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## Realizing the value of recycling - Assessing the elements of a policy package

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# Realizing the value of recycling – assessing the elements of a policy package\*

Xi Sun<sup>†</sup>      Karsten Neuhoff<sup>†</sup>

## Abstract

We investigate policies for increasing recycling to facilitate decarbonization within the basic material sector, including market-based policies, such as carbon pricing, advanced disposal fee and minimum recycled content requirement, and non-market policies, such as product design standard. We develop an analytical model to assess the role of these policy instruments for recycling related choices of manufacturing industry, consumers, and waste management. We find that individual policy instruments can deliver some benefits in terms of emission reductions and welfare improvements, but that a package of policy instruments is necessary to reach the welfare maximum and effective scale of emission reductions and resource saving.

**Keywords:** industry decarbonization, market failure, high-quality recycling, policy package

**JEL classification:** D62, H23, Q53,54

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# 1 Introduction

Approximately one-third of global greenhouse gas emissions today stem from fuel combustion, electricity use, and industrial processing that are linked to manufacturing primary materials (IEA, 2021). Shifting to recycled materials can significantly reduce these emissions. For instance, producing one ton of primary plastics generates 5.1 tonnes of CO<sub>2</sub> equivalent. Cutting-edge mechanical recycling technologies that produce high-quality plastics, in contrast, emits 0.1 tonnes of CO<sub>2</sub>e (Material Economics, 2018).

This paper establishes an analytical model to explore the policy instruments that improve material recycling to socially efficient levels. We model the decision-making of three representative actors: a producer of consumer product deciding on product recyclability and material types as input, a consumer selecting the final product, and a waste manager recovering valuable materials from end-of-life products. The interactions among these actors in markets yield equilibrium levels for total material consumption, recycling, and product design.

This model considers the market failures contributing to inefficient material use and recycling. First, the producer of consumer product fails to take into account material recovery when choosing product design. This increases the cost of downstream recycling (Milios et al., 2018; Nicolli et al., 2012; Calcott and Walls, 2005; Fullerton and Wu, 1998). Second, consumers tend to over-consume as long as the social cost of waste is not brought to their attention when they are making purchase decisions (Taylor and Thompson, 1982; Fullerton and Kinnaman, 1995; Walls and Palmer, 2001; Briguglio, 2021). Third, greenhouse gases are not factored in the prices of raw materials, weakening the economic competitiveness of recycling against primary production and linear waste disposal (Kinnaman, 2006; Acuff and Kaffine, 2013).

Numerous regulations have been either adopted or proposed to address one or multiple of the market failures. First, carbon pricing can strengthen the price competitiveness of recycled materials to the extent of their emission-saving potentials. Today, 17% of global GHG emissions are covered by 28 emission trading systems (ICAP, 2023). Although industrial emissions are covered in the ETS jurisdictions to various extent, most manufacturing plants continue to receive free allowances due to concerns about carbon leakage.<sup>1</sup> Meanwhile, end-of-life emissions from the waste disposal sector remain exempted in most ETS jurisdictions,<sup>2</sup> with only a few countries imposed a waste

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<sup>1</sup>For instance, the EU ETS extended the benchmark-based free allocation of emission allowances for most industrial material manufacturers to 2030. See: Commission Delegated Decision (EU) 2019/708 concerning the determination of sectors and sub-sectors deemed at risk of carbon leakage for the period 2021 to 2030.

<sup>2</sup>In Europe, incineration emissions from municipal and hazardous waste remain exempted from the EU

incineration tax or included the emissions in a national ETS.<sup>3</sup>

Second, various waste policies have sought to internalize the social cost of waste disposal to influence household behavior regarding waste generation and separation. This cost can be transferred to the consumer through increased product price – an added cost commonly referred to as Advanced Disposal Fee (ADF) (OECD, 2016; Palmer et al., 1997; Acuff and Kaffine, 2013), waste fees, or taxes, depending on the entities that bear the responsibilities for waste collection and disposal.<sup>4</sup>

Third, there is a growing emphasis on product design standards, negotiated for example between recyclers and producers.<sup>5</sup> Despite the theoretical advantages of price-based policies, such as a deposit-refund system (a combination of product tax and recycling subsidy) or a take-back scheme in incentivizing producers to improve product recyclability or durability (Fullerton and Wu, 1998; Calcott and Walls, 2005; Eichner and Pethig, 2001; Runkel, 2003), there is limited empirical evidence that these policies have led to material substitution or improved product recyclability (Joltreau, 2022). In this paper, we relax the need for an implicit market for product design.

Fourth, we use this model to analyze product recycled content requirements – a market policy that doesn’t specifically target externalities but can have a positive impact on the efficiency of both material and product markets. Our analysis explains the excess cost of recycling at market equilibrium and the extent to which this cost can be shifted to consumers.

A numerical simulation with data from the European polyethylene terephthalate (PET) market is applied to illustrate the effect of the four types of policy instruments. In particular, we find that carbon pricing for material manufacturing alone contributes to a reduction in CO<sub>2</sub> emissions by 28% and an extension to waste incineration contributes another 1%. In contrast, enforcing a minimum product recycled content requirement of 51% could drastically reduce total emissions by 50%. The model also shows, combining individual policy instruments of life-cycle carbon pricing, ADF and product standard is able to restore the social optimal solution, which marks a 56% reduction in total emissions.

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ETS, according to Directive 2003/87/EC of the European Parliament and of the Council on establishing a system for greenhouse gas emission allowance trading within the Union.

<sup>3</sup>For instance, Germany opted out incineration emissions from the EU ETS but included them into the national ETS (BEHG) starting in 2024, with an initial price of €25/tCO<sub>2</sub>e.

<sup>4</sup>For instance, the German Packaging Law mandates that dual systems, which are legal entities or partnerships responsible for manufacturers’ product stewardship, must collect all empty packaging from private end-users free of charge. See: Verpackungsgesetz §14.

<sup>5</sup>For example, under the new German Packaging Law, a minimum standard for packaging recyclability is annually published through joint effort from the German Central Registration Center for Packaging (ZSVR) and the German Environment Agency (UBA).

In addition, the welfare allocated among the consumer, the recycler and the government varies under different policies. Both carbon pricing and recycled content policies lead to a significant reduction in consumer surplus. On the other hand, these policies also strengthen the recycling businesses. A recycled content requirement alone leads to a notable increase of recycler surplus by 1.13 billion euros. Strengthened price competitiveness of recycled material, improved product recyclability and avoided over-consumption leads to a reduction of the average material cost per unit up to 7.7%.

This paper is structured in the following way. The second section reviews previous theoretical modeling of product design and waste disposal externalities, and explains how our model differs. In the third section, we analytically characterize the economic incentives of three representative actors. On this basis, we derive the social optimum solutions and the theoretical effects of different policy instruments. The fourth section presents the simulation results of a numerical example on the PET polymer market in the EU and the distributive consequences of different policy scenarios. The last section concludes.

## 2 Literature review

A variety of literature investigated the reasons for low recycling rates. This paper aligns with the tradition of theoretical modeling to analyze the policies required to restore the market actors' incentives to achieve socially optimal levels of raw material recycling (Fullerton and Kinnaman, 1995; Palmer et al., 1997; Fullerton and Wu, 1998; Eichner and Pethig, 2001; Walls and Palmer, 2001; Calcott and Walls, 2005; Acuff and Kaffine, 2013).

One key distinction of the model in this paper compared to previous studies is that we do not assume the existence of an implicit market for product design. This implicit market, for example, has been described in Eichner and Pethig (2001) as an indirect market for material content where they interpret product design as a quantitative mass share of useful materials. In Fullerton and Wu (1998), the authors reveal a 'demand schedule' for product recyclability, a product design factor that characterizes higher recycling productivity and less garbage generation. Both of these papers assume a perfectly functioning market at the end of product life, which provides a price signal for the producers' choice of product design. In particular, Fullerton and Wu (1998) assumes the sales revenue of recycled material enters household budget, hence directly signaling the household's demand for product recyclability to the firm. Eichner and Pethig (2001) inserts "a particular

arrangement of property rights” under which the consumer is obliged to hand over all used product to the recycler at the market price, which is partially determined by the recycling productivity. In contrast to these two papers, Calcott and Walls (2005) explicitly models the consequence if this waste market is missing due to high transaction cost. When the value consumers gain from selling their used products to recyclers cannot cover their transaction costs, they may opt to dispose of them in a curbside recycling bin for free. In the latter situation, producers will not be rewarded for increasing the recyclability of their products. Consequently, they will choose the minimum level of product recyclability instead. Furthermore, in the absence of a market for used products, recycling costs cannot be communicated to the producers. In such a scenario, producers incur a unit material cost equal to the price of primary materials, whereas in a socially optimal circular economy solution, the unit material cost should reflect the marginal recycling cost. In this paper, we follow Calcott and Walls (2005) to assume a missing market for used products. However, instead of transaction cost, the rationale for this assumption stems from waste management practices for post-consumer waste that the waste fee charged by a waste manager does not necessarily reflect the retained value from waste.

