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Economic and environmental implications of policy instruments for the circular economy: A case study for postconsumer polyethylene film recycling in Europe

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Spotlight

- Predicts the environmental and economic performance of policy instruments to promote plastic recycling.
- Combines equilibrium model (top-down) with techno-economic and life cycle assessment (bottom-up)
- Policy instruments that do not target a specific technology are more likely to increase thermochemical recycling than mechanical recycling.
- Policy instruments should focus on environmental outcomes rather than increasing recycling rates.
- Future research should include geographical considerations and asses other circular economy strategies.

Abstract

The objective of this paper is to examine the recycling rates for mechanical and thermochemical recycling of postconsumer polyethylene flexible packaging after the implementation of different policy instruments. The study uses a supply chain equilibrium model that incorporates market data and techno-economic assessments to simulate market equilibrium. It combines this with a life cycle assessment to explore the environmental implications of implementing different policy instruments. The results show that instruments that do not target a specific technology are more likely to increase thermochemical recycling than mechanical recycling. Furthermore, a higher recycling rate is not equivalent to a better environmental outcome. An increased collection target that ensures a supply of plastic waste would increase the overall recycling rates the most. A recycled content standard for mechanical recycling would lead to the highest increase in mechanical recycling, with top results for environmental indicators, but low results for economic indicators.

Keywords

Plastic waste, mechanical recycling, thermochemical recycling, recycled content, tax, recycling target, supply chain equilibrium model

Graphical Abstract

1 Introduction

The rise in plastic packaging production and disposal has encouraged the progress of recycling technologies and aroused policy discussion on how to increase recycling rates. In traditional or mechanical recycling, the waste is transformed by physical processes into new plastic granulates. In thermochemical recycling, the polymer chains are broken producing a crude-oil mixture. Key principles of the circular economy include circulating products and materials at their highest value and minimizing their environmental impact throughout their entire life cycle (Ellen MacArthur Foundation et al., 2016). However, without appropriate regulations or incentives, markets will tend to prioritize short-term profit-driven technologies, regardless of their environmental implications. Environmental policies are therefore crucial to steer innovation towards technologies that better meet these principles.

This study investigates how specific policy instruments can influence the adoption of mechanical and thermochemical recycling, considering their environmental and economic consequences under current conditions and potential policy scenarios. With an innovative methodology it links policy issues, market issues, technical issues, and environmental issues to quantitatively predict the effects of regulations in the environment and the economy. The following paragraphs describe how these issues have been partially linked in previous studies.

Palmer and Walls made an early development in the use of equilibrium models to study the influence of policy instruments in waste management (Palmer and Walls, 1997). Dubois (2012) extended this model to study how extended producer responsibility (EPR) schemes would affect waste management. Lately, Lahcen et al. (2022) made an important contribution by studying the effect of policies for a plastic circular economy with a supply chain equilibrium model. The study takes into account how different markets affect each other endogenously through simultaneously determined equilibrium prices along the supply chain of polyethylene terephthalate (PET) bottles.

Economic analysis and environmental analysis can be coupled to study the potential implications of policy interventions that promote the implementation of a new technology. Equilibrium models coupled with life cycle assessment (LCA) are better in providing exhaustive and quantitative information to decision makers than other economic – environmental model coupling such as econometric models, or agent-based models (Loiseau et al., 2019). There are few examples of equilibrium models coupled with LCA in the context of plastic waste. Zhao and You (2021) developed a systematic consequential life cycle optimization framework to determine the economically optimal and environmentally sustainable technology pathways for thermochemical recycling of high-density polyethylene (HDPE). Similarly, Cornago et al. (2021) performed a consequential LCA of a PET chemical recycling technology, evaluating the potential market penetration of its products and consequences on the LCA.

Even though circular economy policy has gained attention in the last years, there is still a need to address circular economy strategies in a holistic and quantitative way (Goyal et al., 2021).On the one hand, the abovementioned studies provide important insights on the consequences of plastics recycling in the packaging markets but haven't connected policy issues with technological issues. The analysis of these interrelations is crucial to design policies that will promote the deployment of the most circular technologies. On the other hand, research that takes an integrative perspective (Milios, 2018; Tencati et al., 2016) has mostly been theoretical or qualitative. Our study fills these gaps by exploring and evaluating the market dynamics in a supply chain equilibrium model that considers thermochemical recycling and mechanical recycling of polyolefin waste and its potential environmental and economic implications.

European countries lead the world in recycling rates, headed by countries like Belgium, Netherlands and Luxembourg (Eurostat, 2023; OECD, 2022). This regional success hinges on recycling PET or HDPE bottles (Thomassen et al., 2022). The reason for this is that, after sorting, these fractions are homogenous and have relatively low contamination levels, thus their recycled products are of high quality and demanded on the market (Faraca and Astrup, 2019).

Nevertheless, there are some types of plastic waste, such as those that come from films that are harder to recycle and that are mainly disposed or incinerated worldwide. Most films are made from polyethylene (PE), both HDPE and low-density polyethylene (LDPE), and have numerous applications across various sectors. In packaging, PE films are used for bags in food packaging, shrink wrapping, and protective wrapping. Due to their heterogenous composition, mechanical recycling has not been profitable yet and additional policies are deemed necessary to promote their recycling. This low recycling levels have caused three major problems: greenhouse gas emissions, inefficient consumption of fossil resources and leak of waste into the natural ecosystems (SYSTEMIQ, 2022).

In spite of their currently low recycling rates, recycling technologies for PE films have evolved in the last years (Antonopoulos et al., 2021). Mechanical recycling technologies are now capable of converting plastic films into regranulates through physical processes such as cleaning and extrusion. In addition, the plastics industry is currently targeting pyrolysis as the dominant pathway for chemical recycling in the 2020s (SYSTEMIQ, 2022). This process, in which polymers are broken down into naphtha at high temperatures and in the absence of oxygen, can also treat highly contaminated waste fractions such as plastic film.

Recycled products, both plastics regranulates and recycled naphtha, can be used more or less as substitutes for products made from virgin oil or natural gas. The amount of recycled products and of plastic recycled by each technology (recycling rates) depend on the cost of the processes, the market for plastic waste and the markets for recycled products. These markets, and consequently recycling rates, are affected by exogenous conditions that disrupt oil prices (Larrain et al., 2020). This effect is evidenced by the decline in recycling rates by mid-2020 (De Meester et al., 2020) and the shortage of recycled material by mid-2022 (Plastics Recyclers Europe, 2022). Mechanical recycling and thermochemical recycling can use the same sorted plastic waste as feedstock and can therefore be considered as market competitors for plastic waste. In addition, recycled plastic, plastic produced from virgin naphtha and plastic produced from recycled naphtha can be substitutes. Thus, mechanical recyclers and thermochemical recyclers can be considered as market competitors for the supply of plastic products. Understanding these market dynamics is therefore necessary to design policy instruments that will promote the most sustainable technology.

Academics and governance actors agree that a mix of different policies, rather than a single policy, is needed to enable a circular economy for plastic packaging (Milios, 2018; Tencati et al., 2016). The Global Plastics Outlook proposes implementing policies in three phases to achieve increasingly ambitious circularity objectives: close leakage pathways, create incentives for recycling by making it more profitable and restrain the demand of fossil-based plastics. Leakage of plastics to the environment can be significantly reduced by investing in waste management infrastructure and banning or taxing items that are frequently littered. Measures that deal with the plastic waste market and the recycled products market can increase recycling profitability. Applying taxes to landfills and implementing Extended Product Responsibility Schemes encourages the provision of plastic waste to recyclers. To create a well-functioning secondary market for recycled products, their prices need competitive when compared to fossil-based product prices. This can be done by removing fossil fuel subsidies or taxing fossil-based plastic, by increasing the demand with recycled content standards (Ellen MacArthur Foundation, 2017) or by stablishing modulated fees in EPR schemes (OECD, 2022).

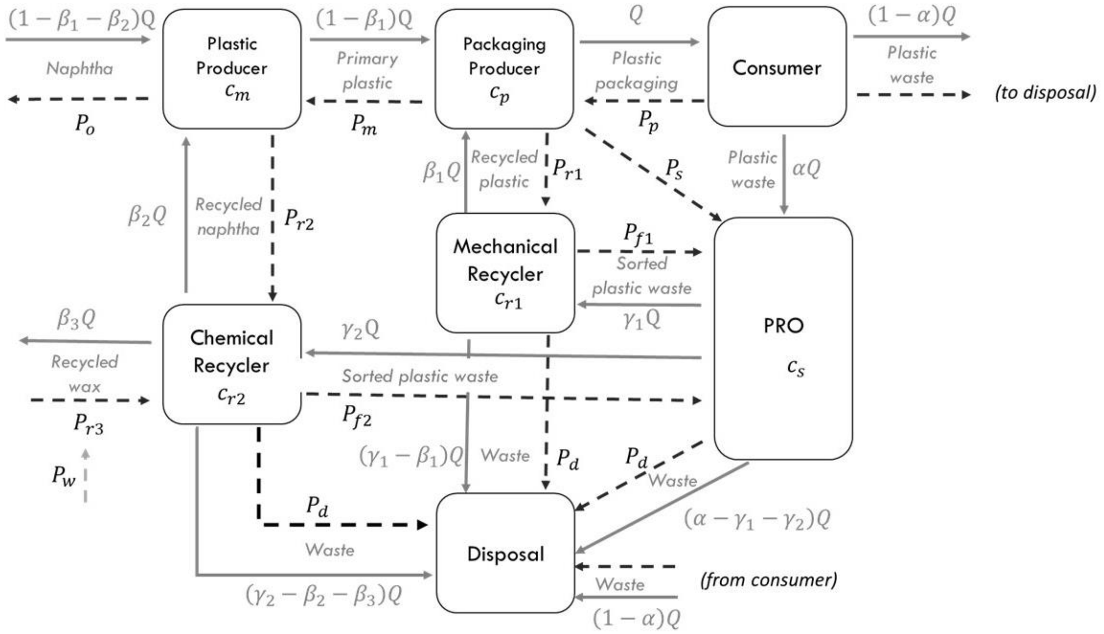
To date, the most implemented policy globally is EPR schemes (Seay and Ternes, 2022). Moreover, a landfill tax or ban has already been imposed in the countries analyzed in this study (Plastics Europe, 2021). The policies that have a higher impact on the circular use of plastics are related to the demand of recycled products, and therefore are the ones considered in this study.

The objective of this study is to predict how much PE film waste would be recycled through mechanical recycling and thermochemical recycling under three oil and energy price levels observed throughout 2019, in April 2020, and in August 2022, and with the implementation of different policy instruments. In addition, the economic and environmental impacts of the implementation of the policy instruments are examined. The main novelty of this study is the coupling of techno-economic assessment (TEA), with a supply chain equilibrium model and LCA. The cost structures of mechanical and thermochemical recycling obtained from TEA are used as inputs for a supply chain equilibrium model and combined with the results of an LCA. The main analysis is carried out for the Benelux region, which consists of Belgium, the Netherlands and Luxembourg. This paper also examines how the equilibrium quantities vary when geographical scales are analyzed: the city of Antwerp, the region of Flanders, the region of Benelux, Western Europe and Europe as a whole.

The paper has been organized in the following way. Section 2 describes the plastics recycling supply chain equilibrium model, including the equations used to calculate the quantities in the equilibrium, and a description of the policy scenarios. Section 3 presents the results: first the recycling rates in the policy scenarios, then the economic and environmental implications and finally a sensitivity analysis. Section 4 discusses policy recommendations and finally section 5 discusses the main conclusions.

