on the communication with waste operators.

Modeling Material Flows in the Mechanical Recycling Plants. *Plant Designs.* This study assumes that the recycling plant is designed for recycling PE film waste, as it is found to be the largest fraction of the nonhousehold end-use plastic film waste (Hestin et al.[5] and Table 3). Two recycling configurations are considered, i.e., the basic recycling plant (Figure 3A) and advanced recycling plant (Figure 3B), adapted from Larrain et al.[47] and Lase et al.[53] It is assumed that the recycling plants can process up to (max. capacity) around 20 500 tonnes/year of waste, equivalent to up to around 2.5 tonnes/h processing capacity.[47]

The basic recycling plant (Figure 3A) consists of a bag opener, shredder, cold washing, density separation, dryers, and a single melt filter extruder. The nonhousehold end-use plastic film waste is assumed to be collected in plastic bags, which are open and then shredded into a material size of roughly 10 mm. After that, the plastic waste stream is washed with "cold" water (25−40 °C), removing contaminants like organic residue, paper, and labels. The cold washing is then followed by density separation to remove higher-density polymers (e.g., PET), metals, and other residues. The floating plastics (mainly polyolefin) are dried using mechanical and thermal drying and then extruded.[47,53,63] According to Bashirgonbadi et al.,[46] additional sorting and hot washing can improve recycling performance, regranulates' quality, and net economic balance of recycling operation. Hence, in the advanced recycling process (Figure 3B), a NIR PE Film Cleaner (i.e., negatively sorting non-PE film items) and "hot" washing (up to around 80 °C with detergents) are introduced. The described recycling process is expected to produce regranulates rich in the PE film, which is called 'rPE$_{basic}$' or 'rPE$_{advanced}$' in this article.

Separation Efficiency. The MFA of nonhousehold end-use plastic in the recycling plant is predicted based on separation efficiency (shown in %), representing the separation of waste items or categories at each recycling equipment. The summary of the separation efficiency used in this research is presented in SI-section 6. Specifically, the separation efficiency of NIR LDPE Cleaner is averaged from the studies of Lase et al.[53] and Kleinhans et al.[64] As for the cold washing, density separation, and extrusion with a single filter and degassing unit, the separation efficiency is averaged from the study by Lase et al.[53] and Brouwer et al.[63]

Economic Assessment of Selective Collection and Recycling Nonhousehold End-Use Plastic Film Waste. The economic assessment of nonhousehold end-use plastic film waste management demonstrates the difference between the costs incurred by waste collection (i.e., the results of the logistic simulation) and mechanical process and the revenue from regranulate sales, i.e., rPE$_{basic/advanced}$.[46,48,65,66] The estimation of capital investment for the mechanical recycling plant follows the approach described by Sinnott and Towler,[67] which is also applied in previous studies.[46−49] The estimated total investment includes the price of individual recycling equipment (in Figure 3) and additional procuring, transport, installation, and running test of the equipment, engineering and project management, and site infrastructure (i.e., building the recycling plant itself). The total investment per piece of equipment is provided in Table SI5, and the economic modeling parameters are provided in Table SI6.

The annual costs of recycling are estimated by calculating the energy costs (i.e., electricity, natural gas, water, and fuel) and residual treatment (incl. transport of residue), fixed and variable production costs (i.e., labor, repair and maintenance, depreciation, and insurance), and general plant overhead expenses (i.e., office expenses, human resources, finance, legal, information technology, etc.). The energy consumption data are estimated from previous studies.[47,49,50,68] In this research, the investment of recycling equipment is depreciated for 6 years and the recycling plant for ten years. The annual cost of insurance, repair, and maintenance for the recycling equipment is set to be 1.5 and 4.0% of the total investment, respectively.[46,47] More information on the energy consumption (i.e., electricity, natural gas, etc.) of each recycling equipment can be found in Table SI8.

The revenue stream of the recycling operation is generated from the regranulate sales (i.e., rPE$_{basic/advanced}$). The range of regranulate prices in this study is taken from the literature.[46,47,69,70] The price of rPE$_{basic}$ is assumed to range from €600/tonne (lower price) to €1000/tonne (higher price) (with a central price of €800/tonne). On the other hand, it is assumed that rPE$_{advanced}$ can reach up to €1500/tonne (higher price). The lower price for rPE$_{advanced}$ is set to €900/tonne, and the central price is set to €1200/tonne. Note that the regranulate prices used in this study are on the higher end of a typical regranulate price shown in the literature.[46,47] This assumption is made because nonhousehold end-use plastic film waste is typically a homogeneous waste stream containing fewer contaminants or impurities than household film waste recycling.[27,44]

Estimation of Greenhouse Gas Emission Associated with Mechanical Recycling of Plastic Film Waste from Urban Areas. The system boundary for carbon footprint calculations (kg CO_2-equiv) starts when the nonhousehold end-use plastic film waste is selectively collected from urban areas (in different collection frequencies). Starting with the zero burden assumption of the waste,[50,71] the selectively collected nonhousehold end-use plastic film waste will be transported to a recycling facility (hub), which is assumed to be located at the Port of Ghent−Belgium. The functional unit of this calculation is defined as 1 tonne of rPE$_{basic/advanced}$ produced through mechanical recycling. While comparing the results, the GHG emission of producing virgin PE granulate and incineration (as EoL treatment in status quo) is considered as the benchmark, which is also applied in previous studies.[51,52]

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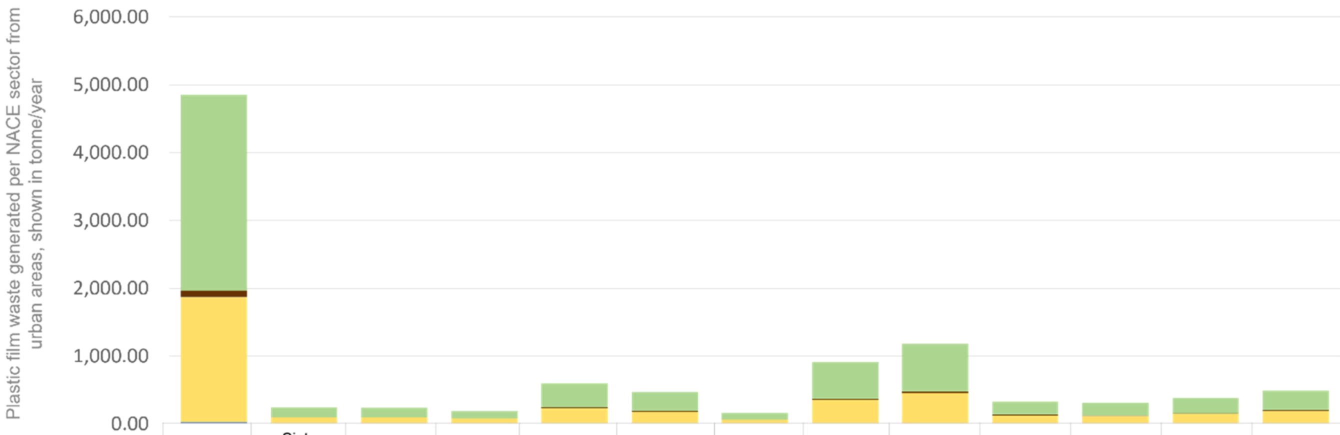

	Ghent	Sint-Martens-Latem	Melle	Zelzate	Wetteren	Merelbeke	De Pinte	Lokeren	Deinze	Nazareth	Lochristi	Evergem	Eeklo
NACE G	2,888	146	143	117	358	279	95	543	701	198	184	231	294
NACE F	95	5	5	4	12	9	3	18	23	6	6	8	10
NACE D	3	0.2	0.2	0.1	0.4	0.3	0.1	0.6	0.8	0.2	0.2	0.3	0.3
NACE C	1,848	93	91	75	229	179	61	348	450	127	118	148	188
NACE B	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
NACE A	24	1	1	1	3	2	1	5	6	2	2	2	2

NACE A. *Agriculture, forestry and fishing* NACE B. *Mining and quarry* NACE C. *Manufacturing*
NACE D. *Electricity, gas, steam and air conditioning supply* NACE F. *Construction* NACE G. *Wholesale and retail trade*

Figure 4. Estimated quantity (in tonnes/year) of nonhousehold end-use plastic film waste from urban areas considered in this study (per NACE sector A−G), excluding NACE sector E *Water Supply, Sewage, Waste Management, and Remediation* because it does not fall under the definition of 'nonhousehold end-use plastic'.[6]

Table 4. Results of the Logistic Simulations to Selectively Collect 10 401 Tonnes/Year Nonhousehold End-Use Plastic Film Waste from Urban Areas

municipality (postcode)	number of stops			total traveled distance (in km/year)			total annual costs (€/year)			costs per tonne collected waste in each respective municipality (€/tonne)		
	weekly	fortnightly	monthly	weekly	fortnightly	monthly	weekly	fortnightly	monthly	weekly	fortnightly	monthly
Ghent (9000−9070)	13 973	13 973	13 999	319 592	256 386	214 044	€2 396 264	€847 470	€310 624	€493	€174	€64
Sint-Martens-Latem (9830)	552	552	554	16 120	14 196	13 068	€111 332	€35 321	€20 904	€454	€144	€85
Melle (9090)	630	630	631	14 456	13 650	10 416	€110 032	€35 438	€18 936	€458	€148	€79
Zelzate (9060)	517	517	517	14 716	11 856	10 608	€91 988	€33 605	€18 390	€467	€171	€93
Merelbeke (9820)	1146	1146	1151	31 720	34 242	24 300	€197 912	€75 998	€40 218	€421	€162	€86
De Pinte (9840)	337	337	337	9412	7904	6924	€57 668	€25 116	€14 484	€360	€157	€91
Lokeren (9160)	1778	1778	1784	74 828	65 728	56 880	€359 476	€139 802	€75 429	€393	€153	€83
Nazareth (9810)	710	710	715	30 680	27 404	26 076	€124 072	€65 884	€30 996	€372	€198	€93
Deinze (9800)	2000	2000	2000	98 800	82 836	68 892	€420 914	€160 576	€83 982	€356	€136	€71
Lochristi (9080)	932	932	932	18 252	14 196	12 600	€159 536	€58 643	€20 088	€514	€189	€65
Evergem (9940)	1031	1031	1037	25 636	18 642	17 376	€171 080	€60 424	€24 564	€441	€156	€63
Eeklo (9900)	1232	1232	1234	51 480	47 892	38 496	€240 916	€86 060	€49 548	€486	€174	€100
Wetteren (9230)	1386	1386	1391	47 372	43 550	37 644	€237 848	€100 607	€45 414	€395	€167	€75
total	26 070	26 070	26 125	753 064	638 482	537 324	€4 679 038	€1 724 944	€753 577	€450[a]	€166[a]	€73[a]

[a]The total selective collection cost per tonne of all nonhousehold end-use plastic film waste, as shown in Figure 4.

