Did Europe Move in the Right Direction on e-Waste Legislation?

Shumail Mazahir
Desautels Faculty of Management, McGill University,
1001 Sherbrooke St. W., Montreal, PQ H3A 1G5, Canada, shumail.mazahir@mcgill.ca

Vedat Verter
Desautels Faculty of Management, McGill University,
1001 Sherbrooke St. W., Montreal, PQ H3A 1G5, Canada, vedat.verter@mcgill.ca

Tamer Boyacı
ESMT Berlin,
Schlossplatz 1, 10178 Berlin, Germany, tamer.boyaci@esmt.org

Luk N. Van Wassenhove
Technology and Operations Management, INSEAD,
Boulevard de Constance, 77305 Fontainebleau Cedex, France, luk.van-wassenhove@insead.edu

This paper presents an analytical framework of the product take back legislation in the context of product reuse. We characterize existing and proposed forms of E-waste legislation and compare their environmental and economic performance. Using stylized models, we analyze an OEM's decision about new and remanufactured product quantity in response to the legislative mechanism. We focus on the 2012 waste electrical and electronic equipment directive in Europe, where the policy-makers intended to create additional incentives for the product reuse. Through a comparison to the original 2002 version of the directive, we find that these incentives translate into improved environmental outcomes only for a limited set of products. We also study a proposed policy that advocates a separate target for the product reuse. Our analysis reveals that from an environmental standpoint, the recast version is always dominated either by the original policy or by the one that advocates a separate target for the product reuse. We show that the benefits of a separate reuse target scheme can be fully replicated with the aid of fiscal levers. Our main message is that there can not be a single best environmental policy that is suitable for all products. Therefore, the consideration of product attributes is essential in identification of the most appropriate policy tool. This can be done either by the implementation of different policies on each product category or by implementation of product based target levels.

Key words: Legislation, product recovery, remanufacturing, recycling, end-of-life products

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1. Introduction

The recent years have seen a growth in the consumer electronics sector. The sale of electrical and electronic devices has surpassed 3 BN units (Balde et al. 2017). Moreover, the consumers are replacing their products at much higher frequency and the useful lifespan of electrical and electronic equipment is shrinking (Guardian 2015). Consequently, the number of electrical and electronic products discarded each year i.e., the e-waste, is the fastest growing waste stream comprising abandoned electrical and electronic products around the globe. According to a United Nations University report (Balde et al. 2017), the global E-Waste generation in 2016 stood at 44.7 million tons. With a continuing trend, it is feared that the world will accumulate 6.8 kg of E-Waste per inhabitant by 2021 (Balde et al. 2017). In recognition of the above facts, governments around the world have been enacting or planning to implement new legislation targeted towards curbing down waste generation and environmental damage. European Union (EU) directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE) is the most well-known regulation, which holds original equipment manufacturers (OEM) responsible for the collection, recovery and disposal of end of life products.

The WEEE Directive is often criticized for being merely a waste diversion attempt that overlooks the potential of high-end recovery in the form of whole product reuse or remanufacturing. Although product reuse is considered a more preferable activity to other forms of material recovery, no specific incentive for the product reuse is provided in the Original WEEE Directive such that it was excluded from the calculation of mandatory recycling rate. The apparent lack of incentives has sent a signal to OEMs that reuse is not as critical as recycling. Accordingly, the OEMs concentrated most of their attention on meeting mandatory recovery and recycling rates, ultimately placing reuse initiatives in the second priority.

This was remedied in July 2012 by the WEEE Recast Directive that recognizes product reuse at least as critical as recycling by stating “the recovery, preparation for reuse and recycling of WEEE should be counted towards achievement of the targets laid down in this directive” (Paragraph 20). With the recognition of product reuse towards achievement of the recycling target, the policy-makers send the message that the firms should undertake steps to develop and strengthen their reuse operations. Although the producer responsibility organizations and the European recycling organizations favorably received this amendment (ORGALIME 2016); some circles including the reuse organizations and the European Committee of Regions were critical and called upon the need of more incentives for the product reuse in the form of a *separate reuse target* (Guardian 2012, Len 2013). The European Union is also contemplating such an initiative as Article 11(6) states “the European Parliament and the Council shall examine the possibility of setting separate targets for WEEE to be prepared for re-use”.

The other major changes enforced by the WEEE Recast Directive include (i) an increase in most of the category-based collection and recycling targets during the transition period from Aug 15, 2015 to Aug 15, 2018, presumably to accommodate the product reuse and (ii) a new classification that includes six new product categories to replace the original ten categories. Once the new categories are in effect, starting Aug 15, 2018, a number of products will face an increase (or, a decrease) in their collection and recycling obligations.

Although much effort has been spent to identify the weaknesses of the WEEE directive, the scholarly literature is remarkably sparse concerning the comparative environmental and economic performance of the original, the recast and the proposed extensions to the directive. In this paper, we address this gap by seeking the answers to the following research questions:

(i) Does the WEEE Recast Directive provide more incentives for the product reuse in comparison with the original WEEE Directive?

(ii) When does the Recast Directive lead to better environmental outcomes?

(iii) How can the enforcement levers (i.e., the collection and recycling targets) be adjusted upon the shift to the Recast Directive?

(iv) What are the implications for introducing a separate target for the product reuse? Can comparable benefits be achieved through alternative means?

(v) Should the future extension of the WEEE directive continue to envisage category-based targets or do product-specific targets provide a better alternative?

The responses to the first three questions would collectively shed light on whether Europe moved in the right direction concerning e-waste legislation via the WEEE Recast Directive. The last two questions, however, are intended to study the alternative directions for the future of e-waste legislation in Europe. To this end, this paper presents stylized models for the six policy options depicted in Table 1.

Our findings suggest that attempts to develop a unified policy tool for all products can be abandoned and instead efforts should be concentrated to identify the right set of products for one of the policy options. We show that each of these policy options are suited for a specific set of products and therefore due consideration to products environmental characteristics as well as market realities, is inevitable for appropriate selection of a policy option. Furthermore, we show that when an appropriate policy option is selected for a

Policy	Description
`O`	Original WEEE Directive
`R`	WEEE Recast Directive
`P`	A Separate Target for Product Reuse
`T`	Tax on Manufacturing and Subsidy on Remanufacturing
$\mathcal{C}$	Targets for each Product Category
$\mathcal{S}$	Targets for each Individual Product

Table 1 Notation and Description of the Policies studied

product, some fears of unintended environmental outcomes as raised by (Esenduran et al. 2015) disappear, i.e., the environmental outcomes do not deteriorate with stricter enforcement levers. We extend our model to compare *category based* versus *product based* policies and the results support our earlier findings. Therefore, future of WEEE legislation may not necessarily lie in the inclusion of more enforcement parameters, but considerations of product characteristics may represent a promising avenue of future extension.

Considering the facts that critical raw material is becoming increasingly scarce around the globe and many policy making initiatives such as European Union Circular Economy Directive prioritize reuse operations; this is a timely, and practically relevant research endeavor. From the analysis of our models, we are able to generate insights on the implications for the OEM and consumers, and draw conclusions that can guide the policy-makers.

The remainder of this paper is organized as follows. §2 reviews the related literature. In §3, we present the detailed modeling framework. Then, in §4, we present the analysis of OEM's problem under the mandatory take-back policies: the Original and the Recast WEEE Directives. We discuss the comparative environmental and economic performance of the two schemes. §5 is dedicated to the policy that incorporates a separate target for the product reuse and compares its performance with the current Recast policy or alternative legislative schemes. In §6 we study the performance of product specific targets versus a category based targets with more enforcement levers. §7 concludes our paper. For expositional clarity, the detailed proofs of the analytical results are presented in Appendix A-2.

2. Related Literature and Contribution

There has been considerable amount of interest within the academic community on product recovery and closed-loop supply chain management issues in the last decade. Within this literature, there is a more recent, but fast growing body of research that investigates the impact of environmental legislation and, in particular, take-back legislation on firm operations. The implications on closed-loop supply chains are discussed also in (Atasu and Boyaci 2010, Esenduran et al. 2016, 2015).

One stream of papers in this domain investigates the impact of take-back legislation and EPR programs on new product introduction, product design and recyclability. Plambeck and Wang (2009) show how EPR influences new product introduction frequency. Subramanian et al. (2009) investigate the effect of EPR on product design and coordination incentives in a durable product supply chain, while Atasu and Subramanian (2009) study the impact of configurational requirements of take-back legislation on the recyclability choices of manufacturers. Gui et al. (2015) study cost-efficient implementation of EPR legislation by presenting a cost allocation model for all stakeholders.

There is another stream of papers, which is more closely related to our work, that looks at the economics of take-back legislation including operational elements. Atasu et al. (2009) develop a stylized economic model of EPR from a social planner (government) perspective. They include multiple stakeholders including producers, consumers and the government. Products are sold in a competitive market; they are collected and recycled at the end of their life. Atasu et al. (2009) suggest that the social planner should set target collection levels according to the intensity of competition in the product market. The model is extended in Atasu et al. (2013) to incorporate alternative take-back policy forms: material recycling rate or material recovery tax. They show that social welfare is maximized under a tax policy, but if the environmental impact is less significant than the cost of taking back products, then both the producers and the environment are better off under the rate policy. We consider rate-type policies in our main framework, but also discuss alternative tax-subsidy type policy tools.

There are also other papers related to take-back legislation based on recycling. Taking a supply chain perspective, Jacobs and Subramanian (2012) analyze the impact of sharing take-back system costs between different members of the supply chain. They show that although the supply chain profits increase with cost sharing, the overall economic and environmental performance of the system depends also on the material recovery rate and environmental externalities. Toyasaki et al. (2011) model and compare monopolistic and competitive take-back schemes for recycling WEEE. Their model is distinct as it includes the recyclers as a major stakeholder, and incorporates scale economies in recycling. They show that consumer and producer preferences are always aligned and they generally prefer a competitive take-back scheme. The recyclers, on the other hand, prefer competitive scheme only when the intensity of competition in the product market and the economies of scale in recycling costs are low, resulting in a win-win outcome for all stakeholders.

To the best of our knowledge, there are two papers that focus on the impact of take back legislation with an emphasis on the product reuse. Esenduran et al. (2016) investigate the impact of take back legislation on the remanufacturing industry by modeling the competition between an OEM and independent remanufacturers. Esenduran et al. (2015), however, study the impact of legislation on the remanufacturing decision of a firm and the resulting environmental and economic implications. They show that regulatory intervention i.e., a recycling target or a separate target for reuse, may prove counterproductive as the total environmental footprint may increase. While we concur with these findings, we show that such undesirable consequences are observed only when inadequate policy choices are made. We find that under correct policy choices, environmental outcomes always improve with stricter enforcement parameters. There are some noteworthy differences between our work and that of Esenduran et al. (2015). First, they study the impact of legislation on environmental and economic outcomes but we capture the effects of transition from one form of legislation to the other. This allowed us to map the product characteristics with environmental performance under each policy, identifying the products that suit a certain policy. Second, we introduce two separate regulatory targets for collection and recycling which allows us to state that the incentives for these two parameters are not completely synchronized. Third, considering the resistance of OEMs towards the proposal of separate reuse target, we show how similar results can be achieved through adjustments of existing parameters or introduction of fiscal levers. Finally, we also study the efficiency of existing category based scheme by extending our model to the case of two-products.

3. Model Development and Assumptions

There is a monopolist with both manufacturing and remanufacturing capabilities, operating under a mandatory take-back legislation such as WEEE. In addition to the costs of manufacturing and remanufacturing, the OEM is also responsible for bearing the costs associated with the collection and recovery of its products that reach end-of-life. OEM's decision-making problem, in general, is well-known in the literature and its variations have been studied (Souza 2013). Articles 7(1) and 3(1)k of the WEEE Recast make it clear that the scope of the directive is restricted only to products that are introduced in the market for the first time, i.e., new products. Therefore, we assume that remanufactured products are exempt from collection and recycling obligations. In the appendix A-3, we examine the effect of expanding the scope of the Directive to remanufactured products.

Let q_n^i and q_r^i denote the quantity of new and remanufactured products offered by the firm under policy i. The original WEEE legislation (i.e., Policy 0), mandates a collection rate (τ) and a recycling rate (σ). Under this policy, the OEM is required to collect a fraction of the new products the firm puts on the market. From what is collected, a fraction must be recycled while the rest is directed to either remanufacturing

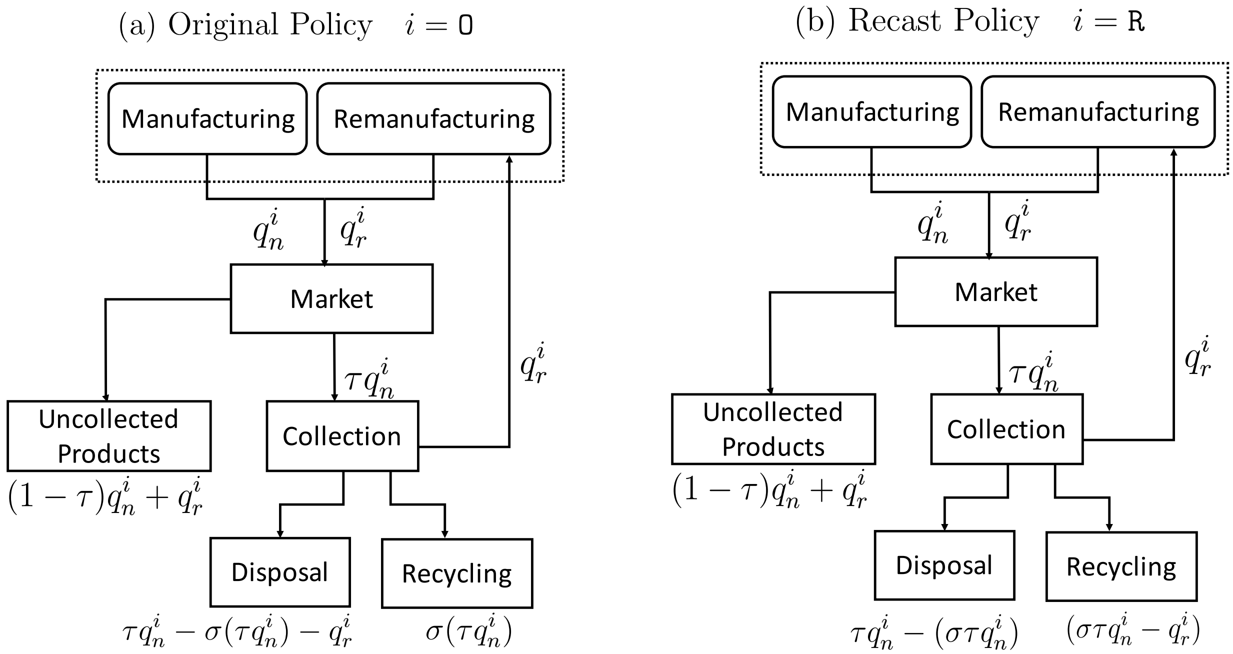

Figure 1 **Description for the Original and Recast policy where** $i \in \{\texttt{0}, \texttt{R}\}$

or disposal. The recycling obligation must be satisfied exclusively through product recycling and product remanufacturing is not counted towards achievement of the recycling target. The WEEE Recast (i.e., Policy R), however, mandates a combined recycling and reuse target rate in addition to a collection rate. In contrast with policy 0, the recycling obligation can be fulfilled through product recycling and/or remanufacturing and we do not make any assumption how the firm chooses to meet it. We presume that the achieved collection and recycling rates satisfy the targets set by the legislation where $\tau \in [0, 1]$, $\sigma \in [0, 1]$. The dynamics of both policies are presented in Figure 1. Note that only the expressions on the bottom level are not the same for Figure 1(a) and Figure 1(b). Also, the respective new and remanufactured quantities under the two polices would be different. In this paper, Policy R is used as the benchmark policy.