2 Methods:

The value chain, depicted in Figure 1 is based on the EPR scheme implemented in Flanders. It shows the plastic producer, packaging producer, consumer, producer responsibility organization (PRO), mechanical recycler, thermochemical recycler and final disposal responsible and the material flows (grey continuous lines) and the financial flows (black dashed lines) between them. The stakeholders obtain or buy the plastic material (plastic, packaging, waste, sorted waste and naphtha), process it at a cost and then sell or transfer the processed material to another stakeholder. Due to the economies of scale observed in recycling centers (Fivga and Dimitriou, 2018; Larrain et al., 2020; Lubongo et al., 2022; Riedewald et al., 2021; Volk et al., 2021), the unitary processing costs for recyclers depend on the amount of plastic recycled. Besides the processing costs, stakeholders usually pay for the material they use as feedstock and are paid for their products. Thus, the profits of the stakeholders are a function of the amount of material processed and the prices at which they buy and sell the material.



Q	Amount of plastic packaging placed in the market (tonne)	c_{m}	Primary plastic production unitary cost (EUR/tonne of primary plastic)
P_m	Primary plastic price (EUR/tonne)	c_p	Packaging production unitary cost (EUR/tonne of plastic packaging)
P_O	Observed naphtha price (EUR/tonne)	c_s	Collection, transport and sorting unitary cost (EUR/tonne of plastic waste)
P_w	Observed wax price (EUR/tonne of wax)	c_{r1}	Mechanical recycling unitary costs (EUR/tonne of input)
P_{r1}	Recycled plastic price (EUR/tonne)	c_{r2}	Thermochemical recycling unitary costs (EUR/tonne of input)
P_{r2}	Recycled naphtha price (EUR/tonne)	α	Plastic waste collected from consumer`s household (tonne of plastic waste/tonne of plastic packaging)
P_{r3}	Recycled wax price (EUR/tonne)	β_1	Recycled plastic products (tonne of recycled plastic/tonne of plastic packaging)
P_d	Final disposal fee (EUR/tonne of waste)	β_2	Naphtha from thermochemical recycling (tonne of recycled naphtha/tonne of plastic packaging)
P_p	Plastic packaging price (EUR/tonne)	β_3	Waxes from thermochemical recycling (tonne of recycled waxes/tonne of plastic packaging)
P_{f1}	Sorted plastic waste price to mechanical recycler (EUR/tonne of sorted waste)	γ_1	Sorted plastic waste treated by mechanical recycling (tonne of sorted plastic waste/tonne of plastic packaging)
P_{f2}	Sorted plastic waste price to thermochemical recycler (EUR/tonne of sorted waste)	γ_2	Sorted waste treated by thermochemical recycling (tonne of sorted plastic waste/tonne of plastic packaging)
P_s	Green dot fee (EUR/tonne of plastic packaging)		

Figure 1: Circular plastic recycling value chain. Continuous grey lines show material flows and black dashed lines show financial flows between stakeholders. The producer responsibility organization (PRO) collects the plastic waste from consumers' household, sorts it and sells it to the recyclers. After processing, the mechanical recycler sells the product to the packaging producer and the thermochemical recycler to the plastic producer and to external buyers.

A supply chain equilibrium model evaluates price and product flows taking into account the independent behavior of the various decision-makers and the effect of their interactions (Nagurney et al., 2002). Using profit functions, we predict how much plastic will be recycled in the equilibrium, the transaction prices and the material processed by each stakeholder for different policy scenarios. Then, we combine these recycled quantities with the results of an LCA for mechanical recycling and thermochemical recycling to estimate the environmental implications and with the profit functions to estimate the economic implications. The complete analysis is carried out with the software Analytica from Lumina.

The PRO collects and sorts the recyclable waste into different fractions. The PE films fraction contains a 85% of PE films and a 15% of other films and impurities (Roosen et al., 2020), which are removed in the recycling process. We evaluate the results under three energy (electricity and natural gas) and oil price level conditions. The low energy and oil price level takes the prices observed after the COVID pandemic in April 2020, the high energy and oil price level takes the prices after the Russian invasion into Ukraine of June 2022, and the median oil and energy price levels observed during 2019. Electricity and natural gas price fluctuations vary the processing costs and oil prices vary product prices. Following the evidence that shows that virgin plastic, naphtha and wax prices are correlated with oil prices (Jiang et al., 2015; Selmi et al., 2022), all product prices are varied proportional to the oil price variation for the three levels. Oil, electricity and natural gas prices in the three conditions are shown in Table A.1 of the Appendix. Additionally, we calculate these equilibrium points for different geographic areas to demonstrate the effects of distance and population. Taking as a center a recycling plant installed in Flanders, the following geographic areas are taken into account: the city of Antwerp, the region of Flanders (Belgium), Benelux (Belgium, Netherlands and Luxemburg), Western Europe and Europe.

2.1 Model description:

The model of the circular plastic packaging value chain (Figure 1), is based on the model presented by (Palmer and Walls, 1997) and improved by (Dubois, 2012). The packaging producer manufactures Q tonne of plastic packaging at a cost c_p, sells it to the consumer at a price P_p and pays a fee (green dot fee) P_s to the PRO. He buys $\beta_1 * Q$ tonne of recycled plastic from the mechanical recycler at a price P_{r1} and $(1 - \beta_1) * Q$ tonne of primary plastic from the plastic producer at a price P_m. In some scenarios, the packaging producer has to pay a tax (τ_P) for every tonne of virgin plastic they use. Equation 1 describes the unitary profit function for the packaging producer.

Equation 1: Profit function for the packaging producer for a tonne of plastic waste placed in the market

$$\frac{\Pi_P}{Q} = P_p - c_p - P_s - \beta_1 * P_{r1} - (1 - \beta_1) * P_m - \tau_P$$

After the consumer uses and separately disposes of a fraction α of the plastic packaging, the PRO collects it from his household and sorts it at a cost c_s. The PRO sells a fraction γ_1 to the mechanical recycler and a fraction γ_2 to the thermochemical recycler at a price P_f. The remaining waste $(\alpha - \gamma_1 - \gamma_2)$ is disposed of at a fee P_d.

Equation 2 shows the unitary profit function for the PRO. The relation between the waxes from thermochemical recycling (β_3) and the naphtha from thermochemical recycling (β_2) used in the second part of Equation 4 is explained later in the text.

Equation 2: Profit function for product responsibility organization

$$\frac{\Pi_C}{Q} = P_s + \gamma_1 P_f + \gamma_2 P_f - (\alpha - \gamma_1 - \gamma_2) P_d - c_s \alpha = P_s + \frac{\beta_1}{Y_1} P_f + \frac{\beta_2}{Y_2} P_f - \left(\alpha - \frac{\beta_1}{Y_1} - \frac{\beta_2}{Y_2}\right) * P_d - c_s$$

The mechanical recycler processes the sorted waste at a cost c_{r1} with a ratio Y_1, and obtains $\beta_1 * Q$ tonne of recycled plastic. They sell the recycled plastic at a price P_{r1} and dispose of the remaining material $(\gamma_1 - \beta_1) * Q$ at a fee P_d. Equation 3 shows the unitary profit function for mechanical recyclers.

Equation 3: Profit function for mechanical recycler for a tonne of plastic waste placed in the market

$$\frac{\Pi_{R1}}{Q} = \beta_1 P_{r1} - \gamma_1 c_{r1} - \gamma_1 P_f - (\gamma_1 - \beta_1) * P_d = \beta_1 P_{r1} - \frac{\beta_1}{Y_1} c_{r1} - \frac{\beta_1}{Y_1} P_f - \left(\frac{\beta_1}{Y_1} - \beta_1\right) * P_d$$

Similarly, the thermochemical recycler processes $\gamma_2 * Q$ tonne of sorted plastic waste at a cost c_{r2} and produces $\beta_2 * Q$ tonne of naphtha with a ratio Y_2 and $\beta_3 * Q$ tonne of wax with a ratio Y_3. They sell the recycled naphtha at a price P_{r2} and the waxes at a price P_{r3} to external buyers. The residues from the recycling process $(\gamma_2 - \beta_2 - \beta_3) * Q$ are disposed of at a fee P_d. Equation 4 shows the unitary profit function for the thermochemical recycler. We choose pyrolysis as a representative of thermochemical recycling because is the most widely implemented thermochemical recycling technology for plastics (Solis and Silveira, 2020).

Equation 4: Profit function for thermochemical recycler for a tonne of plastic waste placed in the market

$$\frac{\Pi_{R2}}{Q} = \beta_2 P_{r2} + \beta_3 P_{r3} - \gamma_2 c_{r2} - \gamma_2 P_{f2} - (\gamma_2 - \beta_2 - \beta_3) * P_d$$

$$= \beta_2 P_{r2} + \frac{\beta_2 * Y_3 * P_{r3}}{Y_2} - \frac{\beta_2}{Y_2} c_{r2} - \frac{\beta_2}{Y_2} P_f - \left(\frac{\beta_2}{Y_2} - \beta_2 - \frac{\beta_2 * Y_3}{Y_2}\right) * P_d$$

The plastic producer manufactures at a cost c_m $(1 - \beta_1) * Q$ tonne of plastic, by using $\beta_2 * Q$ tonne of recycled naphtha and $(1 - \beta_1 - \beta_2) * Q$ tonne of virgin naphtha. We assume naphtha is turned into plastics at a ratio of 1:1. They get P_m for each tonne of plastic sold and pay P_{r2} for the recycled naphtha and P_o for the virgin naphtha. In some scenarios, the plastic producer pays a tax (τ_N) for every tonne of virgin naphtha. Equation 5 shows the unitary profit function for the thermochemical recycler.

Equation 5: Profit function for plastic producer for a tonne of plastic waste placed in the market

$$\frac{\Pi_{\mathrm{M}}}{Q} = (1 - \beta_1) P_m - (1 - \beta_1) c_m - \beta_2 P_{r2} - (1 - \beta_1 - \beta_2) P_O - \tau_N$$

Several assumptions enable solving the supply chain equilibrium model. The first assumption is that the producers choose the amount of recycled material they buy to maximize their profits. The percentage of recycled plastic (β_1) is obtained by maximizing the profit function of the packaging producer. The percentage of recycled naphtha (β_2) is obtained by maximizing the profit function of the plastic producer. Waxes are a co-product of naphtha, so the percentage of waxes produced (β_3) is proportional to the percentage of naphtha produced (β_2). The recycling rate for each technology (γ_1, γ_2) is given by the percentage of recycled product divided by the recycled product to sorted waste ratio (Υ_1, Υ_2, Υ_3). Finally, the collection rate is calculated as the maximum between the minimum collection target of Flanders ((RDC, 2018) and the rate required to meet the total recycling rate.

The second assumption, that allows us to calculate the price for recycled plastic (P_{r1}), is that there is perfect competition among mechanical recyclers and that consequently, their unitary profit is zero ($\Pi_{R1} = 0$). Similarly, the price of naphtha (P_{r2}) is calculated by assuming perfect competition among thermochemical recyclers and taking the unitary profit equivalent to zero ($\Pi_{R2} = 0$). The price for waxes (P_{r3}), decreases with the amount of wax produced with thermochemical recycling, because it is a supply shock to the current wax market. The PRO is considered to be non-profit by law, so its profit is also zero ($\Pi_C = 0$). This is used to estimate the plastic feedstock price (P_f).

It is also assumed that mechanical recycling and thermochemical recycling are equally mature technologies. The mechanical recycling costs ($c_{r1}(\beta_1)$) and the thermochemical recycling cost ($c_{r2}(\beta_2)$) depend on the quantity of plastic recycled, and thus on recycling rates. They are both decreasing power functions, resulting from the combination of TEA for mechanical recycling plants (Larrain et al., 2021) and for thermochemical recycling plants (Larrain et al., 2020) and the total amount of plastic packaging waste placed in the market.

The packaging price (P_p), collection, sorting and transport cost (c_s) depend on the amount of waste that is sorted. The price for plastic packaging (P_P) is negatively correlated with the amount of recycled plastic in the packaging because the latter has a lower perceived quality than virgin plastics (Friedrich et al., 2020) and cannot easily be used for food applications (De Tandt et al., 2021).

Collection costs are considered to be constant for collection rates lower than 80%, after which they increase. Contrarily, sorting costs are considered to decrease with higher collection rates ((Cimpan et al., 2016)). Transport costs are higher if a larger geographic area is covered because they depend on the distance between the collection point (household) and the recycling center.