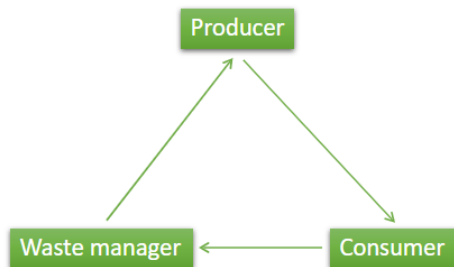
The assumption of incomplete waste markets also allows us to reexamine to what extent a Pigovian pricing policy alone can influence the incentives of different actors along a circular value chain. Previous theoretical analyses agree on a first-best Pigouvian tax at the point of garbage collection to internalize the social cost of waste treatment that has been ignored by consumers (Fullerton and Kinnaman, 1995; Walls and Palmer, 2001). If this policy stimulates unwanted consequence of illicit burning, a first-best policy substitute is to charge a consumption tax (an ADF) and refund for alternative waste treatment methods (Fullerton and Kinnaman, 1995). In case of externalities from both waste treatment and upstream manufacturing, an alternative to a Pigovian policy on each source of externality is a policy combination that subsidizes the environment-neutral input such as labor while taxing the material input that generates the externality (Walls and Palmer, 2001). In contrast to these studies, our model explains the need for an ADF even in the presence of a Pigovian policy on both material manufacturing and waste treatment emissions. While such a policy influences the choices of inputs by producers of consumer product and waste treatment methods by waste managers, it fails to reveal the cost of waste treatment to consumers. The implementation of an ADF on product consumption results in a source reduction of both costs and emissions associated with material manufacturing and waste disposal, consistent with the findings of Palmer et al. (1997) and Acuff and Kaffine (2013).



## 3 Model

### 3.1 Modeling actor incentives

This model characterizes the incentives of three representative actors: a producer of consumer product, a consumer and a waste manager (see Figure 1). The producer of consumer product chooses product design and procures primary or recycled materials from the material market. The consumer purchases the product and benefits from its functionality. After use, the waste manager obtains the end-of-life product at a price and recovers materials from it. These actors interact with each other to form a system in which the material flow at the steady state will be prescribed by market equilibrium in three markets: the waste market, the (recycled) material market, and the consumer product market.



**Figure 1:** A model of three actors.

Recognizing the challenges in obtaining waste of sufficient volume and quality, we acknowledge that the material loop is not completely closed. As a result, some of the end-of-life products will undergo an alternative treatment method: waste incineration. The incineration of waste leads to a loss of materials, necessitating the introduction of primary materials into the system. In a long-term steady state, the mass of primary material entering the system equals the mass of unrecyclable mixed waste disposed in the incineration plant. We assume a constant unit cost of manufacturing, denoted as  $c_v$ , for the exogenous supply of primary materials. Similarly, we assume an exogenous incineration of mixed waste at a constant unit cost, represented as  $c_i$ .

We now characterize the decision-making of each actor. First, we combine the roles of a municipality and a waste management company who usually contracts with municipalities to deliver their waste collection and treatment obligations. To offer waste collection and disposal services, the waste manager assesses a shadow price, denoted as  $P_w$ , which is either financed by the public sector or charged on the households as waste disposal fee. The price of recycled materials

is represented as  $P_r$ , while unrecycled waste will be directed for incineration at the unit cost of  $c_i$ . The profit maximization problem for this waste manager can be formally described as follows:

$$\max_{r,w} \pi_w = P_w \cdot w + P_r \cdot r - k(r, \rho) - c_i \cdot (w - r). \quad (1)$$

$k(r, \rho)$  is the recycling cost function, which is convex in the quantity of output:  $k_r > 0$  and  $k_{rr} > 0$ , to allow for diminishing marginal productivity of the material input given fixed recycling facility or labor scarcity. Symbol  $\rho$  stands for the recyclability of a product, a factor of product design that relaxes the cost of recycling at both aggregate term  $k_\rho < 0$  and marginal term  $k_{r\rho} < 0$ . The negative cross partial derivative of the recycling cost function follows from the observation that a badly designed product can “pollute” other well-designed end-of-life products, hence causing higher cost to recover one additional unit of the useful material.

The producer determines the level of recyclability  $\rho$  of the product subject to a one-off design cost  $\alpha(\rho)$ , with  $\alpha'(\rho) > 0$ . This cost escalates with the challenges in reconciling product recyclability and other characteristics, leading to the assumption of cost nonconcavity,  $\alpha''(\rho) \geq 0$ . Meanwhile, the producer of consumer product is also a buyer on the material market. We assume that recycled material is a perfect substitute for its primary counterpart. Assuming that both materials and the product production are measured in weight, we adopt the mass balance condition:  $x = r + v$ , from which the producer’s profit maximization problem can be characterized as:

$$\max_{x,r,\rho} \pi_x = P_x \cdot x - P_r \cdot r - c_v \cdot (x - r) - \alpha(\rho). \quad (2)$$

Finally, the consumer seeks to maximize utility derived from the functionalities of the consumer product  $x$ . The budget constraint comprises disposal income ( $DI$ ), with deductions for payments related to the waste services. These waste payments are conveyed to the consumer through either a direct waste disposal fee or an indirect taxation system. It is important to note that the consumer only chooses  $x$ , whereas the amount of  $w$  is an outcome of the mass balance condition:  $w = x$ . The consumer utility maximization problem can be defined as follows:

$$\max_x u(x), \quad s.t. \quad P_x \cdot x \leq DI - P_w \cdot w. \quad (3)$$

## 3.2 Data

We will use a numerical simulation to illustrate our analysis on material consumption and recycling. We choose to focus on the European polyethylene terephthalate (PET) market for two main reasons. First, the EU PET market is relatively stable, making it suitable for steady-state scenario analysis. Second, the quality of PET recyclate is comparable to the quality of primary polymer, and an efficient collection system already exists in the EU for PET-based products like beverage bottles, leading to a nearly closed recycling loop.

The value of the global plastics market in 2022 is estimated to be 615 billion US dollars, with a compound annual growth rate (CAGR) of 3.7%.<sup>6</sup> We assume the share of plastic demand in EU remains stable at 13%,<sup>7</sup> of which the PET alone takes a stable share of 8.4%.<sup>8</sup> As a result, we adopt the assumption on the market value of PET alone in EU to be about 6.7 billion Euros. The 2022 estimate for PET production in quantity is 4.45 million tons (Mt), an increase of about 7.5% compared to 2020 production levels.<sup>9</sup> The prices for both primary and recycled PET polymer have experienced significant fluctuations in recent years. However, for the purpose of our analysis, we will use an assumed average PET price of 1500 euros/ton in 2022.<sup>10</sup>

Based on these observations, we assume a linear demand function. We also take up stylized functional specifications for recycling cost and product design cost (see Appendix A). In addition, we assume an exogenous gate fee for incineration plant at 180 euros/ton, which is the average price in North Germany.<sup>11</sup> The emission factors for primary production, recycling process, and waste incineration are, respectively, 2.696, 0.273, and 1 ton of  $CO_2$  equivalent for each ton of material manufacturing or waste incineration with energy recovery (Dormer et al., 2013). The social cost of carbon (SCC) is assumed to take the value of 100 euro per ton of  $CO_2$  equivalent.

## 3.3 Social optimum

Now, we account for the greenhouse gas emissions that stem from economic activities and derive the social optimum solutions for total material use and recycling. We simply assume a unit emission factor,  $e_1$ , associated with the production of one ton of primary material and a discounted emission

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<sup>6</sup>See Statista (2022).

<sup>7</sup>See PlasticsEurope (2021), total plastic demand in the EU27+3 was 49.1 Mt in 2020, taking 13% of the world total production of 367 Mt.

<sup>8</sup>We assume the exchange rate between USD and EUR in 2022 at 1:1.

<sup>9</sup>See PlasticsEurope (2022).

<sup>10</sup>This assumption is similar to the realized market prices in 2022. See: PET crystal clear price.

<sup>11</sup>See EUWID Market report on gate fees for waste incineration and MBT Germany, December 2019.

factor of  $\sigma e_1$  for its recycled counterpart, with  $\sigma < 1$ . The incineration of one-ton residual waste is assumed to emit  $e_2$  tonnes of  $CO_2e$ . For each tonne of emission, we adopt a unit estimate of the social cost of carbon, denoted as  $SCC$ , and provide a sensitivity check for different estimates of this cost in the simulation section.

Combining equations (1) – (3) with the social cost of carbon, we obtain the social objective function as follows:

*Objective Function :*

$$u(x) - \alpha(\rho) - k(r, \rho) - c_v \cdot (x - r) - c_i \cdot (w - r) - SCC \cdot (e_1 \cdot (x - r) + \sigma e_1 \cdot r + e_2 \cdot (w - r)) \quad (4)$$

Adopting the mass balance condition between consumption  $x$  and waste generation  $w$ , the social optimal outcome is defined by three variables: consumption level  $x$ , recycling level  $r$ , and product recyclability level by design  $\rho$ :

$$\begin{aligned} x^{opt} : \quad & u'(x^{opt}) = c_v + c_i + SCC \cdot (e_1 + e_2) \\ r^{opt} : \quad & c_v + c_i = k_r(r^{opt}, \rho^{opt}) + SCC \cdot (-e_1 + \sigma e_1 - e_2) \\ \rho^{opt} : \quad & -\alpha'(\rho^{opt}) = k_\rho(r^{opt}, \rho^{opt}). \end{aligned} \quad (5)$$

By employing the numerical simulation to characterize the social optimal solution, we find an optimal PET consumption level of 2.85 million ton (Mt), composed of an amount of recycled material of 1.44 Mt and primary material of 1.41 Mt, or a socially optimal recycled content ratio of by 51%. The socially optimal level of product design factor is 14.4. Overall, the total  $CO_2$  emission amounts to 5.59 million tonnes of  $CO_2$  equivalent (Mt  $CO_2e$ ).