We capture the salient characteristics of the business problem and the internal dynamics in a single-period model. In essence, we assume a steady-state environment where the firm has both new and remanufactured products in the market (Agrawal et al. 2015). Implicitly, this means products can be remanufactured only once. This assumption is quite common in the related literature (Debo et al. 2005, Ferguson and Toktay 2006, Ferrer and Swaminathan 2006).

Unit manufacturing and remanufacturing costs are denoted as c_n and c_r respectively. For ease of exposition and simplicity, we assume that there is no additional cost of sorting/inspection of the collected products in order to decide their destiny (reuse, recycling or disposal). The cost associated with recycling and disposal are given as c_{rec} and c_d respectively. We assume that $c_{rec} > c_d$ suggesting that recycling cost is higher than the cost to dispose off the products in the landfill. This assumption is reasonable for most product categories, where recycling operations require processing in capital-intensive plants. In some cases, recycling operations may yield a net revenue due to recovery of material with a market value. However, it would require highly efficient recycling technology which is not available for all the products covered in the Directive. Note that each of the collected products is either remanufactured, recycled or channeled for disposal, the collection costs can be embedded into the costs incurred during remanufacturing, recycling and disposal procedures.

Following the standard approach in the literature, we assume that new and remanufactured products are substitutes for each other. We consider a fixed market size which is normalized to unity. Consumers have heterogeneous valuations (willingness-to-pay) for the new product, which is modeled as a uniform distribution between 0 and 1. Remanufactured products have the same functionality as new ones, but are viewed inferior in quality by the consumers. Specifically, a consumer with valuation v for the new product is only willing to pay $\delta\mathsf{v}$ for a remanufactured one, where $\delta \in [0, 1]$. Consumers are assumed to be rational decision-makers, whose product choice (i.e. new or remanufactured) maximizes their net utility. Naturally, a consumer will make a purchase if his/her net utility is positive. The above demand model is used quite commonly in the related literature. The resulting inverse demand functions are given as:

$$p_n = 1 - q_n - \delta q_r, \tag{1}$$

$$p_r = \delta(1 - q_n - q_r), \tag{2}$$

where p_n and p_r are the prices of the new and remanufactured products, respectively.

From a policy-maker's perspective, OEM's performance under each policy is measured through a comprehensive set of economic and environmental criteria. From economic perspective, firm's profitability and consumer surplus are taken into account (Atasu et al. 2009, 2013, Raz et al. 2013). The firm's profit under policies $\mathsf{0}$ and R can be represented as follows:

For Policy $\mathsf{0}$

$$\Pi^0 = q_n(p_n - c_n) + q_r(p_r - c_r) - q_{rec}c_{rec} - q_d c_d \tag{3}$$

subject to:

$$q_{rec} \geq \sigma\tau q_n \qquad q_d \geq \tau q_n - q_{rec} - q_r \tag{3a}$$

$$q_n > 0 \qquad q_r > 0 \qquad q_{rec} > 0 \qquad q_d > 0 \qquad q_n > q_r \tag{3b}$$

For Policy R

$$\Pi^{\mathrm{R}} = q_n(p_n - c_n) + q_r(p_r - c_r) - q_{rec}c_{rec} - q_d c_d \tag{4}$$

subject to:

$$q_{rec} \geq \sigma\tau q_n - q_r \qquad q_d \geq \tau q_n - q_{rec} - q_r \tag{4a}$$

$$q_n > 0 \qquad q_r > 0 \qquad q_{rec} > 0 \qquad q_d > 0 \qquad q_n > q_r \tag{4b}$$

Note that we have dropped the superscripts for the decision variables in equations 3,4 for ease of exposition. Furthermore, we assume that the constraints presented in equations (3a,4a) are binding i.e., the firm will collect, recycle and dispose of no more than what is set by the legislation. The constraints in equations (3b,4b) suggest that remanufacturing volumes are small such that the firm can not satisfy its entire recycling/disposal quota through product remanufacturing alone.

The consumer surplus is given as:

$$S = \int_{\frac{p_n-p_r}{1-\delta}}^{1} (\mathsf{v} - p_n)d\mathsf{v} + \int_{p_r/\delta}^{\frac{p_n-p_r}{1-\delta}} (\delta\mathsf{v} - p_r)d\mathsf{v}, \tag{5}$$

Next, we measure the environmental impact of the policies by computing the total environmental footprint. Quantifying the environmental footprint is notoriously challenging and the prevailing papers have taken a stylized approach to approximate the environmental footprint. Atasu et al. (2009, 2013) consider the hazard potential associated with uncollected products, Galbreth et al. (2013) incorporate environmental footprint through virgin material usage and Raz et al. (2013) accommodate environmental considerations by incorporating the footprint during production and use phase of the product while Ovchinnikov et al. (2014) measure the environmental footprint by incorporating the total energy consumption across life cycle of the product. There is no single metric that can be used to represent the environmental footprint, hence, the Environmental Protection Agency (EPA) considers as many as sixteen impact categories for this purpose.

There is a growing consensus among sustainable operations and industrial ecology literature to incorporate the environmental impact associated with all phases of the life cycle of a product (Esenduran et al. 2015). We implement the same approach by considering environmental footprint with a combination of the production, the use and the end-of-life phases of the product life cycle. These form the major building blocks on the strategic level and design of any incentive structure must accommodate these three phases of life-cycle. There can be other minor components which can be attributed to one of these.

For the production phase, we associate a footprint (e_m) for each new product. Production and manufacturing operations for electronics constitute resource intensive activities that require the extraction of rare earth minerals, energy intensive treatment (e.g., silicon wafer production). The categories of abiotic resource depletion and global warming potential are more relevant to this phase which can be studied in terms of surplus energy. Thus, the footprint of the production under policies `0,R` can be represented as $\mathrm{E_p} = e_m q_n$. Note that although $\mathrm{E_p}$ has the same functional form under each policy, the value of q_n would be different.

Reuse operations generally require data erasure, software update, functionality test, cleaning and minor repair operation and their impact is known to be insignificant in comparison with new products (Lindahl et al. 2006). Therefore, we associate a negligible footprint with the remanufacturing process.

During their use, new and remanufactured products use some energy and consumables and may emit some air particulates and smogs during operational life. We associate a footprint (e_u) with each product during the use phase. The more relevant impact categories are energy usage, acidification and photochemical smog in LCA studies. One may argue that remanufactured products are expected to be less energy efficient than the new ones, but this effect remains insignificant unless effects from radical innovation are considered such as CRT screens and LCD screens are considered to be one product and energy usage of a new LCD screen is compared with that of a remanufactured CRT screen. A remanufactured product undergoes a rigorous functional test before reselling and is expected to perform at comparable levels.[1]

Finally, we also accommodate the environmental footprint from the end of life phase of the products. There are different footprints associated with the products that are channeled to disposal/landfills and those products that remain uncollected. The more relevant impact assessment categories include the effects of landfill usage along with terrestrial and aquatic ecotoxicity as mentioned in LCA studies. Since every item channeled for disposal must comply with treatment standards set out by the European Union, we assume that there is a higher environmental footprint associated with the uncollected products as compared to the products channeled to disposal/landfills i.e., ($\hat{e}_d > e_d$). If the converse were true, there would be no environmental incentive from collection. Therefore, the EOL footprint is $\mathrm{E_{EOL}}^0 = (\tau(1-\sigma)q_n - q_r)e_d + ((1-\tau)q_n + q_r)\hat{e}_d$ for policy `0` and is $\mathrm{E_{EOL}}^{\mathrm{R}} = \tau(1-\sigma)q_n e_d + ((1-\tau)q_n + q_r)\hat{e}_d$ for policy `R`. A high value of $\hat{e}_d$ naturally means a high ecotoxicity potential owing to either higher concentrations of heavy metals or design characteristics that do not prevent the potential escape of such materials. The value of e_d reflects the effectiveness of treatment standards and subsequent technology employed to contain the hazardous effects. A value of e_d closer to $\hat{e}_d$ hints at the ineffectiveness of the treatment standard or of the technology employed.

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[1] Note that the effects of energy consumption during use also depends on the energy portfolio of the market and incremental share of renewable may dilute its effect. Hence, the footprint of the use phase under each policy can be represented as $\mathrm{E_u} = e_u(q_n + q_r)$.

A higher $(\hat{e}_d - e_d)$ highlights the case where contamination potential of toxic agents are substantially curbed down. Although there is some footprint associated with recycling operation, its impact is known to be minor in comparison with production or other operations (Hischier et al. 2005) and therefore we do not consider it in the analysis and the total end-of-life environmental footprint consists of environmental footprint from disposal and uncollected products. Therefore, the total environmental footprint is given as:

$$\mathrm{E}^i = \mathrm{E_p}^i + \mathrm{E_u}^i + \mathrm{E_{EOL}}^i \qquad \text{where} \quad i \in \{0, \mathrm{R}\}, \tag{6}$$

The assessment of the environmental footprint may require a combined assessment of different impact categories with different units of measurements. Although they may not be combined in all cases, in many cases, a conversion can be obtained. For example, resource depletion can be measured by considering the amount of surplus energy that would be required in future to excavate same set of resources(Müller-Wenk 1998). This measurement can be translated into global warming potential which is typically captured in terms of carbon emissions. In Appendix A-3, we review some commonly used methods employed for assessment of multi-criteria life cycle analysis.

Finally, we consider the social welfare which is the sum of the firm's profit, consumer surplus and environmental footprint and is given as:

$$\mathbf{W}^i = \Pi^i + S^i - \gamma \mathrm{E}^i \qquad \text{where} \quad i \in \{0, \mathrm{R}\}, \tag{7}$$

The conversion of environmental footprint into monetary term is required to perform social welfare analysis presented in equation (7). This is a fairly common assumption in sustainable operations literature Atasu et al. (2009, 2013).

Throughout the analysis in the next section, we remain interested in the cases where legislative intervention leads to remanufacturing ($q_r^i > 0$) and there is a non-negative amount of products channeled to disposal or recycling.

4. Comparative Analysis of the Original and the Recast WEEE Directives

In this section, we focus on the effects of shift from the Original WEEE Directive to the Recast policy to investigate its influence on remanufacturing decisions and the overall environmental and economic outcomes. The EPR legislation requires firms to incur the cost of collection and treatment of EOL/EOU products and an OEM may avoid treatment cost by engaging into remanufacturing activity. In general, EPR legislation aims to create incentives for remanufacturing. Our question is : *Does the shift to Recast Directive generate more incentives for remanufacturing?*

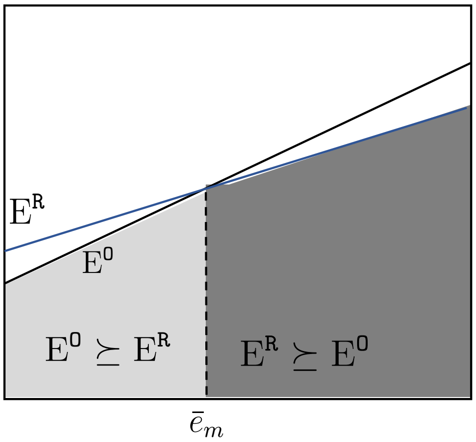

Figure 2 **Comparison of Policies $\mathtt{0}$ and $\mathtt{R}$ with respect to $\mathrm{E}^{\mathtt{0}}$ and $\mathrm{E}^{\mathtt{R}}$**

Proposition 1. *Let $\bar{c}_r^i$ be the highest value for OEM's remanufacturing cost that would trigger remanufacturing. (a) $\bar{c}_r^{\mathtt{R}} \geq \bar{c}_r^{\mathtt{0}}$. (b)$\dfrac{\partial \bar{c}_r^{\mathtt{i}}}{\partial \tau} > 0, \quad \dfrac{\partial \bar{c}_r^{\mathtt{i}}}{\partial \sigma} > 0$ where $i \in \{\mathtt{0}, \mathtt{R}\}$*

Proposition 1(a) shows that under policy $\mathtt{R}$, the OEM would engage into remanufacturing at c_r levels that would be prohibitive under policy $\mathtt{0}$. In other words, some firms which do not remanufacture under policy $\mathtt{0}$ may start remanufacturing when the policy $\mathtt{R}$ is implemented. This is because a firm may count remanufactured products towards fulfilling its recycling obligation. Part (b) of the proposition states that stricter enforcement parameters (τ, σ) lead to a higher accrual of costs under policies $\mathtt{0}, \mathtt{R}$. Under policy $\mathtt{R}$, however, some of the required increase in recycling can be avoided through increased product reuse.

4.1. Environmental and Economic Outcomes of Recast Directive

It has been established that Recast Directive provides additional incentives for the product reuse. Now, we focus our attention to environmental and economic outcomes of the Recast policy in comparison with the Original Directive. *Do the additional incentives for the product reuse in policy* $\mathtt{R}$ *translate into improved environmental outcomes?* In our next proposition, we compare the environmental performance of the two policies:

Proposition 2. *Let* $\bar{e}_m = \dfrac{(1-\delta)(\hat{e}_d + e_u)}{\delta} + \dfrac{e_d(\delta c_n - c_r + c_d + \delta\tau c_d)}{\delta(c_{rec} - c_d)} + \tau(\hat{e}_d - e_d) + 2\tau\sigma e_d,$

$$E^{\mathtt{R}} \succeq \mathrm{E}^{\mathtt{0}} \text{ iff, } e_m \geq \bar{e}_m \quad \text{where, } \succeq \text{ implies preference order}$$

Since Policy $\mathtt{R}$ offers better incentives for remanufactured products that cannibalize the new products, it is clearly preferable from the perspective of virgin material usage. Through the associated market expansion (i.e., larger q_n plus q_r), however, this translates into higher environmental footprint during the use and EOL phases. Consequently, the Recast policy is not expected to strictly dominate the Original policy in terms of total environmental footprint. Proposition 2 spells out the minimum production footprint, which ensures that the above mentioned increases are offset by the reduction in the production phase. This proposition can be also perceived as a means to map products to the preferred policies, since e_m is indeed a product characteristic. Figure 2 characterizes the two regions where policies `O` and `R` are preferable to each other.

