A method to develop potential business cases of plastic recycling from urban areas: A case study on non-household end-use plastic film waste in Belgium

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ABSTRACT

Waste management of non-household 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 non-household end-use plastic film waste from urban areas considering the City of Ghent in Belgium and twelve municipalities nearby as a case study. Three different collection frequencies (weekly, fortnightly, 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 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–€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 plants development; a positive net economic balance (ranging from €5–€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 the recycling systems become economically less favorable when the residue content in the collected plastic film waste exceeds 30–35%. A greenhouse gas emissions calculation indicates 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, Non-household 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) were 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 *non-household end-use plastic waste* – a terminology introduced by Kleinhans et al.[6] sometimes also called commercial and industrial (C&I) waste. Non-household 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, non-household 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 non-household 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 non-household end-use plastic waste is still thrown away in 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 non-household end-use plastic waste remain scarce.[5,10,11] One study by Jacobs et al.[8] indicates that more than half of the non-household 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 non-household 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 non-household 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 domestic waste treatment. Nevertheless, from the waste management perspective, recycling non-household end-use plastic waste also has enormous potential to improve regranulates production, increase recycling rate targets and play a crucial role in the circular economy of plastic in Europe.[6,21]

Non-household 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 non-household 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 plastic film is the most prevalent type of C&I waste in the United States and Australia, respectively. Within the non–household 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 polyethylene terephthalate (PET) (i.e., 1%). Moreover, it is estimated that the non-household end-use rigid plastic waste consists of 64% high-density polyethylene (HDPE), 19% PP, and 16% PET.[5,25] Some studies indicate that non-household 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 non-household end-use plastic film waste has better feedstock quality for mechanical recycling because the waste stream has a relatively homogenous composition.

Currently, the business cases of selective collection and recycling non-household 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 the 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 on non-household 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; public waste agency of Flanders responsible in developing environmental policies and reinforcements).[34,35]

In the context of non-household 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 non-household 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, literature suggests that recycling non-household 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 non-household 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 non-household 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 non-household 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 twelve 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 and benefit analysis (CBA) model. Granular logistic 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-eq) 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 non-household 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 non-household 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 the 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 non-household end-use plastic film. Lastly, the GHG emission associated with collecting and recycling non-household 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).

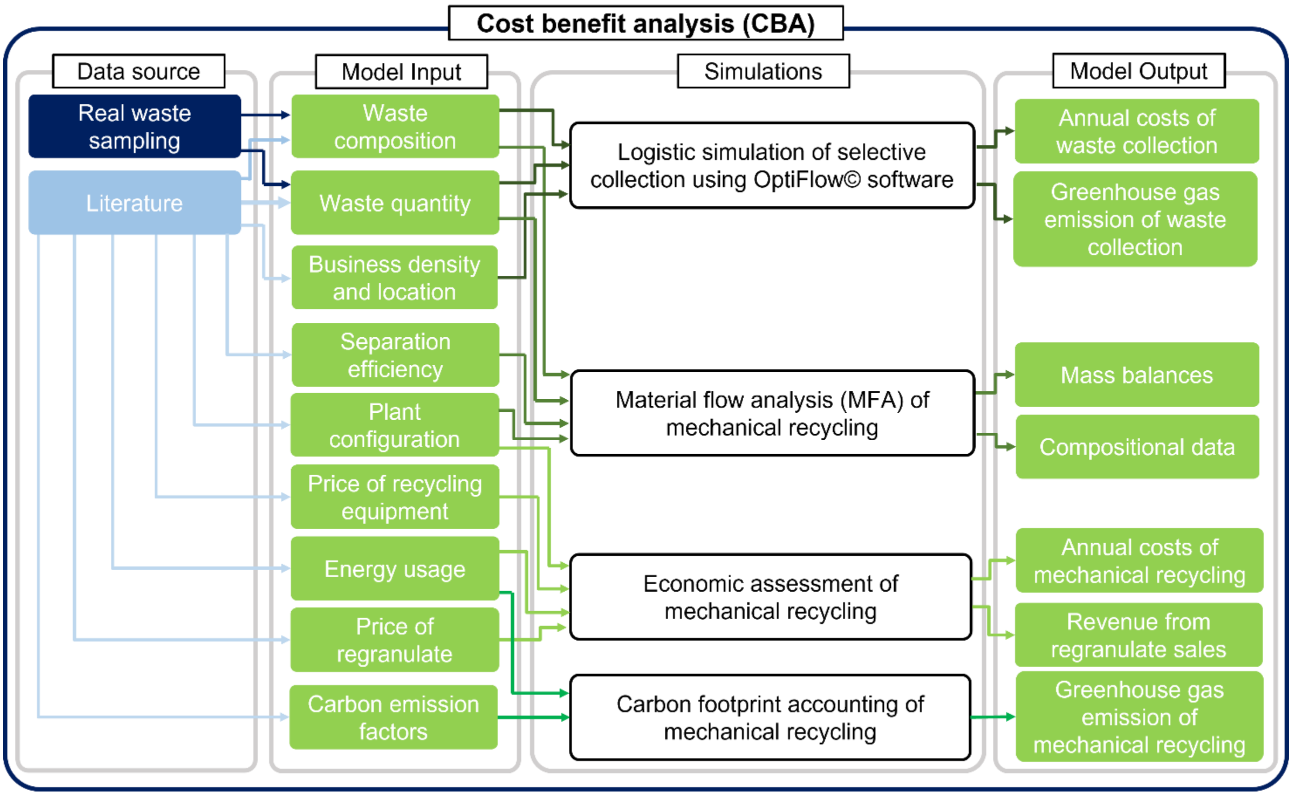


Figure 1. Granular cost benefit analysis (CBA) model methodology (inputs, simulations and outputs) in developing business cases for selective collection and mechanical recycling non-household end-use plastic film waste, including greenhouse gas emission inputs, simulations and outputs.

Description of the system boundary and baseline scenarios

This study considers the urban areas of Ghent and its twelve 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 1,655 inhabitant/km^2. This study also includes the effect of processing scale (in tonne/year waste processed) on recycling operations. For this purpose, twelve neighboring municipalities within approximately ten kilometers (radius) of Ghent are considered, from which the non-household 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 non-household 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 'non-household 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 is elaborated in the following sections. Moreover, in each scenario (S1–S4, Table 1), the processing capacity (i.e., mass input to recycling plant, in tonne/year) is varied from 2,500 tonne/year to 20,500 tonne/year (i.e., maximum processing capacity, in tonne/year[47]). This approach is taken to investigate how i) waste composition (i.e., feedstock quality), ii) selective collection frequencies, and iii) recycling processing capacity affect the overall economic balance and viability of the whole recycling chain.

