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Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste

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Abstract

Increasing plastic recycling rates is crucial to tackle plastic pollution and reduce consumption of fossil resources. Recycling routes for post-consumer plastic fractions that are technologically and economically feasible remain a challenge. Profitable value chains for recycling mixed film and tray-like plastics have hardly been implemented today, in sharp contrast to recycling of relatively pure fractions such as polyethylene terephthalate and high-density polyethylene bottles.

This study examines the economic feasibility of implementing mechanical recycling for plastic waste such as polypropylene, polystyrene, polyethylene films and mixed polyolefins. In most European countries these plastic fractions are usually incinerated or landfilled whilst in fact technologies exist to mechanically recycle them into regranulates or regrinds.

Results show that the economic incentives for the recycling of plastic packaging depend predominantly on the product price and product yield. At current price levels, the most profitable plastic fraction to be recycled is PS rigids, with an internal rate of return of 14%, whereas the least profitable feed is a mixed polyolefin fraction with a negative internal rate of return in a scenario with steadily rising oil prices. Moreover, these values would be substantially reduced if oil prices, and therefore plastic product prices decrease. Considering a discount rate of 15% for a 15-year period, mechanical recycling is not profitable if no policy changes would be imposed by governments. Clearly low oil prices may jeopardize the mechanical recycling industry, inducing the need for policies that would increase the demand of recycled products such as imposing minimal recycled content targets.

Keywords

Techno-economic assessment, plastic recycling, plastic packaging, circular economy, oil, uncertainty

1 Introduction

To enable a circular economy for plastics, reducing the pressure on natural resources and avoiding leakages of waste into ecosystems, an effective after-use of plastics is essential. Direct economic incentives are required to capture more material value and increase resource productivity (World Economic Forum et al., 2016). Extended product responsibility regulations, applied in several European countries, have only increased recycling rates to around 42%. These regulations provide few incentives for packaging manufacturers to improve eco-design and recyclability, failing to strength secondary material markets (Milios, 2018). This is evident in the case of Europe, were in 2018 only 7 500 000 ton of plastic packaging waste were recycled of a total 17 800 000 ton generated (PlasticsEurope, 2020).

Linking technical with economic aspects of recycling technologies and recycled plastics markets is essential to design effective policies. For this purpose, techno-economic assessments (TEA) are a useful tool (Thomassen et al., 2019). The main technical challenge to recycle mixed plastic packaging waste is the differences in melting points and processing temperatures between the polymers in the mixed plastics. This may cause the degradation of the component with lowest melting point reducing the quality of the recycled product (Ragaert et al., 2017). In addition, various polymers may be incompatible and residual additives or impurities may be undesired.

To date, TEA related to recovery and recycling of packaging waste has mainly focused on sorting plants. Using a TEA framework, Athanassiou and Zabaniotou (2007) concluded that higher levels of automation increased the profits of a municipal solid waste sorting plant in Cyprus. Marques et al. (2014) gave important insights of the Belgian after-use plastic market and showed that to the date, the collection and sorting costs were almost fully financed by the gate fees. Cimpan et al. (2016) performed a TEA on different scale lightweight packaging sorting plants. Similarly to Marques et al. (2014), they conclude that most of the costs should be covered by gate fees and that the revenues from their sales are lower than the costs of disposing the non-recyclable material.

For mechanical recycling, research is scarce, because most data is confidential and not readily available (Bora et al., 2020). Eriksson and Finnveden (2009) compare the energy efficiency, cost efficiency and environmental performance of landfilling, incineration, and recycling. An aggregated welfare indicator ranks material recycling first, followed by incineration and landfilling. Faraca et al. (2019) performed a life cycle assessment and life cycle cost assessment of two mechanical recycling options and pyrolysis of rigid polyolefin waste and concluded that economic savings can be achieved with a complex mechanical recycling system when compared to the other two alternatives.

The aforementioned studies provide important insight on market conditions and TEA of recycling processes. However, there are still meaningful improvements to be made. First, the potential economic profits that could be obtained from the recycling of mixed plastic waste in real conditions have not been studied in detail. Moreover, market dynamics and uncertainties have a major effect on decisions undertaken by investors and have not been addressed so far. As a matter of scope, earlier studies ignored the differences in the process flows to recycle the different plastic types.

The objective of this study is to evaluate the economic viability of recycling plastic waste fractions that are currently incinerated or landfilled in most European countries, considering the established prices for products and feedstocks. For the first time, it explores the cost structure of the recycling processes of waste fractions taking into account the fraction compositions. This is done by modelling the process flows and mass and energy balances of each fraction depending on its contamination level and plastic characteristics. It contributes to the field, by exploring the main technological and economic drivers for plastic recycling profitability. We correspondingly highlight the effect of future crude oil prices and their volatility, suggesting that governmental policy can play a crucial role to make sure that mechanical recycling of plastic packaging remains competitive.

2 Methodology

TEA is used to study the economic performance of recycling of different post-consumer plastic packaging waste fractions in Flanders, Belgium. This method translates directly an alteration in a technological parameter into an economic indicator (Thomassen et al., 2019). Following the TEA steps as presented in Van Dael et al. (2015), we first perform a market study to analyze the potential product prices. Then, we obtain the mass and energy balances with a technological assessment. As a third step, to calculate the net present value (NPV) and other indicators, an economic assessment is developed including revenues, investment and operational costs. Finally, with a sensitivity analysis we study how the NPV would change after varying the input variables and with an uncertainty analysis the ranges of the NPV are examined.

This study focuses on the four plastic packaging fractions obtained after the sorting of mixed recyclable post-consumer waste that are usually incinerated or landfilled in European countries but for which technologies for recycling exist: polypropylene bottles and trays (PP rigids), polystyrene trays (PS rigids), polyethylene films (PE films) and mixed polyolefin rigids (MPO rigids), a mix of PP and High Density Polyethylene. The products of the recycling process are PP regranulates, PS regranulates, LDPE regranulates and MPO regrind (flakes), respectively. For the market study, European trading data of recycled products is used, and their temporal variation is projected according to oil price estimations.

These plastic fractions origin from post-consumer packaging waste, so they contain food residue and labels. Besides, the sorting process that precedes the recycling process is not 100% efficient, so some small shares of other plastics are missorted (Kleinhans et al., 2021). Thus, along with the targeted plastic, the plastic fractions will contain other undesired plastics and residues.

The flow diagrams to process each plastic fraction are built depending on its characteristics (residue and moisture content, thickness of the flakes, thermal properties of the plastics, etc.) and the desired product quality specifications. The included process steps are shredding, washing, milling, float-sink, mechanical and thermal drying and regranulation. To calculate the mass and energy balances for each process step, information from an existing recycling plant is combined with recycling equipment specifications, thermodynamic calculations and the feedstock characteristics. By modelling a specific process flow and mass and energy requirement for each fraction, the contamination levels and plastic characteristics are reflected in the product yield and cost structure of the processes. Regarding the operational and investment costs, literature data and other publicly accessible information are used together with industrial experts' interviews.

2.1 Market study

Values from previous offers and bids are collected from databases to estimate the current prices of recycled products. Considering that these prices are coupled to oil prices, their temporal variation is projected with the oil price estimations presented by the world energy outlook of the International Energy Agency (International Energy Agecy, 2018a).

Plasticker.de is a German based trading platform that shows offers and requests for recycled plastics classified by source (postindustrial, postconsumer, etc.), type, color and shape of the product (regrind, regranulates, etc.). To estimate transaction prices, seventy data points of offers and requests placed throughout Europe between October 2019 and January 2020 are collected. For the products for which there was request and offer data we calculated the request/offer price ratio. Then the request/offer price ratio (0.66) is multiplied by the weighted average offer prices of the PP regranulates, PS regranulates, LDPE regranulates and MPO regrind to estimate transaction prices. Final values are validated with expert insights.