In the context of E-waste, it is well-known that low-entropy machining requirements and presence of critical raw materials make virgin material usage footprint much higher for microchips. Some studies such as (Williams et al. 2002) have pointed out that the secondary material used in the production of a microchip is 630 times the weight of original product which by far exceeds any traditional product (e.g., for automobiles this ratio is typically 2). Therefore, the products with significant presence of semi-conductor material have a very high virgin material usage footprint. The examples include computers and LCD/LED screens where virgin material usage respectively accounts for 81% and 60% of the total life cycle footprint (Williams 2004, Bhakar et al. 2015). Our results show that, for all such products, the Recast Directive is clearly a step in the right direction.

The WEEE Directive, however, also includes some products where the life cycle footprint is dominated by the energy consumption during operational life such as refrigerators, lamps where energy consumption during operation contributes to 90%, 80% of the total footprint, respectively (Kim et al. 2006, Welz et al. 2011). For these products, the incentives generated in the Recast Directive may culminate into unintended environmental consequences. It is worth noting that many of these products belong to the category of large appliances where product retention period is long (10-15 years) and eco-innovations have radically improved the energy efficiency. Despite this, some life cycle studies for these appliances still find environmental benefits with the product remanufacturing (OConnell and Fitzpatrick 2013).

Note that $\bar{e}_m$ is increasing in $(e_u, \hat{e}_d)$ implying that higher footprint associated with the use phase and that of uncollected products would make Recast policy less preferable to the Original policy from an environmental viewpoint. This is because the Original policy is better equipped to curtail these two components of footprint. For similar reasons, in presence of more stringent collection and recycling targets, the Original policy is expected to yield better results. If the target levels are less stringent, however, policy `R` may lead to better outcomes. $\bar{e}_m$ is decreasing in (δ) iff $\left(\frac{\hat{e}_d + e_u}{e_d} > \frac{c_r - c_d}{c_{rec} - c_d}\right)$. This means that increasing appeal of remanufactured product would make Recast policy more likely to dominate when a large footprint is associated with use phase or with the uncollected products and/or disposal into sanitary landfills significantly contains the hazard potential of E-waste.

Having compared the environmental performance of the two policies, we now turn our attention to the economic implications and compare the two policies from the perspectives of profitability and consumer surplus.

Proposition 3. *(a)* $\Pi^{\mathrm{R}} \geq \Pi^{0}$ *(b)* $S^{\mathrm{R}} \geq S^{0}$

Proposition 3 shows that the incentives for OEM's profitability and consumer surplus are aligned in the sense that when the former is higher, the latter follows and vice versa. The overall increase in total number of products in the market under policy R protects consumers well-being and therefore consumer surplus is always higher. Similarly, by inclusion of the product reuse into recycling, the policy-maker not only creates incentives to promote product reuse but also eases off the financial burden of product collection and recycling. Therefore, policy R leads to higher profits as well.

A combined overview of propositions 2 and 3 asserts that for products with significantly high virgin material usage, policy R is preferable from both environmental and economic viewpoints. Note that for the analysis of Propositions 2, 3 we consider that remanufactured products are exempt from collection obligations. We relax this assumption in Appendix A-4 of this paper and demonstrate that the qualitative insights remain the same.

4.2. The Use of Collection and Recycling Rates as a Policy Lever

Another outcome of the Recast Directive is the re-demarcation of product categories where the original set of ten different product categories was reduced to six. As a result, a number of products were assigned to new product categories and experienced a change in the respective target levels from the Original Directive. For example, the products placed under category 1 in the Original Directive were distributed to categories 1,4 and 5 in the Recast. As another example, the recycling target for a microwave oven was reduced by 25 % with the implementation of the Recast. In general, there has been a change of ±10% in the recovery target levels, and ±25% in the recycling target levels. It is also observed that this change is always synchronized such that increase in recovery target is always complemented with an increase in the associated recycling target and vice versa. It is important to understand how these target levels should be adjusted with the shift to the Recast. Another question is whether the incentives for both levers are completely aligned such that an increase in one lever is to be essentially coupled with a raise in the other?

	Collection Target τ	Recycling Target σ
$\mathrm{E_{EOL}}^{\mathrm{R}}$	$\tau > \frac{1-\delta-c_n+c_r-c_{rec}}{2(c_d-\sigma c_d+\sigma c_{rec})}$	$\frac{\hat{e}_d-e_d}{e_d} > -2\sigma + \frac{1-\delta-c_n+c_r-c_{rec}-\tau c_d}{\tau(c_{rec}-c_d)}$
$\mathrm{E_{EOL}}^{0}$	$\frac{\hat{e}_d-e_d}{e_d} < -\sigma - \frac{1}{-2\tau+\frac{1-\delta-c_n+c_r-c_d}{c_d-\sigma c_d-\sigma c_{rec}}}$	$\frac{\hat{e}_d-e_d}{e_d} > -2\sigma + \frac{2}{\tau} + \frac{1-\delta-c_n+c_r-c_{rec}-\tau c_d}{\tau(c_{rec}-c_d)}$
E^{R}	$\frac{e_m}{\hat{e}_d-e_d+\sigma e_d} < 2\tau - \frac{1-\delta-c_n+c_r-c_{rec}}{c_d-\sigma c_d+\sigma c_{rec}}$	$\frac{\hat{e}_d-e_d}{e_d} - \frac{e_m}{\tau e_d} > -2\sigma + \frac{1-\delta-c_n+c_r-c_{rec}-\tau c_d}{\tau(c_{rec}-c_d)}$
E^{0}	$\frac{(e_m+e_d)}{(\hat{e}_d-e_d+\sigma e_d)} < 2\tau - \frac{1-\delta-c_n+c_r-c_d}{c_d-\sigma c_d+\sigma c_{rec}}$	$\frac{\hat{e}_d-e_d}{e_d} - \frac{e_m}{\tau e_d} > -2\sigma + \frac{2}{\tau} + \frac{1-\delta-c_n+c_r-c_{rec}-\tau c_d}{\tau(c_{rec}-c_d)}$

Table 2 Conditions for τ, σ so that proposition 4(b) holds

Proposition 4.
(a) $\partial \mathrm{E_p}^i / \partial\tau < 0, \partial \mathrm{E_p}^i / \partial\sigma < 0$ *and* $\partial \mathrm{E_u}^i / \partial\tau, \partial \mathrm{E_u}^i / \partial\sigma = 0$ *for,* $i \in \{0, \mathrm{R}\}$
(b) $\partial \mathrm{E_{EOL}}^i / \partial\tau > 0$, $\partial \mathrm{E_{EOL}}^i / \partial\sigma > 0$ *and* $\partial \mathrm{E}^i / \partial\tau > 0, \partial \mathrm{E}^i / \partial\sigma > 0$ *provided the conditions presented in Table 2 are satisfied.*

As the collection and recycling target levels increase, the firm needs to reduce the new products introduced into the market so as keeping the associated costs the same. This is the reason behind the decreasing virgin material usage under more stringent target levels (Proposition 4a). The decrease in the new products is always complemented with an increase in the remanufactured product quantity such that the total number of products in the market remain the same, regardless of the level of collection and recycling targets. Therefore, the total product quantity and subsequently the environmental footprint associated with energy consumption during operational life of the products (use phase) is independent of collection/recycling targets (Proposition 4a). In a way, the existing target levels are not equipped to address the issue of energy consumption during operational life of products and if it becomes significant then additional policy parameters are required for promotion of energy efficient designs or to minimize overall usage.

The WEEE Directive and the associated collection and recycling targets were introduced with an intention to strengthen collection efforts and promote waste diversion from landfills. However, regulator's efforts stipulated through respective collection and recycling targets may lead to unintended consequences resulting in an increase in the number of products that remain uncollected or end up in landfills. Increased target levels incentivizes remanufacturing. Note that the remanufactured products are exempt from collection and recycling obligations and therefore may lead to higher end-of-life footprint. Therefore, beyond a threshold value, further increase in the collection target will lead to higher end-of-life footprint (Proposition 4b). For a

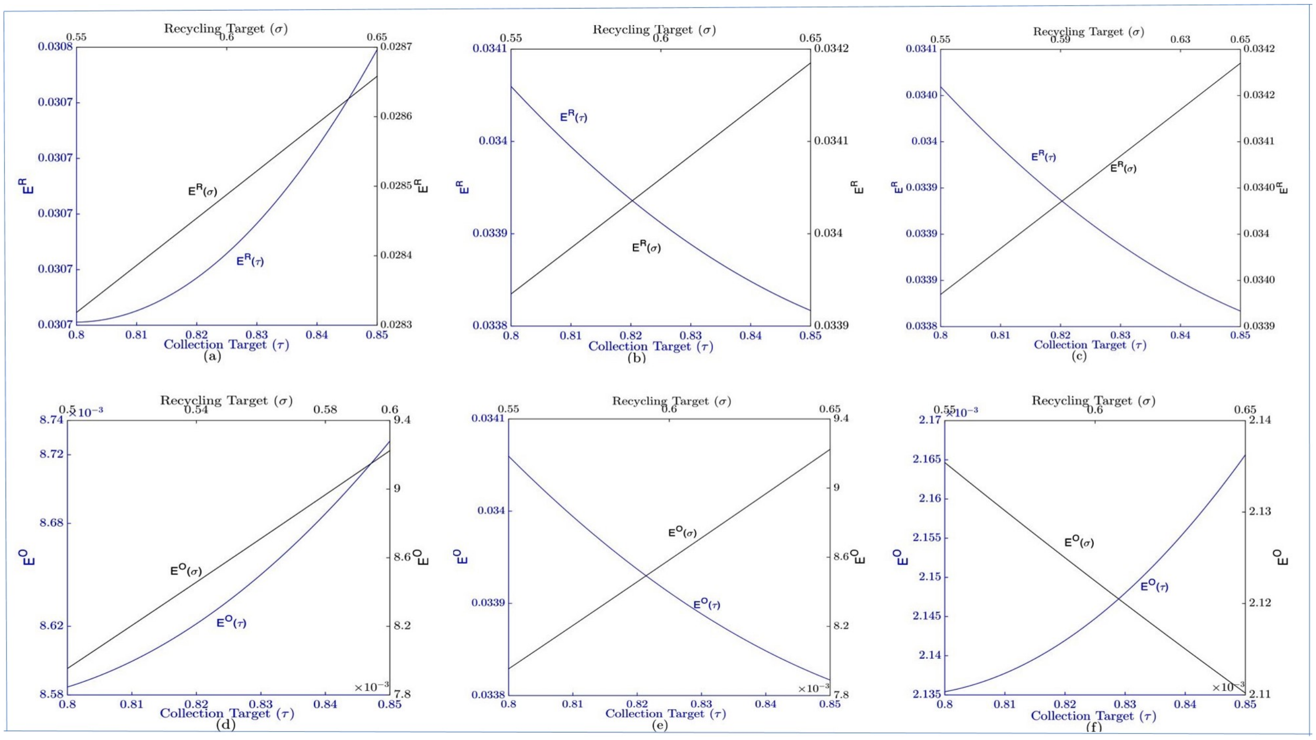

Figure 3 **Change in Total Environmental Footprint with τ and σ (a,b,c) represent Recast policy and (d,e,f) original policy**

Recast policy, this threshold is independent of the environmental characteristics but decreases as the incentives for remanufacturing improve. Regardless of the fact that end of life footprint increases or decreases with collection target, it may also increase with the recycling target. Better remanufacturing incentives make it a more likely case. Besides, this is also contingent upon the environmental characteristics of the product. For products where first treatment of collected products substantially reduces the toxicity potential ($\hat{e}_d >>> e_d$) such as refrigeration and air-conditioning equipment where end of life footprint can be suppressed with mere removal of refrigerating agents, it becomes more probable that further increment in recycling target leads to higher environmental footprint from end of life perspective. Therefore, the incentives for collection and recycling targets may not be perfectly aligned in the sense that when one increases- the other may be required to decrease and vice versa. In presence of the original directive, the environmental footprint may also increase with the enforcement levers, however the conditions are much tighter as compared to the case of recast directive.

For some products, the EOL footprint may offset the environmental benefits due to low virgin material usage; and consequently, the total environmental footprint may increase with stricter target levels (Proposition 4 b). The CRT screens are a good example due to their high toxicity potential. Another example is laptops, albeit their low virgin material usage -in comparison with desktops- (Williams et al. 2008, Musson et al. 2006). Therefore, for such products a decrease in respective collection/recycling targets may be required. The total environmental footprint may increase/decrease with target levels and as it increases with collection target, it may increase/decrease with the recycling target and vice versa. Figure 3 presents the instances under both policies where environmental footprint increases with both target levels 3 (a,d) and where it increases in one level but decreases with the other 3 (b,c,e,f). Although, the environmental footprint may increase with enforcement levers in presence of both the Original and the Recast policies, the conditions are more constrained for the former.

Proposition 4 stipulates that a reduction in the target levels can be a desirable action from a purely environmental perspective with the implementation of the Recast policy. Our next corollary identifies the products where a stricter target level improves the environmental outcomes.

Corollary 1. *Under policy* R, *for all products where* $e_m > \bar{e}_m$, *the total environmental footprint is always decreasing with collection and recycling targets.*

Corollary 1 states that for products where Recast Directive leads to better environmental results in comparison with the Original policy, an increase in collection and recycling targets always culminates into improved environmental results. It basically demonstrates one of the advantages of the Recast policy. If appropriately selected, the environmental outcomes only improve with stricter target levels and a policy-maker does not need to worry about unintended environmental results in response to stricter measures. It also highlights the importance of selecting a right policy tool keeping product characteristics in consideration. The reduction in target levels as proposed in proposition 4 may only be desirable for products for which original policy is a preferable option.