Table 1. Summary of non-household end-use plastic film waste recycling scenarios considered in this study. Three collection scenarios (weekly, fortnightly, and monthly) are included in each recycling scenario (S1–S4).

Scenarios	**Collection frequencies**	**Waste input composition**	**Recycling plant configuration**	**Processing scale** (in tonne/year)
S1	Weekly, fortnightly, and monthly	Higher quality	Basic recycling plant	2,500 – 20,500
S2	Weekly, fortnightly, and monthly	Lower quality	Basic recycling plant	2,500 – 20,500
S3	Weekly, fortnightly, and monthly	Higher quality	Advanced recycling plant	2,500 – 20,500
S4	Weekly, fortnightly, and monthly	Lower quality	Advanced recycling plant	2,500 – 20,500

Estimation of non-household end-use plastic film waste quantity and composition

Waste quantity estimation

Table 2 provides key examples of the dataset used to estimate the quantity of non-household 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 3,470 companies within NACE sector A–G. The data collection from waste sampling provides us with the total waste quantity per NACE sector (in tonne) from several companies. For example, in Table 2, 58 and 400 tonne of non-household 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 tonne and 400 tonne of plastic film waste were collected from 261 and 564 companies within NACE sectors G.45 and G.46, respectively. Therefore, the (average) quantities of the non-household end-use plastic film generated per company within NACE sector G.45 and NACE sector G.46 are estimated to be 0.22 tonne/year.company and 0.71 tonne/year.company, respectively. These estimates are calculated by dividing the weight of non-household end-use plastic film waste collected (in tonne) 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 non-household end-use plastic film waste generation per NACE sector in the whole selected region. This is done by combining (and extrapolating) the dataset 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 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 tonne 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 non-household end-use plastic film waste generated from NACE sector G.45 from urban areas Ghent is estimated to be 107 tonne/year (i.e., 0.22 tonne × 484 companies), as shown in Table 2. The complete dataset on waste quantity can be found in Supporting Information (SI), Table SI1 and Table 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, which generate no plastic waste. Lastly, a similar approach is used to estimate total non-household 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.

Table 2. Examples of datasets from waste sampling conducted in Ghent–Belgium in 2018 and total active companies based on Orbis database.[54] The complete dataset is available in Table SI1 and SI2. *Units*: Waste quantity (*tonne*), waste generated per company (*tonne/year.company*), Total Waste generated (*tonne/year.NACE sector*).

NACE sectors: codes and names	Dataset from waste sampling in 2018 done by Valipac			Orbis[54]	Extrapolation
	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 of motor vehicles and motorcycles*	400	564	0.71	2,128	1,508
G47–*Retail trade, except of motor vehicles and motorcycles*	429	1,065	0.40	3,386	1,354

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–February 2022 by GRCT (a waste management company in Belgium), with a total of 34 companies participating. The results of our waste sampling are provided in Table 3. The waste sampling campaign was performed to determine waste compositional data of non-household end-use plastic film covering *Wholesale* (e.g., NACE G.46), *Retail* (e.g., NACE G.47), *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 non-household end-use plastic film composition estimated by Hestin et al.[5]. Finally, the waste composition of these two studies is averaged and used as 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 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.

Figure 2. A few images of the collected samples from *Construction* sector (e.g., NACE sector F.41) from urban areas of Ghent, , consisting of Transparent PE Film (A), Colored PE Film (B), Transparent PP Film (C), Colored PP Film (D), and Other Plastic Film (E). More information on the samples is available in SI–section 4.

Table 3. Waste compositions used as input for the CBA model. The composition used in the model is averaged from the waste sampling campaign conducted in urban areas of Ghent in December 2021–February 2022 and 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.

Waste Category	**Characteristics**	**Composition (in %)**		**Averaged composition (in %)**	
		Waste sampling	Hestin et al.[5]	[1]*Higher feedstock quality*	[1]*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		[2]5	[2]5	[2]5	[3]25
Total		100	100	100	100

[1]*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.*
[2]*Residue content (i.e., 5%) is taken from previous studies[57,58]*
[3]*Residue content (i.e., 25%) is taken from previous study[59], while the share of the other waste category (i.e., PE transparent, PP Colored, etc.) 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, a sensitivity is carried out to assess the impact of potential variation on the non-household 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 recycling yield and net economic balance are recorded and discussed.

Logistic simulation of non-household end-use plastic film waste selective collection from urban areas

A logistic simulation of collecting non-household 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 tonne) 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 non-household end-use plastic film waste from companies listed in Table SI2 and Table SI3, in which the addresses are collected from Orbis databases.[54] The number of garbage trucks needed for collecting non-household 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/hour, following the standard speed limit in Belgian urban areas.[62] The average service time stop (at each address) is 8 minutes and the unloading time at the recycling facility is assumed to be 10 mins. 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 08.00–18.00. The estimated waste collection and unloading time is obtained from waste operator input. Finally, the estimated driver cost is €19.5/hour 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 non-household 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 tonne/hour 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 non-household end-use plastic film waste is assumed to be collected in plastic bags, which are open and then shredded into materials the size of roughly ten millimeters. 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 PE film, which is called '*rPE*$_{basic}$' or '*rPE*$_{advanced}$' in this article.

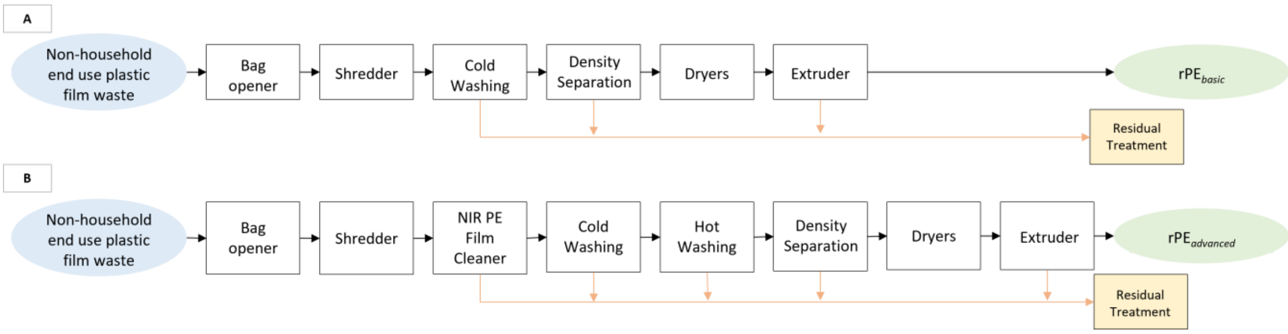


Figure 3. Flow diagram of (A) basic recycling process and (B) advanced recycling process considered in this study adapted from previous studies.[47,53]