These prices are taken as a starting point for year 2019. Because recycled product prices are closely correlated with oil prices (WRAP, 2016, 2007), future product price variations are assumed to be equivalent to oil price variation. The International Energy Agency (International Energy Agency, 2018a) presents forecasts of oil price projection in several scenarios, among which the base case scenario or stated policies scenario and sustainable development scenario (SDS). The SDS projects oil prices, considering that Paris Agreement targets are met and that there is a decarbonization of the electric matrix and a decrease in oil demand (International Energy Agency, 2018b). A more in depth explanation of this method and assumption is presented in Larrain et al. (2020).

2.2 Flow diagrams

The flow diagrams are adapted from a currently operative process flow of the company Eco-Oh! (Belgium), that treats 14 000 ton/year of mixed polyolefin films. This existing process flow is accommodated to each fraction depending on their characteristics and composition after sorting and on the desired characteristics of the products. A typical capacity for plastic recycling facilities, 20 000 ton/y, is adopted as the total sorted plastic waste input that enters each recycling process. Figure 1 shows a generic process flow diagram that is used as a baseline for all fractions, whereas a detailed process flow for each plastic fraction is shown in section S.1 of the supporting information. The methods used to calculate the flows after each process step, represented by the numbers 1 to 20 in the figure, are explained in Section 2.3.

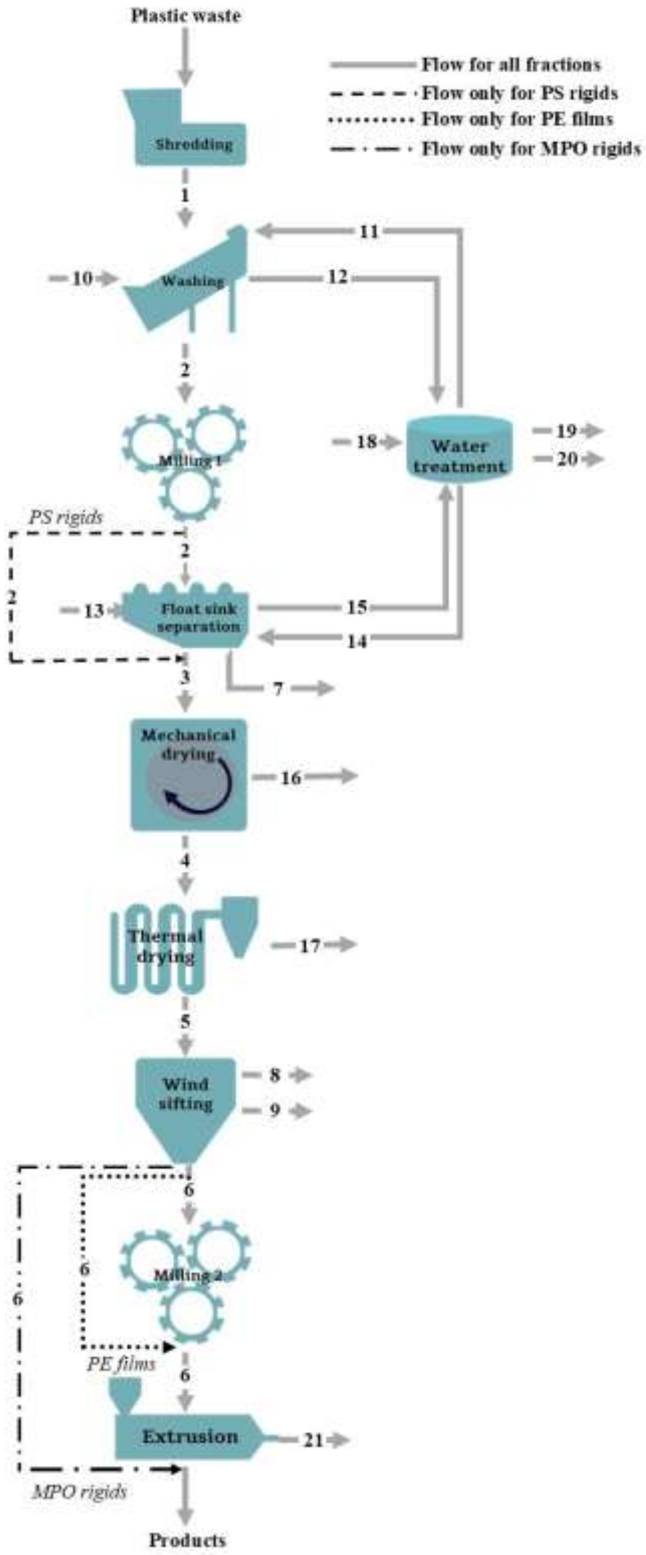


Figure 1: Generic process flow for the recycling process. 1: dirty 10 cm pieces 2: clean and wet 3.5 cm flakes, 3: wet floating flakes, 4: moist floating flakes, 5: dry floating flakes, 6: 0.8 cm flakes selected after wind sifting, 7: sinking flakes, 8: discarded flakes after wind sifting, 9: dust, 10: tap water for washing, 11: recycled water for washing, 12: waste water, 13: tap water for float-sink, 14; recycled water for float-sink, 15: waste water, 16: evaporated water, 17: evaporated water, 18: chemicals for water treatment (NaOH, $FeCl_3$ and polyelectrolyte), 19: filter cakes, 20:pulp, 21: filtered plastic in extrusion

The plastic waste that is processed, starting from post-sorting plant bales, contains residues and other plastics. This cross-contamination causes deviations in tensile, impact, and flexural properties (Simon, 2019). As a consequence, before the targeted plastic is transformed into the final product, these undesired components must be removed by several steps, leaving only a 0.5% of humidity. Prior to washing, the waste is shredded into pieces of approximately 10 cm (flow 1). Once washed, in preparation for the float-sink separation, the pieces are milled into flakes of 3.5 cm (flow 2). After the float-sink, where polyolefins are separated from other plastics such as PVC or PET (flow 7) with a floating tank, the float fraction flakes (flow 3) are dried with a centrifugal dryer (flow 4) and with a hot-air or thermal dryer (flow 5). A float-sink process is not considered for the PS rigids fraction because it has a low content of undesired plastics (Kleinhans et al., 2020).

Following this, a wind sifter separates the rigid float fraction (flow 8 in PE films and flow 6 in others) from the film float fraction (flow 6 in PE films and flow 8 in others). Then, the PP rigids and PS rigids fractions pass through a second milling where the flakes are milled to 0.8 cm. This step is absent in the PE films fraction, because it is possible to feed 3.5 cm films into the extruder. Finally, to obtain regranulates, the flakes are extruded and filtered. The second milling step and extrusion step are not considered in the MPO fraction because the final product in this case is 3.5 cm regrinds. All process flows include a water treatment plant to process the water from washing and float-sink. To convey the plastics between the process steps, transport screws (three for PP and PS rigids and two for PE films and MPO rigids) and ventilators (two for PP and PS rigids and one for PE films and MPO rigids) are added

2.3 Process flows and mass balances

The input flows and output flows of each process step are calculated to constitute the mass balances. The flows that enter the process are plastic waste, water for the washing and float-sink and chemicals for water treatment. As output flows recycled plastic product, plastic residue (sink fraction, discarded fraction after the wind sifting and melt filtration and dust), pulp and filter cakes from the water treatment are obtained.