5. Economic and Environmental Implications of a Separate Reuse Target Policy (P)

Some circles among environmental bodies and social organizations have argued that the Recast Directive remains insufficient for fully exploiting the product reuse potential (Guardian 2012, Len 2013). In particular, a long-standing proposal for implementing a 5% separate target for the product reuse has been overlooked. The promotion of product reuse is aligned with European Union efforts to create a circular economy and complements the circular economy package adopted in December 2015. Some countries such as Spain have already started maintaining a record of their reuse operations. The Recast Directive itself states in the article 11(6) *“ On the basis of a report of the Commission accompanied, if appropriate, by a legislative proposal, the European Parliament and the Council shall, by 14 August 2016, re-examine the recovery targets referred* *to in Annex V, Part 3, examine the possibility of setting separate targets for WEEE to be prepared for reuse"*. There is no consensus among the stakeholders about possible inclusion of a separate reuse target. While the environmental agencies and reuse organizations have firmly backed the proposal (Len 2013), producer responsibility organizations insist that such an initiative is expected to cast undue financial stress with little environmental gains (CECED 2015). Some studies have examined the possibility of a separate target for product reuse (Seyring et al. 2015, Vergunst et al. 2016). Vergunst et al. (2016) reports that only seven out of twenty interviewed member states are in favor of a separate target for the product reuse. This leads us to the next set of questions: When, does a separate reuse target, become indispensable for the environment? What are the economic implications of such a scheme? Can comparable results be achieved through alternative means such as fiscal levers?

We denote this proposed policy with superscript P where in addition to mandatory collection and recycling targets (τ, σ), there is also a separate target for reuse (ϕ) that specifies that the firm shall remanufacture no less than a fraction of products it manufactures as new i.e., $q_r^{\mathrm{P}} \geq \phi q_n^{\mathrm{P}}$. The formulation of this problem is similar to policy R except from an additional binding constraint on the remanufactured quantity.[2]

In presence of the binding constraint on reuse quantity, the problem reduces to a single decision variable problem in lieu of original two-variable problem. The firm's original decision variable is the quantity of new product. The remanufactured product quantity is defined by the regulator as a fraction of new products which also stems a large part of criticism from the OEMs (CECED 2015). The solution is complicated and is a non-linear function of the reuse target (ϕ). Esenduran et al. (2015) present the solution characteristics of this problem and demonstrate that increasing reuse targets may also deteriorate environmental outcomes. We take a different approach and analyze the conditions when this policy leads to more favorable results.

PROPOSITION 5. *(a) Let* $\bar{\bar{e}}_m = \tau(\hat{e}_d - e_d + \sigma e_d) + \dfrac{(1-\delta)(\hat{e}_d + e_u)}{\delta(1+\phi)}$,

$$\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{\mathrm{R}} \quad \textit{iff} \qquad e_m \geq \bar{\bar{e}}_m$$

$$\textit{(b)} \quad S^{\mathrm{R}} \geq S^{\mathrm{P}}, \qquad \Pi^{\mathrm{R}} \geq \Pi^{\mathrm{P}}$$

Proposition 5(a) asserts that improved environmental outcomes can not be guaranteed through implementation of a separate reuse target policy either.[3] With policy P, there are more remanufactured products in the market that cannibalize the new products leading to a lower virgin material usage. The market expansion

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[2] According to this policy, product remanufacturing will continue to be considered into recycling target but there is another target over minimum reuse level.

[3] We remind the readers the similar results in Proposition 2(a)

effect ensures an increase in the total number of products in the market and therefore a higher use phase and EOL footprint. Therefore, policy P is only environmentally advantageous where significant component of product's footprint is associated with virgin material usage i.e., for all products with virgin material usage higher than a threshold value $\bar{\bar{e}}_m$. Note that, similar to Proposition 2, $\bar{\bar{e}}_m$ characterizes the boundary between the two regions where policy R and policy P are preferred, respectively.

Higher values of collection/recycling targets and higher values of environmental footprint associated with the use phase or that of the uncollected products $(e_u, \hat{e}_d)$ would make it less likely for a policy P to dominate the Recast policy. However, higher value of footprint associated with disposed products (e_d) would make policy P more likely to dominate Recast i.e., this policy can be more effective for products where initial treatment procedures and disposal into the sanitary landfills do not significantly reduce the environmental hazard. The higher the incentives for remanufacturing (δ) or the value for the reuse target (ϕ) are, the more the policy P is likely to dominate.

From the perspective of economic outcomes, Proposition 5(b) stipulates that policy P reduces profit and consumer surplus in comparison with policy R. Since, policy P is more constrained than policy R, it is straightforward that the firm's profitability is compromised. However, despite leading to higher number of products in the market, the consumer surplus still remains lower with respect to policy R. From the perspective of social welfare, policy P must accumulate enough merits on environmental front to compensate for the lower economic outcomes associated with it. Therefore, it only dominates policy R for products with a very high virgin material usage footprint. The products with significant presence of semiconductor appear to be appropriate candidates for the implementation of policy P.

Esenduran et al. (2015) warns about the undesirable effects of increase in the environmental footprint in response to the implementation of a separate reuse target (ϕ). Our next corollary identifies conditions where this effect diminishes.

COROLLARY 2. *(a)* E^{P} *is strictly decreasing in collection and recycling targets. (b) For all products where policy* P *outperforms policy* R *i.e.,* $e_m > \bar{\bar{e}}_m$*; the environmental footprint is strictly decreasing in reuse target* (ϕ).

We note that unintended environmental outcomes as pointed out by Esenduran et al. (2015) only appear in presence of inappropriate policy selection. As long as policy P remains the optimal policy option, it is guaranteed that the total environmental footprint is decreasing in the reuse target (ϕ) and consequently fears about deterioration of environmental outcomes would disappear. This underscores the importance of

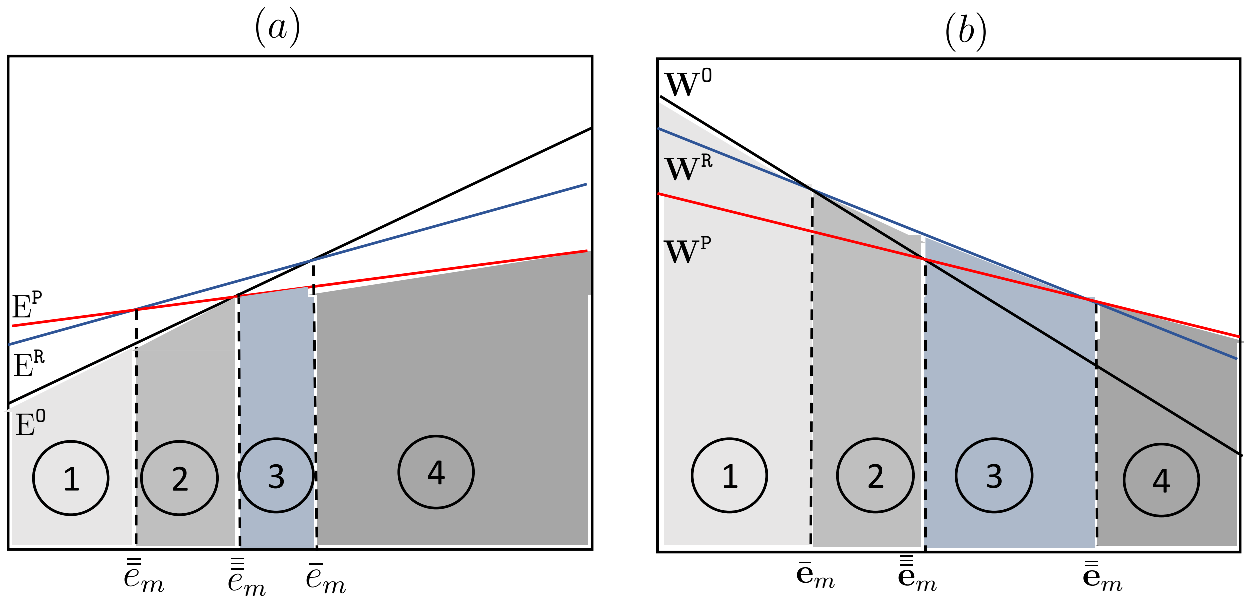

Figure 4 **Comparison of Footprint and Social Welfare**

considering product characteristics before selecting an appropriate policy tool. Regardless of the fact that policy P is the optimal policy choice or not, the environmental footprint is always decreasing with collection and recycling targets (τ, σ).

5.1. Choosing among 0, R and P

Through Propositions 3 and 5, we have established that policy R leads to better economic outcomes than policies 0, P for all products. From the environmental and social welfare perspectives, however, there is no policy option that is preferable for all products. The environmental characteristics of the products play a key role in determining the most appropriate policy for a product. First, we focus on the total environmental footprint:

Proposition 6. *Among Policies* 0, R *and* P, *Policy* 0 *is preferred from an environmental perspective if and only if* $e_m < \bar{\bar{\bar{e}}}_m$ *and Policy* P *is preferred otherwise.*

As depicted in Figure 4 the threshold $\bar{\bar{\bar{e}}}_m$ is the intersection point of the environmental footprints of policies 0 and P. We provide the expression for $\bar{\bar{\bar{e}}}_m$ in the Table 3 in the Appendix. The four regions in Figure 4(a) are defined by the three intersection points among policies 0, R and P. It is important to note that there does not exist a region, where the WEEE Recast i.e., policy R, appears to be the most preferred choice from an environmental viewpoint. It loses its advantage to policy P before it starts to dominate 0.

From the environmental viewpoint, products with low virgin material footprint, e_m, would require the implementation of a recycling focused policy. Therefore, policy 0 is the most effective choice, followed by policy R and P (region 1 of Figure 4 a). For products with high virgin material usage, however, a reuse focused policy becomes exigent. Therefore, policy P emerges as the best policy option (region 4 in Figure 4 a).

Turning to social welfare, the conversion factor for the environmental footprint in (6) is crucial. If the environmental footprint possesses a higher weight in the social welfare function, then the ranking order remains qualitatively the same as in Figure 4(a) albeit, the respective thresholds would be different. However, if the environmental concerns are not too high, the economic implications begin to take part in shaping up the preference order of policies as depicted in Figure 4(b).

Proposition 7. *When the environmental impact is not a priority for the firm, Policy* R *is preferred to Policies* O *and* P *from social welfare perspective if and only if* $\bar{\mathbf{e}}_m < e_m < \bar{\bar{\mathbf{e}}}_m$*, Policy* O *is preferred if and only if* $e_m < \bar{\mathbf{e}}_m$ *and Policy* P *is preferred otherwise.*

All in all, these results resonate with one of the key messages of our paper that if a reuse target based policy is to be implemented, its scope should only be restricted to the products with significantly high virgin material footprint.

5.2. Alternative Policy Schemes

The manufacturing firms opposed the proposal of a separate reuse target ORGALIME (2016), CECED (2015) with the arguments that product remanufacturing should be driven through market mechanism rather than be enforced through a regulatory framework. The implementation of a separate target for reuse represents only one way of generating incentive to promote product reuse. There are alternative means of achieving the same objective which include (i) adjustment to existing enforcement levers (ii) introduction of fiscal levers. Therefore, our next objective is to study the impact of alternative policy measures i.e., a more ambitious combined recycling/reuse target as well as incentive based schemes (tax/subsidy schemes). We investigate if the same level of reuse can be obtained through one of these schemes, and if so, what are the environmental and economic implications in comparison to a separate reuse target based policy?

5.2.1. Adjustments to Target Levels (Policy $\hat{\text{R}}$) The reuse level defined by (q_r/q_n) can also be increased with more stringent collection and recycling targets. Therefore, we consider a variant of policy R, represented as $\hat{\text{R}}$, where target levels are elevated such that the same level of reuse, which is intended through a policy P, is achieved.

Proposition 8. *For any reuse target* $\phi \in \left(0, \frac{\delta c_n + \delta c_{rec} - c_r + c_{rec}}{\delta(1 - \delta - c_n + c_r - 2c_{rec})}\right)$ *in policy* $\mathtt{P}$*, if collection and recycling targets* (τ, σ) *for* $\hat{\mathtt{R}}$ *can be increased to achieve same level of reuse as policy* $\mathtt{P}$ *then,*
(a) $\mathrm{E}^{\hat{\mathtt{R}}} \geq \mathrm{E}^{\mathtt{P}}$ *(b)* $\Pi^{\mathtt{P}} \geq \Pi^{\hat{\mathtt{R}}}$*, (iii)* $S^{\mathtt{P}} \geq S^{\hat{\mathtt{R}}}$

Proposition 8 discusses the implications of having more ambitious enforcement levers and compares it with the policy that advocates a separate reuse target i.e., policy $\mathtt{P}$. Since the collection/recycling targets have upper bounds $(\tau, \sigma < 1)$, there can be a limit to the maximum level of reuse that can be achieved through this adjustment. But if target levers can be raised to achieve the same level of reuse as intended through a separate reuse target based policy, policy $\hat{\mathtt{R}}$ always leads to more favorable environmental outcomes albeit less favorable economic outcomes in comparison with policy $\mathtt{P}$. This is due to the fact that additional strain of increased collection/recycling forces an OEM to reduce the quantity of new products as well as total product quantity in the market. As a result, both virgin material usage and use phase footprint is lower under policy $\hat{\mathtt{R}}$. The higher collection/recycling rates coupled with a lower new product quantity would induce a lower end-of-life footprint as well. However, this additional cost of collection/recycling as well as a lower new product quantity leads to a lower profitability and consumer surplus.

This finding is in contrast with the conventional beliefs among the stakeholders. The environmental and social organizations have backed a separate reuse target but producer bodies had resisted this proposal, albeit had consented to a higher recycling rate (ORGALIME 2016). Our results show that such a policy shift reduces the profitability and consumer surplus contrary to the expectations of the OEMs and leads to a lower environmental footprint in contrast to the arguments of the environmental and social organizations.

5.2.2. Tax on Manufacturing/Subsidy on Remanufacturing (Policy $\mathtt{T}$**)** As the target levels can not be raised beyond a certain extent, the level of reuse that can be achieved with the adjustment of enforcement parameters is sometimes limited. At times, even the most stringent target levels may not lead to the same level of product reuse as intended through a separate reuse target based policy. In such cases, fiscal levers can be introduced in addition to the existing target levels. The fiscal levers may be in the form of taxation on new products, a subsidy on the remanufactured products or a combination of both. Our next proposition studies the performance of this scheme in comparison with policy $\mathtt{P}$. We analyze three different variants. First, we take into account a taxation based policy which introduces a taxation (t_m) on new products. Clearly, this policy transmits the financial burden to the producers. The next variant introduces a subsidy (s_r) on remanufactured products. However, such policy requires external funds and is therefore criticized for transmitting the financial cost to the tax-payers. Therefore, our third policy employs both levers i.e., a taxation on new products is coupled with a subsidy on remanufactured products. Furthermore, we associate a strict cost-neutrality assumption with this policy variant i.e., the funds directed towards subsidies are generated from taxation levers and therefore, no funds are directed to or from the OEM operations. This cost neutrality assumption also warrants a fair comparison with policy P that includes a separate reuse target which is characteristically cost neutral.