The estimated GHG emission from the selective collection in different frequencies (weekly, fortnightly, monthly) is obtained from logistic simulation in OptiFlow software,[45] which is estimated to be 0.165 kg CO_2-equiv/tkm and benchmark against Ecoinvent v3.8 databases (Table S9). Note that the emission factor for selective collection is well-to-wheels (WTW), which implies that the GHG includes the emission at fuel production, transport, distribution, and waste collection from urban areas. The GHG emission from mechanical recycling of nonhousehold end-use plastic film is estimated by calculating the energy usage (electricity, natural gas, and fuel) and assuming that the recycling residues are treated by incineration. The GHG emission (in kg CO_2-equiv) is estimated by multiplying the carbon emission factors with the associated energy usage in the mechanical recycling operation. Data on energy usage for mechanical recycling is obtained from the literature[46,47,49,50,68] and is available in Table SI8. The emission factors (e.g., kg CO_2-equiv/

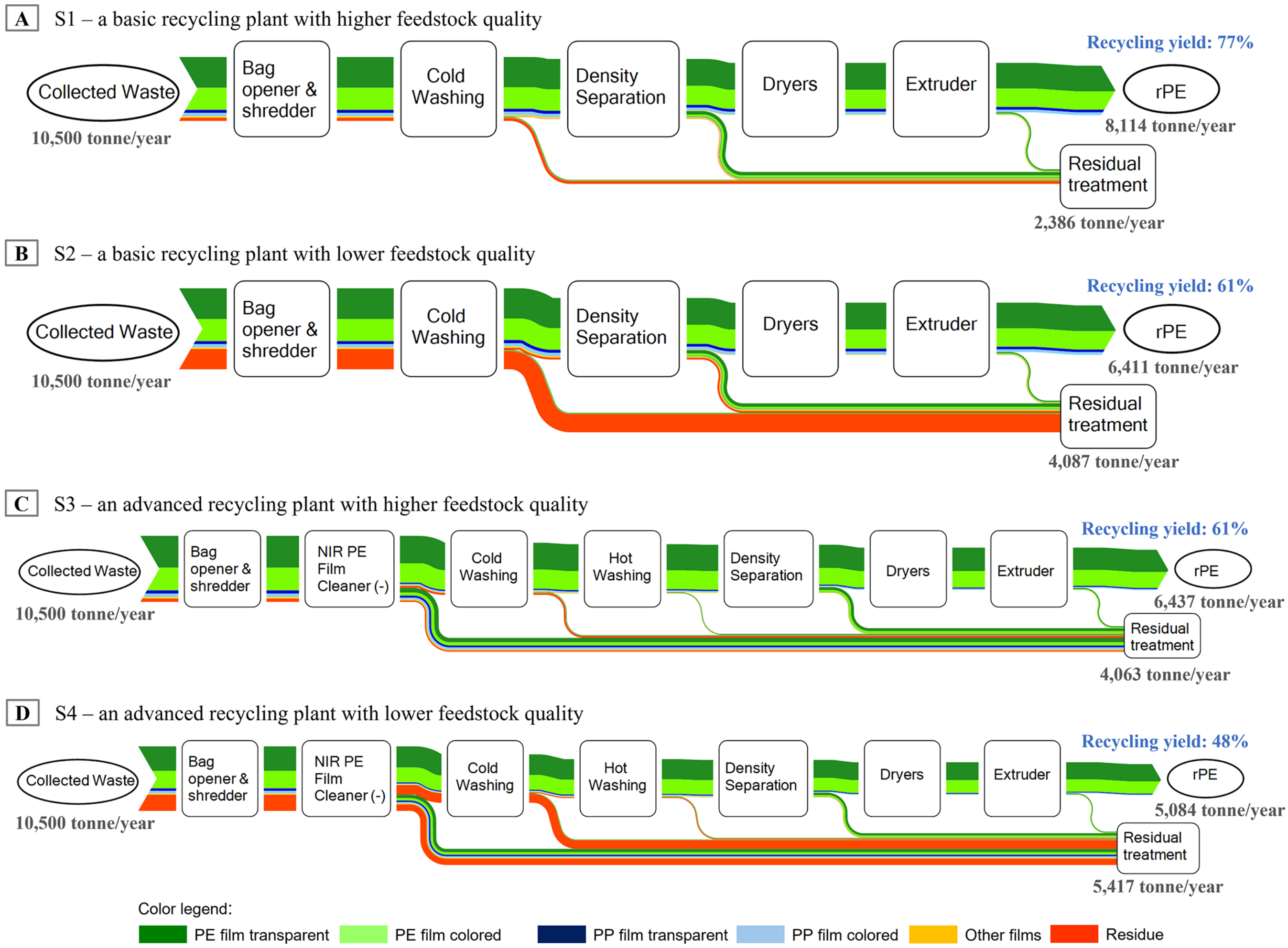

Figure 5. Results of material flow analysis of nonhousehold end-use plastic film recycling in different scenarios: S1, a basic recycling plant with higher feedstock quality (A); S2, a basic recycling plant with lower feedstock quality (B); S3, an advanced recycling plant with higher feedstock quality (C); and S4, an advanced recycling plant with lower feedstock quality (D). This figure only shows the material flow of 10,500 tonnes/year capacity. More information on the other processing capacities (i.e., from 2500 to 20 500) is available in SI-section 9.

kWh) are obtained from Ecoinvent v3.8 databases used in SimaPro v.9, which is also used in previous studies.[50,72] A list of emission factor data sets can be found in the Supporting Information Table SI9, which is based on the ReCiPe 2016 (H) Midpoint impact assessment method.[73]

RESULTS AND DISCUSSION

Estimated Quantity of Nonhousehold End-Use Plastic Film Waste. Figure 4 highlights the estimated total waste quantity of nonhousehold end-use plastic film waste generated in urban areas of Ghent and its 12 neighboring municipalities in Belgium. From Ghent, it is estimated that 4858 tonnes/year of nonhousehold end-use plastic film waste is generated annually. From all urban areas considered in this study, it is estimated that more than 10 400 tonnes of nonhousehold end-use plastic film waste can be collected. The amount of waste generated per municipality varies between 160 tonnes/year in De Pinte (postcode—9840) to 1182 tonnes/year in Deinze (postcode—9800).

The largest waste producer is NACE sector G. *Wholesale and retail trade* (i.e., 2887 tonnes/year), followed by NACE sector C. *Manufacturing* (i.e., 1848 tonnes/year). In the studied areas, a relatively low quantity of nonhousehold end-use plastic film waste is generated from NACE sector A. *Agriculture, forestry, and fishing* (i.e., 24 tonnes/year), NACE sector F. *Construction* (i.e., 95 tonnes/year), and NACE sector D. *Electricity, gas, steam, and air conditioning supply* (i.e., 3 tonnes/year). Figure 4 shows that NACE sector G accounts for 61% of the total waste generated, followed by NACE sector C with 38%. Together, the two sectors account for 99% of total nonhousehold end-use plastic film waste generation, which aligns with the findings of Kleinhans et al.[6] The next chapter discusses the result of logistic simulations, mechanical recycling performance, and the economic performance of collecting and recycling nonhousehold end-use plastic film waste from urban areas.

Logistic Simulation Results of Nonhousehold End-Use Plastic Film Waste Selective Collection. The results of the logistic simulations of nonhousehold end-use plastic film waste selective collection of different frequencies can be found in Table 4. More detailed results are provided in SI-section 8. It can be observed from Table 4 that the number of stops is higher than the total companies listed in the Orbis (2022) databases (in SI, Tables SI2 and SI3) because, typically, the garbage trucks need to make more than one trip to collect the waste generated from urban areas. Moreover, the estimated annual distance (in km/year) of selective collection in Ghent (postcode:9000−9070) ranges between 214 044 and 319 592 km/year, depending on the collection frequencies. The

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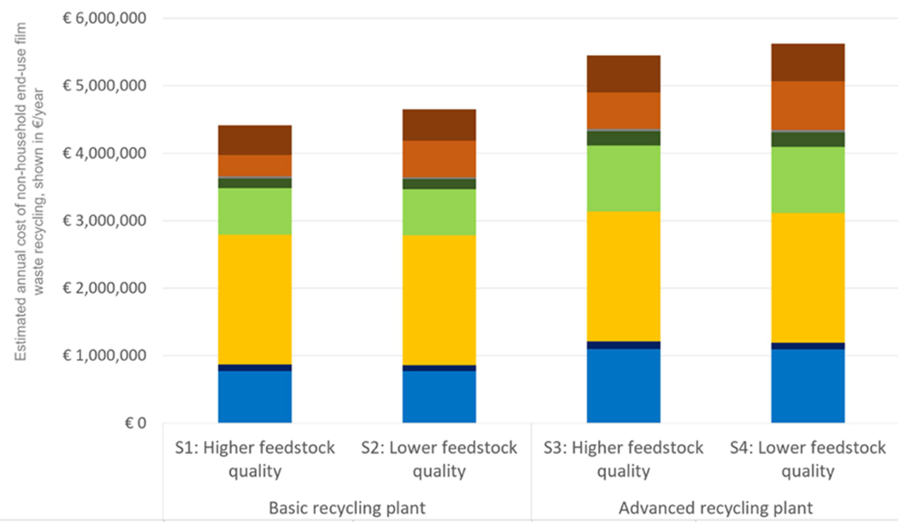
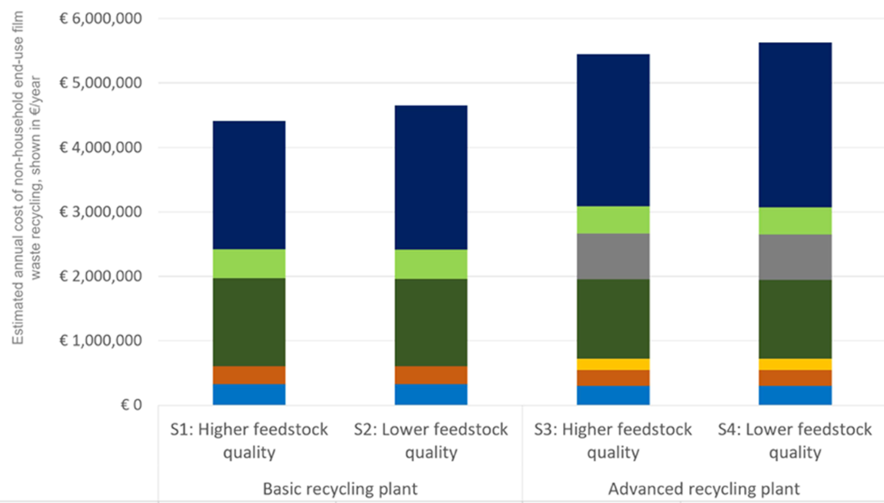
A