It is assumed that the paper residue and organic residue initially found in the plastic fraction (Table 1), is removed completely during the washing process. The undesired plastic is separated from the targeted plastics with a float-sink process, a wind sift process and a melt filtration included in the extrusion process. These processes separate the plastics flakes depending on their density, shape and melting point respectively. The initial composition of the plastic that goes through a float-sink process is taken from Kleinhans et al. (2021). With the float-sink process the float fraction is separated from the sink fraction based on the plastic density. The separation efficiencies of the float-sink process are taken from the transfer coefficients presented in Brouwer et al. (2018) for single-polymer flakes. For multilayer films, the separation is estimated at 73% floating based on the composition on the multilayer films fraction composition showed in Roosen et al. (2020). Later, in the wind sifting the rigid float fraction is separated from the film float fraction depending on the shape of the flakes. The separation efficiencies of the wind-sift process is based on the split coefficients presented in Kleinhans et al. (2021). Finally, remaining plastics with a lower melting point than the targeted plastic are filtered during the extrusion process. The composition of multilayered or other films is obtained from Roosen et al. (2020). Additionally, according to industrial references, approximately 3% of the plastic is lost in the residual water ending in the pulp and as dust. The percentages of plastic that will end in the sink fraction, float fraction, pulp, rigid float fraction, film float fraction, discarded after the melt filtration, initial moisture content and residue and paper content are presented in Table 1.

	Variable		PP rigids	PS rigids	PE films	MPO rigids	Unit	Reference
Fraction initial composition	*Residue*	*Paper*	0.3	2.8	0.0	0.6	%	Roosen et al (2020)
		Organic	7.1	7.0	9.2	7.2	%	
	Plastic		92.6	90.2	90.8	92.2	%	
Plastic component fate (% of total fraction)	*Sink fraction*		2.0	0.0*	5.0	27.0	%	Own elaboration from Kleinhans et al. (2020)
	Plastic losses in pulp		0.5	0.5	0.5	0.5	%	
	Float fraction		90.1	89.7	85.2	64.7	%	
	Rigid float		86.9	86.6	3.8	60.1	%	
	Film float		0.9	0.9	79.2	2.4	%	
	Losses as dust		2.2	2.2	2.2	2.2	%	
	Discarded in melt filtration		0.0	0.1	1.8	0.0**	%	
Flake characteristics	*Layer thickness*		396	259	75	399	µm	Experimental (Omnexus, 2020)
	Average density		0.91	1.05	0.94	0.93	t/m^3	
Residue component fate	*Filter cake*		31	31	31	31	%	Industrial reference
	Pulp		69	69	69	69	%	
Moisture content	*Moisture after mechanical drying****		2.3	3.0	11.5	2.2	%	Own calculation

***Float-sink process is not considered in the PS rigids. **Extrusion with melt filtration is not considered in the MPO rigids. ***The moisture after mechanical drying is calculated based on the thickness of the layers of the different fractions, as described later**.

Table 1: Input plastic fraction and output flows composition and characteristics

The water volume modelled to be required for washing depends on the residue content (paper and organic) removed in this step. The water volume required for the float-sink process depends on the incoming plastic flow mass. The water treatment consumes chemicals such as polyelectrolytes, ferric chloride and sodium hydroxide and generates pulp and filter cakes as residual outputs. Together with the residual plastics, these outputs are directed to an incineration facility. The chemical quantities depend on the dirt contained in water flow and therefore on the fraction residue content. The treated clean water is recycled back to the washing and float-sink process, thus it is not accounted for in the net mass balances. The water requirement, chemical requirement and the percentages of residue that will end up in the pulp and filter cake are taken from the industrial process and are shown in Table 2.

	Variable	Value	Unit
Output flow moisture content	*Filter cake moisture*	60	%
	Pulp moisture	60	%
	Product moisture	0.5	%
Water requirements	*Washing tap water*	2.45	g/g dirt
	Washing recycled water	86.42	g/g dirt
	Float-sink tap water	0.165	g/g plastic
	Float-sink recycled water	5.83	g/g plastic
Chemicals requirements for water treatment	*Ferric chloride*	22.11	g/kg dirt
	Sodium Hydroxide	28.14	g/kg dirt
	Polyelectrolyte	2.68	g/kg dirt
Industrial reference fraction characteristics	*Waste moisture initial content*	0.47	g/g paper and residue
	Moisture after mechanical drying	0.25	g/g plastic
	Flake density	0.93	ton/m^3
	Layer thickness	35	µm

Table 2: Industrial process yields and flows characteristics. Data retrieved from internal data of Eco-Oh! and Sweco Belgium (2016)

Section S.2 of the supporting information shows the equations used to calculate the material flows of plastic , dirt, water and chemicals shown in Figure 1.

2.4 Energy balances

The total energy consumption is the sum of the energy consumption of all process steps. This is obtained by multiplying the energy consumption per ton of dry material of the step, i.e. specific energy consumption, by the dry material (plastic and dirt) flow processed in that step.

Several approaches are used to calculate specific energy consumption of the process steps. Equipment manufacturer specifications about the power and maximum flake throughput for rigids and film plastics (Table S.3 of supporting information) are used for the shredding, milling, washing, float-sink and mechanical drying. The maximum flake throughput represents the maximum amount of dry material (in ton) that a machine can process at maximum capacity. This depends on the number of plastic flakes per ton of material, i.e. the flake density, and consequently on the average flake layer thickness. Therefore, the maximum flake throughput differs between rigids (PP, PS and MPO rigids) and films (PE films). Accordingly, assuming operation at 100% of capacity, the specific energy consumption of process step i for a fraction f is calculated using Equation (I):

Equation (I) $Specific\ Energy\ Consumption_i^f = \frac{Power_i}{Max\ throughout_i^f}$

Additionally, thermodynamic equations are used to calculate the specific energy consumption for thermal drying and extrusion or granulation taking as parameters the physical characteristics and thermodynamic properties of each plastic fraction. The methodology for thermal drying is explained in sections 2.4.1 and for extrusion on section 2.4.2.

2.4.1 Thermal drying energy consumption

The energy used for thermal drying is the energy required to evaporate the residual moisture in the flakes after the mechanical drying (Kemp, 2012). Because all of the analyzed plastics are non-hygroscopic and we assume that all fractions have equal capillarity, the remaining moisture will only depend on the total flake surface in contact with water (Horodytska et al., 2018), that will depend on the flake density (ρ) and layer thickness (th). Using the data from the reference industrial process (Table 2) and the specific characteristics of each plastic fraction (Table 1), the moisture after the centrifugal or mechanical drying (mMd) is calculated with the formula presented in Horodytska et al. (2018):

Equation (I) $$mMd = mMd_{Industrial} * \frac{\rho * th}{\rho_{Industrial} * th_{Industrial}}$$

Considering the heat capacity of water (HC = 1.16 Wh/(kg*K)), vaporization heat of water (VH = 638 Wh/kg), the water content after the centrifugal drying, the temperatures at the input (T_o) and at the output of the dryer (T_d) and the thermal drying efficiency (η_{dryer}) presented in Table 3, the energy consumed for the thermal drying is calculated as:

Equation (II) $$Energy_{thermal\ drying} = \frac{(HC*(T_d - T_o) + VH)*(wMd - product\ moisture)}{\eta_{dryer}}$$