Proposition 9. *(a) There exists a value of taxation on manufacturing* ($t_m > 0$) *with remanufacturing subsidy* $s_r = 0$ *such that policy* T *reaches same reuse level of policy* P *i.e.,* $\phi = {q_r}^{\mathrm{T}}/{q_n}^{\mathrm{T}}$*. In that case,(i)* $\mathrm{E}^{\mathrm{T}} \geq \mathrm{E}^{\mathrm{P}}$*, (ii)* $\Pi^{\mathrm{P}} \geq \Pi^{\mathrm{T}}$*, (iii)* $S^{\mathrm{P}} \geq S^{\mathrm{T}}$

(b) There exists a value for remanufacturing subsidy ($s_r > 0$) *with* $t_m = 0$ *such that policy* T *reaches same reuse level of policy* P *i.e.,* $\phi = {q_r}^{\mathrm{T}}/{q_n}^{\mathrm{T}}$*. In that case,(i)* $\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{\mathrm{T}}$*, (ii)* $\Pi^{\mathrm{T}} \geq \Pi^{\mathrm{P}}$*, (iii)* $S^{\mathrm{T}} \geq S^{\mathrm{P}}$

(c) Any cost-neutral taxation-subsidy based scheme can lead to same environmental and economic outcomes as of policy P.

Part (c) of proposition 9 asserts that any level of reuse with same environmental and economic objectives as desired through a separate reuse target based policy (policy P) can be achieved through a combination of *a cost-neutral tax/subsidy based scheme* with existing collection and recycling targets. Such a scheme can completely replicate the benefits of a reuse target based scheme. Therefore, a policy-maker may consider utilizing fiscal levers as policy tools instead of a separate reuse target. Fiscal levers provide several advantages over obligation or liability based schemes. First, these are considered "soft" incentive structures by OEMs. Second, they are easier to customize in consideration with individual characteristics of the firm and the product it offers, in contrast with target based schemes which usually operate on "one size fits all" principle.

6. Product-Specific Targets versus Category-Based Targets

The earlier discussion highlights the critical role product characteristics play in shaping up the optimal policy choice. A policy that is suitable for one product, may not be optimal for the other. Hence, the existing practice of the "one size fits all" approach may be an obstacle towards better environmental outcomes. The future of WEEE regulation does not necessarily lie in the introduction of more comprehensive set of enforcement levers. In our view, incorporation of product attributes into policy design can be a promising avenue of extension. The collection and recycling targets in the existing Recast Directive are based on product categories. That provides the firm a leverage to meet regulatory obligations through selective collection and recycling of more favorable products within the same category. It is well-known that the producers concentrate most of their collection and recycling efforts on financially rewarding products potentially leaving other products unattended. Interestingly, the policy makers seemed to have made an effort to deal with this issue by reducing the number of product categories from ten to six with the implementation of the Recast. This effort naturally resulted in changes in the classification of a number of products. In this section, we investigate the potential benefits of a product centric approach in contrast with the current product category based scheme.

We extend our model by including an additional product in the same category, offered by the same manufacturer in the monopolistic setting. A single firm that offers refrigerators and freezers (both in category 1) or LCD and CRT screens (both in category 4) would be the examples. For simplicity, we do not consider the effects of market interaction between the products, therefore, assuming that both have distinct markets and do not interfere with each other. This is a reasonable assumption for a number of products such as freezers and refrigerators. The first product retains the notations from the earlier sections of the paper, while a capital letter subscript is used to denote the characteristics of the second product. For convenience, we call them P_1 and P_2 respectively.

Category based scheme is denoted by $\mathcal{C}$. The existing category based scheme constitutes two levers namely collection and recycling targets (τ, σ) applied on the whole product category. As a result, the firms can increase collection and recycling of more favorable products in lieu of less favorable and potentially more hazardous products. The existing policy can be extended to incorporate an additional lever in the form of a reuse target (ϕ_C) to be applied on the whole product category. We study both variants of the category based scheme. We denote $\mathcal{C}^i$ where $i \in \{P, F\}$. The superscript P represent the existing version of the category based scheme with two enforcement levers. The superscript F denotes a future policy where an additional lever in the form of a reuse target is incorporated in addition to existing collection and recycling targets. We denote the product specific scheme as $\mathcal{S}$. Under this policy, the firm is required to meet the collection and recycling targets (τ, σ) for each individual product. In order to ensure a fair comparison, we assume same target levels separately apply to both products in product specific schemes.

The two schemes are compared considering that both products are different in terms of their attractiveness to recycling and reuse options i.e., $c_{REC} > c_{rec}$. For the sake of simplicity, we assume that both products have identical disposal costs $(c_d = c_D)$. Naturally, P_1 is a more attractive recycling option. For a product specific scheme $(\mathcal{S})$, the legislation requires the OEM to collect and recycle both products separately. However, in presence of a category based scheme ($\mathcal{C}^i$), an OEM prefers to fulfill its entire recycling commitment through increased recycling of P_1.

The firm's objective function is the same for policies ($\mathcal{C}, \mathcal{S}$). The policies are merely differentiated by the constraint set. The optimization problem and set of constraints for both policies are stated below:

$$\begin{aligned}
\Pi^i =& q_n(p_n - c_n) + q_N(p_N - c_N) + q_r(p_r - c_r) + q_R(p_R - c_R) - (q_c - q_{rec} - q_r)c_d \\
& + (q_C - q_{REC} - q_R)c_D - q_{rec} \times c_{rec} - q_{REC} \times c_{REC} \qquad \text{where,} \quad i \in \{\mathcal{C}, \mathcal{S}\} \\
& \textbf{Product Specific targets } \mathcal{S} \\
& q_c \geq \tau q_n, \quad q_C \geq \tau q_N, \quad q_{rec} \geq \sigma q_c - q_r, \quad q_{REC} \geq \sigma q_C - q_R \\
& \textbf{Category based Targets } (\mathcal{C}^F) \\
& q_c + q_C \geq \tau(q_n + q_N), \quad q_{rec} + q_{REC} \geq \sigma(q_c + q_C) - q_r - q_R, \quad q_r + q_R \geq \phi_C(q_n + q_N) \\
& \textbf{Category based Targets } (\mathcal{C}^P) \\
& q_c + q_C \geq \tau(q_n + q_N), \quad q_{rec} + q_{REC} \geq \sigma(q_c + q_C) - q_r - q_R,
\end{aligned} \tag{8}$$

There are multiple solution regions with the solution to this problem depending upon the values of various cost parameters. Although a complete characterization is possible, we restrict only to some interesting cases for the sake of brevity and expositional clarity. These cases highlight the role of product recyclability and remanufacturability in the selection of optimal policy. With a product specific scheme ($\mathcal{S}$) in place, the firm is required to meet the targets for both products individually and therefore the difference in recycling costs in both products does not alter firm's recycling and reuse strategy.

6.1. Firm's Recycling/Reuse Strategy under Category based Scheme

With a category based scheme ($\mathcal{C}$) in place, the firm's recycling and reuse decisions for the product P_2 depend upon the relevant cost advantage. The following corollary characterizes the firm's recycling/reuse strategy in presence of category based scheme.

COROLLARY 3. *(a) If* $q_n^i > \sigma\tau(q_n^i + q_N^i) - q_r^i$, then $q_{REC}^i = 0$.
(b) If $q_n^i < \sigma\tau(q_n^i + q_N^i) - q_r^i$, then two cases are possible:
(i) If $c_{REC} < \bar{c}_{REC}^i$ *then* $q_{rec} = q_n^i - q_r^i$ *and* $q_{REC} = \sigma\tau(q_n^i + q_N^i) - q_R^i - q_n^i$;
(ii) If $c_{REC} > \bar{c}_{REC}^i$ *then* $q_{REC}^i = 0$ *and* $q_R^i = \sigma\tau(q_r^i + q_R^i) - q_n^i$.
(c) c_{REC}^i *is decreasing in remanufacturing cost of* P_1 *and is increasing in remanufacturing cost of* P_2 *and recycling cost of* P_1*. where* $i \in \{C^P, C^F\}$.

This corollary underlies the firms recycling and reuse strategy in presence of category based schemes with different recycling characteristics. If the new product quantity of P_1 is sufficiently high in comparison with that of P_2, the firm is incentivized to fulfill its entire recycling quota from increased recycling of P_1. However, when this is not the case, the firm weighs option of either starting recycling of P_2 or meet its recycling quota through increased reuse of P_2. If the recycling cost of P_2 is below a threshold, the firm merely starts to recycle P_2 to meet its mandatory recycling requirement. However, if c^i_{REC} is higher than this threshold then the firm will no longer recycle P_2 but rather increase remanufacturing of P_2 to satisfy its entire recycling quota. This threshold value is decreasing in (c_r) i.e., the lower the reuse potential of P_1 is, the more likely it becomes that the firm satisfies its recycling quota through increased reuse of P_2. Similarly, the low reuse potential of P_2 or low recyclability of P_1 incentivizes firm to start recycling of P_2. A similar behavior is observed in presence of policy C^F when three target levels are implemented instead of the two although the threshold value is different. It can be shown that $\bar{c}^{C^F}_{REC} \leq \bar{c}^{C^P}_{REC}$. This means that that in presence of reuse targets, it is more likely that the firm switch to reuse focused strategy for P_2 i.e., increase reuse to fulfill recycling requirements instead of recycling P_2.

6.2. Comparison of Environmental Footprint

Next, we compare the environmental performance of the two schemes. In order to do so, we focus on specific cases that highlight the effect of product recyclability and reusability in policy choices. More specifically, we discuss two cases. Case 1 presents a scenario where P_2 does not have a reuse potential due to design constraints or market phenomenon i.e., $(q_R = 0)$. However, its recyclability level matches that of P_1 i.e., $(c_{REC} = c_{rec})$. Please recall that throughout the analysis, we have maintained $(c_d = c_D)$. The other case represents a more generic picture. Here, we assume that both products have some reuse potential. However, P_2 incurs a higher cost of recycling. We have already characterized this case in corollary 3.

Proposition 10. *CASE 1: No reuse potential for P_2 and Equal Recycling Costs*
Let, $\bar{\mathsf{e}}_{\mathsf{m}} = \bar{\bar{e}}_m - \dfrac{\hat{e}_d(1+\delta\phi_C)}{\delta(1+\phi_C)} - \dfrac{\delta(1-\delta)(e_M + e_U + \hat{e}_D - \tau\hat{e}_D + \tau e_D - \sigma\tau e_D)}{1+\phi_C}$,

$$(i)\mathrm{E}^{C^P} = \mathrm{E}^{\mathcal{S}} \qquad (ii)\mathrm{E}^{C^F} \geq \mathrm{E}^{\mathcal{S}} \quad iff, \quad e_m \geq \bar{\mathrm{e}}_{\mathrm{m}}$$

CASE 2: Both products have reuse potential but different Recycling Costs i.e., $q_r > 0, q_R > 0, c_{REC} > c_{rec}$

$$If, q^i_n > \sigma\tau(q^i_n + q^i_N) - q^i_r, then \quad \mathrm{E}^{\mathcal{S}} \geq \mathrm{E}^{C^P} iff \quad e_M \geq \mathcal{K}_1$$

$$Otherwise \quad (i) \quad \mathrm{E}^{\mathcal{S}} \geq \mathrm{E}^{C^P} iff \quad e_m \geq \mathcal{K}_2 \quad (when \quad c_{REC} < \bar{c}^P_{REC})$$

$$(ii) \quad \mathrm{E}^{\mathcal{S}} \geq \mathrm{E}^{C^P} \quad iff \quad e_M \leq \mathcal{K}_3 \quad (when \quad c_{REC} > \bar{c}^P_{REC})$$

Proposition 10 identifies conditions when a product centric approach ($\mathcal{S}$) is preferable to category based scheme (C^i). In summary, when a recycling focused policy is followed (e.g., category based scheme with two enforcement levers), the policy ($\mathcal{S}$) is preferable for all products with a significant footprint associated with production/virgin material usage (e_m or e_M). When a reuse focused category based scheme is invoked (e.g., policy with three enforcement parameters); the policy $\mathcal{S}$ becomes preferable as long as the products do not have a very high virgin material usage. Case 1 presents a simpler scenario where both products are equally recyclable and one of them does not have any reuse potential. It is shown that the existing version of category based scheme (C^P) is equivalent to product specific scheme. However, with three enforcement parameters i.e., (C^F) there exists a value of (e_m) below which a product specific policy ($\mathcal{S}$) is preferable. Note that this threshold is smaller than ($\bar{\bar{e}}_m$) as specified in proposition 10. This means for all products where a reuse target based policy was preferable, C^F is a preferable choice as long as one of the products is non-reusable. This is because presence of the reuse target constrains the production of new products when one of the products cannot be remanufactured. While Case 1 demonstrates the effect of product reusability, Case 2 presents a more general case where both products have a reuse potential and have different recycling costs. We have characterized the various plausible regions under this case in corollary 3. The results show that with a recycling focused policy i.e., C^P, the product centric approach is preferable if virgin material footprint is higher than a threshold level. The threshold values for policy C^P are presented. For reuse focused policy C^F, the threshold values are too messy to be presented here. However, they present a threshold value for (e_m or e_M) below which product specific policy is preferable. The complicated nature of expressions makes the comparison of the respective thresholds cumbersome for extraction of analytical insights. Therefore, we resolve to numerical experiments to understand the performance of two policies.

For simplicity, we first assume P_1 and P_2 are identical in terms of environmental characteristics i.e., all components of environmental footprint are the same for both products. In this case, we observe that the condition $e_m > \bar{e}_m$ is no longer sufficient (as in proposition 10 $\mathrm{E}^{C^F} \geq \mathrm{E}^{\mathcal{S}}$) to warrant the superiority of the category based scheme to the product specific scheme from environmental perspective. That is, policy $\mathcal{S}$ can be better for the products with higher virgin material usage footprint than specified in Case 1 of proposition 10. However, for the products where policy $\mathtt{R}$ is preferred to policy $\mathtt{P}$, an extensive numerical study suggests that product specific scheme tends to perform better. Although policy $\mathcal{S}$ demonstrates better results for products with higher EOL footprint, it is also capable of outperforming policy C^i for products with low EOL footprint if both products possess good reuse potential. One may associate a high virgin material usage with this policy in comparison with policy C^i due to fewer enforcement levers (absence of a reuse target), but we find evidences where policy $\mathcal{S}$ leads to lower virgin material usage as well. Thus, better performance of policy $\mathcal{S}$ is not confined to products with low virgin material footprint (e_m) but covers a wide range of products. All in all, we find instances where overall virgin material usage ($\mathrm{E_p}$) or higher end of life footprint ($\mathrm{E_{EOL}}$) may be higher under policy $\mathcal{S}$, yet it leads to better environmental outcomes in comparison with policy C^i. These findings are robust and remain valid even if the environmental characteristics of products P_1, P_2 differ.