Variable	Value
Total PET Consumption	2.85 Mt
Primary PET Production and Use	1.41 Mt
Recycled PET	1.44 Mt
Total $CO_2$ Emission	5.59 Mt $CO_2e$
Product Design Factor	14.4

**Table 1:** Social optimum outcomes

## 4 Market equilibrium under different policy scenarios

### 4.1 Market equilibrium without intervention and market failures

Maximizing consumer utility and the profitability of the producer and the waste manager that are prescribed in (1) – (3), we obtain the market levels for total material consumption, recycling and product design:

$$\begin{aligned}
 x^{me} : \quad & u'(x^{me}) = c_v \\
 r^{me} : \quad & c_v + c_i = k_r(r^{me}, \rho^{me}) \\
 \rho^{me} : \quad & -\alpha'(\rho^{me}) = 0.
 \end{aligned} \tag{6}$$

Using the data above, we calculate the values for these variables that are summarized in the table below. In a baseline scenario without any policy intervention, the total PET consumption is estimated at 4.50 Mt, comprising 3.38 Mt of primary PET and 1.12 Mt of recycled PET. In this scenario, the total CO<sub>2</sub> emissions peak at 12.8 Mt CO<sub>2</sub>e.

Variable	Value
Total PET Consumption	4.50 Mt
Primary PET Production and Use	3.38 Mt
Recycled PET	1.12 Mt
Total CO <sub>2</sub> Emission	12.8 MtCO <sub>2</sub> e
Product Design Factor	0.0

**Table 2:** Market equilibrium outcomes without intervention

Three types of market failures can be concluded from comparing equations (5) and (6). First, a comparison between  $x^{opt}$  and  $x^{me}$  indicates that the waste treatment costs are external to the consumption decisions of consumers. The constant cost of waste incineration  $c_i$  is missing from the market optimizing equation of  $x^{me}$ , compared with the social optimum solution for  $x^{opt}$ . This market failure leads to an inefficiently high consumption of total materials.

Second, a combined comparison between  $x^{opt}$  and  $x^{me}$  as well as  $r^{opt}$  and  $r^{me}$  proves that the environmental externalities associated with material manufacturing and waste disposal are overlooked by all actors. Under an ideal condition for  $r^{opt}$ , the marginal recycling cost is traded off with not only the marginal cost of primary manufacturing and the marginal cost of incineration, but also the net savings of emissions multiplied with the social cost of carbon. The internalization of this latter benefit would motivate the waste manager to recover more useful materials from waste

and the producer of consumer product to procure more recycled material at a higher material price for both types of materials. This internalized cost would eventually be transferred to the consumer, as described in  $x^{opt}$ .

Third, a comparison between  $\rho^{opt}$  and  $\rho^{me}$  clearly demonstrates that the producer of consumer product is not economically compensated for choosing better product recyclability under the free market condition. Owing to cost nonconcavity for product design, the producer consequently tends to opt for the minimum level of product recyclability. In contrast, a social planner directly internalizes the recycling cost savings from a marginal increase of product recyclability,  $k_\rho$ . This cost saving is then balanced with the marginal product design cost to derive the social optimum solution for product design.

## 4.2 Advanced disposal fee

As mentioned previously, a straightforward policy instrument to address this market failure is an advanced disposal fee (ADF), which can be charged on each unit of the consumer product to internalize the cost of waste disposal into the consumption decision:

$$ADF = c_i.$$

After internalizing waste cost to the price signal, we obtain the following market equilibrium solutions:

$$\begin{aligned} x^{adf} : & \quad u'(x^{adf}) = c_v + ADF \\ r^{adf} : & \quad c_v + c_i = k_r(r^{adf}, \rho^{adf}) \\ \rho^{adf} : & \quad -\alpha'(\rho^{adf}) = 0 \end{aligned} \tag{7}$$

This result implies that charging an ADF only influences the level of consumption, while creating no additional incentive for recycling (Palmer et al., 1997; Acuff and Kaffine, 2013). Without any intervention on the cost competitiveness of recycling against waste incineration and primary manufacturing, all residual wastes that cannot be cost-efficiently recycled will end up in incineration plants. Hence, adopting an ADF alone does not change the market equilibrium solution for recycled material:  $r^{adf} = r^{me}$ .

In the absence of carbon cost internalization, the ADF is equivalent to the waste fee established

for each unit of waste disposed, calculated at the constant unit cost of the alternative waste treatment method. With a unit fee of 180 euros per ton, the overall material consumption decreases to 3.96 Mt. The use of primary material decreases accordingly to 2.84 Mt, while the amount of recycled material remains the same as the market solution without intervention.

Variable	Value
Total PET Consumption	3.96 Mt
Primary PET Production and Use	2.84 Mt
Recycled PET	1.12 Mt
Total CO <sub>2</sub> Emission	10.80 MtCO <sub>2</sub> e
Product Design Factor	0.0

**Table 3:** Market outcomes with ADF

### 4.3 Carbon pricing

Next we assume the existence of a Pigouvian policy that fully internalizes the social cost of carbon into each economic activity. The social cost of emissions associated with a recycling process can either be paid by the waste manager who conducts this process or the manufacturer who demands the output of it. We assume the consumer product manufacturer is obliged to pay this carbon price for the emissions from a manufacturing process, including both recycling and primary production, while noting that under perfect competition, the same result will be obtained if this carbon price were levied on the material suppliers. Similarly, we assume the waste manager, who collects all used products and sends unrecycled wastes for incineration, pays the social cost of incineration emissions in addition to the exogenous incineration gate fee. By assuming the carbon price  $t$  equal to social cost of carbon SCC, we obtain the market equilibrium levels of the three choice variables:

$$\begin{aligned}
 x^{cp} : \quad & u'(x^{cp}) = c_v + t \cdot e_1 \\
 r^{cp} : \quad & c_v + c_i + te_1(1 - \sigma) + te_2 = k_r(r^{cp}, \rho^{cp}) \\
 \rho^{cp} : \quad & -\alpha'(\rho^{cp}) = 0.
 \end{aligned} \tag{8}$$

If the emissions from waste disposal are not covered in this carbon pricing policy, we will again obtain a lower level of recycled material, as a recycling plant does not earn additional cost competitiveness against an incineration counterpart. Given this limited scope of carbon pricing, the levels

of total consumption and material recycling are subject to:

$$\begin{aligned}
 x^{lp} : \quad & u'(x^{lp}) = c_v + t \cdot e_1 \\
 r^{lp} : \quad & c_v + c_i + te_1(1 - \sigma) = k_r(r^{lp}, \rho^{lp}) \\
 \rho^{lp} : \quad & -\alpha'(\rho^{lp}) = 0.
 \end{aligned} \tag{9}$$

The implementation of a carbon pricing policy for material manufacturing elevates material prices, with varying degrees of emission intensity, resulting in a reduction of total material consumption to 3.69 Mt, with primary material decreasing to 2.41 Mt, and recycled material increasing to 1.28 Mt. Expanding the carbon pricing policy to encompass end-of-life emissions enhances the competitiveness of recycling in comparison to the more emission-intensive waste incineration treatment. As a result, the quantity of recycled material further increases to 1.35 Mt, while primary material diminishes to 2.34 Mt. The overall material consumption remains unchanged from the scenario with carbon pricing solely on material manufacturing, owing to the baseline assumption that consumers do not pay a unit waste fee.

Variable	Value (lp)	Value (cp)
Total PET Consumption	3.69 Mt	3.69 Mt
Primary PET Production and Use	2.41 Mt	2.34 Mt
Recycled PET	1.28 Mt	1.35 Mt
Total CO <sub>2</sub> Emission	9.26 MtCO <sub>2</sub> e	9.03 MtCO <sub>2</sub> e
Product Design Factor	0.0	0.0

**Table 4:** Market outcomes with carbon pricing

## 4.4 Product standard

The producer opts for the lowest level of product recyclability because the mechanism to incentivize a greater investment in product design costs is absent. Comparing Equations (7)–(9) with Equation (6), we can see that a pricing policy on waste management or carbon emissions has no influence on the producer’s choice of product design. Due to the low level of product recyclability, the marginal cost to recover useful materials will be also higher than in the social optimum scenario, even when carbon costs are fully internalized (see Appendix B for a proof of the monotonicity of recycling with respect to product recyclability).

Several policy instruments have been considered to restore the socially optimal level of product design, including product standards, product design subsidies, and extended producer responsibil-



ity. In practice, such first-best policies require the policymaker to hold perfect information not only about the recycling cost savings from each degree of product design improvement, but also the product design choice of each producer, the product’s share in market, and its influence on the average recyclability of this product group.