Separation efficiency

The MFA of non-household 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 non-household end-use plastic film waste

The economic assessment of non-household 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 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), residual treatment (incl. transport of residue), fixed and variable production costs (i.e., labour, 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 six 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 regranulates 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 €1,000/tonne (higher price) (with a central price of €800/tonne). On the other hand, it is assumed that $rPE_{advanced}$ can reach up to €1,500/tonne (higher price). The lower price for $rPE_{advanced}$ is set to €900/tonne, and the central price is set to €1,200/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 non-household 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 (kgCO_2-eq.) starts when the non-household 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 non-household end-use plastic film waste will be transported to a recycling facility (hub), which is assumed to be located at 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]

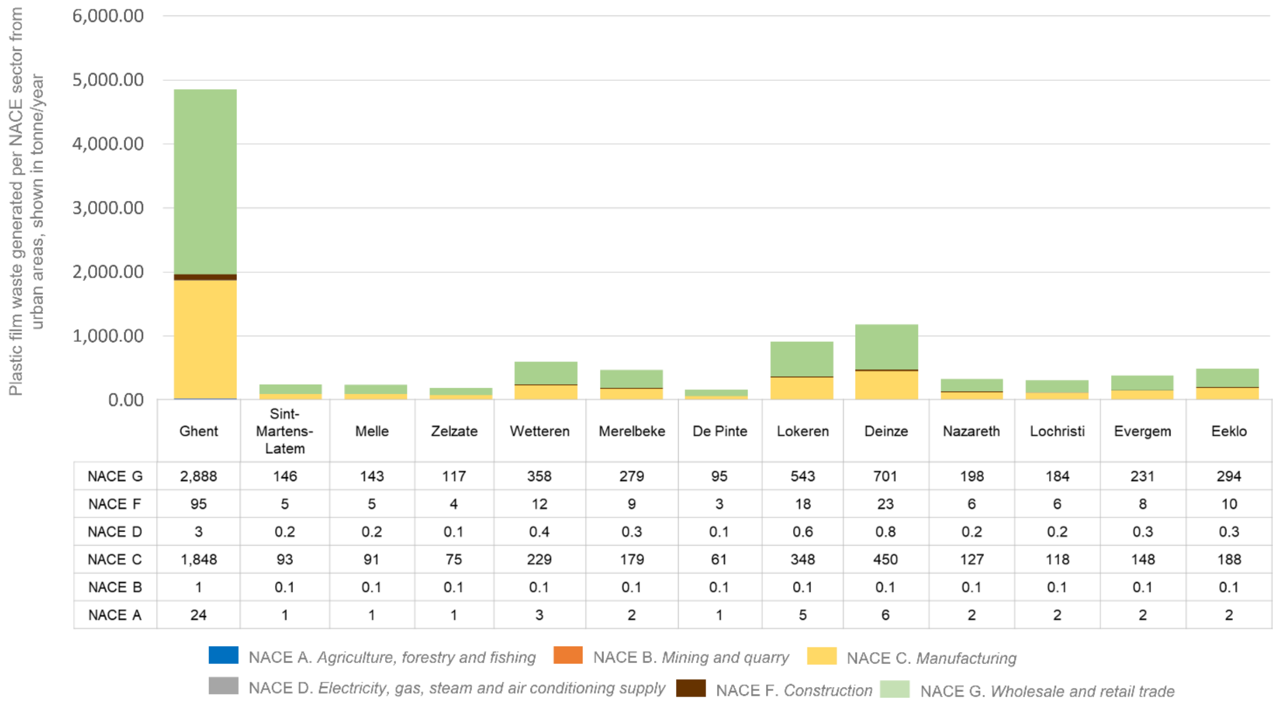
The estimated GHG emission from the selective collection in different frequencies (weekly, fortnightly, monthly) is obtained from logistic simulation in OptiFlow© software[45], which is estimated to be 0.165 kg CO_2-eq/tkm and benchmark against Ecoinvent v3.8 databases (Table S9). Note that the emission factor for selective collection is well-to-wheels (WTW), which implies that the GHG includes the emission at fuel production, transport, distribution, and during waste collection from urban areas. The GHG emission from mechanical recycling of non-household 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-eq.) is estimated by multiplying the carbon emission factors with the associated energy usage in mechanical recycling operation. Data on energy usage for mechanical recycling is obtained from literature[46,47,49,50,68], and is available in Table SI8. The emission factors (e.g., kgCO_2-eq/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 datasets can be found in the supplementary information Table SI9, which is based on ReCiPe 2016 (H) Midpoint impact assessment method.[73]

RESULTS AND DISCUSSION

Estimated quantity of non-household end-use plastic film waste

Figure 4 highlights the estimated total waste quantity of non-household end-use plastic film waste generated in urban areas of Ghent and its 12 neighboring municipalities in Belgium. From Ghent, it is estimated that 4,858 tonne/year of non-household end-use plastic film waste generated annually. From all urban areas considered in this study, it is estimated that more than 10,400 tonne of non-household end-use plastic film waste can be collected. The amount of waste generated per municipality varies between 160 tonne/year in De Pinte (postcode–9840) to 1,182 tonne/year in Deinze (postcode–9800).

The largest waste producer is NACE sector G. *Wholesale and retail trade* (i.e., 2,887 tonne/year), followed by NACE sector C. *Manufacturing* (i.e., 1,848 tonne/year). In the studied areas, a relatively low quantity of non-household end-use plastic film waste is generated from NACE sector A. *Agriculture, forestry, and fishing* (i.e., 24 tonne/year), NACE sector F. *Construction* (i.e., 95 tonne/year), and NACE sector D. *Electricity, gas, steam, and air conditioning supply* (i.e., 3 tonne/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 non-household 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 non-household end-use plastic film waste from urban areas.