Therefore, the evidence supports the effectiveness of product specific targets in curtailing the environmental footprint. We argue that the effectiveness of a category based scheme is contingent upon the realization of market realities along with consideration of environmental characteristics of all the products that are grouped together. A product specific target offers a simplified solution which outperforms a category based scheme in many cases. Therefore, future avenue of WEEE legislation may not necessarily include more enforcement parameters but introduction of product based targets can bring significant improvement.

6.3. Implementation of Product Specific Scheme ($\mathcal{S}$)

The replacement of existing category based scheme with a product centric approach seems to offer a promising avenue for extension of E-Waste laws but implementation of such a scheme would require a fundamental change in the ways E-Waste flows are recorded and reported. Naturally, in order to fully exploit the advantages of a product specific scheme, each product offered by any firm should be considered an individual entity. However, this would increase the accounting costs. A first step towards this can be made through modification to the existing category based scheme. This can be done by creating sub-categories within the existing product category and assigning the same collection target to the entire product category and a different recycling targets to each sub-category within the product category. As an example, both cellular phones and computers belong to the category 6 of the Recast Directive. The creation of sub-category would allow to disconnect the recycling/reuse operations of cellular phones from that of computers. Naturally, similarity in the environmental characteristics form the fundamental criterion for products to be placed in the same sub-category. Our research identifies that recyclability levels and reuse potential of the products should also be taken into account for product classification.

7. Concluding Remarks

The environmental legislation based on the principle of extended producer responsibility such as WEEE directive of the European Union is also under criticism for generating insufficient incentives for the promotion of the product reuse. Several attempts have been made to modify this directive to accommodate incentives for the product reuse. This includes the implementation of the WEEE Recast Directive, which was promulgated ten years after the introduction of the original Directive. Another scheme that advocates a separate target for the product reuse is also under discussion. The academic community has also been engaged in the study of this directive and has warned of the potential pitfalls. While much of the efforts are devoted to identifying a comprehensive set of legislative parameters that could overcome these potential pitfalls, we take an alternative perspective by identifying the right products for each of these policy tools.

To this end, we study three forms of legislation (i) the Original 2002 WEEE directive (ii) the Recast 2012 directive (iii) a proposed policy that advocates for a separate reuse target. We compare the performance of these schemes using a comprehensive set of economic and environmental criteria. Our findings reveal that each of these three policies remains appropriate for a particular set of product categories. From the perspective of the environment, the existing Recast policy is either dominated by the Original version or the one that advocates a separate target for the product reuse. However, if a broader perspective of social welfare is taken into account, a Recast policy is better for a set of products with a medium range of production footprint. Therefore, an appropriate mapping of product characteristics with the policy tools is critical to the success of E-Waste legislation and when products are appropriately matched to the policies, some of the unintended environmental consequences disappear. The proposal of a policy with a separate reuse target is not popular among the producers. We propose an alternative policy tool that incorporates fiscal levers to replicate the benefits.

To understand the effects of product clustering with the implementation of Recast policy, we extend our model to the case of two products. We note that a smaller set of target levels applied to individual products can lead to a better environmental performance than a policy with more target levels applied to a group of products. Therefore, consideration of product characteristics in the policy choice seems a promising avenue for the extension of WEEE Directive. This can be achieved through the implementation of, a recycling-focused policy for products with high hazard potential and a reuse-focused policy for products with high production footprint, or re-evaluation of the product clustering protocols that can be a rewarding direction for future research.

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Appendix A

Appendix A-1 Notations and Threshold Values

Table 3 Notation and Threshold Values

δ	customer valuation discount factor of the remanufactured/reused products
τ	mandatory collection rate on under WEEE Directive
σ	mandatory recycling target under WEEE Directive
ϕ	A separate reuse target
c_n	unit manufacturing cost
c_r	unit remanufacturing cost
c_{rec}	unit processing/recycling cost
c_d	unit disposal/landfilling cost after minimum treatment
q_n	quantity of new products manufactured and sold in the primary market
q_r	quantity of remanufactured products remanufactured and sold in the secondary market
p_n	price of the manufactured product
p_n	price of the remanufactured product
Π_i	OEM's profit
S_i	total consumer surplus
$\mathbf{W}_i$	social welfare
$\bar{\bar{\bar{e}}}_m$	$\bar{\bar{\bar{e}}}_m - \dfrac{(1+\delta\phi_R^2+2\delta\phi)(\phi(-c_{rec}+c_d)(e_u+\hat{e}_d)(-1+\delta)+e_d(1+\phi)(\delta c_n-c_r+c_d-\tau c_d\sigma\delta+\tau c_d\delta+\delta\tau\sigma c_{rec}))}{\delta(1+\phi)\Big(\delta(1+\phi)^2(c_d+c_n+\tau c_d+c_{rec}\sigma\tau-\tau\sigma c_d)-(1-\delta)(\delta\phi+\delta\phi^2-\phi c_{rec}-c_d)-c_r(1+\phi)(1+\delta\phi)\Big)}$
$\bar{\mathbf{e}}_m$	$\bar{e}_m - \dfrac{3}{4}\Big(\dfrac{c_d-2\delta c_d\tau\sigma+2\delta c_d\tau+2\delta c_n+2\delta\sigma\tau c_{rec}-2c_r+c_{rec}}{\delta}\Big)$
$\bar{\bar{\mathbf{e}}}_m$	$\bar{\bar{e}}_m - \dfrac{3}{4}\Big(c_n+\tau c_d+\sigma\tau(c_{rec}-c_d)-\dfrac{(c_{rec}-c_r)(1+\delta\phi)}{\delta(1+\phi)}-\dfrac{\phi(1-\delta)}{1+\phi}\Big)$
$\bar{\bar{\bar{\mathbf{e}}}}_m$	$\bar{\bar{\bar{e}}}_m - \dfrac{3}{4}\dfrac{\Big(\delta(1+\phi)(\sigma\tau c_{rec}-\sigma\tau c_d+c_n+\tau c_d)+\delta\phi(-1-c_r+\delta+c_d)-c_r+c_d\Big)^2}{\delta\Big(\delta(1+\phi^2)(\sigma\tau c_{rec}-\sigma\tau c_d+c_d+c_n+\tau c_d)-(1-\delta)(\delta\phi+\delta\phi^2-\phi c_{rec}-c_d)-c_r(1+\phi)(1+\delta\phi)\Big)}-$ $\dfrac{3}{4}\dfrac{\delta\phi(c_{rec}-c_d)(1-\delta)\Big(-2\delta\phi-\phi c_d+2c_d\tau-2c_d\tau\sigma+2\phi c_r-\phi c_{rec}-2+2\sigma\tau c_{rec}+2c_n\Big)}{\delta\Big(\delta(1+\phi^2)(\sigma\tau c_{rec}-\sigma\tau c_d+c_d+c_n+\tau c_d)-(1-\delta)(\delta\phi+\delta\phi^2-\phi c_{rec}-c_d)-c_r(1+\phi)(1+\delta\phi)\Big)}$
c_{REC}^P	$\dfrac{\delta_2(1-\delta_2)(1-\sigma\tau)(1-c_n+c_r-2c_{rec}-\delta_1-c_d\tau+c_d\tau\sigma)-(1-\delta_1)\Big(\sigma\tau(1-\delta_2)(\delta_2-c_R)-(1+\sigma\tau)(\tau\delta_2c_d\sigma-\tau\delta_2c_d+c_R-\delta_2c_N)\Big)}{\delta_2(\sigma\tau-1)^2(1-\delta_1)(1-\delta_2)(1+2\delta_2\sigma\tau+\delta_2\sigma^2\tau^2)}$
c_{REC}^F	$\dfrac{-1}{2\Big(\phi_C\delta_1\delta_2(\delta_1+\delta_2)(2+\phi_C)+8\phi_C\delta_1\delta_2-\delta_1-\delta_2+\delta_1^2+\delta_2^2\Big)}\Big[\delta_1\phi_C^2\Big((2-\delta_1-\delta_2)(c_R-c_{REC})+\delta_2(3\delta_1-\delta_2+2(2c_{rec}+c_n-1-c_{REC}-c_N-$ $+\sigma\tau\phi_C\Big(\delta_1(\delta_1-2)(c_R-2c_{REC}+c_d)+\delta_2(\delta_2-2)(c_r-c_{rec})+\delta_1\delta_2(-2\delta_1-2\delta_2-c_{rec}+c_d+4+2_{REC}+c_R+c_r)\Big)$ $-\delta_1(1+\delta_2)\phi_C\Big(-2\delta_1+4c_N-5c_{rec}-c_R-3c_n+4c_{REC}+2c_r+c_d\tau+2\Big)-\delta_1\phi(\delta_1c_N+\delta_1\tau c_d+3c_{rec}-c_r+2c_n-5c_N-3c_d\tau-2c_R)$ $-\phi_C\delta_2^2(c_r-c_{rec})-\tau^2\sigma^2(\delta_1+\delta_2)(\delta_2-2+\delta_1)(c_d-c_{REC})+\delta_2^2(-1+c_{rec}+c_n+c_d\tau-c_{REC})(-1+\sigma\tau)-(\delta_1+\delta_2)(c_n-1-c_{REC})(\sigma\tau-1$ $-\delta_1(2c_d\tau+cR-\delta_2c_N+2crec-2c_{REC})(\sigma\tau-1)+(-2\sigma\tau+\tau^2c_d\sigma+\tau\sigma c_N+1)\delta_1^2+\sigma\tau(-1-c_{REC}+c_d)\delta_2^2-c_r-c_{REC}+c_{rec}+c_R$ $+(\sigma\tau+c_R\sigma\tau-c_N-2\tau\sigma c_N+c_{rec}-2\tau^2c_d\sigma)\delta_2+\delta_1\sigma\tau(c_d+c_{rec}+2c_d\tau-2c_{REC}+c_n)\delta_2-\delta_1\delta_2\tau c_d+\delta_1(\sigma\tau-c_r-2c_d\tau\sigma+c_{rec}+c_n)\Big]$
$\mathcal{K}_1$	$\dfrac{+\hat{e}_d\tau-\tau(1-\sigma)e_D+e_U(1-\delta_2)}{\delta_2(1+\sigma\tau)}+\dfrac{\tau(1-\delta_2)(1-\sigma)(\hat{e}_D-\hat{e}_d-e_D+e_d)}{(1-\delta_1)(c_{REC}-c_{rec})(1+\sigma\tau)}\times\mathcal{A}-\dfrac{(1-\delta_2)\hat{e}_D}{\delta_2(1+\sigma\tau)}$ $+(\hat{e}_D-\hat{e}_d)\Big(\dfrac{c_N-c_{rec}\sigma\tau-\tau c_d+\sigma\tau c_d}{c_{REC}-c_{rec}}+\dfrac{(c_R-c_{rec})(1+\sigma\tau\delta_2)}{(c_{REC}-c_{rec})(1+\sigma\tau)\delta_2}-\dfrac{\sigma\tau(1-\delta_2)}{(1+\sigma\tau)(c_{REC}-c_{rec})}\Big)$
$\mathcal{K}_2$	$\dfrac{\tau(e_D-e_d)(1-\sigma)-\hat{e}_D(1-\tau)-\tau\hat{e}_d}{(c_{REC}-c_{rec})(1-\sigma\tau)}\times\Big(\mathcal{A}\Big)-\dfrac{2\hat{e}_d(\delta_1c_n-\delta_1c_{rec}+c_r-c_{rec}-\delta_1\tau c_d+\delta_1\tau\sigma c_d)}{\delta_1(c_{REC}-c_{rec})(1-\sigma\tau)}-\hat{e}_D(1-\tau)-\tau e_D(1-\sigma)-\dfrac{2\hat{e}_dc_{REC}}{c_{REC}-c_{rec}}$ where, $\mathcal{A}=1-c_n-\delta_1-c_{rec}-\sigma\tau c_{rec}-\tau c_d+\tau\sigma c_d$

Appendix A-2 Proofs:

Proof of Proposition 1

The characterization of optimization problem is given as:

$$\begin{aligned}\Pi &= q_n(p_n - c_n) + q_r(p_r - c_r) - (q_c - q_{rec} - q_r)c_d - q_{rec}c_{rec}\\ q_c &\geq \tau q_n\\ q_{rec} &\geq \sigma\tau q_n \quad \textbf{(policy } \mathtt{0}\textbf{)} \quad q_{rec} \geq \sigma\tau q_n - q_r \quad \textbf{(policy } \mathtt{R}\textbf{)}\end{aligned}$$

The values of p_n and p_r from equations (1,2) are inserted in the optimization problem. We remain focussed on the cases where constraints pertaining to legislative interventions are bindings. Therefore, $q_c = \tau q_n$ and $q_{rec} = \sigma\tau q_n$ for policy 0 where product remanufacturing is not considered into recycling obligation and $q_{rec} = \sigma\tau q_n - q_r$ for policy R where product reuse is considered into recycling obligation. The Hessian matrix is negative semidefinite and therefore first order conditions are sufficient. The solution of first order conditions for policy 0 and policy R give the following values for quantities of new and remanufactured products $q_n^{\mathtt{0}} = \dfrac{c_d - 1 + \delta + c_d\tau + c_n + \sigma\tau c_{rec} - c_d\tau\sigma - c_r}{2(-1+\delta)}$, $q_r^{\mathtt{0}} = \dfrac{\delta c_d\tau + \delta c_n + \delta\sigma\tau c_{rec} - c_r - \delta c_d\tau\sigma + c_d}{2\delta(1-\delta)}$ for policy and 0 $q_n^{\mathtt{R}} = \dfrac{c_{rec} - 1 + \delta + c_d\tau + c_n + \sigma\tau c_{rec} - c_d\tau\sigma - c_r}{2(-1+\delta)}$, $q_r^{\mathtt{0}} = \dfrac{\delta c_d\tau + \delta c_n + \delta\sigma\tau c_{rec} - c_r - \delta c_d\tau\sigma + c_{rec}}{2\delta(1-\delta)}$ for policy R. The maximum value of remanufacturing cost that would warrant positive remanufactured products can be obtained by solving $q_n^{\mathtt{R},\mathtt{0}} = 0$ for $\bar{c}_r^{\mathtt{0}}$ and $\bar{c}_r^{\mathtt{R}}$ respectively. $\bar{c}_r^{\mathtt{R}} - \bar{c}_r^{\mathtt{0}} > 0$ if $c_{rec} - c_d > 0$ suggesting that $\bar{c}_r^{\mathtt{R}} > \bar{c}_r^{\mathtt{0}}$ as presented in part (a). The values for $\bar{c}_r^{\mathtt{R}}, \bar{c}_r^{\mathtt{0}}$ can be differentiated with respect to (τ, σ) to validate part (b) of Proposition 1.