Variable	Symbol	PP rigids	PS rigids	PE films	Unit	Source
Thermal dryer input temperature	T_o		293		K	[Assumption]
Thermal dryer outlet temperature	T_d		358		K	Kemp, 2012
Thermal dryer efficiency	η_{dryer}		49		%	
Extruder input temperature	T_1		320		K	[Assumption]
Extruder outlet temperature	T_2	494	505	464	K	Wagner et al., (2014)
*Melting point***	T_m	461		415	K	Gaur and Wunderlich, (1982, 1981a, 1981b)
Molecular weight	MW	42	104	14	g/mol*	
Enthalpy at T_1 for crystalline	$H_{1,c}$	12.1	--	4	kJ/mol*	
Enthalpy at T_m for crystalline	$H_{m,c}$	25.7	--	6.7	kJ/mol*	
Enthalpy at T_1 for amorphous	$H_{1,a}$	14.7	22.3	5.2	kJ/mol*	
Enthalpy at T_m for amorphous	$H_{2,a}$	28.4	--	8.4	kJ/mol*	
Enthalpy at T_2 for amorphous	$H_{2,a}$	31.7	59.3	10	kJ/mol*	
Heat of fusion for crystalline	$H_{F,\alpha}$	0.2	--	0.3	kJ/g	Gaur and Wunderlich, (1982); Li et al., (1999)
Average crystallinity	c	54	--	33	%	(Van Belle et al., 2020)
Extruder efficiency	$\eta_{extruder}$	40	40	40	%	Chung, (2000)

***mol of repeating unit. ** PS is an amorphous plastic and therefore has no melting point.**

Table 3: Thermal drying and extrusion energy consumption data

2.4.2 Extrusion energy consumption

The energy required for the extrusion of a plastic comprises the energy to convey the plastic through the extruder, to elevate its temperature until the extrusion temperature and to melt it (Chung, 2000). The energy required to elevate the pressure and convey the plastic represents a very small portion of the total energy (Chung, 2000), estimated to be less than the 5% (Abeykoon et al., 2014), therefore it is omitted from our calculations.

The energy requirement to elevate the temperature up to the melting point is the weighted sum of the crystalline portion and the amorphous portion. After reaching the melting point, the heat of fusion (H_F) must be applied only to the crystalline portion, because the amorphous plastics have no heat of fusion (Abeykoon et al., 2014). Additionally, heat is applied to reach the extrusion temperatures that are higher than the melting points (Wagner et al., 2014). Above the melting points we consider that all the plastics behave as amorphous, because crystallinity is lost. With this, the energy required to extrude a polymer with crystallinity c at an extrusion temperature of T_2 and melting point T_m is calculated as:

Equation (III)

$$Energy_{requirement} = c * \left(\int_{T_1}^{T_m} C_{p,c} * dT + H_F \right) + (1 - c) * \left(\int_{T_1}^{T_m} C_{p,a} * dT \right) + \int_{T_m}^{T_2} C_{p,a} * dT$$

The integrals of the heat capacities correspond to the difference of the enthalpies between the input temperature and output temperature: $\int_{T_1}^{T_2} C_p * dT = \mathrm{H}(T_2) - \mathrm{H}(T_1) = H_2 - H_1$. Enthalpy values for the crystalline and amorphous fractions of different polymers are presented by the series of papers by Gauer & Winderlich. Taking into consideration the extruder efficiency ($\eta_{extruder}$), the formula used to calculate the total energy consumption of the extrusion process is:

Equation (IV) $$Energy_{extrusion} = \frac{[c*(H_{m,c} - H_{1,c} + H_F) + (1-c)*(H_{m,a} - H_{1,a}) + (H_{2,a} - H_{m,a})]}{\eta_{extruder}}$$

2.5 Economic assessment

The investment cost or CAPEX for the four installations is calculated using as a base the cost of the equipment needed for the different process step and adding to this the infrastructure, project management and contingency charges. The price of the equipment for PE films is obtained from Eco-oh! and validated with a quotation for a recycling line installation. Equipment for rigid fractions (PP, PS and MPO rigids) are sized according to the maximum throughput rigid/film ratio obtained from manufacturer specifications (Table S.3 of supporting information). We then multiply the equipment price for the PE film washing line with the maximum throughput ratio to the power of 0.6, according to the 6/10th rule (Sinnott and Towler, 2019) to estimate the prices of these equipment. Subsequently, infrastructure, project management and contingency charges are calculated with commonly observed ratios for the chemical industry as summarized in Table 4.

Feedstock prices (gate fee for the plastic waste) can be positive or negative depending on whether the recycler must pay or will be paid for recycling the waste. The values for the baseline analysis are taken from a TEA of a collection and sorting plant (Cimpan et al., 2016). Due to the high variability and the high influence of this parameter on the results, a sensitivity analysis on this parameter is presented later.

The operational costs, given in Table 4, include labor, fixed costs (maintenance, land, insurance, and general plant overhead), utilities (tap water, energy, chemicals for the water treatment and solid residual disposal).

	Detail	Value	Source
Operational	Plant capacity	2500 kg/h	[Assumption]
	Operating time	8 000 h/y	
	Land	2500 m^2	
	Shift position operators	1 every 2 process steps	Industrial data
	Regular schedule operators	1	
Financial	Evaluation period	15 years	[Assumption]
	Discount rate	15 %	Van Dael et al., 2015
	Corporate tax rate	25 % over net profits	[Assumption]
	Working capital	15 % of Eq & Inf^{+}	Sinnott and Towler, 2019
	Depreciation rate	10 % for 10 years	
CAPEX	Infrastructure	60% of equipment	Observed
	Project management costs	10 %-30 % of Eq & Inf	Sinnott and Towler, 2019
	Contingency charges	15 % of Eq & Inf	
Operational costs	Operator annual wage	62 400 EUR/year $^{++}$	STATBEL, 2019
	Premium for shift operators	23 % over annual wage	Werner International, 2014
	Cost of labor (including supervision and engineering)	125 % of operator wages	
	Yearly insurance	1.5 % of equipment cost	Sinnott and Towler, 2019
	General plant overhead	30 % of labor and maintenance^{+++}	
	Maintenance	20% of Eq & Inf	Industrial reference
	Land	55 EUR/ m^2	JJL Belgium, 2019
	Gas price	23.7 EUR/MWh	PWC, 2019
	Electricity price	74.2 EUR/MWh	
	Solid residual disposal	132.5 EUR/ton*	OVAM, 2019
	Ferric Chloride	538 EUR/ton	Echemi, 2020
	Sodium Hydroxide	462 EUR/ton	
	Polyelectrolyte	1352 EUR/ton	
Feedstock costs	PP rigids	110 EUR/ton	Cimpan et al., 2016
	PS rigids	110 EUR/ton	
	MPO rigids	-15 EUR/ton	
	PE films	-70 EUR/ton	

Eq & Inf is equipment and infrastructure. $^{+}$Commonly observed ratios for the petrochemical industry. $^{++}$Average gross wage for factory and machinery workers in Flanders. $^{+++}$ For human resources, research and development, information technology, finance, legal, etc.* Gate fee for industrial residue of low heating value.

Table 4: Economic assumptions

The net present value (NPV) of all future cash flows is calculated considering the product revenues, feedstock expenditures or revenues, operational expenditures (OPEX) , CAPEX , the working capital and other assumptions presented in Table 4. The discount rate of 15% is chosen because is commonly used for the expansion of conventional technologies (Van Dael et al., 2015). Other indicators, such as the internal rate of return and the processing cost are also calculated. The internal rate of return corresponds to the discount rate for which the NPV is zero. The processing costs are the OPEX, excluding feedstock expenditures, and the annualized CAPEX divided in the yearly plastic waste input.