	S1: Higher feedstock quality (Basic recycling plant)	S2: Lower feedstock quality (Basic recycling plant)	S3: Higher feedstock quality (Advanced recycling plant)	S4: Lower feedstock quality (Advanced recycling plant)
Energy (incl. electricity, gas, fuel)	€ 771,039	€ 768,817	€ 1,095,855	€ 1,094,102
Water conspumtion (incl. wastewater treatment	€ 98,377	€ 89,485	€ 115,260	€ 98,180
Labour	€ 1,926,000	€ 1,926,000	€ 1,926,000	€ 1,926,000
Depreciation	€ 685,667	€ 685,667	€ 977,680	€ 977,680
Repair and maintenance	€ 149,600	€ 149,600	€ 213,312	€ 213,312
Insurance	€ 26,180	€ 26,180	€ 37,330	€ 37,330
Residual treatment	€ 315.953	€ 542,388	€ 538,150	€ 717,933
General expenses	€ 441,424	€ 465,349	€ 544,843	€ 562,733

B



	S1: Higher feedstock quality (Basic recycling plant)	S2: Lower feedstock quality (Basic recycling plant)	S3: Higher feedstock quality (Advanced recycling plant)	S4: Lower feedstock quality (Advanced recycling plant)
Bag opener	€ 327,081	€ 327,081	€ 298,191	€ 298,191
Shredder	€ 274,098	€ 274,098	€ 245,208	€ 245,208
NIR LDPE Cleaner	€ 0	€ 0	€ 176,066	€ 176,072
Cold washing (incl. mechanical and thermal dryers)	€ 1,370,507	€ 1,361,616	€ 1,233,827	€ 1,224,086
Hot washing (incl. mechanical dryers)	€ 0	€ 0	€ 712,351	€ 705,012
Extrusion	€ 449,010	€ 449,010	€ 420,120	€ 420,120
Recycling plant (incl. handling stations, residual treatment & general expenses)	€ 1,993,543	€ 2,241,671	€ 2,362,667	€ 2,558,629

Figure 6. Costs breakdown of mechanical recycling (10 500 tonnes/year capacity, shown as example) of nonhousehold end-use plastic film waste (A) by cost modeling parameters (energy use, water consumption, depreciation, etc.) and (B) by recycling equipment (incl. residual cost and general expenses that are attributed to the cost of the recycling plant).

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estimated annual distance for the other considered municipalities in this study ranges between 6924 km/year (monthly collection in De Pinte—9840) and 98 800 km/year (weekly collection in Deinze—9800). Table 4 shows that weekly selective collection in Ghent costs €2 396 264 annually (equals €493/tonne collected waste), while fortnightly and monthly selective collection costs €847 470 (equals €174/tonne collected waste) and €310 624 (equals €64/tonne collected waste) annually, respectively. The annual selective collection costs for the other municipalities considered in this study are estimated to range from €14 484 (equals €91/tonne collected waste) for monthly collection in De Pinte to €420 914 (equals €356/tonne collected waste) for weekly waste collection in Deinze.

From Table 4, we can observe that the annual distance traveled (in km/year) for fortnightly and monthly collection (on average) is 15 and 26% less than weekly collection, respectively. Consequently, the fortnightly and monthly collection costs (in €/year) are 62 and 81% lower (on average) than the weekly collection costs. In Ghent, the fortnightly and monthly collection costs are 65 and 87% lower than that for collecting the waste weekly. For the other municipalities, the weekly to fortnightly and monthly collection reduction ranges from 47 to 68% and 75 to 87%, respectively. For the companies (waste producers), different collection schemes would require the purchase of different garbage bin sizes. Companies are required to have bigger garbage bins (e.g., 240−2000 L capacity) when the collection is less frequent (e.g., monthly) compared to a more frequent collection (e.g., 120−240 L garbage bins for weekly collection).[42,74,75] Several options are available for companies, such as purchasing (€70−€350/piece, depending on the size) or renting the garbage bins (€10−€25/month, depending on the size). Note that larger garbage bins require companies to make more space to store their waste.[74−76]

Material Flow Analysis of Nonhousehold End-Use Plastic Film Waste Recycling. The material flow analysis (i.e., Sankey diagram) of nonhousehold end-use plastic film recycling can be found in Figure 5. The recycling yield from a basic recycling plant ranges from 77% when processing higher feedstock quality to 61% when processing lower feedstock quality. As for the advanced recycling plant, the recycling yield ranges from 61 to 48% when processing higher and lower feedstock quality, respectively.

Furthermore, rPE_{basic} is expected to consist of 89% PE and 11% PP, while the expected composition for $rPE_{advanced}$ is 95% PE and 5% PP (Figure SI26). The non-polyolefin material in $rPE_{basic/advanced}$ is expected to be less than 1%. From these results, we can observe that the introduction of additional sorting (using NIR PE Film Cleaner) can improve the $rPE_{advanced}$ quality, at the cost of the recycling yield decreases. More detailed information on the mass input−output from basic and advanced recycling in various processing capacities can be found in SI-section 9.

Overall, the estimated mechanical recycling yields for basic and advanced recycling plants are comparable to the reported mechanical recycling yield in previous studies, i.e., ranges between 60 and 80%.[27,53,63] Moreover, it can be observed that the advanced recycling plant has a lower recycling yield and, subsequently, lower annual $rPE_{advanced}$ production (more in SI-section 9). This is mainly caused by additional (mis)sorting of nonhousehold end-use plastic film waste at NIR PE Film cleaner and a relatively small loss after the hot washing step. However, this can be considered as an unavoidable loss caused by recycling equipment and operation, but a higher quality of regranulate can be expected from such improved recycling processes,[27,46,53] as also shown in Figure SI26.

Economic Assessment of Mechanical Recycling of Nonhousehold End-Use Plastic Film. *Breakdown of the Capital Investment and Annual Costs of the Mechanical Recycling Plant.* The estimated total capital investment (in SI, Figure SI27) needed to build the recycling plants (basic and advanced layouts) is around €5 million and €7 million, respectively, based on the calculations provided in SI-section 6. The investment in washing, extruder, and construction of mechanical recycling plant accounts for 78−82% of the total investment needed. The capital investment in washing and extruder units makes up 28 and 26% of the total investment needed in the basic recycling plant configuration, respectively. For the advanced recycling plant, the washing and extruder constitute 39 and 19% of the total investment needed, respectively (Figure SI27).

When looking at different processing scales (i.e., ranges between 2500 and 20 500 tonnes/year), the annual costs of basic recycling plants vary between €4.1 and €5.3 million per year. Higher annual costs for advanced recycling plants can be expected, ranging from €4.9 to €6.5 million per year, depending on the scale (available in the SI, Table S10). Introducing *NIR PE Film Cleaner* and *Hot Washing* steps increases the annual costs by 21−23% annually.

The detailed breakdown of the annual costs of mechanical recycling nonhousehold end-use plastic film with 10 500 tonnes/year capacity (fixed capacity, shown as an example) is provided in Figure 6. Figure 6A shows the annual costs per cost parameter (energy usage, water consumption, etc.), while Figure 6B shows the annual costs per equipment used in recycling (extruder, washing, etc.). The labor cost, depreciation, and energy usage constitute 35−45, 15−18, and 17−20% of annual mechanical recycling costs, respectively (Figure 6A). The three cost parameters (labor, depreciation, and energy costs) are estimated to make up 73−77% of the annual costs associated with nonhousehold end-use plastic film waste recycling in this study.

Focusing on the costs per equipment used in the mechanical recycling operation, the cost of recycling plant operations (incl. handling stations, residual treatment, and general expenses) accounts for 43−48% of the annual costs (Figure 6B). Note that this study assumes that the investment for the recycling plant is depreciated over ten years. Next, the costs associated with washing (cold and hot) and extrusion processes account for 29−36 and 7−10% of the annual costs, respectively. These findings align with the study of Bashirgonbadi et al.[46] and Larrain et al.,[47] which suggest that washing and extrusion processes are equipment with the highest annual costs in mechanical recycling of the polyolefin flexible plastic film.

Looking at different feedstock qualities, we can observe that the annual cost increases by 3−5% (i.e., equals €180 000 to €240 000 annually) when the residue content increases from 5 to 25% (i.e., S1 vs S2 or S3 vs S4) (Figure 6). For the basic recycling plant (S1−S2), the annual costs of processing 10 500 tonnes/year plastic film waste from urban areas increase from around €4.4 to €4.6 million per year. Similarly, the annual costs of processing 10 500 tonnes/year of plastic film waste from urban areas through the advanced recycling plant (S3−S4) increase from €5.4 to €5.6 million. Such a considerable increase in annual costs is mainly attributed to a higher annual