The green-dot fee (P_s), packaging manufacturing cost (c_p) naphtha price (P_O), disposal fee (P_d), primary plastic manufacturing cost (c_m), are exogenous and independent of the recycling rates. The packaging production cost (c_p) is calculated considering that the operating margin of the packaging industry, calculated as the difference of the revenues with all the costs divided by the revenues, for PET was 10.3% (McKinsey and Company, 2019). The production cost for PE is then assumed to be proportional to the production cost of PET according to their virgin price levels. In a similar way, the plastic production cost (c_m) is calculated by assuming that the profit margin of the plastic producer is 10%. The price for primary plastics (P_M) is obtained from (Plastic Portal EU, 2021).

Finally, the total cost (c_{tot}) to process a tonne of plastic waste is calculated with Equation 6 and includes collection cost, sorting cost, transport cost, disposal cost, thermochemical recycling cost and mechanical recycling cost (without considering landfill tax). Packaging production cost and plastic production cost are omitted from this calculation because they are assumed to be independent of the amount of recycled material.

Equation 6: Total cost for processing a ton of plastic waste

$$c_{tot} = c_s * \alpha + c_{r1} * \gamma_1 + c_{r2} * \gamma_2 + disposal\ cost * (1 - \gamma_1 - \gamma_2)$$

2.2 Policy scenarios:

In addition to the reference case scenario, which considers only the implementation of an EPR scheme, six policy scenarios are studied. These policies aim to increase the supply of recyclable waste and stablishing well-functioning secondary market for recycled products. This can be achieved by making their prices more competitive when compared to fossil-based product prices or by increasing the demand (Ellen MacArthur Foundation, 2017). The policies included in this study, shown in Table 1, seek to increase the availability of feedstock by augmenting current regulations, rise fossil-based material prices with economic or market-based incentives (taxes and bonuses), or increase the demand for recycled materials with recycled content standards.

Table 1: Policy scenarios description

Scenario	Type	Description
Reference case		EPR scheme as described above.
Naphtha tax	Economic	Plastic producer pays a tax of 200 EUR per each tonne of virgin naphtha used to produce plastic packaging.
Packaging tax	Economic	Packaging producer pays a tax of 450 EUR for each tonne of non-recycled plastic packaging placed in the market
Green- dot fee bonus MR	Economic	Packaging producer receives a discount on the green-dot fee (P_s) proportional to the amount of recycled plastic (β_1)
Green dot fee bon MR - CR	Economic	Packaging producer receives a discount on the green-dot fee (P_s) proportional to the amount of plastic made from recycled naphtha and recycled plastic ($\beta_1 + \beta_2$)
Increased collection target	Regulation	PRO must collect up to 90% of the plastic film waste that is placed in the market
Recycled content standard MR	Regulation	Packaging producers must include at least 30% of recycled plastic in their packaging
Recycled content standard MR - CR	Regulation	Packaging producers must include at least 30% of recycled plastic or plastic made from recycled naphtha in their packaging

In the naphtha tax scenario, the plastics producer is required to pay a tax of 200 EUR / tonne of virgin naphtha. Similarly, the packaging tax scenario contemplates that the packaging producer pays a tax of 450 EUR/ tonne of non-recycled plastic packaging. This value was taken from the case of Italy where single use plastic manufacturers have to pay a tax of 450 EUR/tonne for the non-recycled plastic packaging they place on the market (EY Global, 2020). These taxes seek to decrease the demand of virgin material by increasing the price perceived by plastic producers and packaging producers.

There are two policy scenarios that aim to increase the demand of the packaging producers for recycled material by offering a discount in the green-dot fee (P_s). In the green-dot fee bonus MR, the discount is proportional to the percentage of recycled plastic (β_1) of the packaging placed in the market. In the green-dot fee bonus MR-CR, the discount is proportional to the percentage of plastic made from recycled naphtha and recycled plastic $(\beta_1 + \beta_2)$ of the packaging placed in the market. The manufacturers share of his supplier selling price is determined by a manufacturer`s vertical upstream market power (Steiner, 2008). Therefore, in the last scenario, the primary plastic price (P_m) is reduced proportionally to the savings achieved by the packaging producer coming from recycled naphtha $(500 * \beta_2)$ and to the market power (mp) of the plastic producer with respect to the packaging producer.

In the increased collection target scenario, the PRO must collect up to 90% of the plastic film waste that is placed in the market. It is expected that a higher availability of plastic waste would increase recycling rates by taking advantage of economies of scale. Finally, another instrument to increase the demand of packaging producers for recycled material is setting a standard of minimum recycled content. There are two recycled content standard scenarios that consider that the packaging producer must include at least 30% of recycled material in their packaging: the recycled content standard MR considers that this material must come from mechanical recycling and the recycled content standard MR-CR considers that the recycled material can come from mechanical recycling or thermochemical recycling.

2.3 Economic and environmental implications

To study the economic implications, we calculate the profit of the plastic producer with *Equation 5*, the profit of the packaging producer with *Equation 1* and the total cost (c_{tot}) to process a tonne of plastic waste with *Equation 1*.

To calculate the environmental implications, we first multiply the recycling rates $(\gamma_1 and\ \gamma_2)$ resulting from the equilibrium model by the environmental indicators reported in (Civancik-Uslu et al., 2021), a LCA that compares the treatment of 1 tonne of collected plastic waste with mechanical and thermochemical recycling. We select the most commonly reported environmental indicators in the literature of LCA of plastic: global warming, ozone formation, terrestrial acidification, mineral resource scarcity,, fossil resource scarcity and water consumption. Then, we take the difference between the environmental impact of plastic incineration and the environmental indicator of each scenario. The environmental impacts of incineration were taken from the Ecoinvent v3.6 database using the ReCiPe method.

2.4 Sensitivity analysis

The exogenous parameters are varied independently between 50% and 150% of their initial value to assess their impact on the amount of plastic treated in the results. This is done for the reference case scenario and the median energy and oil price levels.

3 Results

3.1 Recycling rates in the equilibrium points of the policy scenarios

Figure 2 shows (a) the recycling rate for mechanical recycling (γ_1), the (b) recycling rate for thermochemical recycling (γ_2) and the (c) total recycling rate ($\gamma_1 + \gamma_2$) when low oil and energy prices are observed (inverted triangles), when intermediate oil and energy prices are expected (circles) or high oil and energy prices are expected (triangles). The figure reveals that low oil and energy prices (inverted triangles) will entail lower recycling rates, because the effect of lower oil prices on product prices is more pronounced than the effect of lower energy prices in decreasing processing costs. Since mechanical recycling requires more external energy than thermochemical recycling, the effect is more pronounced for the former (red symbols) than for the latter (purple symbols).

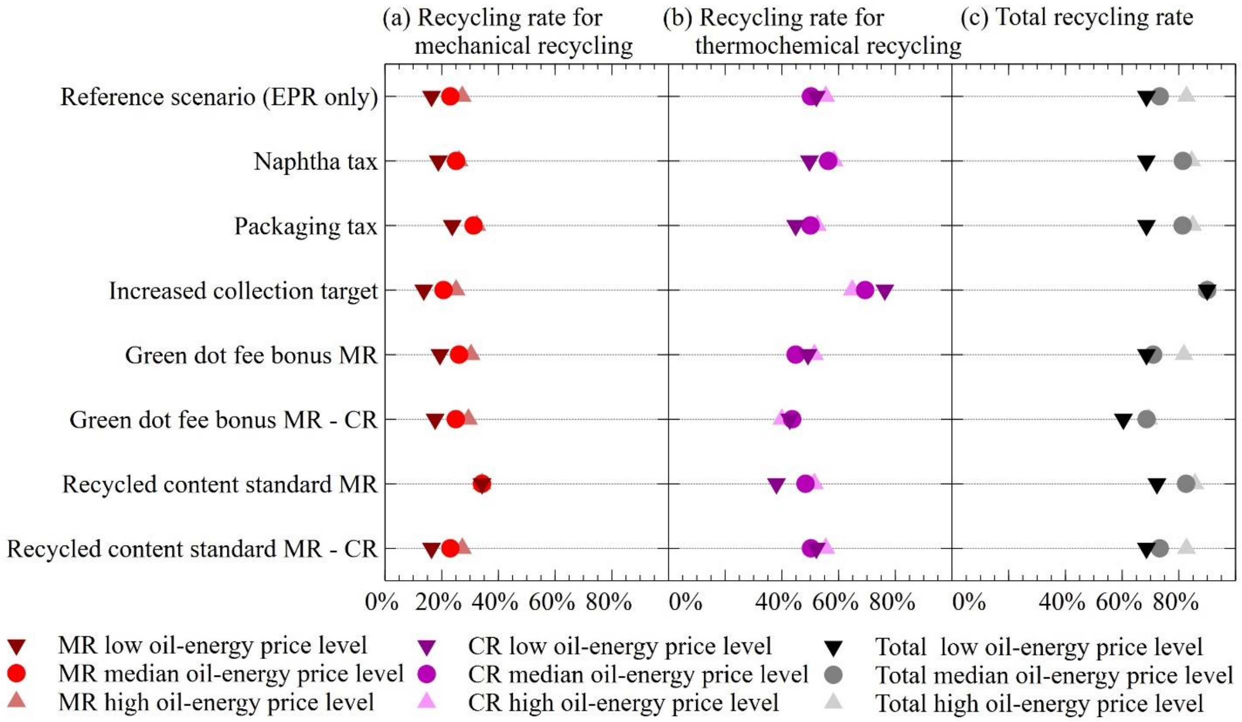


Figure 2: Recycling rates for mechanical recycling (a), thermochemical recycling (b), and for both technologies (c) in the policy scenarios for low, median, and high oil and energy price levels.

The figure also shows that for all policy instruments and oil and energy price levels, more plastic waste is recycled with thermochemical recycling (purple symbols) than with mechanical recycling (red symbols).

The main reason for this is that the quality of recycled naphtha is assumed to be the same as its virgin alternative, while the quality of recycled plastic is assumed to be lower than its virgin alternatives.

When comparing the policy scenarios, the naphtha tax increases the amount of plastic recycled by thermochemical recycling when oil and energy prices are medium or high. This is due to the reduction in the relative price of recycled naphtha compared to virgin naphtha. Similarly, the packaging tax applied to the primary plastic fraction of packaging increases the level of mechanical recycling. In this policy scenario, packaging managers will have to pay more for primary plastic, increasing the demand for recycled plastic despite the potential decrease in the price of plastic packaging.

Increasing the collection target is the policy with the largest increase in overall recycling rates. This policy tool increases the amount of waste recycled through thermochemical recycling (purple symbols) and reduces the amount of waste recycled through mechanical recycling (red symbols). This is because at these recycling levels, economies of scale are relevant for thermochemical recycling but not for mechanical recycling. In addition, increasing the recycled content in mechanical recycling would reduce the price of packaging, an effect that is more pronounced when oil and energy prices are low (inverted triangles).

The Green Dot fee bonus MR increases the overall recycling rate by increasing the price of sorted waste and the price of recycled products. These two prices also increase when the bonus is applied to both technologies (green dot fee bonus MR-CR), but their effect is offset by an increase in the price of plastic (P_M) . Figure A.3 in Appendix III shows these results in more detail.

Regarding the recycled content standard, Figure 2 shows that when it is applied to mechanical recycling only (MR standard), the amount of plastic recycled increases up to the target level. However, the thermochemical recycling rate decreases compared to the reference case scenario when oil and energy prices are low (purple inverted triangles) or average (purple circles).

When the 30% standard applies to recycled products from mechanical and thermochemical recycling, the recycling rates do not change because the overall recycling rate in the Reference Case scenario is higher than 30%. It should be noted that a higher recycled content is technically feasible for thermochemical recycling. If this tool were applied with a higher standard, the results would be similar to those of the increased collection standard.