We consider a second-best alternative, which is to impose a minimum recyclability standard for products to rule out poorly designed products that depreciate the value of recycling output (Calcott and Walls, 2005). The information needed for this policy is considerably less stringent.

Enforcing a minimum standard for product recyclability effectively reduces recycling cost, resulting our model in a notable increase in the quantity of recycled material to 1.22 Mt, a level surpassing that achieved under a life-cycle carbon pricing policy. In this scenario, total consumption remains the same as in the baseline scenario without any policy intervention, since the one-off cost for product design is assumed not to be passed to the consumer in our model.

Variable	Value
Total PET Consumption	4.50 Mt
Primary PET Production and Use	3.28 Mt
Recycled PET	1.22 Mt
Total CO <sub>2</sub> Emission	12.47 MtCO <sub>2</sub> e
Product Design Factor	14.4

**Table 5:** Market outcomes with product standard

## 4.5 Minimum recycled content requirement

A policy targeting material recycling rate can be implemented in two ways: as a fraction of material input purchased from a recycler or a recycled material dealer – a minimum recycled content requirement, or as a fraction of waste sent for sorting and recycling rather than incineration or landfill – a minimum recycling rate requirement. In this section, we only analyze the effect of the former, while leaving a similar analysis on the minimum recycling rate requirement in Appendix D. As long as the waste fee is factored in to influence consumer consumption decisions, these two policies have in our model the same effect.

Assume a regulatory requirement on the minimum recycled content of total material input is imposed on the product producer:  $\frac{r}{x} \geq \bar{\theta}$ . The profit-maximization problem of the producer now becomes a constrained optimization problem:

$$\max_{x, r, \rho} \pi_x = P_x \cdot x - P_r \cdot r - c_v \cdot (x - r) - \alpha(\rho), \text{ s.t. } \frac{r}{x} \geq \bar{\theta}.$$

If this regulation is binding, meaning that the mandated recycled portion of the material input is equal to or greater than what would occur without the requirement, the three-choice-variable problem will simplify to a two-choice-variable problem:

$$\max_{x, \rho} \pi_x = P_x \cdot x - P_r \cdot \bar{\theta} \cdot x - c_v \cdot (1 - \bar{\theta}) \cdot x - \alpha(\rho).$$

The first-order condition provides the relationship among the prices of inputs and the output that this producer faces when maximizing profit:

$$P_x = \bar{\theta} \cdot (P_r - c_v) + c_v.$$

By replacing  $P_r$  in this equation with the price of recycled material paid to the waste manager at market equilibrium ( $P_r = k_r(r, \rho) - c_i$ ), we derive the equation for the price of output at market equilibrium:

$$P_x = \bar{\theta} \cdot (k_r(r^{mr}, \rho^{mr}) - c_i - c_v) + c_v. \quad (10)$$

Intuitively, when the regulation requires a greater proportion of recycled material in production, the producer must offer a higher price for recycled material to incentivize the waste manager to recover more material. The excess marginal cost of recycling is denoted as  $\lambda$ , with  $\lambda \equiv k_r(r^{mr}, \rho^{mr}) - c_i - c_v$ . This increased input cost then, to the extent of the required recycling rate  $\bar{\theta}$ , be passed on to the consumer, as indicated in the price-setting equation. As a result, a recycled content requirement effectively integrates the marginal recycling cost into the determination of the consumer product's price. The consumer product prices rise, and the total consumption level decreases. On the other hand, this policy raises the price of recycled material over the price of primary material by a margin equal to the excess recycling cost. However, the impact of this regulation on the absolute level of recycling is more ambiguous, since it arises from changes in both final consumption and the recycling rate (for a formal derivation, please refer to Appendix C).

A significant reduction in both material consumption and CO<sub>2</sub> emissions is evident with the enforcement of a minimum recycled content of 50%. In this case, the cost to recover the last unit recycled material reaches 2312 euro per ton, with an excess cost of 812 euro compared to the price of primary material. 51% of this excess cost is shifted to the consumer, leading to a product price of 1914 euro per ton. As a result, total PET consumption falls to 3.26 Mt, including 1.66 Mt recycled

materials, surpassing the amount of primary materials by 0.06 Mt.

Variable	Value
Total PET Consumption	3.26 Mt
Primary PET Production and Use	1.60 Mt
Recycled PET	1.66 Mt
Total CO <sub>2</sub> Emission	6.35 MtCO <sub>2</sub> e
Product Design Factor	0.0

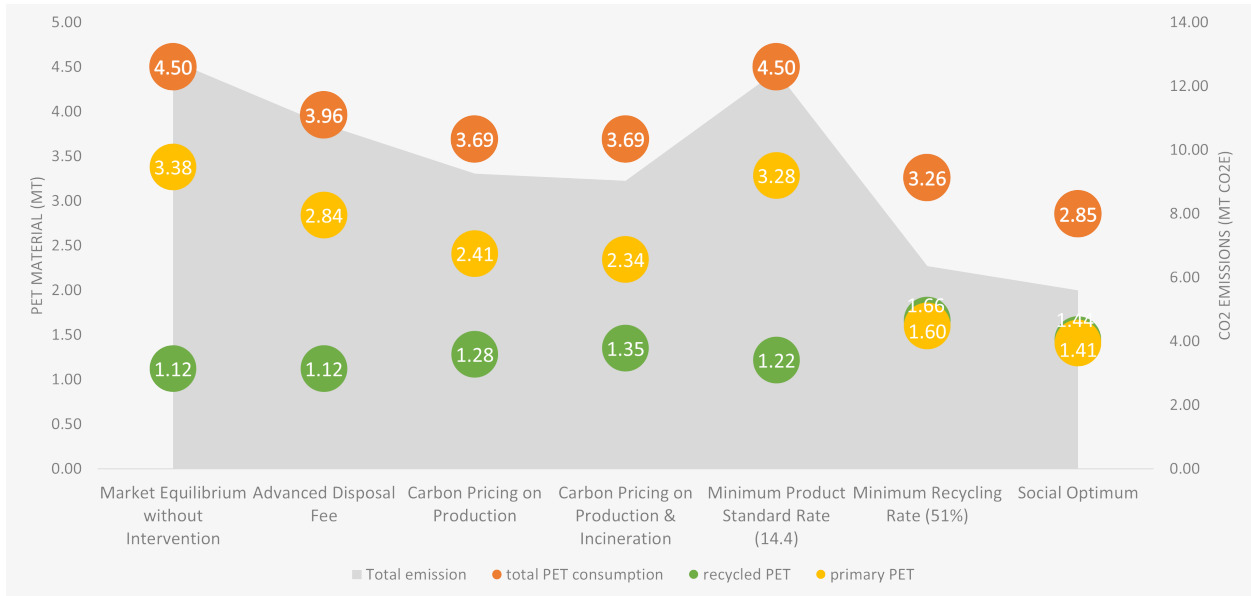
**Table 6:** Market outcomes with minimum recycling rate

## 5 Simulation results and discussion

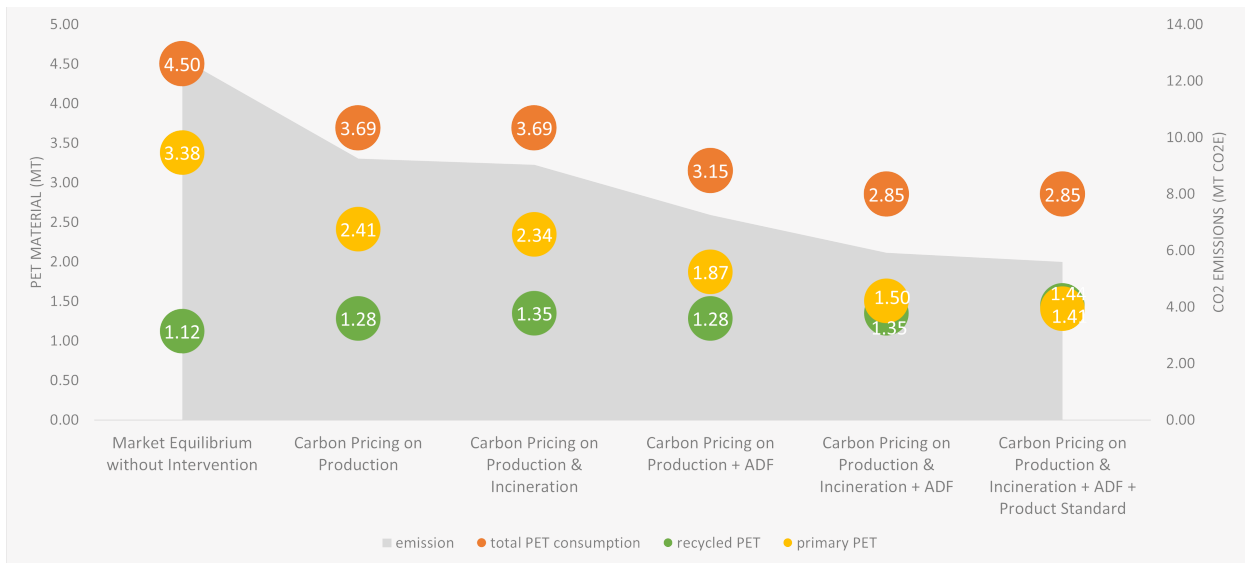
### 5.1 Comparing policy instruments and packages