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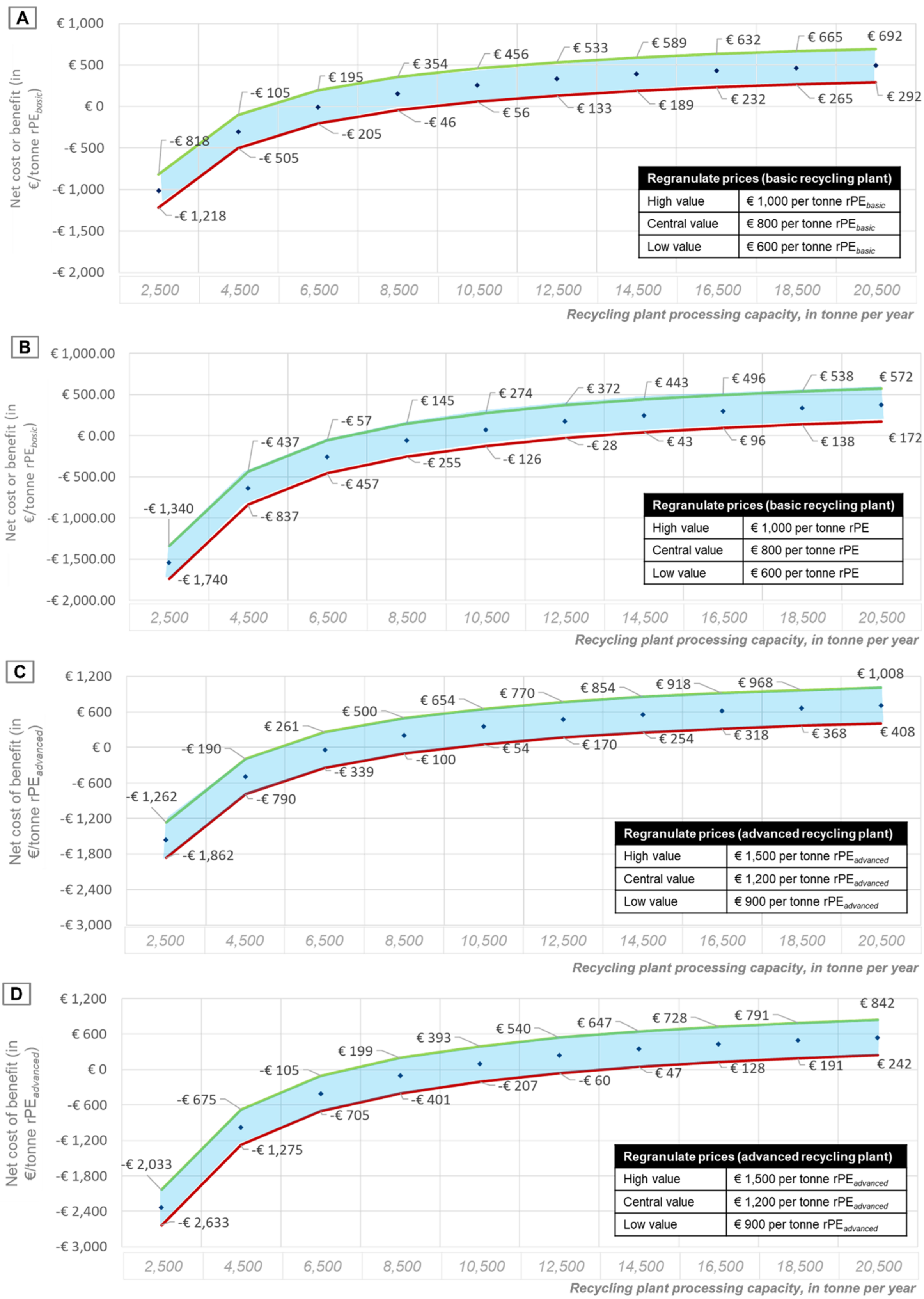

Figure 7. Estimated net loss or profit (green line, high regranulate price; red line, low regranulate price; blue dots, central regranulate price) of nonhousehold end-use plastic film waste recycling in S1(A), S2(B), S3(C), and S4(D). The costs and revenue are shown in €/tonne rPE Film (*y*-axis) across different recycling plant processing capacities (*x*-axis, from 2500 tonnes/year up to 20 500 tonnes/year capacity). These graphs exclude gate fees. Collection costs are listed in Figure 9.

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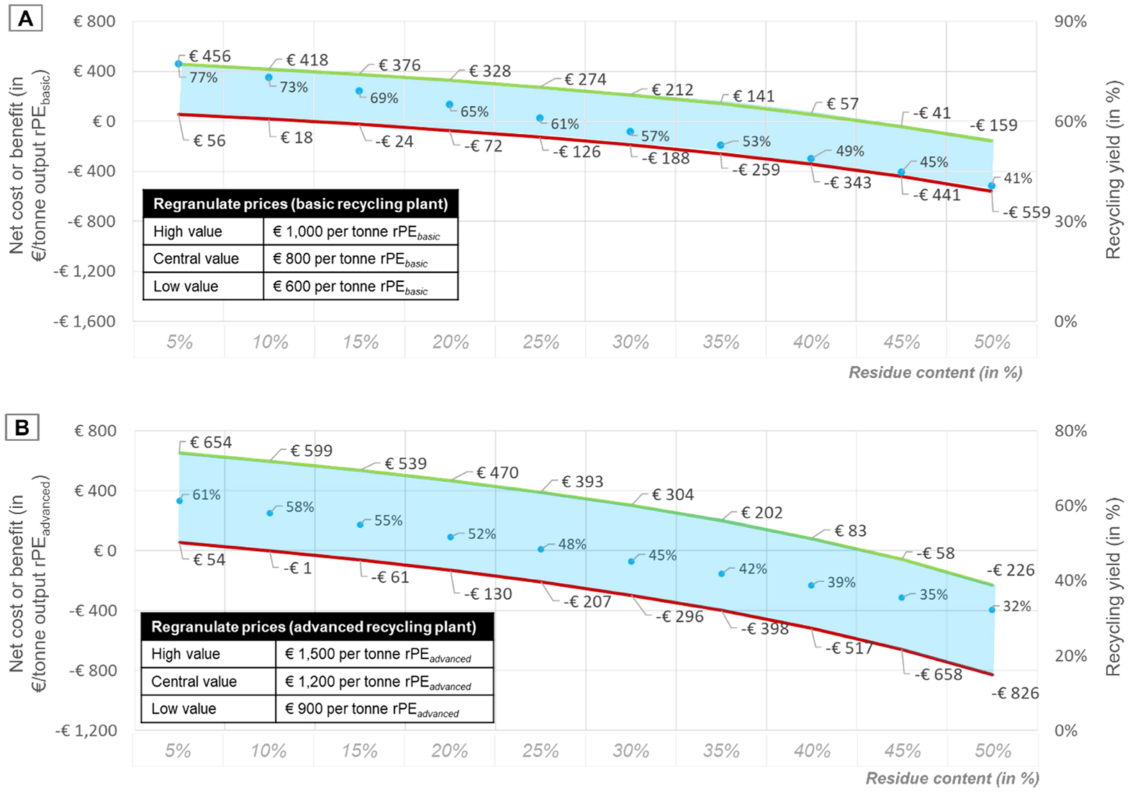

Figure 8. Sensitivity analysis toward recycling yield (blue dots) and net cost or benefit of nonhousehold end-use plastic film waste recycling: (A) basic recycling plant and (B) advanced recycling plant. The green line shows the net cost/benefit of high regranulate prices, while the red line shows the net cost/benefit of low regranulate prices. In this figure, the recycling plant capacity is fixed at 10 500 tonnes/year, which equals the nonhousehold end-use plastic waste collected from the urban areas considered in this study.

cost of residual treatment (equals €132.5/tonne residue in this study), which is €542 388 and €717 993 in S2 and S4, respectively (light brown bars in Figure 6B).

Scale Dependency on Mechanical Recycling. Figure 7 presents the net economic balances (i.e., net cost or benefit, in €/tonne $rPE_{basic/advanced}$) of recycling nonhousehold end-use plastic film waste for all scenarios (S1−S4). The green and red lines refer to the net economic balances of the recycling plant (in S1−S4) when the regranulate prices are high and low, respectively. The blue dots refer to the net economic balance of the recycling plant when the central regranulate price is considered. The blue area (between green and red lines) illustrates the potential variations of net economic balances given volatile regranulate prices. More information on the cost and revenue per one tonne of $rPE_{basic/advanced}$ production from mechanical recycling in different recycling capacities (ranges from 2500 to 20 500 tonnes/year) is provided in the SI, Table SI10.

The results in Figure 7 suggest that recycling nonhousehold end-use plastic film waste benefits from the economy of scale, as shown by an improvement in the net economic balance (Figure 7). When benchmarking our analysis to the low regranulate values (red line in Figure 7), a positive economic balance for processing higher feedstock quality via basic and advanced recycling plants (net benefit €56/tonne rPE_{basic} and €54/tonne $rPE_{advanced}$) can be observed from 10 500 tonnes/year capacity onward. However, this holds true only when a higher feedstock quality is maintained (Figure 7A,7C). As expected, there is a shift in the overall net economic balance when the feedstock quality gets lower, as shown in Figure 7B (for a basic recycling plant) and Figure 7D (for an advanced recycling plant). Selling rPE at higher prices (€1000/tonne rPE_{basic} and €1500/tonne $rPE_{advanced}$) is needed to make recycling nonhousehold end-use plastic film waste at 10 500 tonnes/year capacity economically viable (net benefit €75/tonne rPE_{basic} and €90/tonne $rPE_{advanced}$, in Figure 7B,7D). This can be explained by the fact that the recycling yield, and subsequently the $rPE_{basic/advanced}$ production, considerably drops when we process waste with lower feedstock quality, as discussed in a previous section. The link between recycling operations and the scale of the economic viability of mechanical recycling of plastics aligns with the previous studies on waste management facilities, which suggest that the economic performance of sorting plants, anaerobic digestion facilities, and mechanical−biological treatment plants becomes more positive as the facilities get bigger.[49,77]

The findings shown in Figure 7 indicate that collecting nonhousehold end-use plastic film waste from the urban areas considered in this study is crucial to make self-sustaining mechanical recycling operations. Around 10 500 tonnes of plastic film waste can be processed from urban areas of Ghent and its neighboring municipalities (Figure 4) to make recycling economically viable. A "partial" collection of the plastic film waste is still possible (i.e., 6500−8500 tonnes/year), but the regranulates must be sold at higher prices (€1000 and €1500/tonne $rPE_{basic/advanced}$), and a high feedstock quality must be maintained, as illustrated in Figure 7. Alternatively, it is possible to process household plastic film waste (in different batches) to meet the minimum recycling capacity for economic reasons. However, there is concern about cross-contamination