3.2 Effect of the geographic scale on the amount of plastic recycled with mechanical and thermochemical recycling

Figure 3 shows that economies of scale have a critical role on the amount of plastic waste that would be recycled for low oil and energy price levels (a), median oil and energy price levels (b) and high oil and energy price levels (c). These results agree with a previous study from Chen et. al. (2012), that showed that larger towns were able to obtain more products. Mechanical recycling is feasible for low population levels because mechanical recycling plants are profitable at a small scale. Thermochemical recycling is only feasible if the plant is located in a region with a population larger than 6.6 M habitants for all oil and energy price scenarios. The larger the area in which the plastic waste is treated, the higher the fraction of plastics that would be treated with thermochemical recycling. This result is related to the larger economy of scale of thermochemical recycling when compared to mechanical recycling. The fact that the cost – plant size curve is steeper for thermochemical recycling than for mechanical recycling makes the former a more competitive technology for larger amounts of plastic waste.

Since transport costs are higher for a larger area, Figure 3 also shows that the total recycling rate is lower for all Europe than for Western Europe only if oil and energy prices are expected to be median or high. This supports that, from a certain point, plants that cover a smaller geographic are more cost efficient than larger plants.

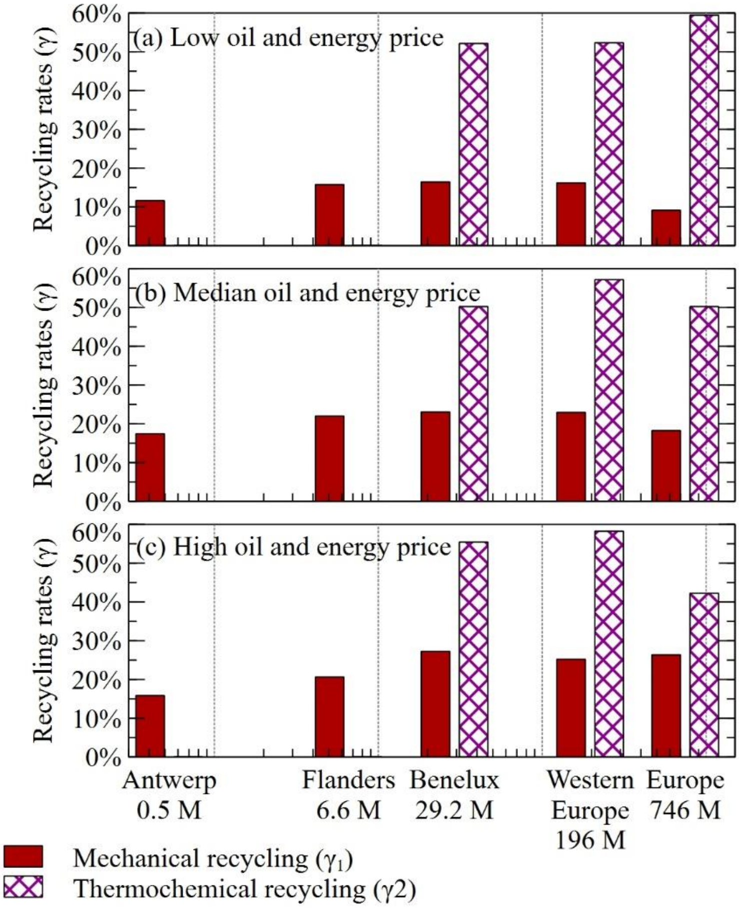


Figure 3: Plastics recycled with each technology for regions with different population levels

3.3 Economic and environmental implications

Figure 4 shows environmental and economic performance indicators of the policy scenarios for the low oil-energy price scenario (inverted triangles), median oil-energy price scenario (bars), and high oil-energy price scenario (triangles). To calculate the environmental performance indicator, we first took the differences of life cycle indicators of mechanical and thermochemical recycling with incineration from Civancik-Uslu et al. (2021) and multiply them by the recycling rates. The economic indicators were calculated using the profit functions and the total cost. The best performing scenario takes the value of 1, the worst performing scenario takes the value of zero, and the remaining scenarios are linearly interpolated. Since the performance indicators are always higher for the scenarios with a better outcome, the size of the shaded area gives an idea of which scenario performs best.

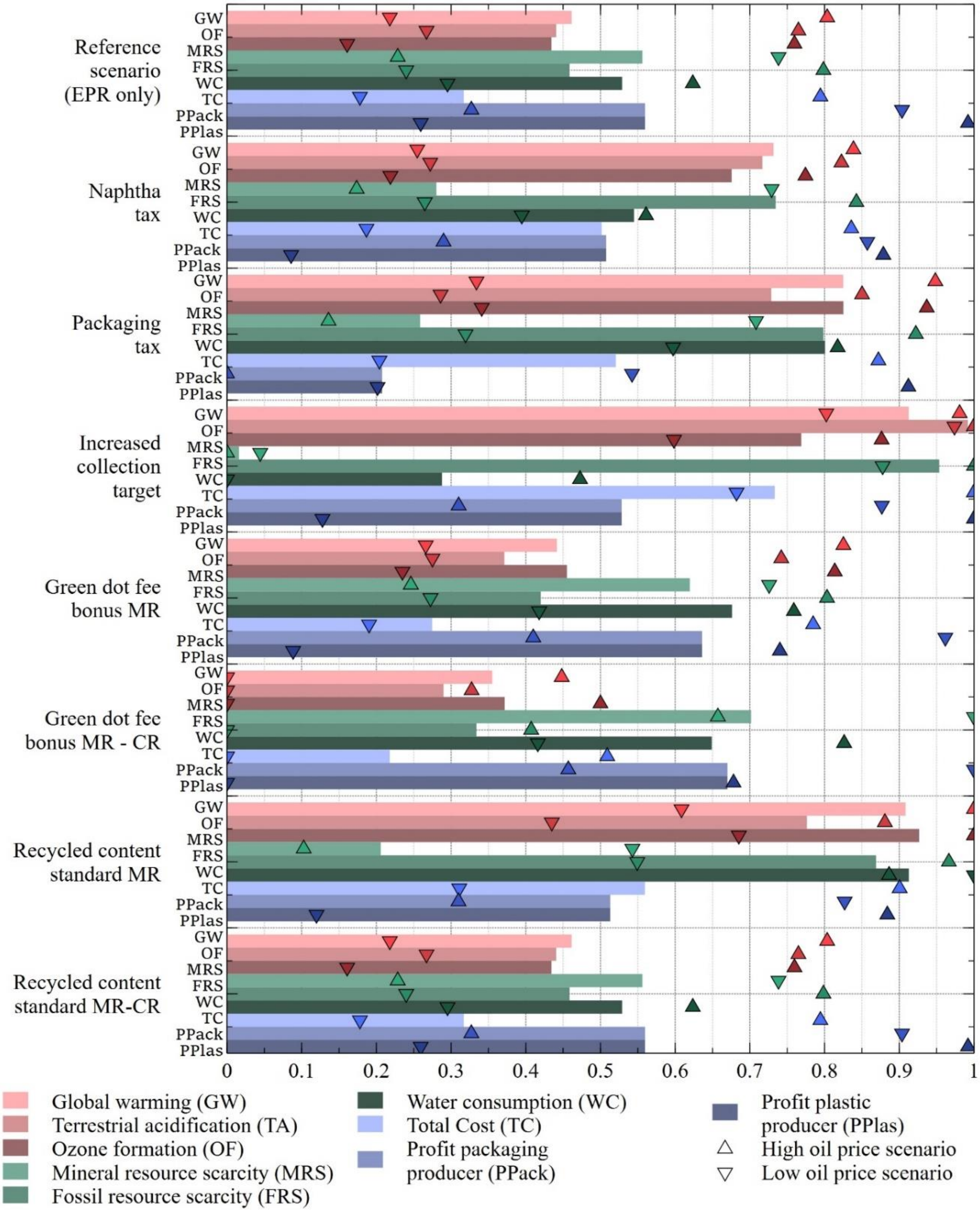


Figure 4: Economic and environmental indicators in the policy scenarios. Results are shown as performance indicators, varying between 0 and 1. The environmental indicators were calculated by combining the results from Figure 2 with the results from an LCA of recycling technologies (Civancik-Uslu et al., 2021). *The economic indicators were calculated using the profit functions of mechanical and thermochemical recyclers and the total costs.*

This figure is revealing in several ways. The environmental indicators in the reference case scenario for high oil and energy price levels (triangles) are better than for low price levels (inverted triangles) and the latter are better than the ones of the median price levels (bar). An explanation for this is that with high price levels both recycling rates increase and with low price levels mechanical recycling decreases significantly, but thermochemical recycling slightly increases.

The figure also shows that the packaging tax scenario and the naphtha tax scenario perform better than the reference scenario in terms of fossil resource consumption and emissions. It can also be seen that in these scenarios the profits of the plastic and packaging producers are lower than in the reference case, which can be translated into a resistance of the producers in case one of these policies would be implemented.

Looking at the green dot fee bonuses, the figure illustrates that the emissions indicators, the fossil resource scarcity and water consumption are better than in the reference scenario. Besides, both policies increase the profit of the packaging producer and reduce the one of the plastic producer.

Finally, a recycled content standard for mechanical recycling would show the best environmental performance for ozone formation and water consumption. Global warming performs equally well in recycled content standard for mechanical recycling and increased collection target. Fossil resource scarcity and terrestrial acidification also perform best in the increased collection target. These two policy scenarios, comparatively perform worse than the reference case scenario for all economic indicators.

A detail of the collection, transport, sorting, recycling and total costs of processing the plastic waste is provided in Table A.3 of Appendix II. It can be seen that collection, transport and sorting costs and total processing costs are the highest for the increased collection target scenario, the scenario with the highest recycling rates. On the contrary, recycling costs decrease with higher recycling rates. For mechanical recycling this is the recycled content MR scenario and for thermochemical recycling the increased collection target scenario. Comparatively, mechanical recycling costs are always lower than those of thermochemical recycling.

Given the scale effects of collection, transport, and recycling costs, it should be noted that these results may vary for the different geographical scales. Recycled content standard for MR should have a positive effect in all scales. For smaller areas, in which thermochemical recycling is not expected to occur (see Figure 3(b)), policies that promote this technology could increase overall recycling rates. In contrast, increasing the availability of feedstock by increasing higher collection targets would be useful for larger areas.

3.4 Sensitivity analysis

In the sensitivity analysis, to analyze how the recycling rates of mechanical recycling (γ_1) and thermochemical recycling (γ_2) fluctuate, the exogenous parameters are independently varied between 50% and 150% in the reference case scenario and the median oil-energy price level. Figure 5 shows the results of the most influencing parameters and Figure A.4 of the appendix shows the results of all parameters that were varied. The mechanical recycling rate is mostly affected positively by the primary plastic price (P_m) and the green dot fee (P_s). An increase on the primary plastic price (P_m) would increase the demand for recycled plastic. A higher green dot fee (P_s) would cause a higher sorted plastic waste price $\left(P_f\right)$, and consequently provide more incentives for mechanical recycling.