Figure 2 summarizes the impact of a single policy instrument on material consumption and the resulting total emissions. Charging an ADF on top of product price reduces total PET consumption from 4.50 Mt to 3.96 Mt. Because this policy has no impact on recycling cost or the relative price of materials, the amount of recycled PET remains the same while the amount of primary PET reduces accordingly. This policy alone could lead to CO<sub>2</sub> emission reduction by 16%, compared to the market solution without any policy intervention. Imposing a carbon price on material manufacturing alone raises the prices of materials as well as the price of the consumer product. This price rise leads a reduction in total PET consumption to 3.69 Mt and a substitution of primary PET with recycled PET. An extension of the carbon pricing policy scope to waste disposal strengthens this substitution effect. However, this policy extension does not influence consumption as the consumer fails to perceive the increased shadow waste price. Carbon pricing on material manufacturing alone contributes to a reduction in CO<sub>2</sub> emissions by 28% and an extension to waste incineration contributes another 1%. Coordinating product design through a minimum product standard could significantly reduce recycling cost, increasing the amount of material recovery to replace primary material. However, we find that a minimum product standard alone has limited effect, if recycling remains overall uneconomic as a result of the low primary material prices or the lack of policies for internalization of carbon externalities. The contribution of this policy to emission reduction is a limited 3%, as the total amount of material consumption remains inefficiently high. Lastly, if a minimum recycled content of 51% is enforced, total emission would drastically reduce by 50%. In this case, total PET consumption shrinks to 3.26 Mt (a 27.5% reduction) and 1.66 Mt

recycled materials would be used to produce the products (a 48.2% increase).



**Figure 2:** Material consumption and emission under different single policy instruments



**Figure 3:** Material consumption and emission under different policy combinations

A combination of policy instruments targeting at different externalities could effectively achieve more efficient market solutions, as illustrated in Figure 3. Adding an ADF on top of a carbon pricing policy further reduces total PET consumption without affecting the relative competitiveness of recycled material. For a carbon pricing policy with limited scope, an ADF that captures waste incineration cost reduces total material consumption to 3.15 Mt, and further down to the social

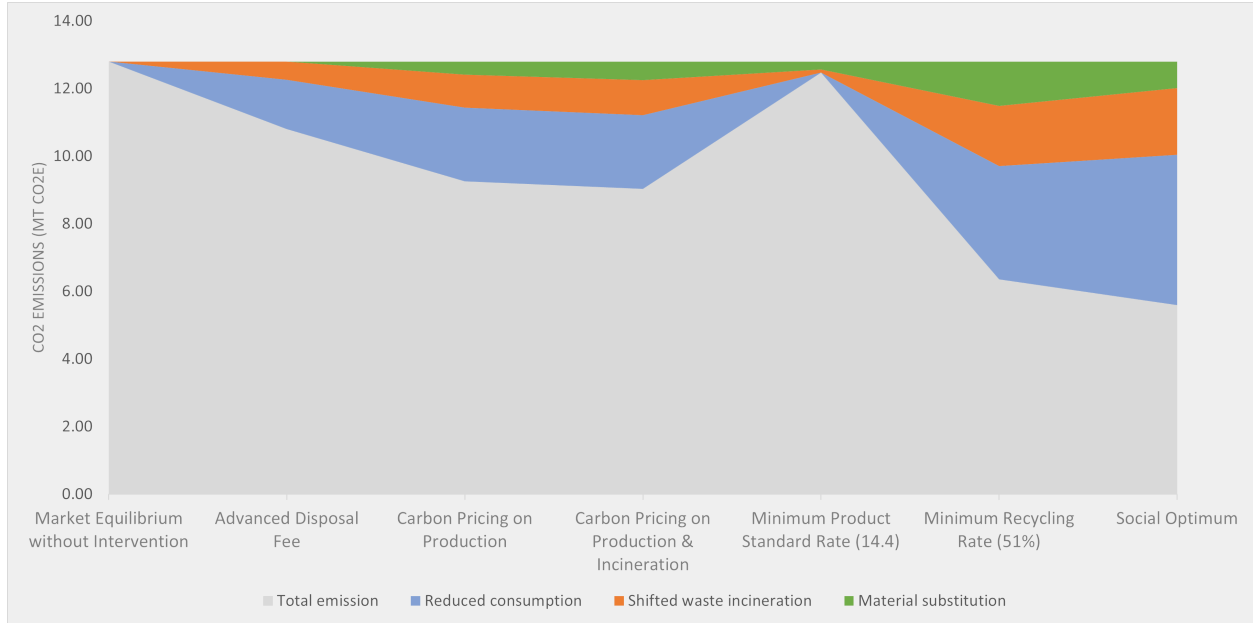
optimal solution of 2.85 Mt, when the emission cost is internalized by the waste manager. This latter policy combination enables a reduction of total emissions from 12.20 Mt CO<sub>2e</sub>, in the absence of regulation, to 5.92 Mt CO<sub>2e</sub> (a 54% reduction), and an increase in the material recovery level to 1.35 Mt materials. Only when a minimum product standard on recyclability is enforced can the social optimum solution be fully recovered, with 5.59 Mt CO<sub>2e</sub> of total emissions (a 56% reduction) and 1.44 Mt recycled material returning back to the economy. Therefore, a policy combination of life-cycle carbon pricing, ADF and product standard on recyclability restores the social optimal solution, which marks a 56% reduction in total emissions, a 28% increase in absolute material recovery, and a 36% reduction in overall material consumption.

## 5.2 Mitigation decomposition

The contribution to total emission reduction can be divided into three key components: reduced consumption, shifted waste incineration, and material substitution. We compute the emissions saved from reduced consumption as the product of the emission intensity of primary manufacturing and the change in total consumption. In contrast, material substitution is determined by multiplying the emission intensity difference between primary manufacturing and recycling processes by the change in the amount of recycled materials. Finally, source reduction from waste disposal is equal to the product of the emission intensity of waste incineration and the change in non-recycled waste.

Figure 4 visualizes the contribution of each component to total emission reductions under different policy instruments, given our modeling assumptions. For example, emission reduction under an ADF is only attributed to reduced consumption and shifted waste incineration, while emission reduction under a product design standard alone is very small, but mostly traced to material substitution. Under a minimum recycling rate requirement, all three components play a crucial role.

According to model assumptions, any additional demand for materials beyond the amount of recycled materials recoverable at a cost not exceeding the unit cost of primary materials must be met using primary materials. Therefore, these variations can be ascribed, at least partially, to the impact of a policy instrument on the pricing of consumer products and the relative marginal costs of materials. In Appendix E, Table 7 summarize these prices under different policy instruments and their combinations, while Table 8 presents the numerical outcomes of the PET simulation.



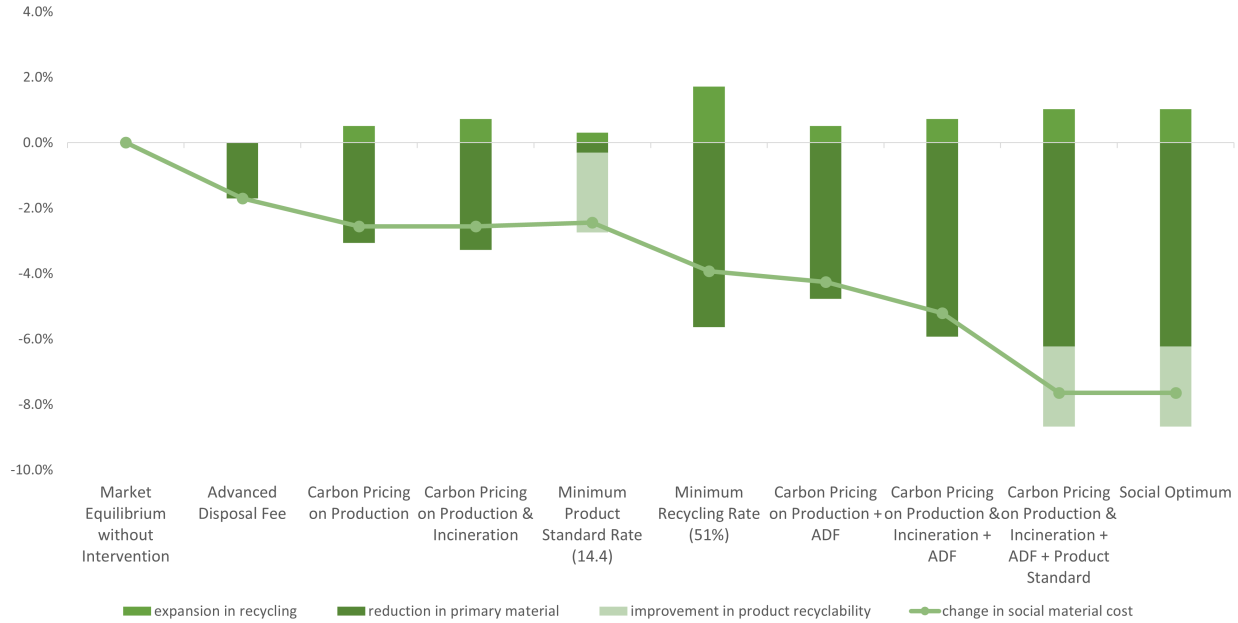
**Figure 4:** Emission reduction contributors under different policy instruments

### 5.3 Distribution

In this section, we present simulation results to illustrate how unit material cost, surplus allocation, and environmental cost change across different policy scenarios.