2.6 Sensitivity analysis

As a first approach a one-at-a-time sensitivity analysis is done to detect the variables that have a higher influence on the results. For this purpose, each variable is altered independently a +10% and a -10% and the new NPV is registered. Then, another sensitivity analysis is developed considering that the recycled plastics price would vary between the current recycled product prices and the virgin plastic price. This is assuming that technological development could increase the product quality and thus, the product price could go up to a hypothetical maximum equivalent to the prices of the virgin plastics. Additionally, the maximum feedstock price that a recycler would be willing to pay is calculated for different product prices, i.e. feedstock price for which the NPV is zero. This value is given by the processing cost, the product price and the product yield and can be expressed as:

Equation (V)

$$Max\ Feedstock\ Price = -Processing\ cost + Product\ Yield * Product\ price$$

2.7 Uncertainty analysis

The probability range of the NPV is studied with a Monte Carlo simulation, where the most important variables detected with the one-at-a-time sensitivity analysis are defined as probabilistic. The probability density functions of the variables are constructed using the Sobol sampling technique (20 000 sampling points). These uncertainties are propagated with a Monte Carlo simulation using kernel density smoothing (Analytica, n.d.) with the software Analytica. Finally, a global sensitivity analysis reveals the contribution to the variance of each probabilistic variable to the NPV variance.

3 Results

3.1 Market study

Figure 2 shows the prices of recycled product from post-consumer waste in the base case (a) that considers steadily increasing oil prices and SDS (b) that assumes a decrease in oil prices from 2025. Current transaction prices are projected into the future according to oil price forecasts of the World Energy Outlook (International Energy Agency, 2018a). It can be observed that the price for the LDPE regranulates and MPO regrind is significantly lower than the price for PP and PS regranulates. There are two possible explanations for this. First, due to technological development, the quality of the PP and PS regranulates obtained is higher and closer to that of virgin plastics. Second, the prices for the virgin version of these plastics is also higher.

Upon comparing the base case and SDS, it appears that in the latter prices remain almost stable whereas in the base case scenario they gradually increase.

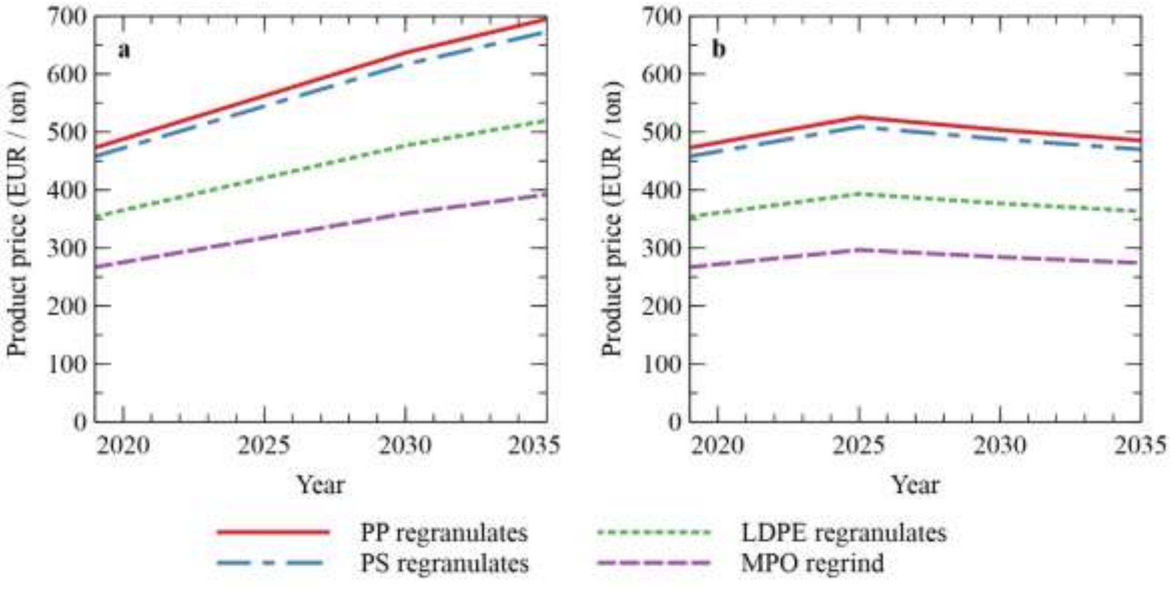
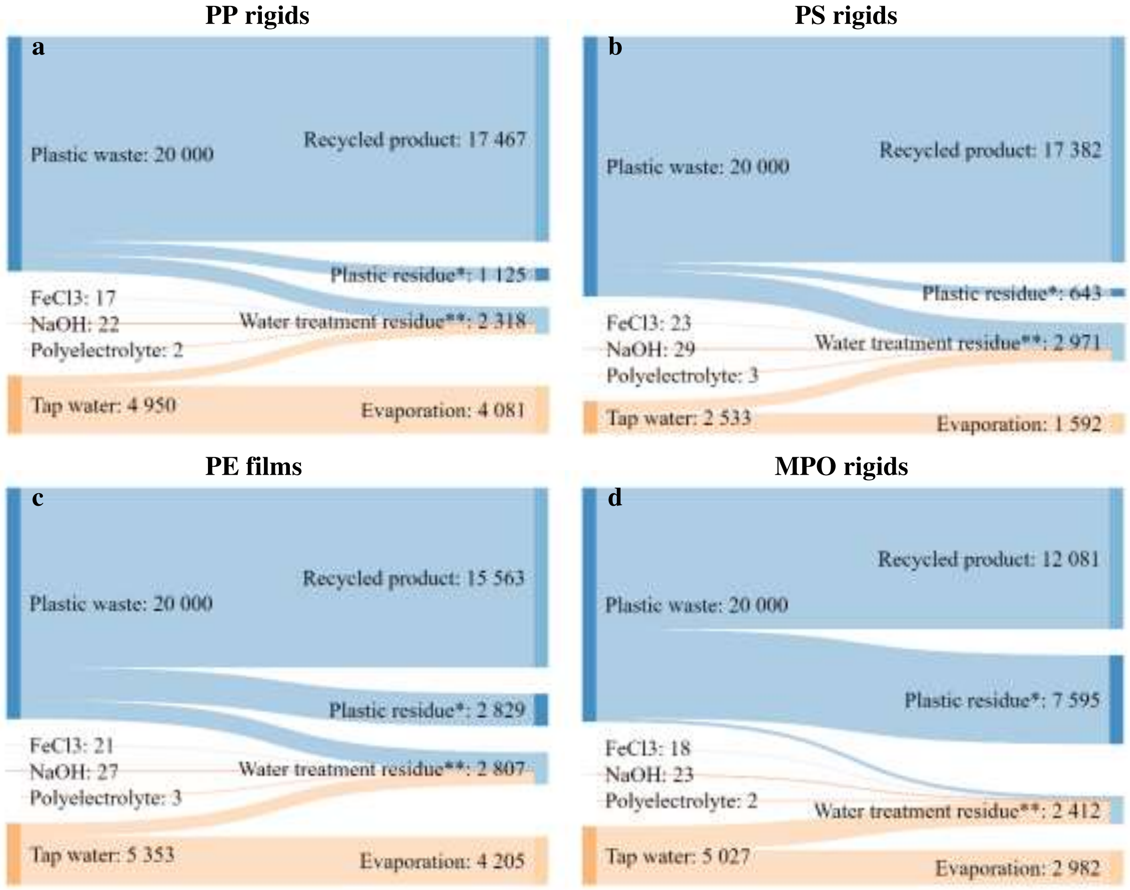


Figure 2: Recycled product prices in base case (a) and sustainable development scenario (b)

3.2 Process flows and mass balances

Figure 3 shows the mass balances, i.e. the net input and outputs, for the recycling of the four waste fractions studied. It can be observed that the yield of feedstock (plastic waste) to product varies between 71%, for the MPO fraction, to 91%, for the PS rigids fraction. This is due to the high level of purity of the incoming plastic waste, which reflects on less plastic lost in the float-sink and wind-sift processes as seen on Table 1.