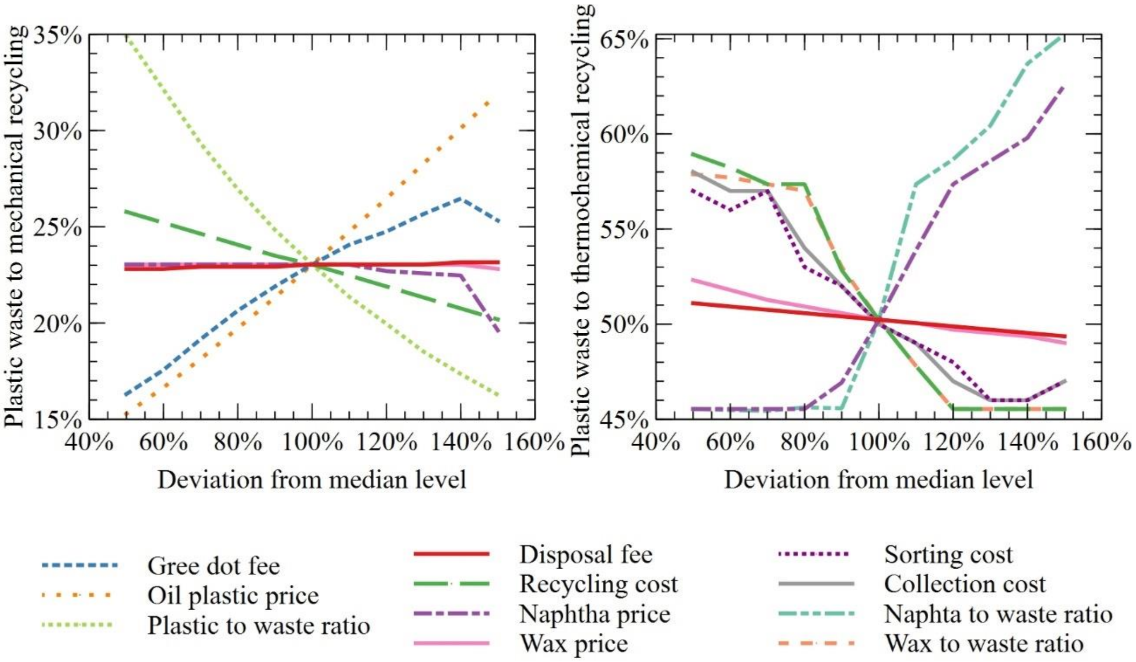


Figure 5: Sensitivity analysis. Parameters are varied between a 50% and a 150% on the horizontal axis in the reference case policy scenario. The response is shown on the vertical axis.

On the other hand, the recycled plastic to sorted waste ratio (Y_1) and mechanical recycling unitary costs (c_{r1}) have a negative correlation with the amount of plastic waste that would be treated with mechanical recycling (γ_1).

The figure also shows that the naphtha price (P_O), the naphtha to sorted waste ratio (Y_2), thermochemical recycling unitary costs (c_{r2}), the green dot fee (P_s) and the price elasticity of demand for waxes (η) have a positive effect on the thermochemical recycling rate (γ_2). The effect of the naphtha price is due to the positive effect on the demand for recycled naphtha, given by the profit function of the plastic producer. Similarly, a higher naphtha to sorted waste ratio (Y_2) and lower thermochemical recycling unitary costs (c_{r2}) would increase the profitability of thermochemical recycling. As it is the case for mechanical recycling, a higher green dot fee (P_s) would increase the sorted plastic waste price $\left(P_f\right)$, and provide more incentives for recycling.

The sensitivity analysis is also useful in proving the robustness of the model, by demonstrating that there is no variable that changes the results more than 15 percentage points. Furthermore, this analysis exposes that caution should be applied when extrapolating these results to regions with different economic contexts, as the model uses specific costs and product to sorted waste ratios for the recycling processes. The recycling costs rely on variables that are specific to each country, such as labor cost or discount rates. The product to waste ratios depend on the contamination levels of the sorted plastic waste which are determined by the behavior of the households and the sorting systems of each country. Further research could enhance the results of this study by including region or country specific economic variations.

4 Discussion

The first important finding of this research is that low oil and energy prices decrease recycling rates and that this effect is more pronounced for mechanical recycling than thermochemical recycling. This means that mechanical recycling is more vulnerable to oil and energy price fluctuations than thermochemical recycling.

The second important outcome is that different policy instruments trigger distinct impacts on the type of technology promoted, leading to a diverse landscape of economic and environmental outcomes. Taxes, such as packaging tax and naphtha tax, would increase the overall environmental performance compared to the one observed in the reference case, but they could decrease the profit of the packaging and plastic producers. Policy makers should be aware that some resistance could be expected from these industries when trying to implement these interventions. Palliative measures, like implementing taxes gradually, could help firms, especially those with lower market power, to adopt policies. A naphtha tax would mainly promote thermochemical recycling and have a balanced positive effect on most indicators. A packaging tax would mainly promote mechanical recycling and could significantly reduce the consumption of fossil resources, but would worsen the profitability of the packaging producer.

Command and control regulations, such as increased collection target and recycled content standard for mechanical recycling, are the best performing interventions of the ones analyzed in this study in terms of emissions (related to global warming, terrestrial acidification and ozone formation) and fossil resource consumption. An increased collection target, that secures the supply of plastic waste, would increase the overall recycling rates the most. Nevertheless, most of the increase will be due to thermochemical recycling, which has a larger water consumption than mechanical recycling.

Furthermore, a recycled content standard for mechanical recycling is the intervention that increases mechanical recycling the most. This intervention ranks first or second place for all environmental indicators, except for mineral resource scarcity, but it is one of the worst performing interventions for all economic indicators. As in the case of taxes, implementing the targets or standards gradually would help small and medium firms adopt the measures.

Regarding the robustness of the various policy interventions to oil and energy price variation, in agreement with Larrain et al. (2022), the study shows that direct interventions like increased collection target or recycled content standards can increase recycling rates regardless of the external market conditions. On the contrary, the effect of economic interventions like taxes depends on external market conditions. Taking this into consideration, a combination of economic and direct interventions would secure recycling activities regardless of external market conditions and ensure innovation.

Replication of these results to other countries should be done carefully, considering their geographic characteristics, cost levels and policy development. The specific price levels of a country (labor, transport, equipment, etc.), and geographic characteristics (density, distance between towns) will affect the cost structure of both recycling technologies, and consequently the recycling rates. To take advantage of the economies of scale seen in thermochemical recycling, a coordinated action from different territories would allow higher recycling rates at a lower cost, in agreement with policy briefs. Finally, the policy implementation should follow the phases proposed by the Global Plastics Outlook: first, implementing adequate waste management system, then EPR schemes and finally, securing the secondary markets.

This study has some limitations. It is based on the EPR scheme implemented in Flanders, in which the PRO is responsible for the collection and sorting of the waste and then sells the sorted fractions to recyclers. The green dot fee scenarios results would probably vary in countries with different EPR schemes, but the model would still be reliable for the tax, increased collection targets and recycled content standards scenarios. Besides, it assumes that producers have all market power when interacting with recyclers and that the packaging producer and plastic producer share equal market power. Since market power affects the sustainability transition (Biely and Van Passel, 2022), further research should be undertaken to assess the effect of market power on the presented results.

In addition, it has been assumed that both technologies, mechanical and thermochemical recycling are equally mature. This could be shifting the equilibrium point towards higher thermochemical recycling and lower mechanical recycling rates than what would be observed if learning effects were considered. Despite this limitation may affect the specific values, the model is still reliable in terms of the direction of the effects of the policy interventions.

Previous academic and governance organization papers have emphasized the importance of implementing a policy mix of downstream and upstream measures and of advanced measures like modulated fees, taxes and recycled content standards (Ellen Mc Arthur (2017), SYSTEMIQ (2022), Milios (2018)). This study contributes to the existing literature by providing evidence that a mix of economic and regulatory policies are necessary for decoupling recycling rates from oil prices and providing incentives for innovation. The choice of a best policy instrument will depend on the relevance given to the different environmental outcomes, which can be deducted with a multicriteria assessment.

5 Conclusions

This paper fills the gap in the academic literature by quantitatively studying the market dynamics between mechanical and thermochemical recycling of plastic waste. It digs deeper into the evaluation of several policy instruments and its implications on the economic and environmental performance. It also examines the effects of the geographic scale at which the policies are studied.

There are four main conclusions that emerge from this paper. First, mechanical recycling is more vulnerable to oil and energy price fluctuations than thermochemical recycling. Second, policy instruments that do not target a specific technology are more likely to increase thermochemical recycling instead of mechanical recycling of PE films. Hence, if increasing mechanical recycling is desired, the policy instruments should specifically target this technology.

Third, higher recycling rates are not equivalent to a better environmental outcome. This particular finding points to the need for evaluating policy instruments case by case and according to the objectives that are expected to be met, rather than focusing the attention on recycling rates solely. And finally, policy makers should consider the potential economic impacts of the policies on the different stakeholders. For example, packaging producers could be strongly opposed to a packaging tax because of the expected profit reduction, but this could be balanced by government stakeholders given the funding that it would provide for them.

This work contributes to the existing knowledge of circular economy by providing a simulated scenario of the possible outcomes of the implementation of several policy instruments. It can be used by policy makers to assess the potential implications of the interventions and industrial stakeholders to understand how an intervention could impact their industry. Moreover, the novel methodology can be replicated to any other environmental technology development.

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Supporting Information

Appendix I: Variable calculation

In this section we briefly describe how the quantity variables, price variables and cost variables are calculated to find the equilibrium point of each policy scenarios. The equations that are used to calculate these values are shown in Appendix I.

Recycled sorted waste (γ_1, γ_2)

It is assumed that producers buy the amount of recycled products that maximize their profits. In every scenario, except the recycled content standard scenarios, the amount of recycled products is obtained by maximizing the profit function of the packaging producer, maximizing the profit function of the plastic producer and intercepting the resulting functions. Waxes are a co-product of naphtha from thermochemical recycling so the amount of waxes produced (β_3) is proportional to the amount of naphtha produced (β_2). Following this, the amount of sorted waste that would be recycled with each technology (γ_1, γ_2) is given by the amount of recycled product divided by the recycled product to sorted waste ratio (Y_1, Y_2, Y_3). Finally, the collection rate is calculated as the maximum between the minimum collection target of Flanders ((RDC, 2018) and the rate required to meet the total recycling rate.

The amount of sorted waste that would be recycled with each technology (γ_1, γ_2) is given by the amount of recycled product and by the recycled product to sorted waste ratio (Y_i). Equation A.1 and Equation A.2 show how these values are calculated for mechanical and thermochemical recycling respectively.

Equation A.1: Sorted waste recycled with mechanical recycling

$$\gamma_1 = \frac{\beta_1}{Y_1}$$

Equation A.2: Sorted waste recycled with thermochemical recycling

$$\gamma_2 = \frac{\beta_2}{Y_2} \ \ and \ \ \gamma_2 = \frac{\beta_3}{Y_3}$$

Recycled products (β_1, β_2, β_3)

Waxes are a co-product of naphtha from thermochemical recycling (Larrain et.al. 2020). Hence, the amount of waxes produced (β_3) is proportional to the amount of naphtha produced (β_2). Equation A.3, that comes from Equation A.2, shows this relationship.

Equation A.3: Waxes products

$$\beta_3 = \frac{\beta_2 * Y_3}{Y_2}$$

To calculate the amount of recycled plastic (β_1) the profit function for packaging producer for a tonne of plastic waste placed in the market, shown in Equation 1 is maximized. After replacing the values of recycled plastic price (P_{r1}) and sorted waste price (P_f), this profit function depends on the recycled plastic (β_1) and recycled products from thermochemical recycling (β_2 *and* β_3). Therefore, when it is maximized with respect to the plastic product (β_1), a function F of the amount of recycled products is obtained.

Equation A.4

$$\beta_1^{\wedge} = max\left(\frac{\Pi_{P(\beta_1,\beta_2,\beta_3)}}{Q}\right) = F(\beta_2,\beta_3) = F\left(\beta_2,\frac{\beta_2 * Y_3}{Y_2}\right) = F(\beta_2)$$

Likewise, the amount of recycled naphtha (β_2) is given by the maximization of the unitary profit function of plastics producer, shown in Equation 5. The profit function also depends on the recycled plastic on the recycled plastic (β_1) and recycled naphtha (β_2 and β_3). A function G of the recycled plastic results from this maximization.

Equation A.5

$$\beta_2^{\wedge} = max\left(\frac{\Pi_{M(\beta_1,\beta_2,\beta_3)}}{Q}\right) = G(\beta_1)$$

Finally, the recycled naphtha and recycled plastic in equilibrium is given by the intersection of the maximized functions F and G.

Equation A.6

$$\beta_1^* = F(\beta_2^{\wedge}) = F(G(\beta_1^*))$$

For the recycled content standard MR scenario the recycled plastic (β_1) is set at 30% and the recycled naphtha is given by the maximized function of the plastic producer when the recycled plastic is 30%.