**Average Social Unit Material Cost.** Figure 5 illustrates how the average social unit material cost varies under each policy scenario compared to the market solutions without intervention. These savings are decomposed into three factors: expansion of recycling process, reduction in primary manufacturing and incineration, and improvement in product recyclability. We combine the costs associated with primary manufacturing and waste incineration, because according to the mass-balance condition, the amount of material enters the economy equals to the amount of materials coming out of the economy at the end-of-life. Appendix F provides the derivation for the decomposition of the average unit material cost.

Under a carbon pricing scheme, the average unit material cost decreases by 2.6%, which is largely attributed to the savings in primary manufacturing and incineration costs (a 3.1% to 3.3% reduction, depending on whether emissions from incineration is included). The expansion in recycling contributes to a 0.5% to 0.7% increase in the unit cost. As previously clarified, introducing an ADF alone does not lead to material substitution. Therefore, the 1.7% decrease in average unit cost can be exclusively attributed to the reduction in primary materials, given that the average unit cost for recycled materials is lower. For the same reason, incorporating an ADF in conjunction



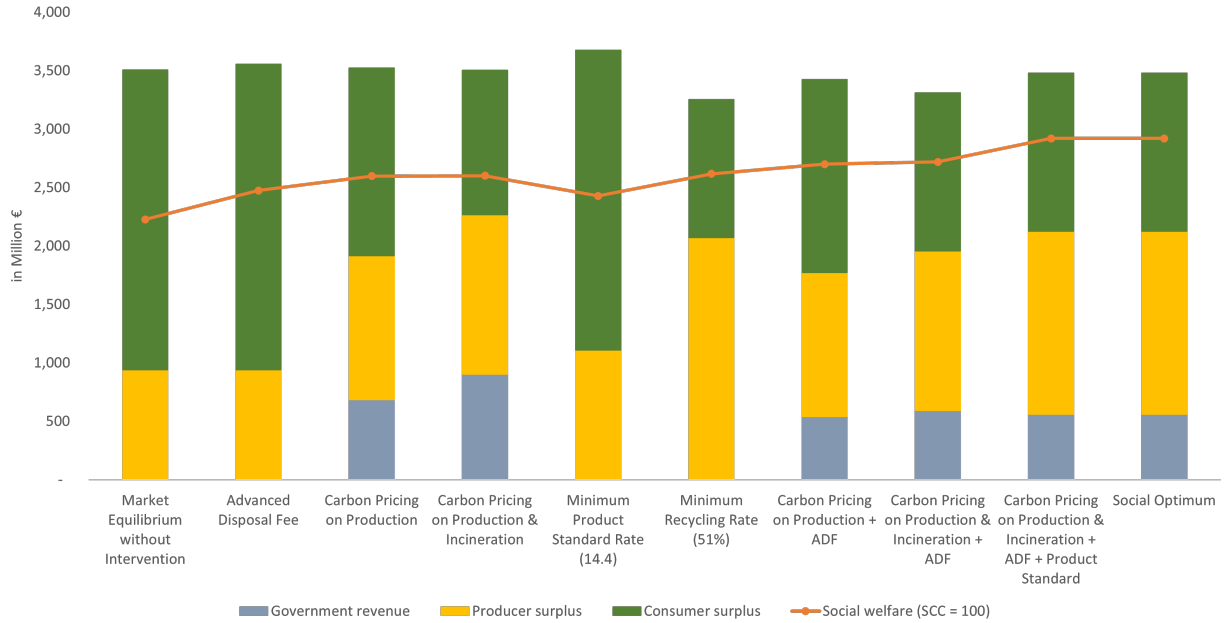
**Figure 5:** Variations in the average unit material cost and its decomposition under different policy scenarios.

with a carbon pricing scheme additionally results in a further reduction of the average unit cost by 4.3% and 5.2%, depending on the policy coverage of carbon pricing.

On the other hand, a minimum product standard alone does not affect total material consumption, but it enables material substitution due to decreased marginal recycling cost. In this case, product recyclability improvement contributes a 2.4% reduction in the average cost for each material unit in the economy. This policy also contributes to an overall unit cost reduction by 7.7% for the policy combination of carbon pricing, ADF and product standard.

With the implementation of a mandatory recycled content policy alone, the economy realizes a cost savings of 3.9% for each unit of material. This saving comprises a 5.6% reduction due to primary material reduction and a 1.7% increase due to the expansion of recycling. Both the reduction in primary costs and the increase in recycling cost is remarkable when compared to the effects of any other individual policy instrument.

**Sharing of Surplus.** Figure 6 illustrates the distribution of surplus among consumers, recyclers, and the government across various policy scenarios. Social welfare is then calculated by adding the negative environmental cost to the overall surplus. We characterize the allocation of welfare respectively under a carbon pricing and a mandatory recycled content policy in Appendix G.



**Figure 6:** Surplus distribution among consumer, recycler and government: a comparison across different policy combinations

On the one hand, consumer surplus reduces significantly under some policies but slightly increases under some other policies. Carbon pricing on manufacturing alone leads to a reduction in consumer surplus by 959 million euros, when the price of the consumer product rises to 1770 euros per unit. Extending this policy to also cover the end-of-life emissions further reduces consumer surplus to 1.33 billion euros. In contrast, implementing an ADF alone increases consumer surplus by 49 million euros, since an ADF saves the part of consumption resulting from the consumer over-looking waste treatment costs.<sup>12</sup> Under a recycled content requirement, the consumer product price integrates a fraction of the marginal recycling cost. In our simulation, the additional recycling cost raises consumer product price to 1914 euros per unit, resulting in a decrease in consumer surplus by 1.38 billion euros, a reduction even larger than that under a life-cycle carbon pricing scheme. Under a policy combination of life-cycle carbon pricing and ADF, the consumer surplus reduction is 1.21 billion euros, indicating less negative impact on consumer surplus than a recycled content requirement.

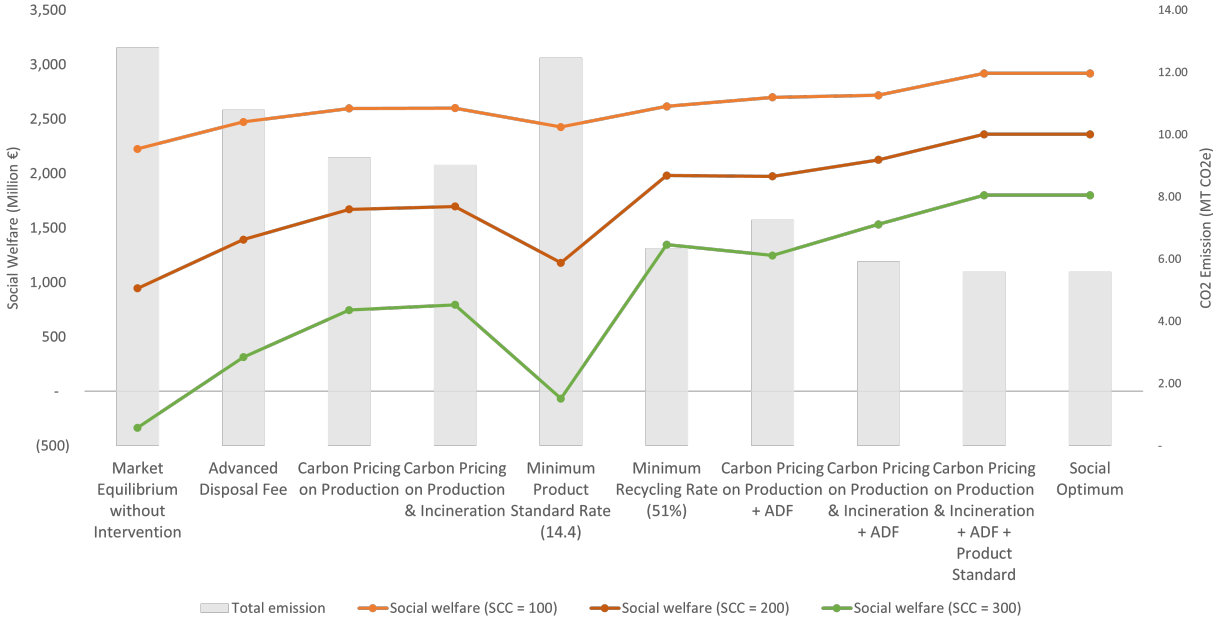
On the other hand, the competitiveness of recycling businesses is strengthened under several policies. First, a carbon pricing policy raises the relative price of recycled materials to the extent

<sup>12</sup>In this simulation, we assume the ADF serves to disclose the social cost of waste disposal to the consumer, who is already bearing this cost through implicit tax or waste fee. Therefore, we assume this policy does not open a new source of governmental revenue.



of material life-cycle emission intensity reduction that is measured by the social cost of carbon. In our simulation example, the carbon price in material manufacturing alone will generate 291 million euros more for the recycler, with an extension to incineration adding another 131 million euros. Moreover, a higher level of product recyclability reduces the marginal cost of recycling, thereby raising recycler surplus by 169 million euros. Third, under a recycled content mandate, the waste manager could sell the recycled material at a price even higher than the price of the consumer product. Multiplying this high price with the higher recovery level stimulated by this policy leads to an increase of recycler surplus by 1.13 billion euros.