	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

Figure 4. Estimated quantity (in tonne/year) of non-household 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 'non-household end-use plastic'.[6]

Logistic simulation results of non-household end-use plastic film waste selective collection

Results of the logistic simulations of non-household 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 Orbis (2022) databases (in SI, Table SI2 and Table 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 214,044–319,592 km/year, depending on the collection frequencies. The estimated annual distance for the other considered municipalities in this study ranges between 6,924 km/year (monthly collection in De Pinte–9840) to 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 cost €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 collecting the waste weekly. For the other municipalities, the weekly to fortnightly and monthly collection reduction ranges from 47–68% and 75–87%, respectively. For the companies (waste producers), different collection schemes would mean purchasing different garbage bin sizes. Companies are required to have bigger garbage bins (e.g., 240–2000 liter capacity) when the collection is less frequent (e.g., monthly) compared to a more frequent collection (e.g., 120–240 liter 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]

Table 4. Results of the logistic simulations to selectively collect 10,401 tonne/year non-household 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	9,412	7,904	6,924	€ 57,668	€ 25,116	€ 14,484	€ 360	€ 157	€ 91
Lokeren (9160)	1,778	1,778	1,784	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)	2,000	2,000	2,000	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)	1,031	1,031	1,037	25,636	18,642	17,376	€ 171,080	€ 60,424	€ 24,564	€ 441	€ 156	€ 63
Eeklo (9900)	1,232	1,232	1,234	51,480	47,892	38,496	€ 240,916	€ 86,060	€ 49,548	€ 486	€ 174	€ 100
Wetteren (9230)	1,386	1,386	1,391	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*****	€ 166*****	€ 73*****

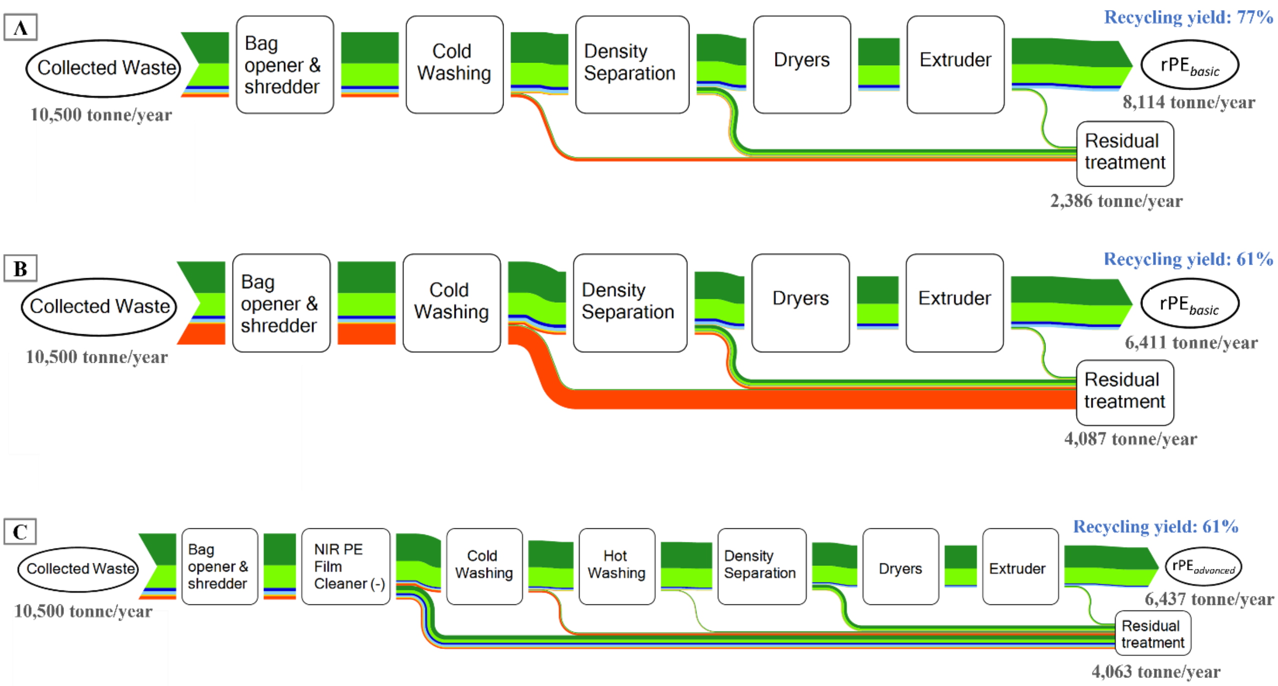
**The total selective collection cost per tonne of all non-household end-use plastic film waste, as shown in Figure 4.*

Material flow analysis of non-household end-use plastic film waste recycling

The material flow analysis (i.e., Sankey diagram) of non-household 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, the 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 60–80%.[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 non-household 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.



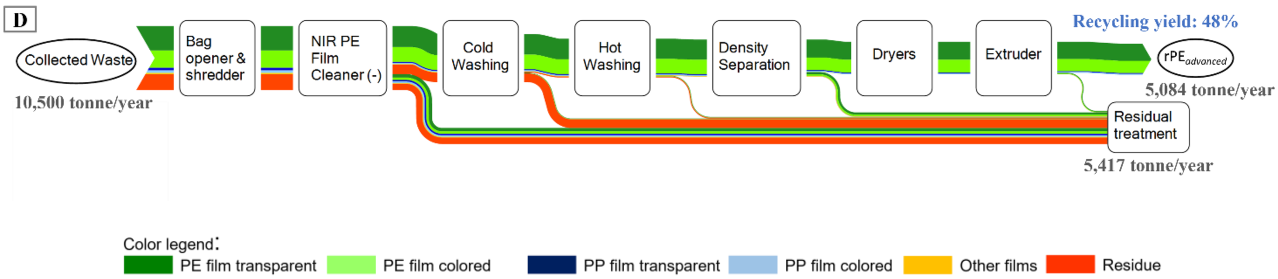


Figure 5. Results of material flow analysis of non-household end-use plastic film recycling in different scenarios: S1–basic recycling plant with higher feedstock quality (A), S2–basic recycling plant with lower feedstock quality (B), S3–advanced recycling plant with higher feedstock quality (C), and S4–advanced recycling plant with lower feedstock quality (D). This figure only shows the material flow of 10,500 tonne/year capacity. More information on the other processing capacities (i.e., from 2,500 – 20,500) is available in SI–section 9.

Economic assessment of mechanical recycling non-household end-use plastic film

Breakdown of the capital investment and annual costs of the mechanical recycling plant

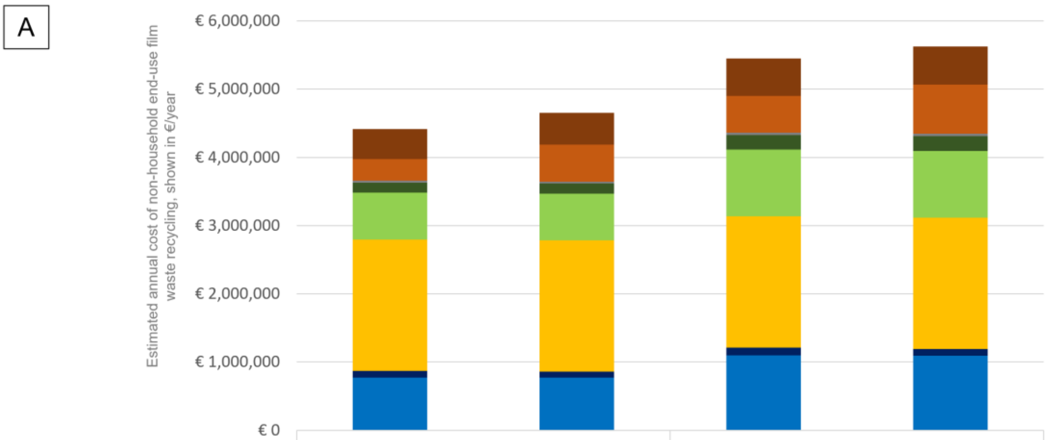
The estimated total capital investment (in SI, Figure SI27) needed to build the recycling plants (basic and advanced layouts) is around €5 million and €7 million respectively, based on the calculations provided in SI–section 6. The investment in washing, extruder, and construction of mechanical recycling 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. For the advanced recycling plant, the washing and extruder constitute 39% and 19% of the total investment needed (Figure SI27).