Equation A.7

$$(\beta_1^* = 30\% \; and \; \beta_2^* = G(30\%))$$

For the recycled content standard MR-CR scenario the recycled naphtha and recycled plastic must be at least a 30% ($\beta_1 + \beta_2 \geq 30\%$). It is considered that the packaging producer maximizes their profit and that the plastic producer manufactures the remaining necessary naphtha to achieve the standard ($\beta_2^* = 30\% - \beta_1$)

Equation A.8

$\beta_1^{\wedge} = 30\% - \mathrm{F}(\beta_2^{\wedge})$ and $\beta_1^* = F(\beta_2^{\wedge})$).

We evaluate the results under three energy (electricity and natural gas) and oil price level conditions. The low energy and oil price level takes the prices observed after the COVID pandemic in April 2020, the high energy and oil price level takes the prices after the Russia invasion into Ukraine of June 2022, and the median oil and energy price levels observed during 2019. Electricity and natural gas price fluctuations vary the processing costs and oil prices vary product prices. Following the evidence that shows that virgin plastic, naphtha and wax prices are correlated with oil prices (Jiang et al., 2015; Selmi et al., 2022), all product prices are varied proportional to the oil price variation for the three levels. Oil, electricity and natural gas prices in the three conditions are shown in Table A.1 of the Appendix.

Collection rate (α)

The minimum collection target of Flanders ((RDC, 2018) established by the EPR scheme, is corrected by the food waste and humidity (Chapter 3). Then, the collection rate is calculated depending on the corrected minimum collection rate ($\alpha^{\min}$) and the collected waste required to meet collection targets. Table A.1 shows the minimum collection rate.

Equation A.9

$$\alpha = max\left(\alpha^{min}, \gamma\right)$$

Table A.1: Data

	Variable	Value	Unit	Source
	Low oil price/ Median oil price	0.58	EUR/EUR	(Oil Pricez, 2022)
	High oil price/ Median oil price	1.25	EUR/EUR	
	Low electricity price/ Median electricity price	0.78	EUR/EUR	(GlobalPetrolPrices, 2022a)
	High electricity price/ Median electricity price	7.7	EUR/EUR	
	Low natural gas price/ median natural gas price	0.8	EUR/EUR	(GlobalPetrolPrices, 2022b)
	Gas	8.12	EUR/EUR	
P_m	*Primary plastic price*	980	EUR/ton of plastic	(Plastic Portal EU, 2021)
P_O	*Observed naphtha price*	525	EUR/ton of naphtha	(International Energy Agency (IEA), 2020)
P_w	*Observed wax price*	707	EUR/ton of wax	(Argus Media, 2018)
P_d	*Final disposal fee*	133	EUR/ton of waste	(OVAM, 2019)
P_p^o	*Virgin plastic packaging price*	4976	EUR/ton of plastic packaging	Chapter 4
L	*Perceived quality parameter*	0.66	-	Own calculation from Eriksen et al. (2019) and Polymer Comply Europe (2019)
P_s	*Green dot fee*	510	EUR/ton of plastic packaging	Fostplus 2020
c_{r1}^0	*Unitary mechanical recycling cost for* $\beta_1 = 1$	267	EUR/ton of sorted plastic waste	Own calculation from Chapter 3
$s1$	*Cost scale factor for mechanical recycling*	-0.1	-	
c_{r2}^0	*Unitary thermochemical recycling cost for* $\beta_2 = 1$	234	EUR/ton of sorted plastic waste	Own calculation from Chapter 2
$s2$	*Cost scale factor thermochemical recycling*	-0.5	-	
α^{min}	*Plastic waste collected from consumer`s households*	0.685	ton of plastic waste/ton of plastic packaging	(RDC, 2018)
Y_1	*Recycled plastic to sorted waste ratio*	0.88	ton of recycled plastic/ tonne of sorted plastic waste	Chapter 3
Y_2	*Recycled naphtha to sorted waste ratio*	0.58	ton of recycled naphtha/ tonne of sorted plastic waste	Chapter 2
Y_3	*Recycled waxes to sorted waste ratio*	0.31	ton of recycled naphtha/ tonne of sorted plastic waste	

η	*Price elasticity of demand for waxes*	-0.14	-	(Caldara et al., 2019)
Q_{pw}	*Amount of waxes sold*	90.2	tonne of waxes	(Datawheel, 2021)

Recycled product prices (P_{r1}, P_{r2}, P_{r3})

According to the first assumption, the price for recycled plastic (P_{r1}) is calculated by making the unitary profit function for mechanical recycler, shown in Equation 3 equivalent to zero. Similarly, the price of naphtha (P_{r2}) is calculated by considering that the profit function for thermochemical recycler, shown in Equation 4, is equal to zero.

Equation A.10 shows how the recycled plastic price is calculated to find the equilibrium point. According to the first assumption, the price for recycled plastic (P_{r1}) is calculated by making the unitary profit function for mechanical recycler, shown in Equation 3 equivalent to zero.

Equation A.10: Recycled plastic price

$$P_{r1} = \frac{c_{r1}(\beta_1) + P_{f1} + P_d * (1 - Y_1)}{Y_1}$$

Similarly, for the price of naphtha (P_{r2}) we consider that the profit function for thermochemical recycler for a tonne of plastic waste placed in the market, shown in Equation 4, is equal to zero.

Equation A.11: Recycled naphtha price in equilibrium

$$P_{r2} = \frac{c_{r2}(\beta_2) + P_{f2} + P_d * (1 - Y_2 - Y_3) - Y_3 P_{r3}}{Y_2}$$

Wax is an open-loop recycling product. Therefore, in the circular supply chain its price (P_{r3}) will depend on factors that are external to the plastic packaging value chain. The waxes produced with thermochemical recycling will be added to the current wax market, produced from petroleum and natural (biobased) sources. Since this is a technological advance, the supply curve for waxes will be shifted to the right in this same amount as the supply shock. Consequently, after the supply shock that is produced by the introduction of the waxes coming from thermochemical recycling, the price for waxes could be expected to decrease. If $\beta_3 * Q$ tonne of waxes are produced, the supply curve for waxes will be shifted to the right in this same amount.

The slope of the supply curve is: $m = \frac{P_2 - P_1}{Q_2 - Q_1}$ and the elasticity of the demand curve can be defined as: $\eta = \frac{\frac{Q_2 - Q_1}{Q_1}}{\frac{P_2 - P_1}{P_1}}$. Therefore: $m = \frac{1}{\eta}\frac{P_2}{Q_2}$

Therefore, the price of waxes (P_{wax}), after a shock in the supply of Q_{wax}, if the price of the wax was P_{wax}^{O} when the supply was Q_{pw} can be calculated as:

$$P_{wax} = P_w + m * (Q_{pw} + \beta_3 * Q - Q_{pw}) = P_w + \frac{P_w}{\eta * Q_{pw}} * (Q_{pw} + \beta_3 * Q - Q_{pw})$$

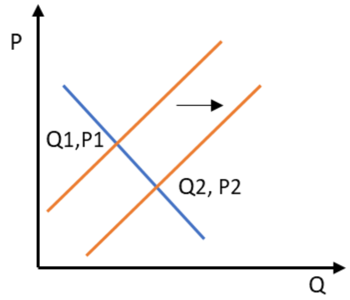


Figure A. 1: Price change after and input shock

Equation A.12 shows the price for wax (P_{r3}) after a supply shock of $\beta_3 * Q\ ton$ of waxes.

Equation A.12: Recycled wax price in equilibrium

$$P_{r3} = P_w * \left(1 + \frac{Q * \beta_3}{\eta * Q_{pw}}\right)$$

+

Equation 1

$$c_{tot} = c_s * \alpha + c_{r1} * \gamma_1 + c_{r2} * \gamma_2 + disposal\ cost * (1 - \gamma_1 - \gamma_2)$$

It is assumed that producers choose to buy the amount of recycled products that maximize their profits. In every scenario, but the recycled content standard scenarios, the amount of recycled products is obtained by maximizing the profit function of the packaging producer, maximizing the profit function of the plastic producer and intercepting the resulting functions.

Sorted plastic waste prices (P_f)

The price of sorted plastic waste (P_f) is given by assuming that the profit of the PRO, presented in Equation 2 is zero and that the PRO sells the sorted waste at the same price to all recyclers. In addition, the price for plastic packaging (P_P) is negatively correlated with the amount of recycled plastic in the packaging because the latter has a lower perceived quality than virgin plastics (Friedrich et al., 2020) and cannot easily be used food applications (De Tandt et al., 2021). In accordance to what is shown in (Larrain et al., 2022) the packaging price will be a concave function of a perceived quality parameter (L) negatively related to the recycled content of the packaging.

Equation A.13: Waste feedstock price in the equilibrium

$$P_f = \frac{\left(\alpha - \frac{\beta_1}{Y_1} - \frac{\beta_2}{Y_2}\right) * P_d - c_s \alpha - P_s}{\frac{\beta_1}{Y_1} + \frac{\beta_2}{Y_2}}$$

Price for plastic packaging (P_p):

Packaging producer and packaging manager are defined as a single stakeholder. Though in reality they are mostly different firms, this is equivalent to define them as two different stakeholders and assume that the packaging managers pass the total cost of packaging to the consumer and that there is no transaction cost between packaging producers or packaging managers. The price of plastic packaging is negatively correlated with the amount of recycled plastic in the packaging. The main reason for this is that packaging with recycled plastic has a lower perceived quality than virgin plastics (Friedrich et al., 2020) and cannot be used food applications (De Tandt et al., 2021).

Equation A.14 describes the function for the packaging price, with a perceived quality parameter L and recycled plastic content of β_1, where P_p^o represents the prices for plastic packaging with only virgin material. In accordance to what is shown by Larrain et.al. 2021 packaging price will be a concave function of a perceived quality parameter (L) negatively related to the recycled content of the packaging. The perceived quality (L) is calculated as the average between the non-food packaging applications ((Eriksen et al., 2019) and the percentage of converters that consider that recycled plastic are not of enough quality (Polymer Comply Europe, 2019).

Equation A.14: Plastic packaging price

$$P_p(\beta_1) = P_p^o * (1 - L * \beta_1^2)$$

Green-dot fee (P_s)

In a EPR scheme, packaging manufacturers have to pay a green dot fee to the PRO. In this model we consider the value fixed and exogenous for most scenarios but the green dot fee bonus MR and the green dot fee bonus MR scenarios. In the green-dot fee bonus MR, the fee P_s is reduced proportional to the amount of recycled plastic included:

Equation A.15: Bonus green dot fee bonus MR scenario

$$bonus = 500 * \beta_1$$

In a similar way, in the green-dot fee bonus MR-CR the reduction in the fee is given for the recycled plastic and the plastic made from recycled naphtha:

Equation A.16: Bonus in green dot fee bonus MR - CR scenario

$$bonus = 500 * (\beta_1 + \beta_2)$$

Naphtha tax (τ_N)

The naphtha tax is set at 200 EUR/tonne for the naphtha tax scenario and packaging tax at 450 EUR/tonne for the packaging tax scenario. The naphtha tax is set based on the experience of Italy, where in 2020 a tax of this magnitude was implemented (EY Global, 2020).

Equation A.17: Naphtha tax in naphtha tax scenario

$$\tau_N = (1 - \beta_1 - \beta_2) * 200$$

Packaging tax (τ_P)

The packaging tax is zero for all scenarios but the packaging tax scenario, where it is calculated as:

Equation A.18: Packaging tax in the packaging tax scenario

$$\tau_P = (1 - \beta_1) * 450$$

Price for primary plastics (P_m):

The price for primary plastics is obtained from (Plastic Portal EU, 2021). This value is considered fixed in all scenarios, but the green-dot fee bonus MR-CR scenario and the naphtha tax scenario.

In the green dot fee bonus MR-CR scenario, the price is considered to increase with the bonus. The packaging producer partially trespass the savings obtained from the bonus related to the packaging made with recycled naphtha to the plastic producer. This is represented with increase of the price proportional to the market power of packaging producer when compared to the one of the plastic producer (mp). For simplicity we take a value of 0.5.