**Environmental Cost.** The variation of social welfare under different policy instruments or combinations increases with the value of the social cost of carbon, as illustrated in Figure 7. It is worth noting that the implementation of a minimum product standard remains less effective compared to other policy instruments. The result, however, depends on whether our assumption on the functional specification for recycling cost reflects the industrial reality.



**Figure 7:** Social welfare under different social costs of carbon

## 6 Conclusion

In this paper, we construct an analytical model on three representative actors: a producer of consumer product, a consumer and a waste manager. Based on a characterization of the market

incentives of these actors, we identify three types of market failures that contribute to a low level of material recycling and excessive material use. First, the social cost of waste treatment remains external, as long as the consumer is unaware of this cost when making consumption decisions. Second, the net emission savings from a recycling process compared to a primary manufacturing process and a waste incineration process remain ignored, as long as the environmental costs are not factored in market prices. Third, the producer does not have economic incentive to design product with improved product recyclability, as long as the additional design cost is not compensated.

We then model policy instruments to tackle with these market failures and simulated their effects with a numerical example of PET polymer. An advanced disposal fee is a straightforward policy to reveal the cost of waste disposal to consumers. Theoretically, it leads to a minor decrease in consumption, but does not affect the volume of material recovery. A carbon pricing policy that factors in emission cost in the price of raw materials increases the amount of recycled material while lowering total consumption by shifting the emission cost to the consumer. Coordinating and enforcing a minimum standard for product recyclability reduces recycling cost, thereby increasing the amount of recycled material. This policy alone also does not influence total consumption. A policy package comprising these three policies effectively reestablish the socially optimal solution in our model. Last but not the least, enforcing a minimum product recycling content raises the marginal cost of recycling, which is partially integrated into the price of the consumer product and also leads to consumption reduction. Implementing this policy instrument alone could even outperform the social optimal levels of emission reduction and material recovery, but at the significantly lower levels of overall welfare and consumer surplus than that under the implementation of a policy package.

The effects of the policy instruments are also evaluated along several other aspects, including the average social unit material cost, the consumer surplus and the recycler surplus. Based on the simulation assumptions, we find that (i) a full-coverage carbon pricing policy leads to a 2.6% reduction in average unit material cost, a 1.33-billion-euro reduction in consumer surplus and 422-million-euro increase in recycling surplus; (ii) an ADF leads to a 1.7% reduction in average unit material cost and a 49-million-euro increase in consumer surplus; (iii) a minimum product standard on recyclability leads to a 2.4% reduction in average unit material cost and a 169-million-euro increase in recycler surplus; (iv) a minimum recycled content requirement leads to a 3.9% reduction in average unit material cost, a 1.38-billion-euro reduction in consumer surplus, and a 1.13-billion-euro increase in recycler surplus; and (v) a combination of carbon pricing, ADF and

product standard can achieve the social optimal levels of material use, emission reduction, and social welfare.

In this analysis we assume all actors maximize their individual economic benefits. Factors beyond this economic rationale, including the lack of information, organizational behavior, individual inertia, and the barriers related to infrastructure investment, will need to be accounted in future analysis. Moreover, this study does not specify the economic and transaction costs related to the policy-making processes and their implementation. Further studies are expected to look into this aspect.

# Appendices

## A Function specifications for simulation

- Linear:  $P = 3000 - x/3000$
- Recycling cost:  $K = 0.00075r^2 - 20 \cdot r \cdot \rho$
- Product design cost:  $A = 0.5 \times 10^6 \rho^2$

## B Monotonicity in material recovery with respect to product design

Given the market equilibrium equation on  $r$ :

$$c_v + te_1(1 - \sigma) + c_i + te_2 = k'_r(r, \rho)$$

Take total derivation:

$$\frac{dr}{d\rho} = -\frac{\frac{\partial k'_r}{\partial \rho}}{\frac{\partial k'_r}{\partial r}} > 0. \blacksquare$$

## C Comparative statics of minimum recycled content

After inserting market equilibrium conditions for both waste and consumer product markets, we get:

$$k'_r - c_v - c_i - te_1(1 - \sigma) - te_2 = \frac{u' \left( \frac{1}{\bar{\theta}} r \right) - (c_v + te_1 + c_i + te_2)}{\bar{\theta}}$$

Using the implicit function theorem, we obtain:

$$\frac{dr}{d\bar{\theta}} = \frac{u'_x - (c_v + te_1 + c_i + te_2) + \frac{1}{\bar{\theta}} u''_x \cdot r}{u''_x - \bar{\theta}^2 (\beta''_r + k''_r)} = \frac{\mu \cdot \bar{\theta} + u''_x \cdot \frac{r}{\bar{\theta}}}{u''_x - \bar{\theta}^2 \cdot k''_r}$$

and

$$\frac{dx}{d\bar{\theta}} = \frac{1}{\bar{\theta}} \frac{dr}{d\bar{\theta}} - \frac{x}{\bar{\theta}} = \frac{\mu + k''_r \cdot r}{u''_x - \bar{\theta}^2 \cdot k''_r}.$$

If recycled content criterion is binding, i.e.,  $\mu$  is positive, we get:

$$\frac{dx}{d\theta} < 0$$

,while

$$\frac{dr}{d\theta} > 0, \text{ only if } -u''_x > \frac{\bar{\theta}}{x} \cdot \mu. \blacksquare$$

## D Minimum recycling rate

A minimum recycling rate requirement is a supply-driven policy for material recovery that a waste manager must comply with:  $\frac{r}{w} \geq \bar{\delta}$ . The waste manager now faces a constrained optimization problem:

$$\max_{r, w} \pi_w = P_w \cdot w + P_r \cdot r - k(r, \rho) - c_i \cdot (w - r), \text{ s.t. } \frac{r}{w} \geq \bar{\delta}$$

If this regulation is binding, there will be again a fixed linear relation between  $w$  and  $r$ :  $r = \bar{\delta} \cdot w$ . In this case, the choice of waste treatment method is no longer left to the discretion of the waste manager. In fact, only one choice variable still persists in the profit-maximization problem:

$$\max_w \pi_w = P_w \cdot w + P_r \cdot \bar{\delta} \cdot w - k(\bar{\delta} \cdot w, \rho) - c_i \cdot (1 - \bar{\delta}) \cdot w$$

The first-order condition describes the acceptance of waste quantity and the supply of recycled material:

$$P_w + P_r \cdot \bar{\delta} = k_r(\bar{\delta} \cdot w, \rho) \cdot \bar{\delta} + c_i \cdot (1 - \bar{\delta}).$$

Note that the price of recycled material that a producer of consumer product is willing to accept must be equal to the price of primary material in a free market. Therefore, by substituting  $P_r$  with  $c_v$ , we derive the price equation for the waste fee:

$$P_w = \bar{\delta} \cdot (k_r(r, \rho) - c_i - c_v) + c_i.$$

Furthermore, if the waste fee is funded through the public budget, individual consumption behavior will remain unaffected by this regulation. However, if an Advanced Disposal Fee increases consumer awareness through higher prices for consumption products, this supply-side regulation will have precisely the same effect as a demand-driven minimum requirement for recycled content.

Once again, the impact of this regulation on the quantity of recycled material is ambiguous, with an increase occurring only under specific conditions (see below).

## D.1 Comparative statics of minimum recycling rate

After inserting market equilibrium conditions for both waste and consumer product markets, we obtain the following equation:

$$k'_r - c_v - c_i - te_1(1 - \sigma) - te_2 = \frac{u' \left( \frac{1}{\bar{\delta}} r \right) - (c_v + te_1 + c_i + te_2)}{\bar{\delta}}$$

Using the implicit function theorem, we can derive the marginal influence of the minimum recycling rate  $\bar{\delta}$  on choice variables  $r$  and  $x$ :

$$\frac{dr}{d\bar{\delta}} = \frac{\bar{\delta} \cdot \lambda + u''_x \cdot \frac{r}{\bar{\delta}}}{u''_x - \bar{\delta}^2 \cdot k''_r},$$

and,

$$\frac{dx}{d\bar{\delta}} = \left( \frac{dr}{d\bar{\delta}} - x \right) \cdot \frac{1}{\bar{\delta}} = \frac{\lambda + k''_r \cdot r}{u''_x - \bar{\delta}^2 \cdot k''_r}.$$

If the recycling rate is binding, i.e. the sign of shadow price  $\lambda$  is positive, we get:

$$\frac{dx}{d\bar{\delta}} < 0,$$

while

$$\frac{dr}{d\bar{\delta}} > 0, \text{ only if } -u''_x > \frac{\bar{\delta}}{x} \cdot \lambda. \blacksquare$$

## E Prices in different policy scenarios

Table 7 summarizes the (shadow) prices for the consumer product  $x$  and the recycled material  $r$  under different policy instruments and their combinations. To explicitly account for the role of the advanced disposal fee, we differentiate a shadow price for consumption that the consumer perceives in the absence of an explicit waste fee.