When looking at different processing scales (i.e., ranges between 2,500–20,500 tonne/year), the annual costs of basic recycling plants vary between €4.1–€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.

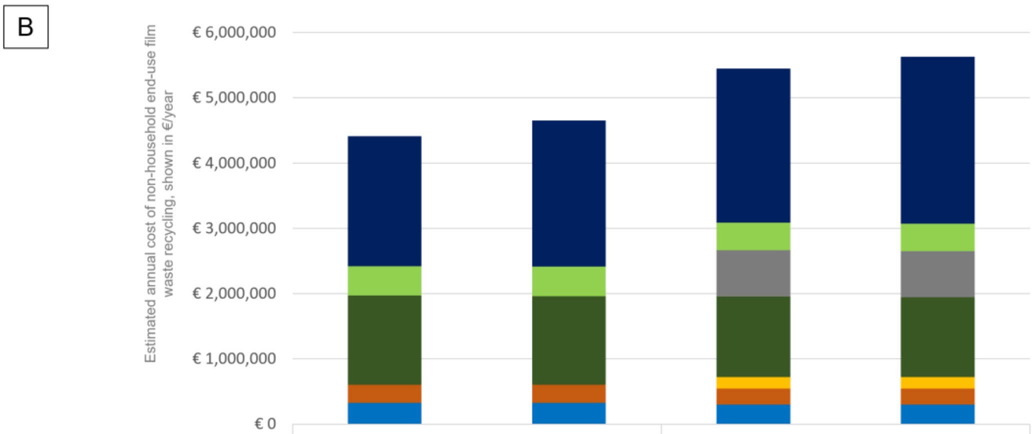
The detailed breakdown of the annual costs of mechanical recycling non-household end-use plastic film with 10,500 tonne/year capacity (fixed capacity, shown as an example) is provided in Figure 6. Figure 6a shows the annual costs per cost parameter (energy usage, water consumption, etc.), whilst Figure 6b shows the annual costs per equipment used in recycling (extruder, washing, etc.). The labour 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 (labour, depreciation, and energy costs) are estimated to make up 73–77% of the annual costs associated with non-household 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 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 tonne/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 tonne/year of plastic film waste from urban areas through advanced recycling plant (S3–S4) increases from €5.4 to €5.6 million. Such a considerable increase in annual costs is mainly attributed to a higher annual 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).



	S1: Higher feedstock quality	S2: Lower feedstock quality	S3: Higher feedstock quality	S4: Lower feedstock quality
	Basic recycling plant		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



	S1: Higher feedstock quality	S2: Lower feedstock quality	S3: Higher feedstock quality	S4: Lower feedstock quality
	Basic recycling plant		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 tonne/year capacity, shown as example) of non-household end-use plastic film waste (A) by cost modeling parameters (energy use, water

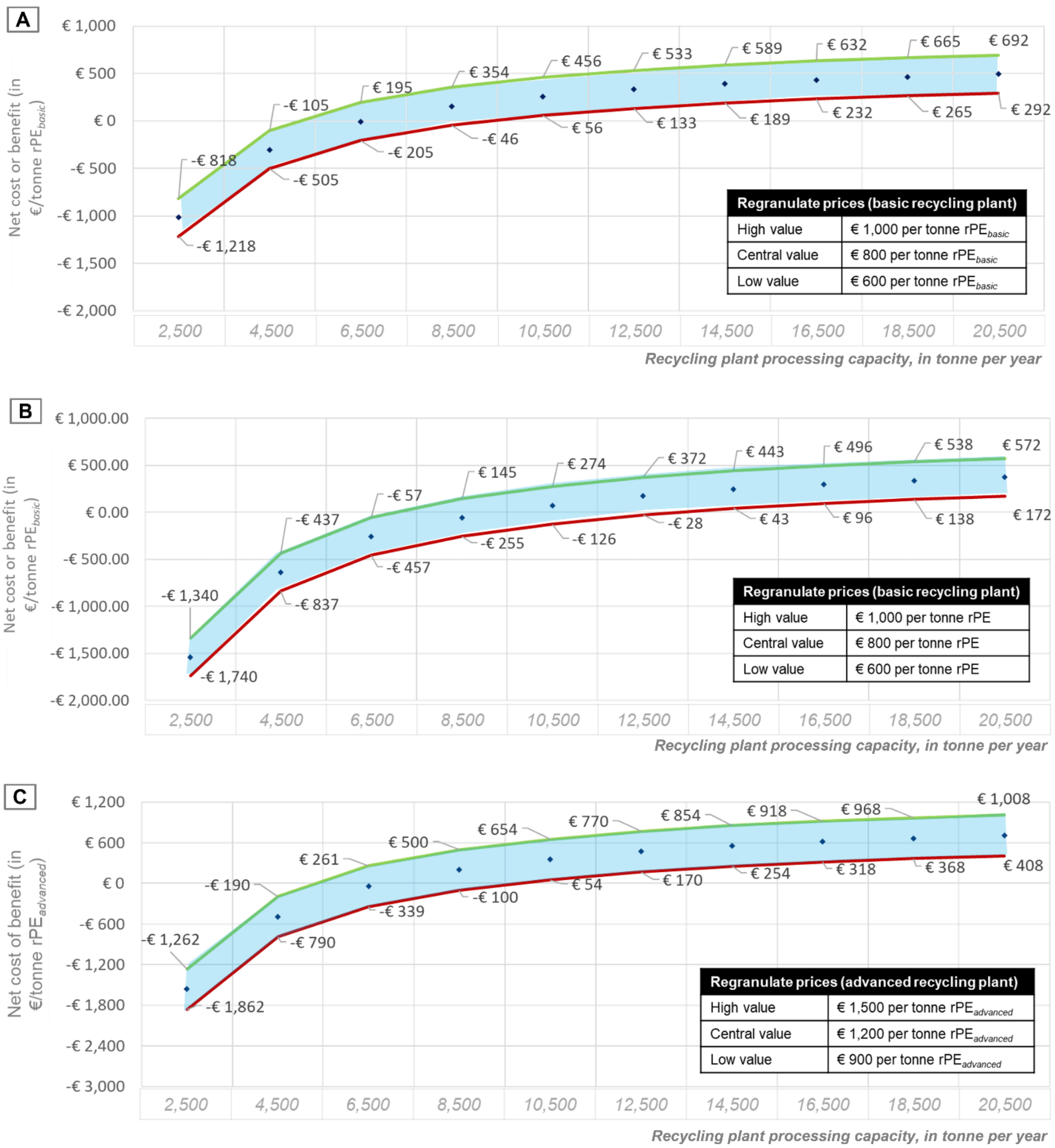
consumption, depreciation, etc.) and (B) by recycling equipment (incl. residual cost and general expenses that are attributed to the cost of recycling plant).