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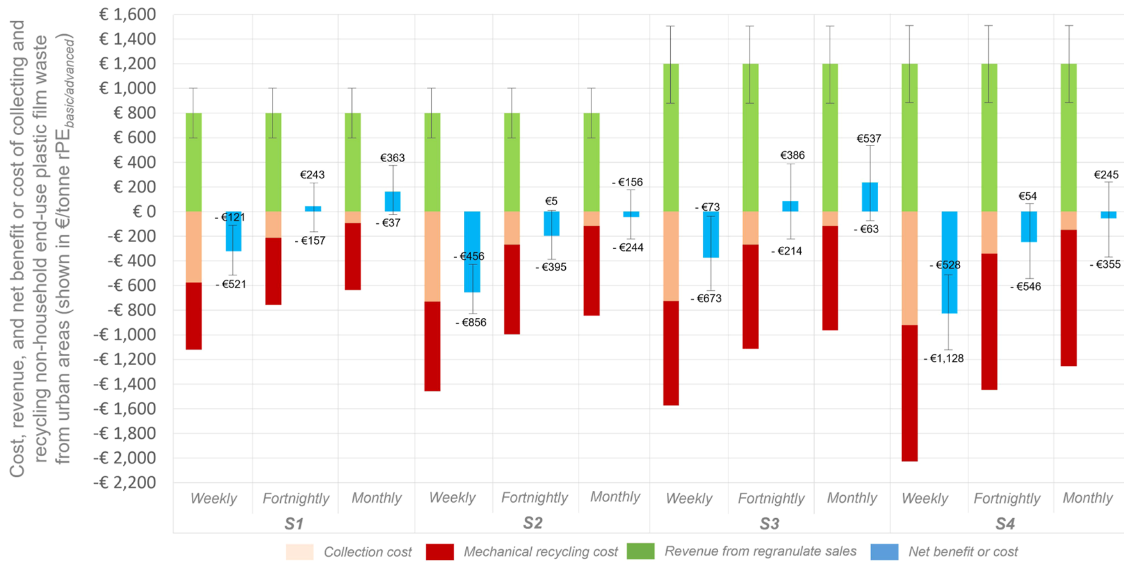

Figure 9. Cost, revenue, and net benefit or cost of collecting (weekly, fortnightly, or monthly collection) and mechanical recycling (10 500 tonnes/year, in S1−S4) of nonhousehold end-use plastic film waste from urban areas, shown in €/tonne rPE$_{basic/advanced}$. The blue bar reflects the net benefit or cost of selling rPE$_{basic/advanced}$ at central prices. The error bars indicate potential net benefit or cost changes when rPE$_{basic/advanced}$ is sold at lower or higher prices.

from household waste (typically more contaminated[27]), which can result in a lower rPE$_{basic/advanced}$ quality, and subsequently regranulate price. Furthermore, the net economic balance of collecting and mechanical recycling of nonhousehold end-use plastic film waste from urban areas considered in this study (i.e., 10 500 tonnes/year) is discussed in the next section.

Dependency of Mechanical Recycling Performance on Source Separation Efficiency. Figure 8 shows the results of the sensitivity analysis toward the economic balance (i.e., net benefit or cost, in €/tonne rPE$_{basic/advanced}$) of the basic recycling plant (Figure 8A) and advanced recycling plant (Figure 8B) when the residue content (in %) in the incoming waste increases. Sensitivity analysis results (Figure 8) suggest that the net economic balance of basic and advanced recycling plants can drop up to -€559/tonne rPE$_{basic}$ and -€826/tonne rPE$_{advanced}$, respectively, when the residue content reaches 50%, and regranulates are sold at low prices (€600/tonne rPE$_{basic}$ and €900/tonne rPE$_{advanced}$, red line in Figure 8). A similar trend can be observed in the recycling yield, which can drop to 41 and 32% (blue dot in Figure 8) when the residue content is high (50%) and the price of regranulates drops simultaneously. We can also observe that rPE$_{basic/advanced}$ should be sold at higher prices (€1000/tonne rPE$_{basic}$ and €1500/tonne rPE$_{advanced}$) when the residue content exceeds 30−35%; otherwise, the mechanical recycling of nonhousehold end-use plastic waste is economically unfeasible, even without selective collection cost. Fogt Jacobsen et al.[78] highlight the importance of having well-established waste management systems and waste producers' engagements to improve the purity of source-separated plastic waste. Thus, this study can serve as a tool to set the maximum allowable residue content from an economic perspective.

Cost-Benefit Analysis of Selective Collection and Mechanical Recycling of Plastic Film Waste from Urban Areas. The estimated annual costs of nonhousehold end-use plastic film waste selective collection (in different frequencies: weekly, fortnightly, or monthly) and mechanical recycling from urban areas in this study (10 500 tonnes/year capacity) per tonne rPE$_{basic/advanced}$ is shown in Figure 9. Next to that, the revenue and net benefit or cost of producing rPE from nonhousehold end-use plastic film waste in urban areas in this study are also presented in Figure 9. Note that the revenue (green bars) and net benefit or cost (blue bars) reflect the central regranulate price, which is €800/tonne rPE$_{basic}$ and €1200/tonne rPE$_{advanced}$. The error bars shown in Figure 9 indicate the potential net benefit or cost changes if the rPE$_{basic/advanced}$ price drops or rises, as elaborated in the previous section and in Larrain et al.[47] study.

As seen in Figure 9, a viable business case for selective collection and mechanical recycling of nonhousehold end-use plastic film waste from urban areas can be profitable only in a few cases, when assuming no fees are applied to the actors generating the waste. First, waste management can only be profitable when waste is selectively collected fortnightly or monthly and not weekly, as presented in Figure 9. The estimated fortnightly and monthly collection costs range from €90/tonne rPE$_{basic}$ (S1, monthly) to €340/tonne rPE$_{advanced}$ (S4, fortnightly), while the estimated costs or recycling range from €545/tonne rPE$_{basic}$ (S1) to €1100/tonne rPE$_{advanced}$ (S4). Second, the rPE$_{basic/advanced}$ should be sold at central (€800/tonne rPE$_{basic}$ and €1200/tonne rPE$_{advanced}$) or higher prices (€1000/tonne rPE$_{basic}$ and €1500/tonne rPE$_{advanced}$), and high-quality feedstock should be maintained (S1 and S3 in Figure 9). When the waste composition for the waste collection worsens (S2 and S4 in Figure 9), selective collection and recycling nonhousehold end-use plastic film waste is economically feasible only when the rPE is sold at a higher price (€1000/tonne rPE$_{basic}$ and €1500/tonne rPE$_{advanced}$). Overall, the total costs of selective collection (fortnightly or monthly) and mechanical recycling of nonhousehold end-use plastic film from urban areas are estimated to range from €635/tonne rPE$_{basic}$ (S1, monthly) to €1445 per tonne rPE$_{advanced}$ (S4, fortnightly), while the net benefit ranging from €5/tonne rPE$_{basic}$ to €537/tonne rPE$_{advanced}$.

Furthermore, related to the business case for nonhousehold end-use plastic film waste, the CBA results suggest that it is

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ACS Sustainable Chem. Eng. 2023, 11, 12677−12694

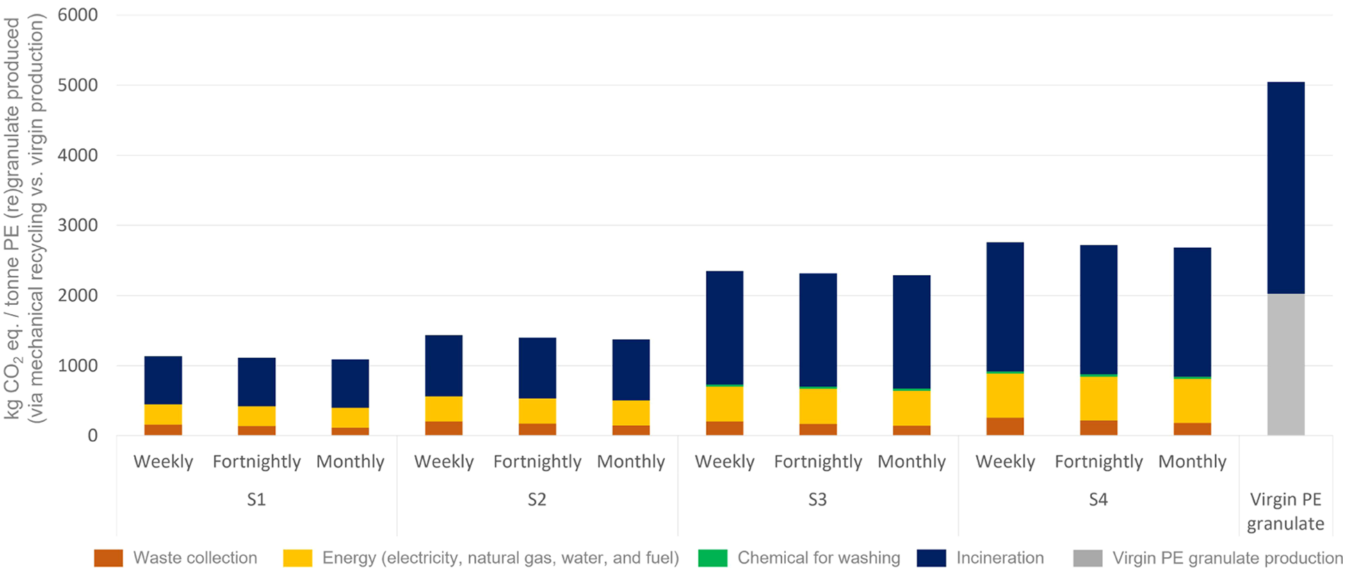

Figure 10. Greenhouse gas estimation of collecting and recycling nonhousehold end-use plastic film waste from urban areas considered in this study to produce 1 tonne rPE (in S1−S4) compared to 1 tonne virgin PE granulate production. S1 is a basic recycling plant with higher feedstock quality, S2 is a basic recycling plant with lower feedstock quality, S3 is an advanced recycling plant with higher feedstock quality, and S4 is an advanced recycling plant with lower feedstock quality.

economically unfeasible to make a profit from weekly waste collection, even when the $rPE_{basic/advanced}$ is sold at a higher price (€1000/tonne rPEbasic or €1500/tonne rPEadvanced), as shown in Figure 9. However, Figure S28 in the SI indicates that the mechanical recycling plant becomes more cost-effective as more waste is processed (capacity increases), with an overall cost reduction of about 41−43%. The annual cost per tonne rPE_{basic} in S1 drops from -€544/tonne to -€308/tonne as the waste processed increases from 10 500 to 20 500 tonnes/year. Similarly, the annual cost per tonne of $rPE_{advanced}$ in S3 drops from -€846/tonne to -€492/tonne as the capacity increases (Figure S28). Further research is needed to develop a business case for weekly collection depending on the total plant capacity and gate fees. As the capacity increases, garbage trucks need to travel more distance and collect more waste to supply waste feedstock for recycling, in which the increase of additional collection cost would mainly depend on (i) the type of business activity (NACE sector), (ii) business density, (iii) waste composition, and (iv) waste quantity in the new municipality or region(s). Next to this, the collection scheme would also depend on the desire and general behavior of the businesses to agree on a less frequent collection, which would mean they have to store the waste longer to increase the economic feasibility of the whole system. These behavioral aspects are subjected to future research.