Regarding the water consumption, the figures bellow only show the tap water consumption and not the water that is treated and recycled to the process. The consumption of tap water and chemicals for water treatment is the lowest for the PS rigids fraction, because a float-sink process step is not considered and the highest for the PE films fraction, because it has a higher residue content compared to the other fractions (Table 1).



*** Sink fraction, losses as dust, discarded after wind sifting and after melt filtration . ** Pulp and filter cakes.**

Figure 3: Mass balance (in ton/year) for PP rigids (a), PS rigids (b), PE films (c) and MPO rigids (d)

3.3 Energy balance

As seen in Table 5, the specific energy consumption (energy consumption per ton of dry mass) for the washing, milling, float-sink and drying is lower for the rigids fractions (PP, PS and MPO rigids) than for the films fraction (PE films). This is because the energy consumption is proportional to the number of flakes that needs to be processed. In other words, the maximum throughput of an equipment will depend on the flake density, which is different for rigids and films. For an identical mass with a higher flake density, a larger number of flakes will be cut, washed and dried. The ratio for the maximum throughput between rigids and films is also shown in Table 5. Differently, the energy consumption of the extrusion process relies on the type of polymer: it is the lowest for PS, an amorphous plastic, and highest for PP, the polymer with the highest crystallinity.

Process step	**Max throughput rigid/film ratio**	Specific energy consumption (kWh/ton)			
		PP rigids	**PS rigids**	**PE films**	**MPO rigids**
Shredding	1	47.8	47.8	47.8	47.8
Washing	0.55	28.8	28.8	52.2	28.8
Milling 1	0.41	41.8	41.8	103.3	41.8
Float-sink	0.33	3.5		9.7	3.5
Mechanical drying	0.57	34.5	34.5	58.4	34.5
Thermal drying (Electric energy)	0.53	18.2	18.2	24.8	18.2
Wind sifting	1	4.5	4.5	4.5	4.5
Milling 2		41.8	41.8		
Transport screw	1			*16*	
Ventilator	1			*20*	
Thermal drying (thermal drying)		*25.8*	*36.6*	*162.4*	*24.9*
Extrusion		*351*	*247*	*299*	

Table 5: Specific electricity consumption for process steps

A consumption of 1.4 kWh/ton residual water treated is added.

Figure 4 shows the electricity and thermal energy consumption for the different process step. The total energy required for the PE films fraction is higher compared to the other fractions, because of the higher flake density that makes up for the absence of the second milling step.

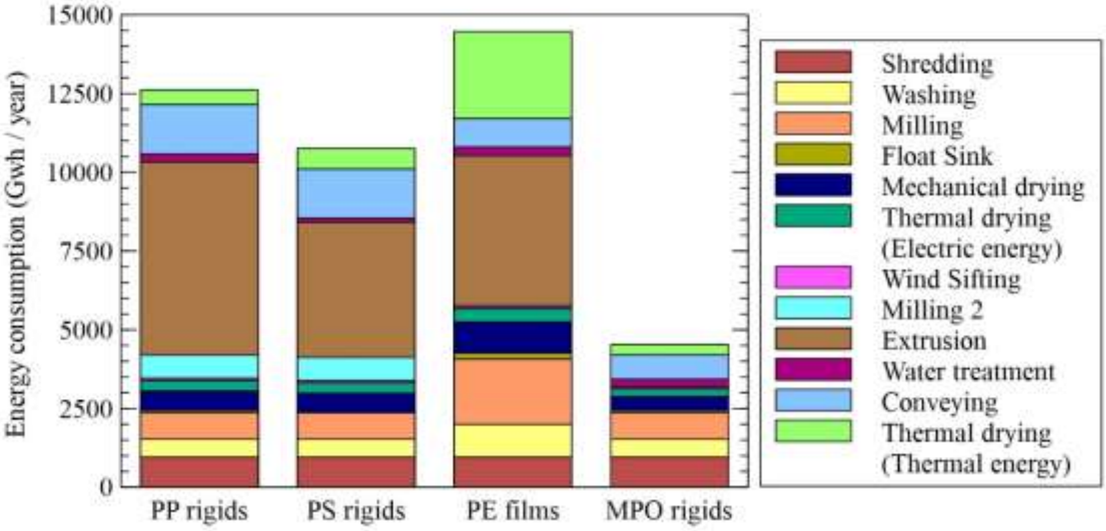


Figure 4: Electricity and thermal energy consumption per process step.

It can be observed that the extrusion is by far the most energy intensive process. For the case of PE films, the thermal drying and milling steps consume a significant amount of energy as well. Overall, the lowest energy consumption is observed in the MPO fraction, due to the lower flake density and the absence of the second milling and extrusion process steps.

3.4 Economic assessment

Figure 5 presents the internal rate of return and net present value of the product revenues, feedstock revenues or expenditures, OPEX, CAPEX and taxes for a 20 000 ton/year plant in the base case scenario (a) and in the SDS (b). These figures are quite revealing in several ways. First, the NPV is negative in both price scenarios for all fraction. This may be explained by the small gap between the feedstock cost (Table 4) and product prices (Figure 2). The internal rate of return is positive for PP rigids, PS rigids and PE films in both scenarios. Contrarily, for MPO rigids is negative in the base case scenario and impossible to calculate in the SDS, because the OPEX are higher than the revenues. Second, for all fractions, the net present value of all OPEX are greater in magnitude than the CAPEX. Moreover, CAPEX are slightly higher for the PE films fraction, because it requires equipment of a larger size due to the higher flake density. Finally, for all fractions the NPV is substantially lower in the SDS (b) when compared to the base case scenario (a). This indicates that, if oil prices decrease and recycled product prices remain coupled to oil prices, the incentives to recycle plastic waste diminish.

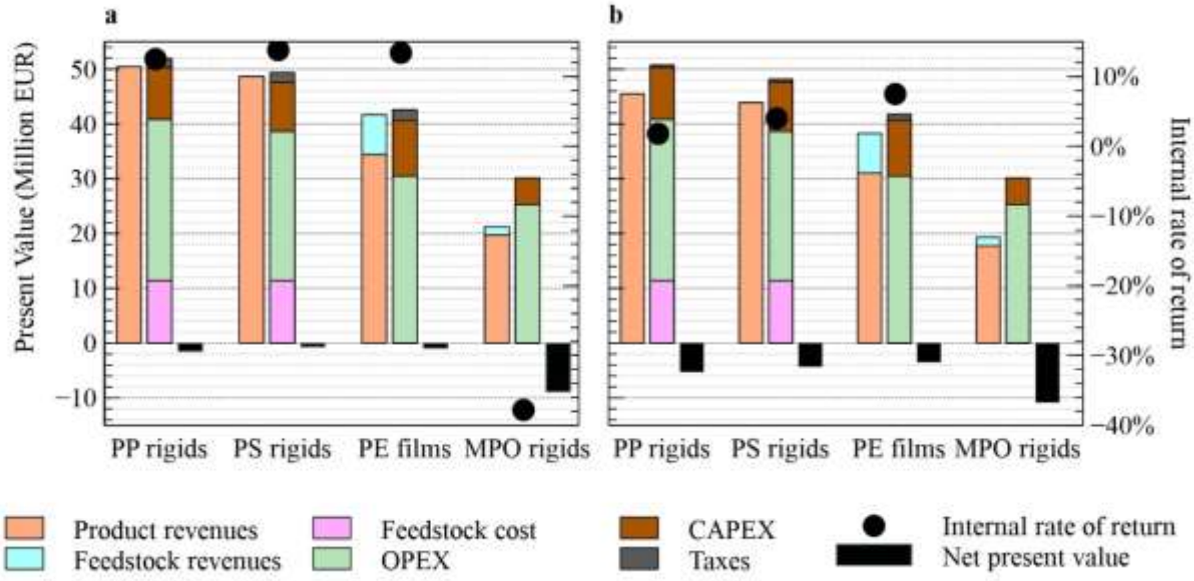


Figure 5: Present value of revenues and expenditures and net present value in base case (a) and sustainable development scenario (b). The first bar shows the present value of the revenues, the second bar the present value of the expenditures and the third bar the net present value.