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 non-household 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 regranulates prices. More information on the cost and revenue per one tonne $rPE_{basic/advanced}$ production from mechanical recycling in different recycling capacities (ranges from 2,500 – 20,500 tonne/year) is provided in the SI, Table SI10.

The results in Figure 7 suggest that recycling non-household 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 tonne/year capacity onwards. However, this holds true only when a higher feedstock quality is maintained (Figure 7A and 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 basic recycling plant) and Figure 7D (for advanced recycling plant). Selling rPE at higher prices (€1,000/tonne rPE_{basic} and €1,500/tonne $rPE_{advanced}$) is needed to make recycling non-household end-use plastic film waste at 10,500 tonne/year capacity economically viable (net benefit €75/tonne rPE_{basic} and €90/tonne $rPE_{advanced}$, in Figure 7B and 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 previous section. The link between recycling operations and the scale on 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 non-household 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 tonne 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., 6,500–8,500 tonne/year), but the regranulates must be sold at higher prices (€1,000 and €1,500/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 from household waste (typically more contaminated[27]), which can result in a lower rPE$_{basic/advanced}$ quality, and subsequently regranulates price. Furthermore, the net economic balance of collecting and mechanical recycling of non-household end-use plastic film waste from urban areas considered in this study (i.e., 10,500 tonne/year) is discussed in the next section.



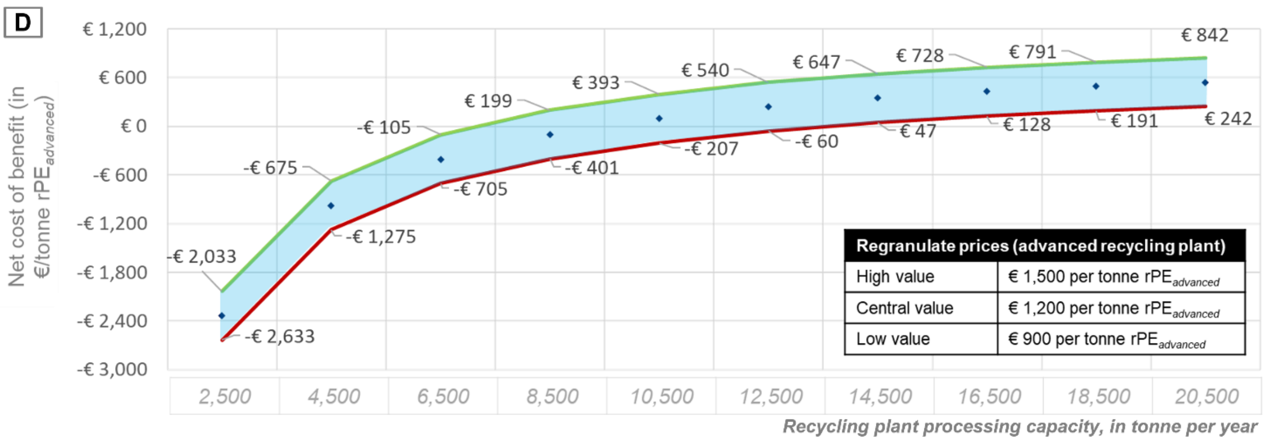


Figure 7. Estimated net loss or profit (green line, high regranulate price; red line, low regranulate price; blue dots, central regranulate price) of non-household end-use plastic film waste recycling in S1(A), S2(B), S3(C), and S4(D). The costs and revenue are shown in €/tonne rPE Film (y-axis) across different recycling plant processing capacities (x-axis, from 2,500 tonne/year up to 20,500 tonne/year capacity). These graphs exclude gate fees. Collection costs are included in Figure 9.

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 (€1,000/tonne rPE_{basic} and €1,500/tonne $rPE_{advanced}$) when the residue content exceeds 30–35%, otherwise mechanical recycling non-household end-use plastic waste is economically unfeasible, even without selective collection cost. 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.