The CBA of selective collection and recycling of waste from urban areas suggests that financial instruments are needed in many scenarios to support the recycling chain. For example, a positive economic balance and viable business case can only be achieved when the $rPE_{basic/advanced}$ is sold at a higher price if the residue content gets higher (25 wt %), as shown in S2 and S4 (Figure 9). This can be achieved when the market is "forced" to use recycled content (e.g., by minimum recycled content target),[88] and nonhousehold waste can play a crucial role because of its homogeneous composition, at least per type of business activity (NACE code classification).[25−27] However, as a precautionary action, especially when regranulate (or plastic in a broader sense) price drops, sustainable financial support for waste operators (e.g., recyclers) should be established, for example, by applying gate fees or EPR scheme (fees).[79] Furthermore, the CBA results (Figure 9) also indicate that a viable business case of recycling nonhousehold end-use plastic film waste relies upon good source separation by actors generating the waste. In this sense, giving financial incentives to companies can be used as an interesting option to ensure a proper separate waste collection at the source (e.g., €30/tonne as done by Valipac[12]). An administrative fine can also be imposed to minimize improper source separation by waste producers, similar to what has been implemented for household waste, such as an administrative fine of €75 for not complying with household waste sorting guidelines.[86,87] Several studies also suggest that financial incentive is one of the enablers of stakeholders' participation in doing a source separation by companies in urban areas.[9,40,41,43,78,80] This way, the feedstock quality and the required (minimum) quantity can be achieved to ensure a viable business case. Yet, appropriate measurements should be sought to analyze (and monitor) the waste quality (as feedstock to recycling facility) per actor generating waste, in which artificial intelligence technology could play a role here in the future.

GHG Emission from Mechanical Recycling of Plastic Film Waste from Urban Areas. As visualized in Figure 10, the GHG emissions of producing one tonne rPE_{basic} (S1−S2) ranges from 1089 to 1433 kg of CO_2-equiv, mainly depending on the selective collection scheme. For every one tonne $rPE_{advanced}$ (S3−S4), the GHG emissions range from 2289 to 2761 kg CO_2-equiv, also depending on the selective collection scheme (Figure 10). It can be observed from Figure 10 that producing $rPE_{basic/advanced}$ results in 74−79 and 49−56% less GHG emissions compared to virgin PE granulate production plus incineration (5048 kg of CO_2-equiv/tonne of rPE), respectively. Figure 10 also presents the breakdown of GHG emissions during waste collection from energy consumption, NaOH consumption (during hot washing), and residual treatment. It can be observed that the GHG emissions mainly come from residual treatment (60−70% of the total carbon

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ACS Sustainable Chem. Eng. 2023, 11, 12677−12694

footprint), followed by energy consumption (23−28%) and the waste collection phase (2−9%). The environmental performance of mechanical recycling of plastic film waste from urban areas through advanced recycling plants can still be improved by minimizing the residue. As shown in Figure 5 and discussed in a previous section, the mechanical recycling yields in S3 (61%) and S4 (48%) are relatively low compared to S1 (77%) and S2 (61%).

Finally, when comparing the GHG emissions of different collection frequencies only, it can be observed that GHG emission of monthly collection is 3−4% lower than those of weekly and fortnightly collection. When the feedstock quality gets lower (in S2 and S4), it can be observed that the GHG emissions increase by 15−21% (compared to S1 and S3). In S2 and S4, a higher GHG emission is mainly caused by the increase of residual treatment by 42 and 25% compared to S1 and S3, respectively (as visualized in Figure 5). As illustrated in Figure 10, the overall GHG emission from an advanced recycling plant (in S3 and S4) is 48−52% higher compared to that from a basic recycling plant (in S1 and S2). However, further research should be performed to assess the substitution rate (and environmental savings) of $rPE_{basic/advanced}$, which have different qualities, as indicated in Figure S26. To date, different methods have been investigated in previous studies,[81,82] which require further analysis of the technical properties (e.g., melt flow index, viscosity, etc.) of $rPE_{basic/advanced}$.[83−85]

CONCLUSIONS

This study uses the cost-benefit analysis model to develop potential business cases for selective collection and mechanical recycling of nonhousehold end-use plastic film from urban areas. The City of Ghent in Belgium and 12 municipalities nearby are chosen as the case study. This study also analyzes the waste composition and quantity based on real waste sampling combined with data from the literature.

The logistic simulation results indicate that fortnightly and monthly selective collection is most favorable in terms of costs. The material flow analysis results indicate that the recycling yield ranges from 61 to 77% depending on the plant layouts (i.e., basic vs advanced recycling plant with extra NIR sorting and hot washing steps). When the residue content is increased to 25%, the recycling yield can drop to 48−61%.

It is estimated that around €4−€7 million is needed to build the recycling plants, depending on the configurations. Given the economic parameters (adjusted to the Belgian market), the annual costs are expected to be around €4−€6.5 million per year. The cost-benefit analysis shows a positive net economic balance ranging from €5/tonne rPE_{basic} to €537/tonne $rPE_{advanced}$ (i.e., the recycling chains generate profit) when around 10 500 tonnes/year of waste is collected and recycled, indicating processing capacity related to the economy of scale. In the positive scenarios, annual costs from the waste collection (fortnightly or monthly) range from €90/tonne rPE_{basic} to €340/tonne $rPE_{advanced}$, while mechanical recycling costs range from €545/tonne rPE_{basic} to €1100/tonne $rPE_{advanced}$. The positive net economic balance can be achieved when the regranulates are sold at €800/tonne rPE_{basic} and €1500/tonne $rPE_{advanced}$ (depending on the recycling plant layouts and regranulate quality). The modeling results indicate a positive economic balance of selective collection and mechanical recycling of nonhousehold end-use plastic film waste from urban areas when (i) the high-quality feedstock is maintained and (ii) the waste is collected fortnightly or monthly.

Furthermore, the greenhouse gas emission calculation suggests that minimizing residual streams and maintaining high-quality feedstock from waste collection are keys to lowering the carbon footprint. The results indicate that the carbon footprint from mechanical recycling of nonhousehold end-use plastic film waste can be 49−79% less than the current linear economic model of using virgin polyethylene granulate and waste incineration.

Concluding, selective collection and recycling of nonhousehold end-use plastic film waste from urban areas can be economically attractive when a few operating conditions are met. To realize this, waste producers, waste operators, and regulators must establish effective waste management systems in the future. Targets and extended producer responsibilities schemes should be established to incentivize nonhousehold end-use plastic waste treatment, especially to sustain plastic recycling operations when regranulate price drops (e.g., due to low oil prices). Financial incentives for waste producers to properly separate waste at the source can be promoted to ensure feedstock quality and quantity. Nevertheless, given the large quantity of plastic films in nonhousehold waste, society will need this feedstock to achieve its recycling targets. Thus, the developed method presented in this study can be applied in broader European regions (and beyond) to improve plastic circularity, especially in commercial and industrial sectors.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.3c02748.

Providing details related to the use of Orbis database; nonhousehold end-use plastic film waste samples; logistic simulation results; material flow analysis and economic results; and life cycle inventory; Figures S1−S28 and Tables (S1−S11) (PDF)

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Notes

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■ REFERENCES

(1) Plastics Europe. Plastics − the Facts 2020 2020 https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020. (Accessed 30 August 2022).

(2) Material Economics. Europe's Missing Plastics 2022 https://materialeconomics.com/publications/europes-missing-plastics. (Accessed 30 August 2022).

(3) Agora Industry. Mobilising the Circular Economy for Energy-Intensive Materials Mobilising the Circular Economy for Energy-Intensive Materials 2022 https://www.agora-energiewende.de/en/publications/mobilising-the-circular-economy-for-energy-intensive-materials-study/. (Accessed 30 August 2022).

(4) Plastics Europe. The Circular Economy for Plastics − A European Overview 2019 https://plasticseurope.org/fr/knowledge-hub/the-circular-economy-for-plastics-a-european-overview/. (Accessed 30 August 2022).

(5) Hestin, M.; Mitsios, A.; Said, S.; Fouret, F.; Berwald, A.; Senlis, V. Blueprint for Plastics Packaging Waste: Quality Sorting & Recycling. Deloitte Sustainability. 2017, https://www2.deloitte.com/my/en/pages/risk/articles/blueprint-for-plastics-packaging-waste.html.

(6) Kleinhans, K.; Demets, R.; Dewulf, J.; Ragaert, K.; De Meester, S. Non-household end-use plastics: the 'forgotten' plastics for the circular economy. *Current Opin. Chem. Eng.* **2021**, *32*, No. 100680.

(7) ISO. ISO 140212016 − Environmental Labels and Declarations Self-declared Environmental Claims (Type II Environmental Labelling). 2016.

(8) Jacobs, M.; Vanderreydt, I.; De Weerdt, L.; Alaerts, L. Exploration of the plastic recycling landscape in Flanders 2018 https://vlaanderen-circulair.be/src/Frontend/Files/userfiles/files/Summa%20-%20Exploration%20of%20the%20plastic%20recycling%20landscape%20in%20Flanders.pdf. (Accessed 27 October 2022).

(9) Kleinhans, K.; De Meester, S.; Ragaert, K.; Dewulf, J. Analyzing the Status Quo of Non-household End-user Plastic Waste in Urban Areas 2021 Circular Plastics Conferences. Recorded presentation: https://www.youtube.com/watch?v=szH6LiyVMHQ. (Accessed 24 June 2022).

(10) Huysveld, S.; Hubo, S.; Ragaert, K.; Dewulf, J. Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. *J. Cleaner Prod.* **2019**, *211*, 1−13.

(11) Salhofer, S. Modelling commercial/industrial waste generation: a Vienna, Austria case study. *Waste Manage. Res.* **2000**, *18*, 269−282.

(12) Valipac. Sorting Waste in Your Company 2022 https://www.valipac.be/en/sorting-waste-in-your-company/ (Accessed 29 August 2022).