The main operational expenditure for all fractions is labor (see Figure S.4 of supporting information), because mechanical recycling is a labor-intensive activity. Other important costs are related to the maintenance and operation of the plant. Furthermore, the disposal costs increase as the feedstock to product yield decreases. In general, operational costs are significantly lower for the MPO fraction due to the absence of certain process steps, as described in section 2.2.

Operational expenditures and annualized investment costs per ton of waste treated are summarized by the indicator '*processing cost*' shown in Table 6. In accordance to what is observed in Figure 4, this indicator is the lowest for MPO rigids fraction and the largest for the PE films fraction.

Indicator		Unit	PP rigids	PS rigids	PE films	MPO rigid
Product price (2021 Base case scenario)		$\frac{EUR}{ton}$	488	463	365	275
Product-feedstock price difference (2021 Base case scenario)		$\frac{EUR}{ton}$	363	348	424	282
Processing cost		$\frac{EUR}{ton\ feedstock}$	367	342	383	287
Product yield		$\frac{ton\ product}{ton\ feedstock}$	0.87	0.87	0.80	0.60
Base case scenario	*NPV*	*M EUR*	-4.76	-2.2	-2.96	-27.84
	Internal rate of return	%	13%	14%	13%	-
SDS	*NPV*	*M EUR*	-16.51	-13.46	-10.91	-33.89
	Internal rate of return	%	2%	4%	8%	-

Table 6: Economic assessment result

4 Sensitivity analysis

Feedstock prices and product prices, two of the most important parameters, are expected to be linked in the long term. Figure 6 shows the maximum feedstock price that a recycler would be willing to pay for different product prices to observe a positive NPV over a 15-year period with a 15% discount rate, as commonly used for the expansion of conventional technologies (Van Dael et al., 2015). The higher the product price recyclers can get, the more can be spent on feedstock to still achieve a positive NPV. Feedstock prices for the fractions with higher processing cost are lower than those easy to process. Additionally, the effect of the product price on the feedstock cost will be higher for those fractions with a higher product yield.

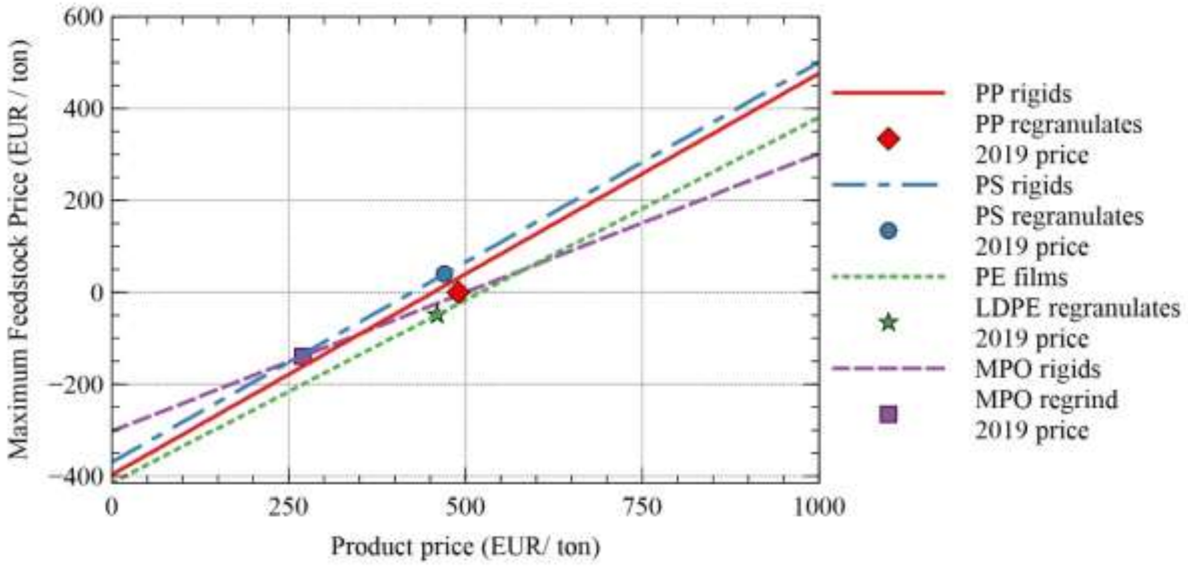


Figure 6: Maximum feedstock price for a positive NPV under different price levels

Product prices are also related with the quality that can be achieved with the recycling process. For this analysis we assume that recycled products with a similar quality to that of virgin plastics may be sold at the same price. Therefore, in S.6 of the supporting information product prices are varied between the current recycled product prices and the prices of the virgin version of the plastics in the base case (a) and SDS(b). Results show that higher quality products improve significantly the NPV outcomes, meaning that investments in technology are important for closing the loop in the plastic packaging value chain.

It can be expected that for plastic fractions with higher demand or larger market size, such as LDPE or PP, plants with a higher capacity than the one considered in this study could be built. In this case, several washing lines should be installed in parallel, reducing some fixed operational costs (i.e. supervision and general plant overhead) and investment cost. Consequently, a slightly improved NPV could be expected in these cases.

The one-at-a-time sensitivity analysis indicates that the most important parameters for the NPV are product price, feedstock to product yield, cost of labor, feedstock price and the discount rate (Figure S.5 of the supporting information). These results are consistent with the findings of Faraca et al. (2019) that mention that the product prices have an important influence on the life cycle cost of a recycling plant for rigids.

5 Uncertainty analysis

In accordance to the one-at-a-time sensitivity analysis results the product price, feedstock price, feedstock to product yield and cost of labor are modelled as probabilistic variables. Following the approach used by Kuppens et al. (2015), the uncertainty of these variable was propagated with a Monte Carlo simulation taking 20 000 sampling points for each variable.

As considered in Larrain et al. (2020), the yearly price projection is modelled by a normal distribution with a standard deviation equivalent to the observed mean of forecasted errors of the “World energy outlook” oil price projection from 2000 to 2016, as presented by Wachtmeister et al. (2018).

The feedstock to product yield will depend mainly on the composition of the incoming plastic waste that may vary because of consumer behavior and the efficiencies of the sorting lines that precede the recycling process. It is assumed to have a Hadlock-Bickel-Johnson quantile-parameterized distribution, that it is calculated with known values of established percentiles (Hadlock and Bickel, 2017). For this cases we take the 25th and 75th percentiles of the effective main polymer content presented in Roosen et al (2020), bounded between 0 and 1.

Labor costs are assumed to have a Pert distribution, with a minimum of 83% of the presented cost and a maximum of 120% of the median costs. These ranges correspond to the wages of 0 to 20 or more years of work experience presented in the Belgian statistics database (STATBEL, 2019).