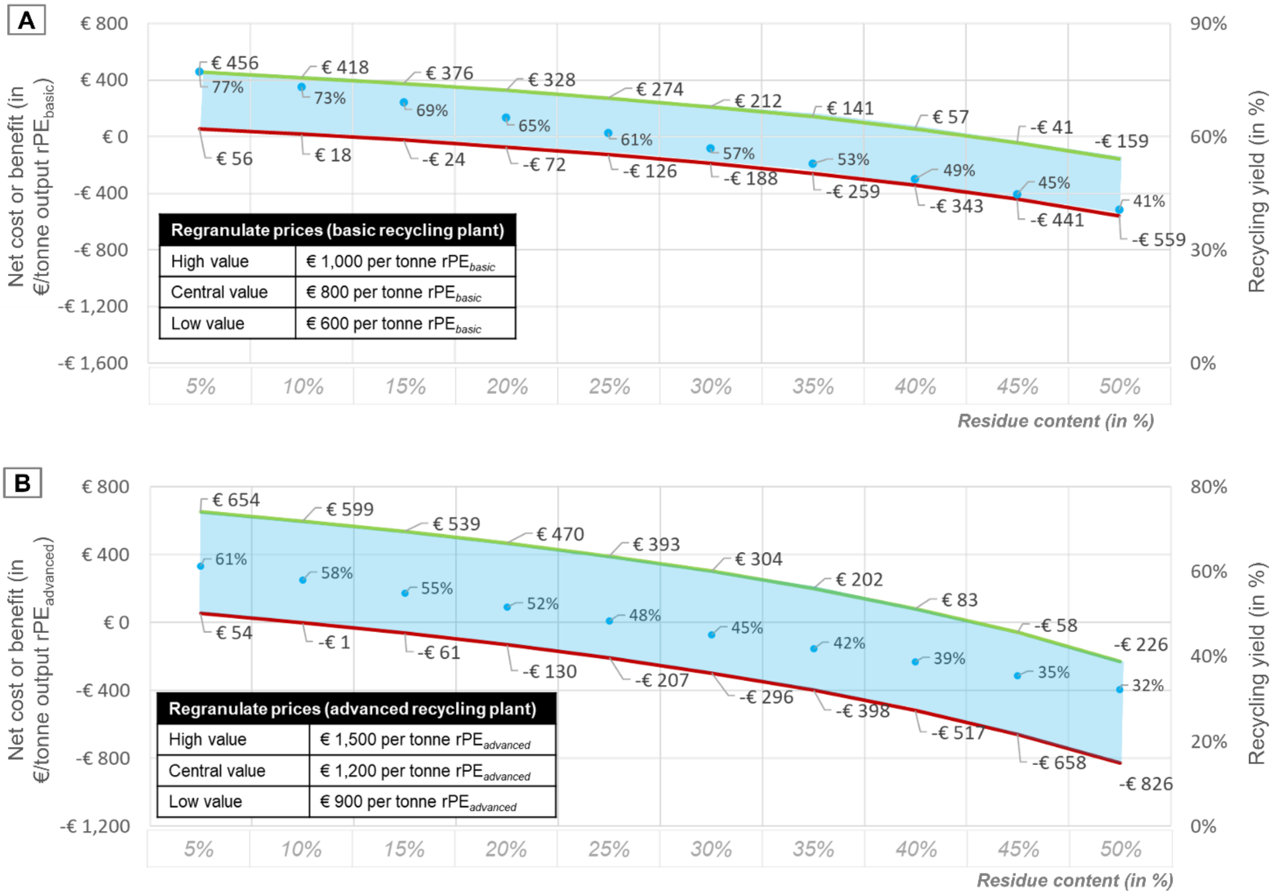


Figure 8. Sensitivity analysis towards recycling yield (blue dots) and net cost or benefit of non-household end-use plastic film waste recycling: A) basic recycling plant and B) advanced recycling plant. The green line shows the net cost/benefit of high regranulate prices while red line shows the net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

Cost benefit analysis of selective collection and mechanical recycling plastic film waste from urban areas

The estimated annual costs of non-household 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 tonne/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 non-household 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 €1,200/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 previous section and in Larrain et al.[47] study.

As seen in Figure 9, viable business case for selective collection and mechanical recycling of non-household 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 €1,100/tonne $rPE_{advanced}$ (S4). Second, the $rPE_{basic/advanced}$ should be sold at central (€800/tonne rPE_{basic} and €1,200/tonne $rPE_{advanced}$) or higher prices (€1,000/tonne rPE_{basic} and €1,500/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 non-household end-use plastic film waste is economically feasible only when the rPE is sold at a higher price (€1,000/tonne rPE_{basic} and €1,500/tonne $rPE_{advanced}$). Overall, the total costs of selective collection (fortnightly or monthly) and mechanical recycling on non-household end-use plastic film from urban areas are estimated to range from €635/tonne rPE_{basic} (S1, monthly) to €1,445 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 non-household end-use plastic film waste, the CBA results suggest that it is economically unfeasible to make profit from weekly waste collection, even when the $rPE_{basic/advanced}$ is sold at higher price (€1,000/tonne rPEbasic or €1,500/tonne rPEadvanced), as shown in Figure 9. However, Figure S28 in the SI indicates that mechanical recycling plant becomes more cost-effective as more waste is processed (capacity increases) with an overall a 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 tonne/year. Similarly, the annual cost per tonne $rPE_{advanced}$ 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) 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 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 higher price if the residue content gets higher (25w%), 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 non-household waste can play a crucial role because of its homogenous 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, a 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 viable business case of recycling non-household end-use plastic film waste rely 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 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 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 to do 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 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.

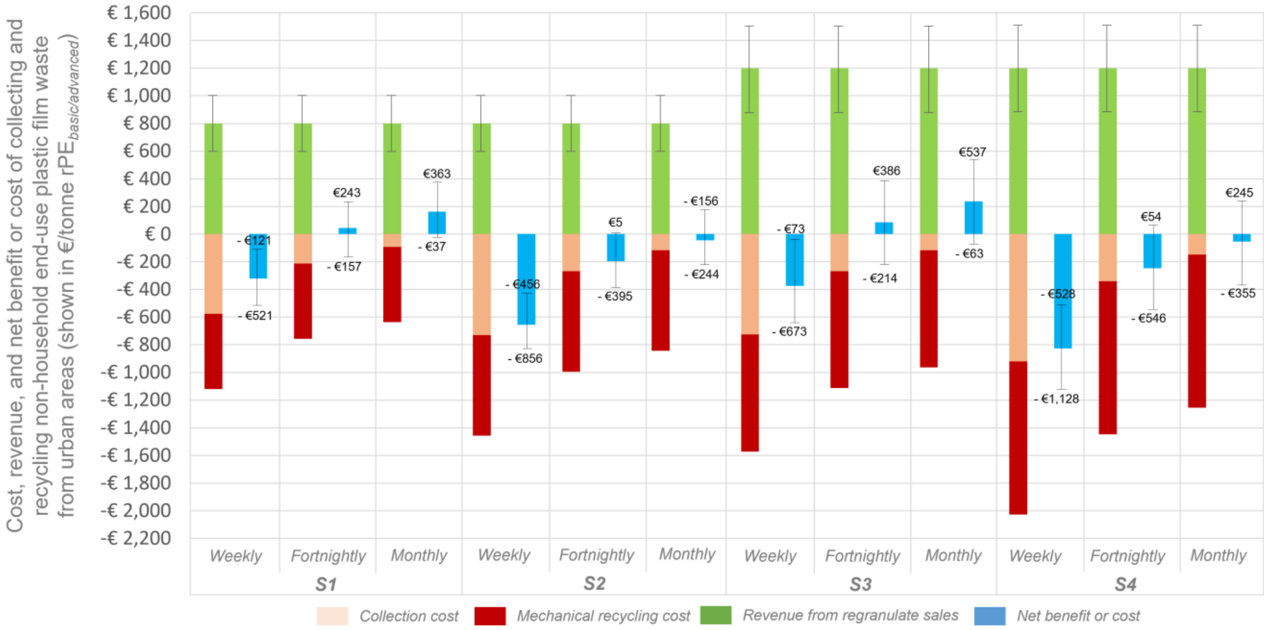


Figure 9. Cost, revenue, and net benefit or cost of collecting (weekly, fortnightly, or monthly collection) and mechanical recycling (10,500 tonne/year, in S1–S4) of non-household end-use plastic film waste from urban areas, shown in €/tonne $rPE_{basic/advanced}$. The blue bar reflects the net benefit or

cost from 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.