(13) Salhofer, S.; Jandric, A.; Soudachanh, S.; Le Xuan, T.; Tran, T. D. Plastic recycling practices in Vietnam and related hazards for health and the environment. *Int. J. Environ. Res. Public Health* **2021**, *18*, No. 4203, DOI: 10.3390/ijerph18084203.

(14) Liang, Y.; Tan, Q.; Song, Q.; Li, J. An analysis of the plastic waste trade and management in Asia. *Waste Manage.* **2021**, *119*, 242−253.

(15) Petrlik, J.; Ismawati, Y.; DiGangi, J.; Arisandi, P.; Bell, L.; Beeler, B. Plastic Waste Flooding Indonesia Leads to Toxic Chemical Contamination of the Food Chain 2019 https://ipen.org/sites/default/files/documents/indonesia-egg-report-long-v1_2web-en.pdf (Accessed 30 August 2022).

(16) Chen, H. L.; Nath, T. K.; Chong, S.; Foo, V.; Gibbins, C.; Lechner, A. M. The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste. *SN Appl. Sci.* **2021**, *3*, 437.

(17) Yong, Z. J.; Bashir, M. J. K.; Ng, C. A.; Sethupathi, S.; Lim, J. W.; Show, P. L. Sustainable waste-to-energy development in Malaysia: Appraisal of environmental, financial, and public issues related with energy recovery from municipal solid waste. *Processes* **2019**, *7*, 676.

(18) Essenscia The Belgian Plastics Industry and The Circular Economy − How Far Have We Come? 2019 https://www.essenscia.be/wp-content/uploads/2019/11/Plast_BROCH_A5_HR.pdf (accessed 30 August 2022).

(19) Mazzanti, M.; Zoboli, R. Resource taxation and regional planning: revenue recycling for local sustainability in the aggregates sector. *J. Environ. Plann. Manage.* **2013**, *56*, 893−916.

(20) D'Amato, A.; Paleari, S.; Pohjakallio, M.; Vanderreydt, I.; Zoboli, R. Plastics Waste Trade and the Environment 2019 https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/plastics-waste-trade-and-the-environment (Accessed 23 June 2022).

(21) Lange, J.-P. Managing plastic waste − sorting, recycling, disposal, and product redesign. *ACS Sustainable Chem. Eng.* **2021**, *9*, 15722−15738.

(22) OECD. Improving Plastics Management: Trends, Policy Responses, and the Role of International Co-operation and Trade. In *Environmental Policy Paper No. 12, 12, 20*; OECD Publishing, 2018 DOI: 10.1787/23097841.

(23) De Weerdt, L.; Sasao, T.; Compernolle, T.; Van Passel, S.; De Jaeger, S. The effect of waste incineration taxation on industrial plastic waste generation: a panel analysis. *Resour., Conserv. Recycl.* **2020**, *157*, No. 104717, DOI: 10.1016/j.resconrec.2020.104717.

(24) Bracken, R. Commercial And Industrial Plastic Waste: Waste Stream Composition And the Potential for Recycling In Alamance County 1990 https://p2infohouse.org/ref/24/23607.pdf (Accessed 30 August 2022).

(25) Horodytska, O.; Valdés, F. J.; Fullana, A. Plastic flexible films waste management – A state of art review. *Waste Manage.* **2018**, *77*, 413–425.

(26) Nimmegeers, P.; Billen, P. Quantifying the Separation Complexity of Mixed Plastic Waste Streams with Statistical Entropy: A Plastic Packaging Waste Case Study in Belgium. *ACS Sustainable Chem. Eng.* **2021**, *9*, 9813–9822.

(27) Horodytska, O.; Kiritsis, D.; Fullana, A. Upcycling of printed plastic films: LCA analysis and effects on the circular economy. *J. Cleaner Prod.* **2020**, *268*, No. 122138.

(28) Bendix, P.; Berg, H.; Sebestyen, J.; Ritthoff, M.; Perschel, L. Promoting the High-quality Recycling of Plastics From Demolition Waste and Enhancing the Use of Recycled Materials in Construction Products in Accordance with the European Plastics Strategy 2021 https://www.umweltbundesamt.de/en/publikationen/promoting-the-high-quality-recycling-of-plastics (accessed 30 August 2022).

(29) Gardner, J. CIRCULAR PLASTICS ALLIANCE STATE OF PLAY FOR COLLECTED AND SORTED PLASTIC WASTE Construction Working Group June 2020 2020 https://ec.europa.eu/docsroom/documents/43694/attachments/4/translations/en/renditions/native (accessed 29 August 2022).

(30) Bauer, J. Agricultural Waste Management in Europe – the European EPR-Model. *Acta Hortic.* **2019**, *1252*, 105–108, DOI: 10.17660/ActaHortic.2019.1252.14.

(31) Scarascia-Mugnozza, G.; Sica, C.; Russo, G. Plastic Materials in European Agriculture: Actual Use and Perspectives. *J. Agric. Eng.* **2011**, *42*, 15–28.

(32) Agriculture Plastic Environment. The European Plasticulture Strategy - A Contribution to an European Agri-Plastic Waste Management 2021 https://apeeurope.eu/wp-content/uploads/2020/12/EPS-EPA-ENG-FR-APE.pdf (Accessed 28 August 2022).

(33) Vlaamse Regering. Besluit van de Vlaamse Regering tot wijziging van het besluit van de Vlaamse Regering van 12 december 2008 tot uitvoering van titel XVI van het decreet van 5 april 1995 houdende algemene bepalingen inzake milieubeleid en het besluit van de Vlaamse Regeringvan 17 februari 2012 tot vaststelling van het Vlaams reglement betreffende het duurzaam beheer van materiaalkringlopen en afvalstoffen 2021 https://beslissingenvlaamseregering.vlaanderen.be/document-view/60DD6FFA364ED90008000393 (Accessed 21 February 2023).

(34) Renewi. Bedrijfsafval Sorteren en Laten Ophalen Volgens Het VLAREMA 2023 https://www.renewi.com/nl-be/vlarema (Accessed 14 March 2023).

(35) OVAM. Selectieve Inzameling: uw verplichtingen als bedrijf 2023 https://ovam.vlaanderen.be/selectieve-inzameling-uw-verplichtingen-als-bedrijf (Accessed 21 February 2023).

(36) Tonini, D.; Wandl, A.; Meister, K.; Unceta, P. M.; Taelman, S. E.; Sanjuan-Delmas, D.; Dewulf, J.; Huygens, D. Quantitative sustainability assessment of household food waste management in the Amsterdam Metropolitan Area. *Resour., Conserv. Recycl.* **2020**, *160*, No. 104854, DOI: 10.1016/j.resconrec.2020.104854.

(37) Acke, A.; Taelman, S. E.; Dewulf, J. A multi-stakeholder and interdisciplinary approach to waste management and circular economy: the case of Flanders and Ghent, Belgium. *Eur. Spatial Res. Pol.* **2020**, *27*, 43 DOI: 10.18778/1231-1952.27.2.04.

(38) Derrible, S.; Chaeah, L.; Arora, M.; Yeow, L. W. Chapter 7: Urban Metabolism. In *The Urban Book Series*; Shi, W.; Goodchild, M. F.; Batty, M.; Kwan, M.; Zhang, A., Eds.; Springer, 2021 DOI: 10.1007/978-981-15-8983-6.

(39) Zhang, Y.; Yang, Z.; Yu, X. Urban metabolism: a review of current knowledge and directions for future study. *Environ. Sci. Technol.* **2015**, *49*, 11247–11263.

(40) da Cruz, N. F.; Simões, P.; Marques, R. C. Economic cost recovery in the recycling of packaging waste: the case of Portugal. *J. Cleaner Prod.* **2012**, *37*, 8–18.

(41) Da Cruz, N. F.; Ferreira, S.; Cabral, M.; Simões, P.; Marques, R. C. Packaging waste recycling in Europe: Is the industry paying for it? *Waste Manage.* **2014**, *34*, 298–308.

(42) Boskovic, G.; Jovicic, N.; Jovanovic, S.; Simovic, V. Calculating the costs of waste collection: A methodological proposal. *Waste Manage. Res.* **2016**, *34*, 775–783, DOI: 10.1177/0734242X16654980.

(43) Marques, R. C.; Da Cruz, N. F.; Simões, P.; Ferreira, S. F.; Pereira, M. C.; De Jaeger, S. Economic viability of packaging waste recycling systems: A comparison between Belgium and Portugal. *Resour., Conserv. Recycl.* **2014**, *85*, 22–33, DOI: 10.1016/j.resconrec.2013.12.015.

(44) Huysman, S.; De Schaepmeester, J.; Ragaert, K.; Dewulf, J.; De Meester, J. Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resour., Conserv. Recycl.* **2017**, *120*, 46–54, DOI: 10.1016/j.resconrec.2017.01.013.

(45) Conundra. OptiFlow Rout Optimization 2023 https://www.conundra.eu/optiflow-route-optimization-software (Accessed 21 February 2023).

(46) Bashirgonbadi, A.; Lase, I. S.; Delva, L.; Van Geem, K.; De Meester, S.; Ragaert, K. Quality Evaluation and Economic Assessment of an Improved Mechanical Recycling for Post-Consumer Flexible Plastics. *Waste Manage.* **2022**, *153*, 41–51.

(47) Larrain, M.; Van Passel, S.; Thomassen, G.; Van Gorp, B.; Nhu, T. T.; Huysveld, S.; Van Geem, K. M.; De Meester, S.; Billen, P. Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. *Resour., Conserv. Recycl.* **2021**, *170*, No. 105607, DOI: 10.1016/j.resconrec.2021.105607.

(48) Hernández, B.; Kots, P.; Selvam, E.; Vlachos, D. G.; Ierapetritou, M. G. Techno-Economic and Life Cycle Analyses of Thermochemical Upcycling Technologies of Low-Density Polyethylene Waste. *ACS Sustainable Chem. Eng.* **2023**, *11*, 7170–7181, DOI: 10.1021/acssuschemeng.3c00636.

(49) Cimpan, C.; Maul, A.; Wenzel, H.; Pretz, T. Techno-economic assessment of central sorting at material recovery facilities – the case of lightweight packaging waste. *J. Cleaner Prod.* **2016**, *112*, 4387–4397.