Finally, feedstock prices are considered to have a modified Pert distribution (Buchsbaum, 2012; VOSE, 2000) with a most likely value weight equivalent to the minimum and maximum value ($\lambda = 1$). The most likely values are the ones used for the baseline analysis, while as extreme values we considered the minimum and maximum from Cimpan et al. (2016) and a study for the Belgian collector FostPlus (RDC, 2018) and are shown on Table S.7 of the supporting information. It is important to notice that the ranges of possible values differ among fractions mainly due to the different qualities of waste fractions available in the market and considered in both studies.

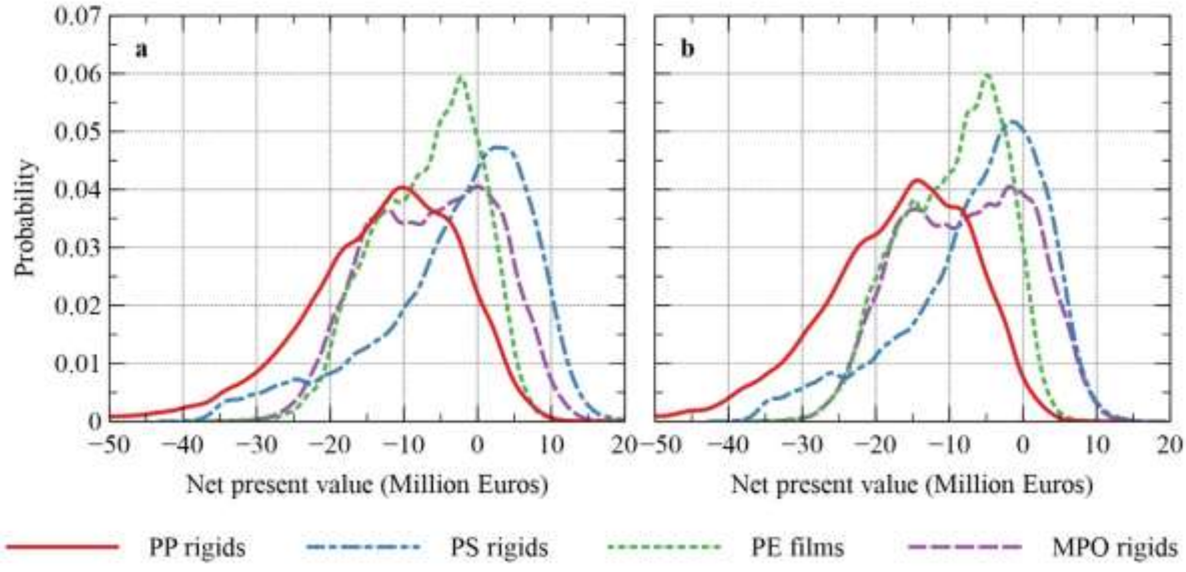


Figure 7: Monte Carlo simulation of the NPV in base case (a) and sustainable development scenario (b)

From Figure 7 it appears that the variability is larger for those fractions with a higher uncertainty range on the feedstock price. Moreover, in fractions PP rigids, PE films and MPO rigids the probability of observing negative results is substantial (see also Table S.8 of supporting information). This is more significant for the SDS, were the probability of observing negative results is always higher than 74%.

Finally, from the global sensitivity analysis shown in Table S.8 of the supporting information it can be observed that for all fractions and in both scenarios, product and feedstock prices are the variables that have a larger contribution to the variance. This may be explained by the high variability of these variables, that reflects the difference in product qualities traded in the market, and by the important effect of these variables on the results.

6 Discussions

This study leads to a better understanding of the potential economic performance of recycling process of sorted fractions of mixed plastic waste, under the observed market conditions and expert projections for 2019. At the studied plastic input compositions and considered price levels there are little incentives to recycle any plastic waste fraction, and this effect is even more pronounced for PE films and MPO rigids. Furthermore, with the SDS assumed price levels there is a high probability of observing a negative NPV for the four fractions analyzed. This can be explained by the quality of the feedstock, translating into a more complex recycling process, and relatively high feedstock prices when compared to the product prices.

Plastic recyclates are seen as inferior substitutes for virgin plastics and therefore, their prices are coupled to virgin plastic prices and consequently to oil prices. This could represent a promising future in scenarios where oil price increase. However, this research has shown that a sustained decline in oil prices, as presented in the SDS, diminishes significantly the incentives for investing in plastic packaging recycling. This is especially important if we consider the recent trends and forecasts of this market. Latest expert projections suggest an early peak in the world oil demand and a continued decrease in oil prices due to carbon taxes and increased shares of renewable energies (British Petroleum, 2020). Furthermore, extreme shocks on oil prices, such as the one observed with the COVID-19 pandemic, decrease the virgin plastics prices and therefore the demand of recycled products. For example, in this case, taking studies for oil price observed on April 2020 (23 USD/barrel) into account, the gross profit (Revenues - OPEX) would have been reduced between 170% for MPO rigids and 860% for PP rigids. Even though the future oil prices are subject of great debate, it is clear that the current recycling market structure present a high risk for potential investors and a threat for the recycling industry and the circular economy for plastic packaging.

The results presented above do not include potential economic returns originating from the environmental benefits of recycling. The paper Civancik-Uslu et al., (2021) presents the life cycle assessment of these same processes. In case these environmental benefits would be monetarized, which is a complex policy issue, the profitability would increase. Since the recycling of mixed plastic is beneficial from an aggregated environmental-economic perspective, several measures could be taken to increase the incentives for private investors. Overall, economic incentives for plastics recycling are driven by recycled product prices, processing costs and feedstock quality.

Higher product price could be achieved by enhancing product quality with technological development and by policy incentives that would decouple recycled product prices from virgin plastic prices. For example, a recycled content target would increase the demand for state-of-the art quality recycled plastics and create a separate market for recyclates in which their prices would no longer behave as inferior substitutes of virgin product prices. Consequently, the prices would be driven by the competition of the different recyclers, decoupled from oil prices.

Feedstock quality, reflected in the product yield, can be regulated to a certain extent and would effectively increase recycling quantities. Regarding the cost structure, a major finding is that the CAPEX has a significantly lower weight than the OPEX. This means that incentives to reduce cost should mainly focus on the operational cost such as labor or energy rather than in investment costs. For example, an innovation to increase thermal drying efficiency up to 80% could improve the NPV of PE films fraction with 14%, but generate a comparatively small change in the other fractions.

One of the limitations of this study is its reliance on Belgian market conditions. However, the model could be replicated to other markets, territories or waste types by replacing the input values. The overall cost structure remains identical, as are insights in the feedstock-product price gap. On the other hand, results may not reflect the previous behavior of Belgian or European recycling market because it takes as an input modelled plastic fraction compositions that are expected to be obtained in a sorting plant in Flanders.

Moreover, the study does not take into account the correlation between the variability of product prices and feedstock prices or energy prices. A broader understanding on the relationship between product prices and feedstock prices would be an important addition to the field and could help to design more accurate incentives for the transition to circular economy.

These findings are essential for industry and policy-makers by providing important information related to the cost structure of the recycling processes and the necessary incentives to enable the circular plastic packaging value chain for the main types of plastic waste.

7 Conclusions

This paper studied the economic incentives for the mechanical recycling of postconsumer plastic packaging waste. The sensitivity analysis has shown that the potential profitability of a mechanical recycling plant is highly vulnerable to oil price variabilities and to the composition of the plastic waste that is treated, provided that the prices of recyclates remain linked to the oil price. Moreover, with current market conditions the expected NPVs are negative for the four sorted fractions studied; PP rigids, PS rigids, PE films and MPO rigids. This indicates that policy incentives are needed to effectively increase recycling rates. These incentives should focus on strengthening the market for secondary materials, by for example decoupling product prices from oil prices, or increasing the plastic waste feedstock quality and decreasing its variability.

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