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 1,089–1,433 kg CO_2-eq. mainly depending on the selective collection scheme. For every one tonne $rPE_{advanced}$ (S3–S4), the GHG emissions ranges from 2,289–2,761 kg CO_2-eq., 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 (5,048 kg CO_2-eq/tonne rPE), respectively. Figure 10 also presents the breakdown of GHG emissions during waste collection, from the 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 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 plant can still be improved by minimizing the residue. As shown in Figure 5 and discussed in 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 emissions of monthly collection is 3–4% lower than weekly and fortnightly collection. When the feedstock quality gets lower (in S2 and S4), it can be observed that the GHG emissions increases by 15–21% (compared to S1 and S3). In S2 and S4, a higher GHG emission is mainly caused 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 advanced recycling plant (in S3 and S4) is 48–52% higher compared to basic recycling plant (in S1 and S2). However, further research should be performed to assess the substitution rate (and environmental saving) of $rPE_{basic/advanced}$, which have different quality 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]

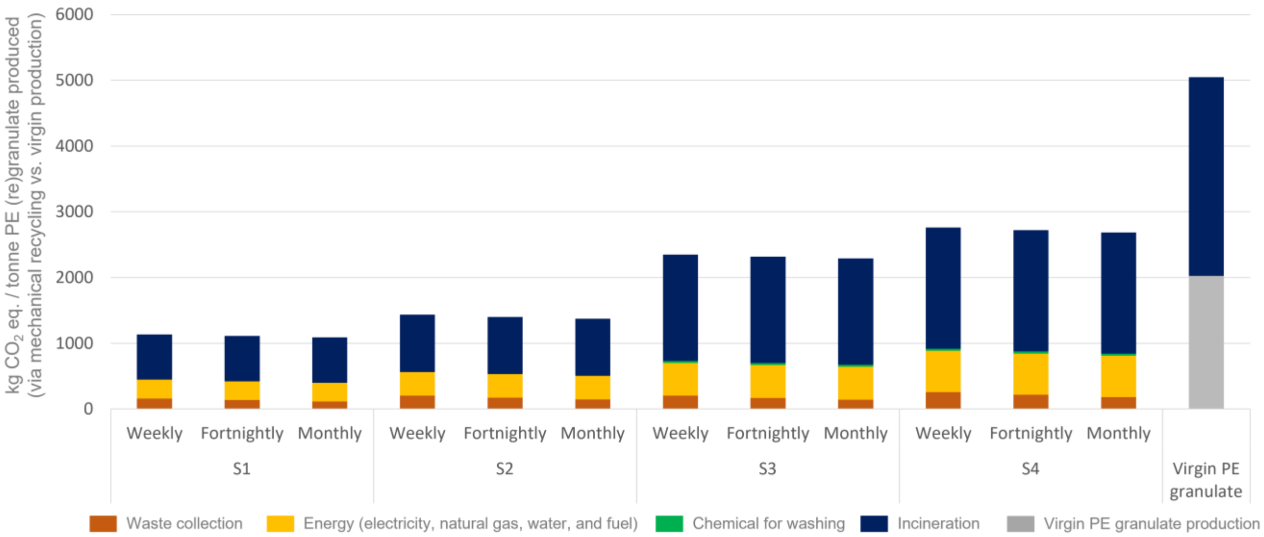


Figure 10. Greenhouse gas estimation of collecting and recycling non-household end-use plastic film waste from urban areas considered in this study to produce 1 tonne rPE (in S1–S4) compared to 1 tonne virgin PE granulate production. S1: basic recycling plant with higher feedstock quality, S2: basic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

CONCLUSION

This study uses the cost-benefit analysis model to develop potential business cases for selective collection and mechanical recycling of non-household end-use plastic film from urban areas. The City of Ghent in Belgium and twelve 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 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 up 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 costs-benefits 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 tonne/year of waste is collected and recycled, indicating processing capacity related to the economy of scale. In the positive scenarios, annual costs from 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 €1,100/tonne $rPE_{advanced}$. The positive net economic balance can be achieved when the regraulates are sold at €800/tonne rPE$_{basic}$ and €1,500/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 non-household 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 emissions calculation suggests that minimizing residual streams and maintaining high-quality feedstock from the waste collection are keys to lowering the carbon footprint. Results indicate that the carbon footprint from mechanical recycling non-household end-use plastic film waste can be 49–79% less than current linear economic model of using virgin polyethylene granulate and waste incineration.

Concluding, selective collection and recycling non-household 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 non-household end-use plastic waste treatment, especially to sustain plastic recycling operations when regranulate price drop (e.g., due to low oil prices). Financial incentives for waste producers to properly separate waste at source can be promoted to ensure feedstock quality and quantity. Nevertheless, given the large quantity of plastic films in non-household 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

Providing details related to the use of Orbis database, non-household 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).

CrediT authorship contribution statement

Irdanto Saputra Lase: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Software, Data Curation, Formal Analysis, Visualization. **Regina Frei**: Writing – review & editing, Conceptualization, Methodology, Software, Data Curation, Validation, Resources. **Mengfeng Gong**: Writing – review & editing, Conceptualization, Methodology, Software, Data Curation, Validation, Resources. **Diego Vazquez-Brust**: Writing – review & editing, Validation, Validation, Supervision. **Evelien Peeters**: Writing – review & editing, Conceptualization, Methodology, Data Curation, Validation, Resources. **Geert Roelans**: Writing – review & editing, Validation, Validation, Supervision. **Jo Dewulf:** Writing – review & editing, Validation, Supervision. **Kim Ragaert:** Writing – review & editing, Validation, Validation, Supervision. **Steven De Meester:** Writing – review & editing, Conceptualization, Methodology, Resources, Validation, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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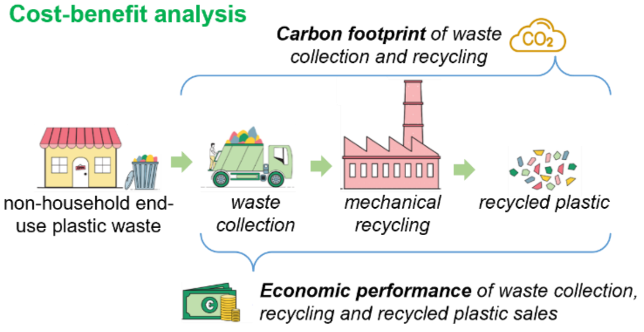
Synopsis

Cost-benefit analysis of selective collection and recycling of non-household end-use plastic waste indicate that it is economically attractive and crucial towards plastic sustainability.

Graphical Abstract



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