Proof of Proposition 2

We plug the respective values for q_n, q_r for policy 0, R as obtained from Proposition 1 into the individual components of environmental footprint under both policies

(i) Virgin Material usage comparison is given as $e_m(q_n^{\mathtt{R}} - q_n^{\mathtt{0}}) = \dfrac{-(c_{rec} - c_d)e_m}{2(1-\delta)} < 0 \implies {\mathrm{E}_{\mathrm{p}}}^{\mathtt{R}} < {\mathrm{E}_{\mathrm{p}}}^{\mathtt{0}}$.

(ii) Use Phase comparison is given as $e_u(q_n^{\mathtt{R}} + q_r^{\mathtt{R}}) - e_u(q_n^{\mathtt{0}} + q_r^{\mathtt{0}}) = \dfrac{(c_{rec} - c_d)e_u}{2\delta} > 0 \implies {\mathrm{E}_{\mathrm{p}}}^{\mathtt{R}} > {\mathrm{E}_{\mathrm{p}}}^{\mathtt{0}}$.

(iii)End of Life Footprint comparison is given as:

${\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{R}} - {\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{0}} = q_r^{\mathtt{0}}e_d + \dfrac{(c_{rec} - c_d)(\hat{e}_d - e_d + \sigma e_d)}{2(1-\delta)} + \dfrac{(c_{rec} - c_d)\hat{e}_d}{2\delta} > 0$ iff $c_{rec} > c_d, \hat{e}_d > e_d \implies {\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{R}} > {\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{0}}$.

(iv) Total environmental Footprint can be compared solving for inequality $({\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{R}} + {\mathrm{E}_{\mathrm{u}}}^{\mathtt{R}} + {\mathrm{E}_{\mathrm{p}}}^{\mathtt{R}}) < ({\mathrm{E}_{\mathrm{EOL}}}^{\mathtt{0}} + {\mathrm{E}_{\mathrm{u}}}^{\mathtt{0}} + {\mathrm{E}_{\mathrm{p}}}^{\mathtt{0}})$ for e_m which gives the value of e_m presented as $\bar{e}_m$ in proposition 2.

Proof of Proposition 3

We plug the values of respective quantities under each policy in the equations (3,4,5). We compute the difference as:

(i) Comparison of Profit is given as $\Pi^{\mathtt{R}} - \Pi^{\mathtt{0}} = \dfrac{(c_{rec} - c_d)(q_r^{\mathtt{R}} + q_r^{\mathtt{0}})}{2} > 0 \implies \Pi^{\mathtt{R}} > \Pi^{\mathtt{0}}$.

(ii) Comparison of Consumer Surplus is given as $S^{\mathtt{R}} - S^{\mathtt{0}} = \dfrac{(c_{rec} - c_d)(q_r^{\mathtt{R}} + q_r^{\mathtt{0}})}{4} > 0 \implies S^{\mathtt{R}} > S^{\mathtt{0}}$.

Proof of Proposition 4

(i) Virgin Material usage: The comparative statics of virgin material usage footprint with respect to collection and recycling targets $\dfrac{\partial {\mathrm{E}_{\mathrm{p}}}^{\mathtt{R}}}{\partial\tau} = \dfrac{\partial e_m q_n^{\mathtt{R}}}{\partial\tau} = \dfrac{-c_d - \sigma c_{rec} + \sigma c_d}{2(1-\delta)} < 0$ and $\dfrac{\partial {\mathrm{E}_{\mathrm{p}}}^{\mathtt{R}}}{\partial\sigma} = \dfrac{\partial e_m q_n^{\mathtt{R}}}{\partial\sigma} = \dfrac{-\tau(c_{rec} - c_d)}{2(1-\delta)} < 0$ for policy R. For policy 0, $\dfrac{\partial {\mathrm{E}_{\mathrm{p}}}^{\mathtt{0}}}{\partial\tau} = \dfrac{\partial e_m q_n^{\mathtt{0}}}{\partial\tau} = \dfrac{-c_d + \sigma c_d - \sigma c_{rec}}{2(1-\delta)} < 0$ and $\dfrac{\partial {\mathrm{E}_{\mathrm{p}}}^{\mathtt{0}}}{\partial\sigma} = \dfrac{\partial e_m q_n^{\mathtt{0}}}{\partial\sigma} = \dfrac{-\tau(c_{rec} - c_d)}{2(1-\delta)} < 0$.

(ii) From use phase: It is given as: $\frac{\partial \mathrm{E_u}^{\mathrm{R}}}{\partial \tau} = \frac{\partial e_u(q_n^{\mathrm{R}} + q_r^{\mathrm{R}})}{\partial \tau} = 0$ and $\frac{\partial \mathrm{E_u}^{\mathrm{R}}}{\partial \sigma} = \frac{\partial e_u(q_n^{\mathrm{R}} + q_r^{\mathrm{R}})}{\partial \sigma} = 0$ for policy `R`. For policy `0`, its given $\frac{\partial \mathrm{E_u}^{0}}{\partial \tau} = \frac{\partial e_u(q_n^{0} + q_r^{0})}{\partial \tau} = 0$ and $\frac{\partial \mathrm{E_u}^{0}}{\partial \sigma} = \frac{\partial e_u(q_n^{0} + q_r^{0})}{\partial \sigma} = 0$.

(iii) End of Life Footprint: It is given as: $\frac{\partial \mathrm{E_{EOL}}^{\mathrm{R}}}{\partial \tau} = \frac{(\hat{e}_d - e_d + \sigma e_d)(-1 + c_n + 2c_d\tau + c_{rec} + \delta - c_r + 2\tau\sigma c_{rec} - 2\tau\sigma c_d)}{2(1-\delta)}$. It is clear that the derivative is independent of environmental characteristics. Solving $\frac{\mathrm{E_{EOL}}^{\mathrm{R}}}{\partial \tau} > 0$ gives the condition $\tau > \frac{1 - c_n - \delta + c_r - c_{rec}}{2(c_d - \sigma c_d + \sigma c_{rec})}$ as stated in Table1. Similarly from recycling target, it is given as: $\frac{\partial \mathrm{E_{EOL}}^{\mathrm{R}}}{\partial \sigma} = \frac{(c_{rec} - c_d)\tau^2(\hat{e}_d - e_d + 2\sigma e_d)}{2(1-\delta)} + \frac{\tau e_d(\delta + \tau c_d + c_n + c_{rec} - c_r - 1)}{2(1-\delta)}$. Solving for $\frac{\partial \mathrm{E_{EOL}}^{\mathrm{R}}}{\partial \sigma} > 0$ gives the condition presented in table 1. Observe that environmental characteristics do not play a role in determining if it increases or decreases with collection target (τ) but decide if it increases/decreases with recycling target (σ). A similar exercise is done to ascertain all the conditions presented in table 2.

Proof of Corollary 1

From proposition 2, we know that $e_m > \bar{e}_m$ for all products where $\mathrm{E^R} \geq \mathrm{E^0}$. And Table 2 provides us conditions where environmental footprint increases with collection/recycling targets.

From Collection Target

Therefore, $\frac{\partial \mathrm{E^R}}{\partial \tau} = -(\hat{e}_d - e_d + \sigma e_d)\frac{\delta(-1 + \delta + c_n - c_r + c_{rec} + 2c_d\tau + 2\sigma\tau c_{rec}\delta - 2c_d\tau\sigma\delta)}{2\delta(1-\delta)} - \frac{e_m(c_d - \sigma c_d + \sigma c_{rec})}{2(1-\delta)}$

RHS is decreasing in e_m. For $\mathrm{E^R} \geq \mathrm{E^0}$ the minimum value for e_m is ($e_m = \bar{e}_m$). Plugging this value above we get,

$$\frac{\partial \mathrm{E^R}}{\partial \tau} = -(\hat{e}_d - e_d + \sigma e_d)\Big(\overbrace{\frac{1 - \delta - c_n + c_r - c_{rec} - \tau c_d - \tau\sigma c_{rec} + \tau\sigma c_d}{2(1-\delta)}}^{>0 \quad \text{iff,} \quad q_n^{\mathrm{R}}>0}\Big) - \frac{(\hat{e}_d + e_u)(c_d - \sigma c_d + \sigma c_{rec})}{2\delta}$$
$$-e_d\frac{c_d - \sigma c_d + \sigma c_{rec}}{c_{rec} - c_d}\underbrace{\Big(\frac{\delta c_n - c_r + c_d + \delta\tau c_d + \delta\tau\sigma c_{rec} - \delta\tau\sigma c_d}{2\delta(1-\delta)}\Big)}_{>0 \quad \text{iff,} \quad q_r^{0}>0}$$

Therefore, $\frac{\partial \mathrm{E^R}}{\partial \tau} < 0$.

From Recycling Target

$\frac{\partial \mathrm{E^R}}{\partial \sigma} = \frac{\tau(c_{rec} - c_d)(\tau\hat{e}_d - e_m - \tau e_d + 2\tau\sigma e_d)}{2(1-\delta)} + \frac{\tau e_d(-1 + \delta + c_n - c_r + c_{rec} + \tau c_d)}{2(1-\delta)}$. Clearly, RHS is decreasing in (e_m). We plug ($e_m = \bar{e}_m$) and simplify;

$$\frac{\partial \mathrm{E^R}}{\partial \sigma} = -\tau\frac{(\hat{e}_d + e_u)(c_{rec} - c_d)}{2\delta} - \tau e_d\Big(\overbrace{\frac{1 - \delta - c_n + c_r - c_{rec} - \tau c_d - \tau\sigma c_{rec} + \tau\sigma c_d}{2(1-\delta)}}^{>0 \quad \text{iff,} \quad q_n^{\mathrm{R}}>0} + \overbrace{\frac{\delta c_n - c_r + c_d + \delta\tau c_d + \delta\tau\sigma c_{rec} - \delta\tau\sigma c_d}{2\delta(1-\delta)}}^{>0 \quad \text{iff,} \quad q_r^{0}>0}\Big)$$

Therefore, $\frac{\partial \mathrm{E^R}}{\partial \sigma} < 0$.

Proof of Proposition 5

Comparison of policy `P with R`: The firm solves the following optimization problem

$$\Pi^{\mathrm{P}} = q_n(p_n - c_n) + q_r(p_r - c_r) - (q_c - q_{rec} - q_r)c_d - q_{rec}c_{rec}$$
$$s.t \quad q_c \geq \tau q_n \qquad q_{rec} \geq q_c - q_r \qquad q_r \geq \phi q_n \qquad \text{Reuse target}$$

All the constraints are binding and in addition we consider $\phi \geq \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}}$ which ensures that the imposed target leads to higher reuse level than voluntarily achieved under policy R. The solution leads to the optimal quantities given as: $q_n^{\mathrm{P}} = \frac{1 - c_n + \phi c_{rec} - \phi c_r + \delta\phi + \tau\sigma c_d - \tau c_d - \tau\sigma c_{rec}}{2(1 + 2\delta\phi + \delta\phi^2)}$ and $q_r^{\mathrm{P}} = \phi q_n^{\mathrm{P}}$.

Comparison of virgin material usage is given as $e_m(q_n^{\mathrm{P}} - q_n^{\mathrm{R}}) = \frac{e_m(1+\phi)\Big((1+\phi)(\delta c_n - c_r + c_{rec} + \delta\tau c_d + \delta\tau\sigma c_{rec} - \delta\tau\sigma c_d) - \phi(1-\delta)(\delta - c_r + c_{rec})\Big)}{2(1-\delta)(1 + 2\delta\phi^2 + \delta\phi^2)}$ which is negative iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{0}} \implies {\mathrm{E_p}}^{\mathrm{P}} < {\mathrm{E_p}}^{\mathrm{R}}$. Similarly, we compare the **use phase and EOL footprint** of the two policies and find ${\mathrm{E_u}}^{\mathrm{P}} > {\mathrm{E_u}}^{\mathrm{R}}$ and ${\mathrm{E_{EOL}}}^{\mathrm{P}} > {\mathrm{E_{EOL}}}^{\mathrm{R}}$.

Then we solve the inequality ${\mathrm{E_p}}^{\mathrm{R}} + {\mathrm{E_u}}^{\mathrm{R}} + {\mathrm{E_{EOL}}}^{\mathrm{R}} > {\mathrm{E_p}}^{\mathrm{P}} + {\mathrm{E_u}}^{\mathrm{P}} + {\mathrm{E_{EOL}}}^{\mathrm{P}}$ for (e_m) which provides the threshold as indicated in Proposition 5.