Equation A.19: Primary plastic price in green dot fee bonus scenario

$$P_m = P_m^o + mp * 500 * \beta_2$$

The naphtha tax scenario presents a similar situation. The plastic producer trespass partially the increased cost of taxes to the packaging producer. The proportion in which it is increased is also given by the market power of the of packaging producer when compared to the one of the plastic producer (mp).

Equation A.20: Primary plastic price in naphtha tax scenario

$$P_m = P_m^o + mp * (1 - \beta_1 - \beta_2) * 200$$

Collection, transport and sorting costs (C_s)

Waste is collected from the households (curbside collection), sorted and transported to the recycling center. We take a collection cost of 192 EUR/ tonne (Environment, 2018) and discount 100 EUR/ton that is paid by the consumer. Economies of scale of sorting plants are also taken into account. According to (Cimpan et al., 2016), sorting costs can vary from 72 EUR/ tonne for plants that sort more than 100 kton/ year to 112 EUR/ton for plants with a capacity smaller than 50 kton/year.

Transport costs depend on the distance between the collection point (household) and the recycling center. The larger the amount of plastic waste recycled, the larger the amount of household from which it needs to be collected and the longer the average distance from the household to the recycling point. To calculate transport costs, a circular collection area and a homogeneous distribution of households the area is assumed.

The average distance from a point to the center of the circle is calculated as 0.61 times the radius (Stone, 1991). The radius of the circular area is given by the population of the circular area and the population density. As a base case we take the area composed by Belgium, Netherlands and Luxembug (Benelux) and then to study the effect of the geographic scales, four representative areas with decreasing population density are taken into account: the city of Antwerp, the region of Flanders, Benelux, Western Europe and Europe.

Finally, we take the average cost of transporting plastic waste in Germany of 0.24 EUR /Km /ton (Velzen et al., 2013). Table A.2 shows the average transport costs calculated with Equation A.21:

Equation A.21: Transport cost function

$$c_t = 0.24 * 0.61 * \sqrt{\frac{Population}{density * \pi}}$$

Table A.2: Transport cost for geographic scales

Geographic scale	Population (M hab)	Density (hab/km2)	Average distance (km)	Transport cost (EUR/ton)
City of Antwerp	0.53	2600	5	1.2
Flanders	6.6	483	40	9.5
Benelux	29	394	93	22.1
West Europe	196	177	361	85.6
Europe	746	34	1607	381

Mechanical recycling cost (c_{r1}) and thermochemical recycling cost (c_{r2})

The costs of mechanical recycling for different recycled plastic levels $c_{r1}(\beta_1)$ and for thermochemical recycling for different recycled naphtha levels $c_{r2}(\beta_2)$ are decreasing power functions. The functions are a result of the combination of TEA for mechanical recycling plants ((Larrain et al., 2021) and for thermochemical recycling plants (Larrain et al., 2020) and the total amount of plastic packaging waste placed in the market (Environment, 2018). Equation A.22 represents the cost function for mechanical recycling and Equation A.23 the cost function for thermochemical recycling. In both cases c_{r1}^0 and c_{r2}^0 is the unitary costs for plant that recycle 100% of the PE films placed in a market and $s1$ and $s2$ are cost scale factors that represent the increased cost for plants of smaller capacities.

Equation A.22: Mechanical recycling cost functions

$$c_{r1}(\beta_1) = c_{r1}^0 * \beta_1^{s1}$$

Equation A.23: Thermochemical recycling cost function

$$c_{r2}(\beta_2) = c_{r2}^0 * \beta_2^{s2}$$

Production costs (c_p and c_m)

The packaging production cost (c_p) are calculated considering that the operating margin of packaging industry for PET was 10.3% (McKinsey and Company, 2019). The operating margin is calculated as the difference of the revenues with all the cost, divided by the revenues. The production cost for PE is then assumed to be proportional to production cost of PET according to their virgin price levels.

The plastic production cost (c_m) is calculated by assuming that the profit margin of the plastic producer is 10%.

Appendix II: Results

Prices in the equilibrium

Figure A.2 show the prices for the different materials in the equilibrium points of the policy scenarios. We can observe that in the reference scenario, the naphtha tax scenario and packaging tax scenario the prices for recycled plastics (P_{r1}) and recycled naphtha (P_{r2}) are negative. There are two main reasons for this. First, the recycling system is mainly funded by the sorted waste that has a negative price $\left(P_f\right)$. This means that recyclers will actually be paid for recycling the sorted plastic waste. The second one is related to the price of waxes (P_{r3}) that is mostly determined outside the circular plastic packaging value chain. The price for recycled waxes is always positive because the amount of waxes that are produced with thermochemical recycling are a small fraction of the total wax market. Hence, the revenues from thermochemical recycling come only from the waxes and P_{r2} is negative. This lowers the prices for sorted waste price $\left(P_f\right)$ and also pushes down the prices for recycled plastics (P_{r1}**).**

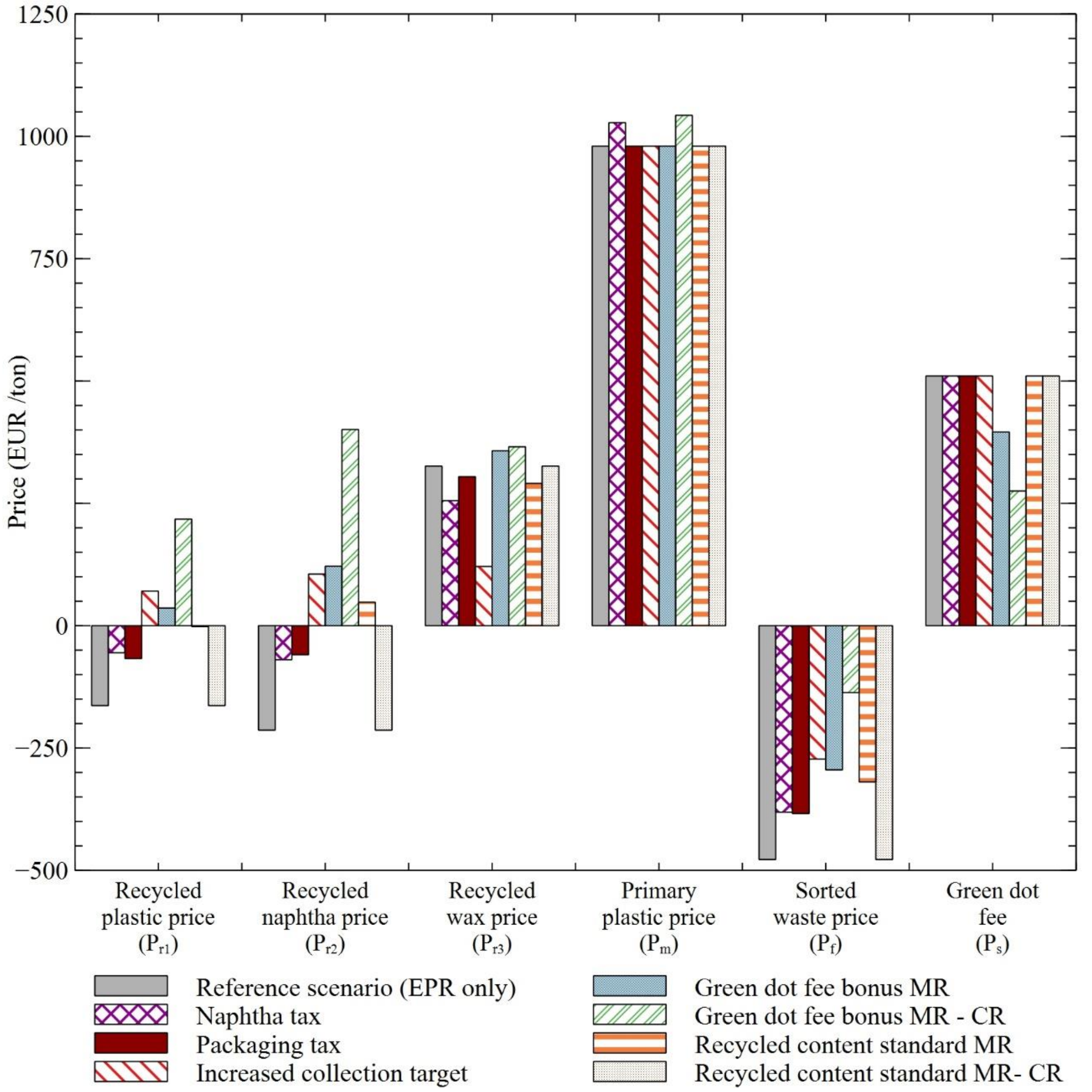


Figure A.2: Prices for material in the equilibrium points of the policy scenarios in median oil and energy price levels

Contrarily, in the increased collection target scenario the amount of waxes produced is higher, an therefore the price for waxes (P_{r3}) decreases. In this case, the price of recycled naphtha (P_{r2}) has to be positive, as well as the price for sorted waste price $\left(P_f\right)$ and the price for recycled plastics (P_{r1}) .

In the scenario where there is a bonus applied to the green dot fee the prices for recycled plastic (P_{r1}) and recycled naphtha (P_{r2}) are positive. This is because the feedstock price $\left(P_f\right)$ is higher (less negative) in order to make the operation of the PRO feasible since the income coming from the green dot fee is lower due to the discount applied to it.

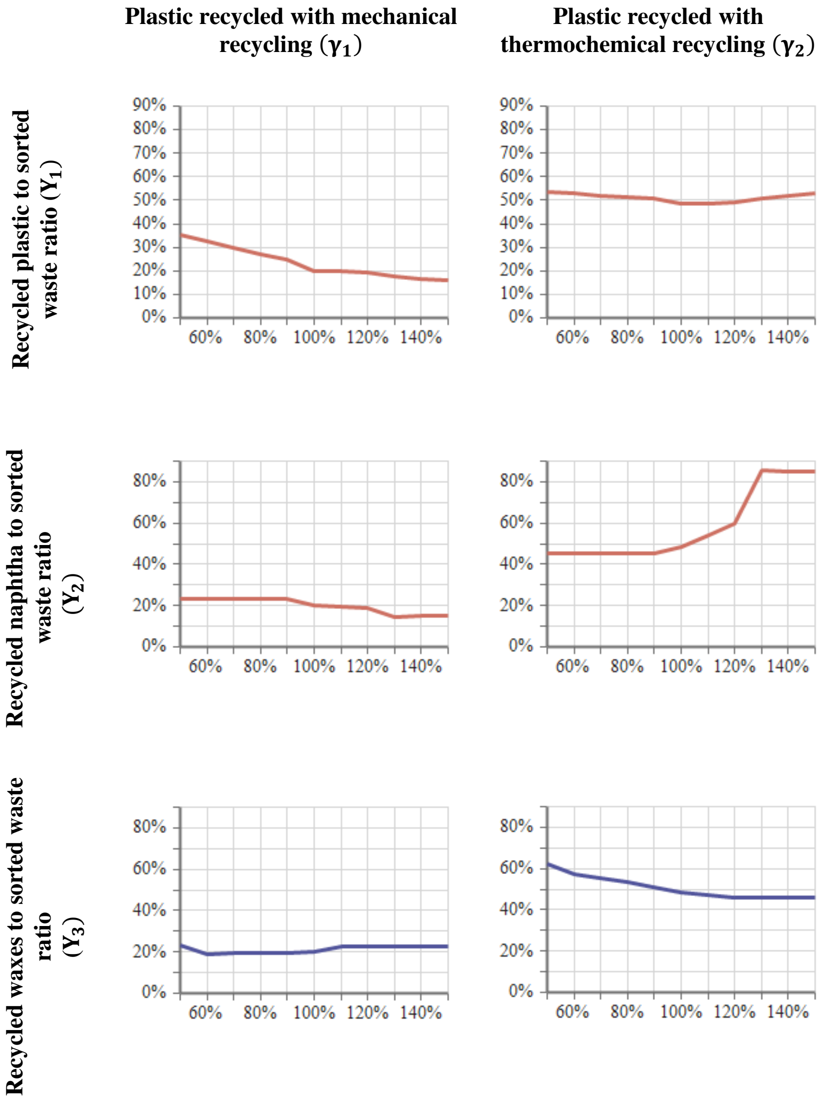
Finally, in the recycled content standard MR scenario the recycled plastic price is close to zero and the recycled naphtha price (P_{r2}) is positive but has a low value. This can be explained by a decrease in the feedstock price $\left(P_f\right)$ and the recycling costs (c_{r1}), owing to economies of scale. The recycled naphtha price remains positive, but lower because the effect of the price of waxes is higher than the increased cost due to a lower recycling quantity.