<i>Policy Scenarios</i>	$P_x + P_w$	$P_x$	$P_r$
Market Solution without Intervention	$c_v + c_i$	$c_v$	$c_v$
Advanced Disposal Fee	$c_v + c_i$	$c_v + c_i$	$c_v$
Carbon Pricing on Production	$c_v + te_1 + c_i$	$c_v + te_1$	$c_v + te_1(1 - \sigma)$
Carbon Pricing on Production and Incineration	$c_v + te_1 + c_i + te_2$	$c_v + te_1$	$c_v + te_1(1 - \sigma)$
Minimum Product Standard	$c_v + c_i$	$c_v$	$c_v$
Minimum Recycling Rate $\bar{\theta}$	$\bar{\theta} \cdot (k_r(r^{mr}, \rho^{mr}) - c_i - c_v) + c_v + c_i$	$\bar{\theta} \cdot (k_r(r^{mr}, \rho^{mr}) - c_i - c_v) + c_v$	$k_r(r^{mr}, \rho^{mr}) - c_i$
Carbon Pricing on Production and ADF	$c_v + te_1 + c_i$	$c_v + te_1 + c_i$	$c_v + te_1(1 - \sigma)$
Carbon Pricing on Production and Incineration and ADF	$c_v + te_1 + c_i + te_2$	$c_v + te_1 + c_i + te_2$	$c_v + te_1(1 - \sigma)$

**Table 7:** (Shadow) prices for consumer product and recycled material under different policies combinations

<i>Policy Scenarios</i>	$P_x(\text{€})$	$P_r(\text{€})$
Market Solution without Intervention	1500	1500
Advanced Disposal Fee	1680	1500
Carbon Pricing on Production	1770	1742
Carbon Pricing on Production and Incineration	1770	1742
Minimum Product Standard	1500	1500
Minimum Recycling Rate $\bar{\theta}$	1914	2312
Carbon Pricing on Production and ADF	1950	1742
Carbon Pricing on Production and Incineration and ADF	2050	1742

**Table 8:** Prices for PET product and recycled PET under different policies combinations



## F Decomposition of average unit material cost

The average unit material cost refers to the allocation of the total costs associated with primary manufacturing, recycling, and end-of-life incineration to each unit of material consumed within the economy. This concept helps to exclude the impact of total demand changes on material costs. The average unit material cost is defined as  $z$  in this context:

$$z \equiv \frac{k(r, \rho) + (c_v + c_i) \cdot v}{v + r}.$$

Taking the total differential of this function, we obtain:

$$\begin{aligned} dz &= \frac{\partial z}{\partial r} dr + \frac{\partial z}{\partial v} dv + \frac{\partial z}{\partial \rho} d\rho \\ &= \frac{k_r(r, \rho) - \frac{k(r, \rho) + (c_v + c_i) \cdot v}{v + r}}{v + r} dr + \frac{c_v + c_i - \frac{k(r, \rho) + (c_v + c_i) \cdot v}{v + r}}{v + r} dv + \frac{k_\rho(r, \rho)}{v + r} d\rho. \end{aligned}$$

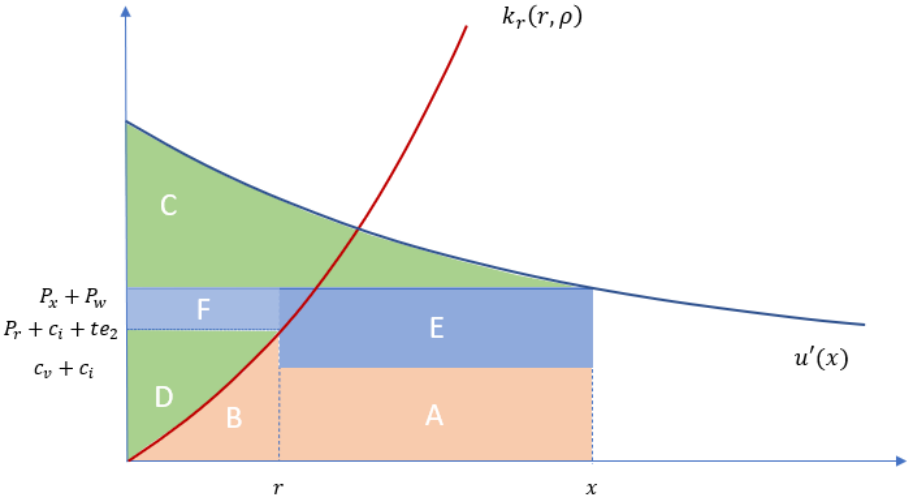
Using the Taylor's theorem, we can approximate the variation in the average unit cost across different policy instruments as the following:

$$z_j - z_i \approx dz = \frac{\partial z}{\partial r}(i) \cdot (r_j - r_i) + \frac{\partial z}{\partial v}(i) \cdot (v_j - v_i) + \frac{\partial z}{\partial \rho}(i) \cdot (\rho_j - \rho_i),$$

where  $i$  and  $j$  represent different policy scenarios. Thus, the variation in the average unit material cost can be attributed to three key components: the product of the change in recycled material and the difference between marginal recycling cost and previous average unit material cost, the product of the change in primary material and the difference between marginal primary cost (including primary manufacturing and incineration) and previous average unit material cost, and the product of the change in product recyclability and the marginal recycling cost with respect to product recyclability. Although this approximation with first-order differential leaves non-zero residuals, it is still helpful to reveal the relative share of contribution from each component, as illustrated in Figure 5.

# G Welfare allocation: a comparison between a carbon pricing policy and a mandatory recycled content policy

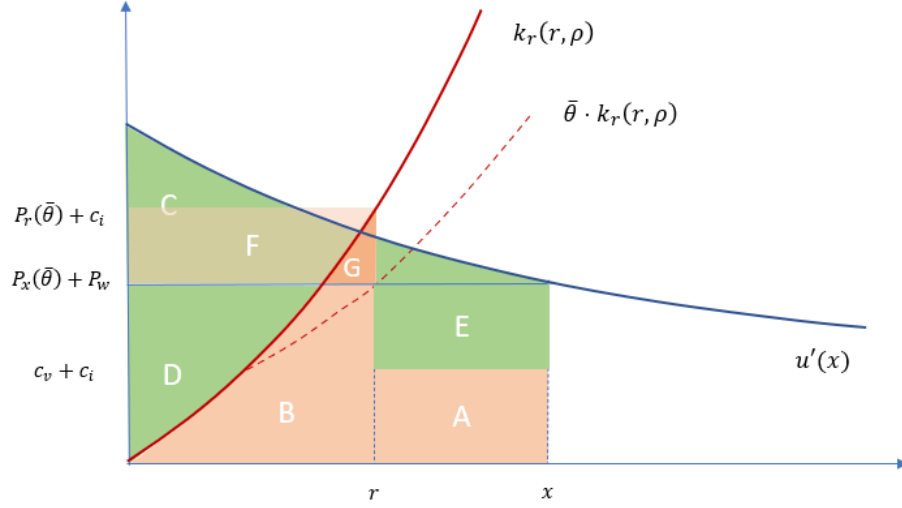
The figures below compares the impact of a carbon pricing policy and a mandatory recycled content policy on surplus distribution among consumers, producers, and the government. Figure 8 illustrates the distribution of welfare across (A) costs of primary material and waste incineration, (B) cost of recycling, (C) consumer surplus, (D) recycler surplus, and (E+F) tax revenue for the government. When a mandatory recycled content policy (Figure 9) were enforced, the government does not collect tax revenue. Instead, recycler surplus now equals to (D+E-G), with the small triangle (G) representing the excess cost of the additional recycled material units for which the marginal recycling cost becomes even higher than the price of the consumer product. Below we derive the welfare allocation for this latter case.



**Figure 8:** Welfare allocation under a carbon pricing policy

In this paper, we assume a perfectly competitive market for the consumer product. Therefore, the producer of consumer product should claim zero surplus. Using the letters in Figure 9, we derive the producer surplus as the net of revenues and material costs:

$$\begin{aligned}
 PS &= D + (B - G) + E + A - (F + D + B - G) - A \\
 &= E - F = 0.
 \end{aligned}$$



**Figure 9:** Welfare allocation under a minimum recycled content policy

Intuitively, this result indicates that the extra cost a producer of consumer product has to pay on recycled materials to meet the regulatory requirement is equal to the additional rent she obtains from the primary materials used in the product, as the consumer product price is now higher than the price of the primary material.

Similarly, the net profit that a recycler obtains, or recycler surplus, can be characterized as:

$$\begin{aligned}
 RS &= F + D + (B - G) - B \\
 &= F + D - G.
 \end{aligned}$$

Applying the condition that derived from net zero surplus for the consumer producer, we obtain the recycler surplus as  $E + D - G$ .

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