(50) Civancik-Uslu, D.; Nhu, T. T.; Van Gorp, B.; Kresovic, U.; Larrain, M.; Billen, P.; Ragaert, K.; De Meester, S.; Dewulf, J.; Huysveld, S. Moving from Linear to Circular Household Plastic Packaging in Belgium: Prospective Life Cycle Assessment of Mechanical and Thermochemical Recycling. *Resour., Conserv. Recycl.* **2021**, *171*, No. 105633, DOI: 10.1016/j.resconrec.2021.105633.

(51) Quantis. Life Cycle Assessment of Plastic Energy for the Chemical Recycling of Mixed Plastic Waste 2020 https://plasticenergy.com/wp-content/uploads/2020/10/Plastic-Energy-LCA-Executive-Summary.pdf (Accessed 12 February 2023).

(52) Zero Waste Europe. Understanding the Environmental Impacts of Chemical Recycling – Ten Concerns with Existing Life Cycle Assessments 2020. (Accessed 21 February 2023) https://zerowasteeurope.eu/wp-content/uploads/2020/12/zwe_jointpaper_UnderstandingEnvironmentalImpactsofCR_en.pdf.

(53) Lase, I. S.; Bashirgonbadi, A.; van Rhijn, F.; Dewulf, J.; Ragaert, K.; Delva, L.; Roosen, M.; Brandsma, M.; Langen, M.; De Meester, S. Material Flow Analysis and Recycling Performance of an Improved Mechanical Recycling Process for Post-Consumer Flexible Plastics. *Waste Manage.* **2022**, *153*, 249–263.

(54) Orbis. Number of Companies in Ghent 2022 https://orbiseurope.bvdinfo.com/version-202283/Orbis4Europe/1/Companies/Search (Accessed 24 June 2022).

(55) Kerselaers, E.; Coussement, A.; Charles, J.; Goethijn, L.; Naessens, E.; Tency, H.; Vereecke, D. PROSPERA Regional Report – City of Ghent: An Analysis of the Peri-urban Area that Surrounds the City of Ghent 2020 https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/file_1612109316.pdf (Accessed 30 August 2022).

(56) Eurostat. Generation of Waste by Waste Category, Hazardousness, and NACE Rev. 2 Activity 2022 http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=env_wasgen (accessed 11 July 2022).

(57) Roosen, M.; Mys, N.; Kusenberg, M.; Billen, P.; Dumoulin, A.; Dewulf, J.; Van Geem, K. M.; Ragaert, K.; De Meester, S. A detailed analysis of the composition of plastic packaging waste in Belgium and its implications for mechanical and thermochemical recycling. *Environ. Sci. Technol.* **2020**, *54*, 13282−13293, DOI: 10.1021/acs.est.0c03371.
(58) Thoden van Velzen, E. U.; Brouwer, M. T.; Augustinus, A. Contributions of Municipalities to the Recycling of Post-consumer Packages, FBR 1687 2016 https://www.kidv.nl/6825/contributions-of-municipalities-to-the-recycling-of-post-consumer-packages.pdf (Wageningen Food & Biobased Research Wageningen, NL177).
(59) Van Velzen, E. T.; Brouwer, M. T. Samenstelling van gescheiden ingezamelde kunststofverpakkingen *Wageningen UR-Food & Biobased Research* 2014.
(60) Tellus. Publications − Solid Waste 2023.(Accessed 11 February 2023)https://www.tellus.org/publications/solid-waste.
(61) Federal Recycling & Waste Solutions. Materials We Recycle: Reduce Reuse Recycle Repeat 2022.(Accessed 10 February 2023)https://www.federalinternational.com/services-we-offer/materials-we-recycle.
(62) European Commission. Transport: Road Safety − Belgium 2021 https://ec.europa.eu/transport/road_safety/going_abroad/belgium/speed_limits_en.htm#:~:text=Standard%20speed%20limits%20(unless%20otherwise,30%20km%2Fh%20in%20Brussels (accessed 13 March 2023).
(63) Brouwer, M. T.; Thoden van Velzen, E. U.; Augustinus, A.; Soethoudt, H.; De Meester, S.; Ragaert, K. Predictive Model for the Dutch Post-Consumer Plastic Packaging Recycling System and Implications for the Circular Economy. *Waste Manage.* **2018**, *71*, 62−85.
(64) Kleinhans, K.; Hallemans, M.; Huysveld, S.; Thomassen, G.; Ragaert, K.; Van Geem, K. M.; Roosen, M.; Mys, N.; Dewulf, J.; De Meester, S. Development and Application of a Predictive Modeling Approach for Household Packaging Waste Flows in Sorting Facilities. *Waste Manage.* **2021**, *120*, 290−302.
(65) Sartori, D.; Catalano, G.; Genco, M.; Pancotti, C.; Sirtori, E.; Vignetti, S.; Del Bo, C. *Guide to Cost-benefit Analysis of Investment Project − Economic Appraisal Tool for Cohesion Policy 2014−2020*; Publication office of the European Union: Luxembourg, 2015 DOI: 10.2776/97516.
(66) Denne, T.; Irvine, R.; Atreya, N.; Robinson, M. Recycling: Cost Benefit Analysis Prepared for Ministry of Environment 2007 https://environment.govt.nz/assets/Publications/Files/recycling-cost-benefit-analysis-apr07.pdf. (accessed 21 February 2023).
(67) Sinnott, R.; Towler, G. *Chemical Engineering Design*, SIth ed.; Butterworth- Heinemann, 2019.
(68) WRAP. A Financial Assessment of Recycling Mixed Plastics in the UK 2009 https://www.yumpu.com/en/document/view/40248968/financial-assessment-of-mixed-plastics-recycling-in-the-uk-wrap. (Accessed 25 July 2022).
(69) Plastic Portal EU. Weekly Commodity Price Report 2021 https://www.plasticportal.eu/en/cenove-reporty?year=2021&week=2. (Accessed 28 November 2022).
(70) Plasticker. Plasticker the Home of Plastics 2021 https://plasticker.de/. (Accessed 27 November 2022).
(71) Aryan, V.; Maga, D.; Majgaonkar, P.; Hanich, R. Valorization of polylactic acid (PLA) waste: a comparative life cycle assessment of various solvent-based chemical recycling technologies. *Resour., Conserv. Recycl.* **2021**, *172*, No. 105670, DOI: 10.1016/j.resconrec.2021.105670.
(72) Ügdüler, S.; Van Geem, K. M.; Denolf, R.; Roosen, M.; Mys, N.; Ragaert, K.; De Meester, S. Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. *Green Chem.* **2020**, *22*, 5376−5394, DOI: 10.1039/D0GC00894J.
(73) Huijbregts, M. A. J.; Steinmann, Z. J. N.; Elshout, P. M. F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; Van Zelm, R. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138−147.
(74) D'Onza, G.; Greco, G.; Allegrini, M. Full cost accounting in the analysis of separated waste collection efficiency: A methodological proposal. *J. Environ. Manage.* **2016**, *167*, 59−95.
(75) Greco, G.; Allegrini, M.; Del Lungo, C.; Savellini, P. G.; Gabellini, L. Drivers of solid waste collection costs. Empirical evidence from Italy. *J. Cleaner Prod.* **2015**, *106*, 364−371, DOI: 10.1016/j.jclepro.2014.07.011.
(76) Renewi. Container Voor Bedrijven (Accessed March 14, 2023) https://www.renewi.com/nl-nl/container-huren?business=true#?page=2.
(77) Tsilemou, K.; Panagiotakopoulos, D. Approximate cost functions for solid waste treatment facilities. *Waste Manage. Res.* **2006**, *24*, 310−322.
(78) Fogt Jacobsen, L.; Pedersen, S.; Thøgersen, J. Drivers of and barriers to consumers' plastic packaging waste avoidance and recycling − A systematic literature review. *Waste Manage.* **2022**, *141*, 63−78.
(79) Bening, C. R.; Pruess, J. T.; Blum, N. U. Towards a circular plastics economy: Interacting barriers and contested solutions for flexible packaging recycling. *J. Cleaner Prod.* **2021**, *302*, No. 126966.
(80) Klotz, M.; Haupt, M.; Hellweg, S. Limited utilization options for secondary plastics may restrict their circularity. *Waste Manag.* **2022**, *141*, 251−270.
(81) Garcia-Gutierrez, P.; Amadei, A. M.; Klenert, D.; Nessi, S.; Tonini, D.; Tosches, D.; Ardente, F.; Saveyn, H. *Environmental and Economic Assessment of Plastic Waste Recycling* 2023 DOI: 10.2760/0472. ISBN 978−92−76−99528−9.
(82) Tonini, D.; Albizzati, P. F.; Caro, D.; De Meester, S.; Garbarino, E.; Blengini, G. A. Quality of Recycling: Urgent and Undefined. *Waste Manage.* **2022**, *146*, 11−19.
(83) Demets, R.; Van Kets, K.; Huysveld, S.; Dewulf, J.; De Meester, S.; Ragaert, K. Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics. *Resour., Conserv. Recycl.* **2021**, *174*, No. 105826, DOI: 10.1016/j.resconrec.2021.105826.
(84) Huysveld, S.; Ragaert, K.; Demets, R.; Nhu, T. T.; Civancik-Uslu, D.; Kusenberg, M.; Van Geem, K. M.; De Meester, S.; Dewulf, J. Technical and Market Substitutability of Recycled Materials: Calculating the Environmental Benefits of Mechanical and Chemical Recycling of Plastic Packaging Waste. *Waste Manage.* **2022**, *152*, 69−79.
(85) Uekert, T.; Singh, A.; DesVeaux, J. S.; Ghosh, T.; Bhatt, A.; Yadav, G.; Afzal, S.; Walzberg, J.; Knauer, K. M.; Nicholson, S. R.; Beckham, G. T.; Carpenter, A. C. Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. *Sustainable Chem. Eng.* **2023**, *11*, 965−978.
(86) ARP-GAN. Fines: If You Commit and Offence, Get Ready to Pay! (Accessed June 16, 2023) https://www.arp-gan.be/en/fines.
(87) European Commission. Council Decision (EU, Euratom) 2020/2053 of 14 Decmber 2020 on the system of own resources of the European Union and repealing Decision 2014/335/EU, Euratom: Official Journal of the European Union 2020 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020D2053. (Accessed 16 June 2023).
(88) European Commission. Proposal for a Revision of EU Legislation Packaging and Packaging Waste 2022 https://environment.ec.europa.eu/publications/proposal-packaging-and-packaging-waste_en.

https://doi.org/10.1021/acssuschemeng.3c02748
ACS Sustainable Chem. Eng. 2023, 11, 12677−12694