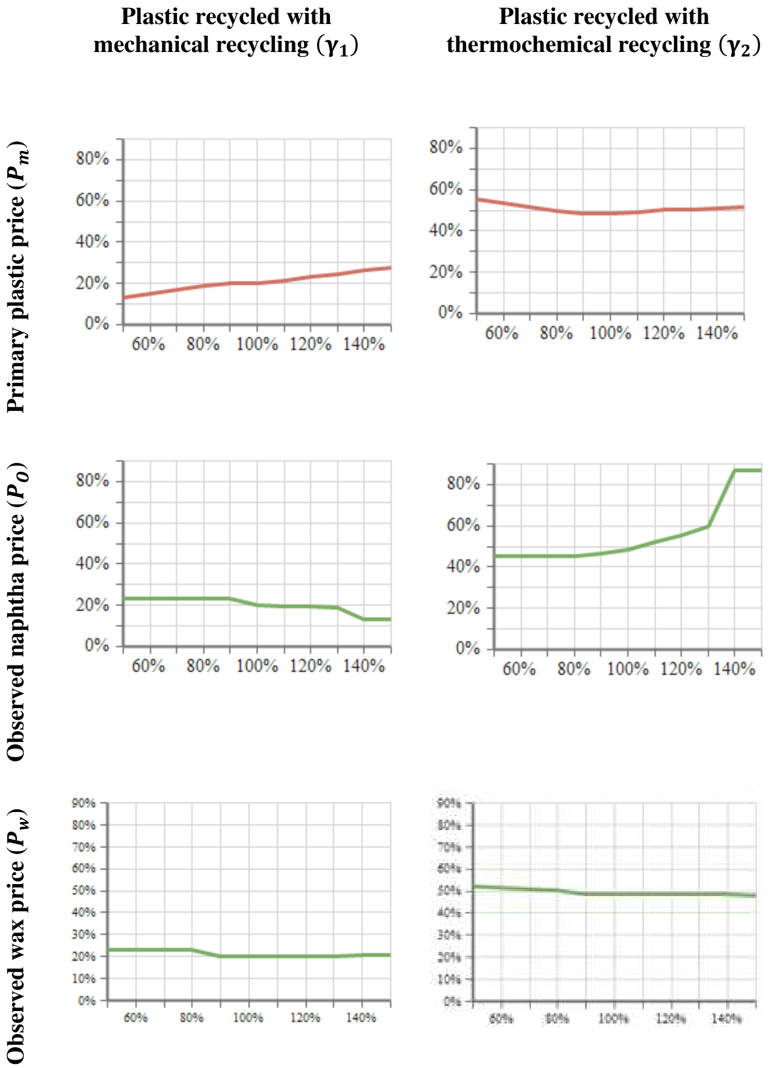
Processing costs in the equilibrium

Table A.3: Processing cost in the different scenarios (values in EUR/tonne)

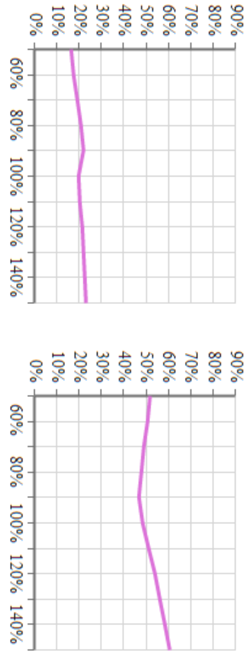
	Collection, transport and sorting cost (c_s)			**Mechanical recycling cost (c_{r1})**			**Chemical recycling cost (c_{r2})**			**Total cost (c_{tot})**		
Policy Scenario/ Oil price scenario	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Reference scenario (EPR only)	265	265	265	345	334	424	431	441	461	478	505	599
Naphtha tax	265	265	268	339	330	430	441	416	447	480	542	607
Packaging tax	265	264	268	329	320	400	465	442	475	483	545	614
Increased collection target	280	280	280	354	340	436	355	374	420	577	587	639
Green dot fee bonus MR	265	265	265	338	328	409	444	467	481	481	497	597
Green dot fee bonus MR-CR	265	265	265	342	330	413	476	474	557	443	486	543
Recycled content standard MR	265	265	269	313	316	392	505	450	481	504	553	620
Recycled content standard MR-CR	265	265	265	345	334	424	431	441	461	478	505	599

Appendix III: Sensitivity Analysis for all variables

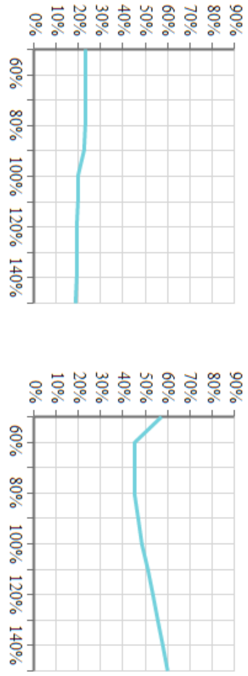




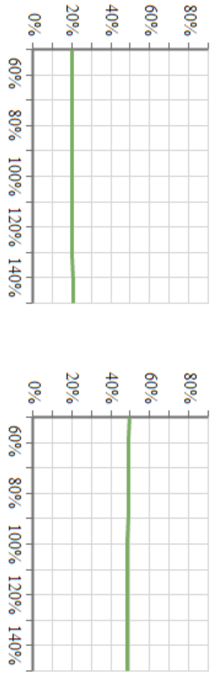
Green dot fee (P_s)



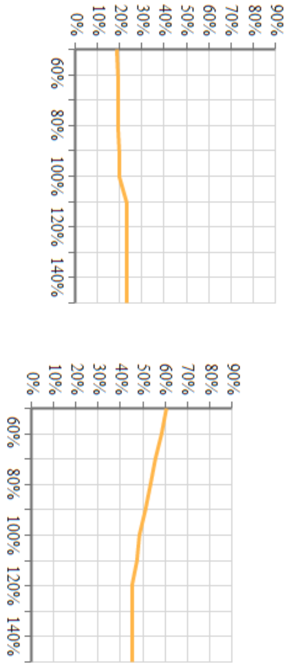
Price elasticity of demand for waxes (η)



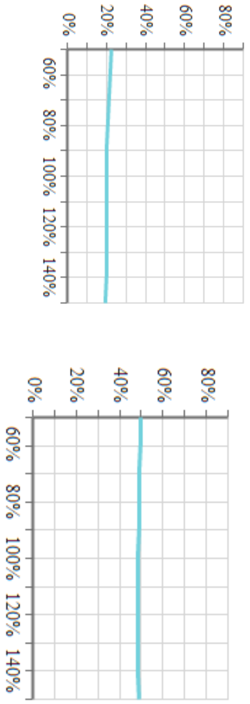
Final disposal fee (P_d)



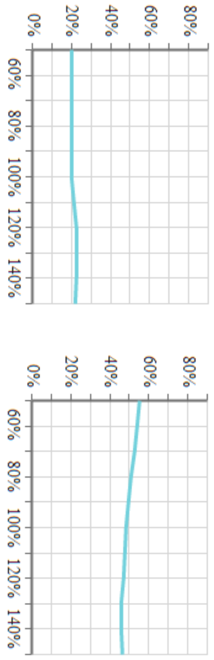
Chemical recycling unitary costs (c_{r2})



Mechanical recycling unitary costs (c_{r1})



Sorting unitary cost (c_{s3})



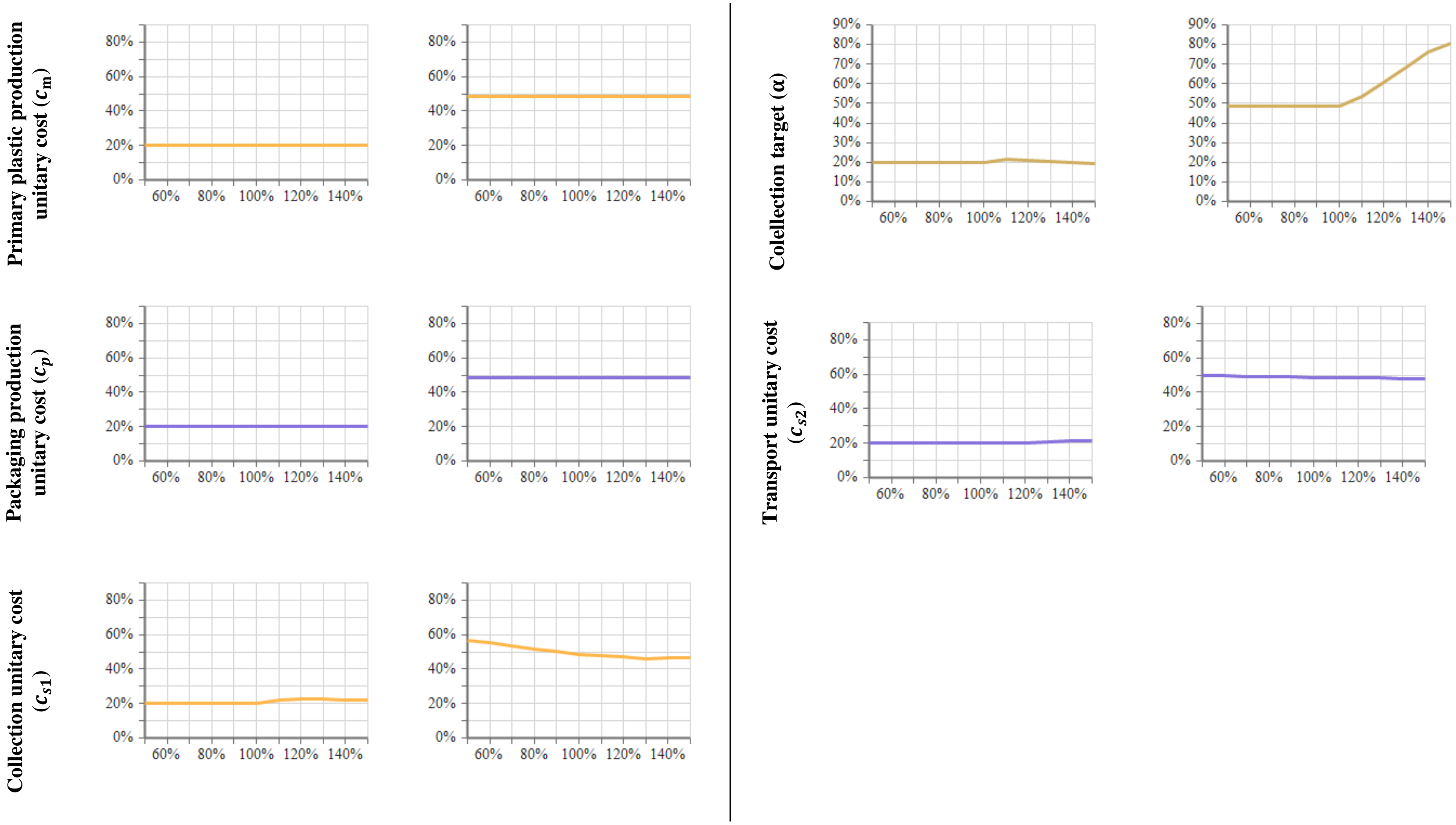


Figure A.4: Sensitivity analysis for the equilibrium model