Proof of Corollary 2

In part (i), we do the comparative statics for the environmental footprint with this policy:

$$\frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \tau} = -\frac{(c_d - \sigma c_d + \sigma c_{rec})(e_m + e_u + \phi(e_u + \hat{e}_d) + \hat{e}_d(1-\tau) + \tau e_d(1-\sigma))}{2(1 + 2\delta\phi + \delta\phi^2)}$$

$$-(\hat{e}_d - e_d + \sigma e_d)\frac{\overbrace{\phi\delta + c_d\tau\sigma + 1 - \sigma\tau c_{rec} - c_n - c_d\tau + \phi c_{rec} + \phi c_r}^{>0 \quad \text{iff,} \quad q_n^{\mathrm{P}}>0}}{2(1 + 2\delta\phi + \delta\phi^2)} \implies \frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \tau} < 0$$

$$\frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \sigma} = -\frac{\tau(c_{rec} - c_d)(e_m + e_u - \phi e_u + \hat{e}_d - \tau\hat{e}_d + \phi\hat{e}_d + \tau e_d - \tau\sigma e_d)}{2(\delta\phi^2 + 2\phi\delta + 1)}$$

$$-\tau e_d \frac{\overbrace{1 - c_n + \delta\phi - \phi c_r + \phi c_{rec} - \tau c_d - \tau\sigma c_{rec} + \tau\sigma c_d}^{>0 \quad \text{iff,} \quad q_n^{\mathrm{P}}>0}}{\delta\phi^2 + 2\phi\delta + 1} \implies \frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \tau} < 0$$

With Reuse Target We differentiate total environmental footprint under policy P with respect to ϕ,

$$\begin{aligned}\frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \phi} &= \frac{(\delta + c_{rec} - c_r)(e_u + e_u\phi + e_m + \hat{e}_d - \hat{e}_d\tau + \hat{e}_d\phi + \tau e_d - \tau e_d\sigma)}{2(\delta\phi^2 + 2\phi\delta + 1)} \\ &+ \frac{(\hat{e}_d + e_u)(-\phi\delta - c_d\tau\sigma - 1 + \sigma\tau c_{rec} + c_n + c_d\tau - \phi c_{rec} + \phi c_r)}{2(\delta\phi^2 + 2\phi\delta + 1)} \\ &- \frac{\delta(1+\phi)(-e_u - e_u\phi - e_m - \hat{e}_d + \hat{e}_d\tau - \hat{e}_d\phi - \tau e_d + \tau e_d\sigma)(-\phi\delta - c_d\tau\sigma - 1 + \sigma\tau c_{rec} + c_n + c_d\tau - \phi c_{rec} + \phi c_r)}{(\delta\phi^2 + 2\phi\delta + 1)^2}\end{aligned}$$

RHS can be positive or negative but is strictly decreasing in e_m. If $\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{\mathrm{R}}$ then $e_m > \bar{\bar{e}}_m$ (proposition 5). We plug this minimum value of e_m and after simplification we get, $\frac{\partial \mathrm{E}^{\mathrm{P}}}{\partial \phi} = \frac{(\hat{e}_d + e_u)\Big(-(q_n^{\mathrm{P}} + q_r^{\mathrm{P}}) + (q_n^{\mathrm{R}} + q_r^{\mathrm{R}})\Big)}{1+\phi} < 0$ since total product quantity is always higher in policy P.

Proof of Proposition 6

Environmental Footprint E^i We know that $\mathrm{E}^{\mathrm{R}} \geq \mathrm{E}^{0}\ \forall e_m > \bar{e}_m$, $\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{\mathrm{R}}\ \forall e_m > \bar{\bar{e}}_m$ and $\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{0}\ \forall e_m > \bar{\bar{\bar{e}}}_m$ .In order to compare the performance of policies $\{0, \mathrm{R}, \mathrm{P}\}$, we compare $\bar{e}_m, \bar{\bar{e}}_m, \bar{\bar{\bar{e}}}_m$. We first prove that, $\bar{e}_m - \bar{\bar{e}}_m > 0$. $\bar{e}_m - \bar{\bar{e}}_m = \frac{(1-\delta)(\hat{e}_d + e_u)}{\delta(1+\phi)} + e_d\frac{\delta c_n - c_r + c_d + \delta\tau c_d + \delta\tau\sigma c_{rec} - \delta\tau\sigma c_d}{\delta(c_{rec} - c_d)} > 0$ iff $(q_r^{0} > 0)$.

Next, $\bar{\bar{\bar{e}}}_m - \bar{\bar{e}}_m = \frac{(1 + \delta\phi^2 + 2\delta\phi)\Big(\phi(c_{rec} - c_d)(e_u + \hat{e}_d)(1-\delta) + (1+\phi)2\delta(1-\delta)q_r^{0}e_d\Big)}{\delta(1+\phi)\Big(2\delta(1+\phi)(q_n^{\mathrm{R}}\phi - q_r^{\mathrm{R}})(1-\delta) + (c_{rec} - c_d)(1 + \delta\phi^2 + 2\delta\phi)\Big)} > 0 \implies \bar{\bar{\bar{e}}}_m > \bar{\bar{e}}_m$.

$$\bar{e}_m - \bar{\bar{\bar{e}}}_m = \frac{2\delta(q_n^{\mathrm{R}}\phi - q_r^{0})(1-\delta)\Big(\phi(c_{rec}-c_d)(e_u+\hat{e}_d)(1-\delta) + (1+\phi)2\delta(1-\delta)q_r^{0}e_d\Big)}{\delta(c_{rec}-c_d)\Big(2\delta(1+\phi)(q_n^{\mathrm{R}}\phi - q_r^{\mathrm{R}})(1-\delta) + (c_{rec}-c_d)(1+\delta\phi^2+2\delta\phi)\Big)} > 0 \implies \bar{e}_m > \bar{\bar{\bar{e}}}_m.$$

$\therefore \bar{e}_m > \bar{\bar{\bar{e}}}_m > \bar{\bar{e}}_m$.

$\because \bar{e}_m > \bar{\bar{e}}_m$, it also suggests before $\mathrm{E}^{\mathrm{R}} \geq \mathrm{E}^{0}$, policy P dominates policy R ($\mathrm{E}^{\mathrm{P}} \geq \mathrm{E}^{\mathrm{R}}$) i.e., policy R can not be the best environmental policy. Hence, we prove proposition 6.

Proof of Proposition 7

Social Welfare $\mathbf{W}^i$ We do a similar exercise (as done in the proof of proposition 6) to develop preference order from the perspective of social welfare. Propositions 3 and 5 showed that policy R has clear economic advantages over both policies. Therefore, despite the fact that it is dominated on environmental front by other two polices, from the perspective of social welfare, it can still dominate the other policies. Note that $\mathbf{W}^i$ is a linear decreasing function of (e_m) with the slope steepest for 0 and shallowest for P. First we solve the inequalities $\mathbf{W}^{\mathrm{R}} > \mathbf{W}^{0}$, $\mathbf{W}^{\mathrm{P}} > \mathbf{W}^{\mathrm{R}}$ and $\mathbf{W}^{\mathrm{P}} > \mathbf{W}^{0}$ for e_m to get respective thresholds $\bar{\mathbf{e}}_m, \bar{\bar{\mathbf{e}}}_m, \bar{\bar{\bar{\mathbf{e}}}}_m$ as presented in Table 2 of Appendix. Then, we take a difference,

$$\bar{\mathbf{e}}_m - \bar{\bar{\mathbf{e}}}_m = \bar{e}_m - \bar{\bar{e}}_m - \frac{3(2\delta(1-\delta)q_r^{0})}{4\delta} - \frac{3\phi(1-\delta)(q_n^{\mathrm{R}}+q_r^{\mathrm{R}})}{4\delta(1+\phi)} \qquad \mathrm{A}(1)$$

$$\bar{\bar{\bar{\mathbf{e}}}}_m - \bar{\bar{e}}_m = \bar{\bar{\bar{e}}}_m - \bar{\bar{e}}_m - \frac{3(c_{rec}-c_d)(1+2\delta\phi+\delta\phi^2)}{4}\,\frac{2\delta(1-\delta)q_r^{0}(1+\phi)+\phi(1-\delta)(q_n^{\mathrm{R}}+q_r^{\mathrm{R}})}{\delta(1+\phi)\Big((c_{rec}-c_d)(1+2\delta\phi+\delta\phi^2)+2\delta(1-\delta)(1+\phi)(\phi q_n^{\mathrm{R}}-q_r^{\mathrm{R}})\Big)} \qquad \mathrm{A}(2)$$

Observe A(1) and A(2), the first two terms represent environmental aspects wile the last two terms represent economic aspects. Further, from part(a) of proposition 6, the sum of first two terms is positive. While the last two are negative. Clearly, it indicates if the environmental concerns are sufficiently higher then $\bar{\mathbf{e}}_m > \bar{\bar{\mathbf{e}}}_m$ and from social welfare perspective, a similar ranking order persists although with different thresholds i.e., policy 0 is dominant for products with smaller e_m and policy P is dominant for products with larger e_m . However, if environmental concerns are not high enough i.e., $\bar{\mathbf{e}}_m < \bar{\bar{\mathbf{e}}}_m$, it basically implies that there exist a range of values where policy R dominates 0 and is not dominated by P. It is straightforward to show that iff $\bar{\mathbf{e}}_m < \bar{\bar{\mathbf{e}}}_m$, then $\bar{\bar{\mathbf{e}}}_m > \bar{\bar{\bar{\mathbf{e}}}}_m > \bar{\mathbf{e}}_m$

Proof of Proposition 8

$\because \dfrac{\partial q_n^{\mathrm{R}}}{\partial(\tau,\sigma)} < 0. \dfrac{\partial q_r^{\mathrm{R}}}{\partial(\tau,\sigma)} > 0$, reuse level can be increased by elevation of collection and recycling targets $\dfrac{\partial q_r^{\mathrm{R}}/q_n^{\mathrm{R}}}{\partial(\tau,\sigma)} > 0$. Since, $(\tau, \sigma \leq 1)$, there is an upper bound on the level of reuse that can be achieved by increasing collection and recycling targets as given in proposition 7.

Comparison with policy P. Consider a variant of policy R which we call $\hat{\mathrm{R}}$ where τ is increased to achieve the same level of reuse as intended through a policy P. $\dfrac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}} = \phi \implies$

$$\frac{-(1/2)(\delta c_d\tau + \delta c_n + \delta\sigma\tau c_{rec} - c_r - \delta c_d\tau\sigma + c_{rec})/(\delta(-1+\delta))}{(1/2)(c_{rec} - 1 + \delta + c_d\tau + c + \sigma\tau c_{rec} - c_d\tau\sigma - c_r)/(-1+\delta)} = \phi.$$

We solve for τ given as $\tau = \dfrac{\delta c_n - c_r + c_{rec} + \delta\phi c_{rec} + \delta^2\phi - \delta\phi + \delta\phi c - \delta\phi c_r}{\delta(-c_d - c_{rec}\sigma + c_d\sigma - \phi c_d - \phi c_{rec}\sigma + \phi c_d\sigma)}$. The respective quantities are given as $q_n^{\hat{\mathrm{R}}} = \dfrac{\delta - c_r + c_{rec}}{2\delta(1+\phi)}$ and $q_r^{\hat{\mathrm{R}}} = \phi\dfrac{\delta - c_r + c_{rec}}{2\delta(1+\phi)}$.

(i) Comparison of Environmental Footprint

(a) $\mathrm{E_p}^{\mathrm{P}} - \mathrm{E_p}^{\hat{\mathrm{R}}} = \dfrac{\delta\phi(1-\delta) + (c_r - c_{rec})(1+\delta\phi) - \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)}{2(1+\delta\phi^2+2\delta\phi)(1+\phi)\delta} \times e_m \therefore \mathrm{E_p}^{\mathrm{P}} > \mathrm{E_p}^{\hat{\mathrm{R}}}$ iff $\phi > q_r^{\mathrm{R}}/q_n^{\mathrm{R}}$.

(b) $\mathrm{E_u}^{\mathrm{P}} - \mathrm{E_u}^{\hat{\mathrm{R}}} = \dfrac{\delta\phi(1-\delta) + (c_r - c_{rec})(1+\delta\phi) - \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)}{2(1+\delta\phi^2+2\delta\phi)\delta} \times e_u \therefore \mathrm{E_u}^{\mathrm{P}} > \mathrm{E_u}^{\hat{\mathrm{R}}}$.

(c) Now we compare the EOL- footprint from both schemes. With policy P, collection target (τ) is implemented.

In presence of policy $\hat{\mathrm{R}}$, collection target is increased such that the new collection target is $\tau + \Delta$. Using $(\tau + \Delta)$ as collection target with policy $\hat{\mathrm{R}}$ and taking the difference between the EOL-footprint associated with both policies. ${\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{P}} - {\mathrm{E}_{\mathrm{EOL}}}^{\hat{\mathrm{R}}} = \frac{\Big((1-\tau)(\hat{e}_d - e_d) + e_d(1-\tau\sigma) + \phi\hat{e}_d\Big)\Big(\delta\phi(1-\delta) + (c_r - c_{rec})(1+\delta\phi) - \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)\Big)}{2(1+\delta\phi^2+2\delta\phi)(1+\phi)\delta} + \frac{(\delta - c_r + c_{rec})\Delta(\hat{e}_d - e_d + \sigma e_d)}{2\delta(1+\phi)}$.The second term is always positive.

The first term is also positive iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}} \therefore {\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{P}} > {\mathrm{E}_{\mathrm{EOL}}}^{\hat{\mathrm{R}}}; \because {\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{P}} > {\mathrm{E}_{\mathrm{EOL}}}^{\hat{\mathrm{R}}}, {\mathrm{E}_{\mathrm{u}}}^{\mathrm{P}} > {\mathrm{E}_{\mathrm{u}}}^{\hat{\mathrm{R}}}, {\mathrm{E}_{\mathrm{p}}}^{\mathrm{P}} > {\mathrm{E}_{\mathrm{p}}}^{\hat{\mathrm{R}}} \therefore \mathrm{E}^{\mathrm{P}} > \mathrm{E}^{\hat{\mathrm{R}}}$.

(ii) Comparison of Consumer Surplus $S^{\mathrm{P}} - S^{\hat{\mathrm{R}}} = \frac{\Big(-\delta\phi(1-\delta) - (c_r - c_{rec})(1+\delta\phi) + \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)) - 2(\delta - c_r + c_{rec})(1+\delta\phi^2+2\delta\phi)\Big)}{8\delta^2(1+\phi)^2(1+\delta\phi^2+2\delta\phi)} \times \Big(-\delta\phi(1-\delta) - (c_r - c_{rec})(1+\delta\phi) + \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)\Big)$.

$\because -\delta\phi(1-\delta) - (c_r - c_{rec})(1+\delta\phi) + \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d) < 0$ iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}} \therefore S^{\mathrm{P}} \geq S^{\hat{\mathrm{R}}}$.

(iii) Comparison of Profits

$$\Pi^{\mathrm{P}} - \Pi^{\hat{\mathrm{R}}} = \frac{\Big(-\delta\phi(1-\delta) - (c_r - c_{rec})(1+\delta\phi) + \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)\Big)^2}{4(1+\delta\phi^2+2\delta\phi)(1+\phi)^2\delta^2} > 0; \therefore \Pi^{\mathrm{P}} > \Pi^{\hat{\mathrm{R}}}$$

It can be similarly proved that these findings remain valid for an elevated recycling target.

Proof of Proposition 9

With Taxation policy $\because \frac{\partial q_n^{\mathrm{R}}}{\partial c} < 0, \frac{\partial q_r^{\mathrm{R}}}{\partial c} > 0 \therefore \frac{\partial q_n^{\mathrm{R}}/q_r^{\mathrm{R}}}{\partial c} > 0$. Therefore, reuse level can be increased by adding a taxation (t_m) on the sale of new products. Let t_m be the taxation imposed on new products such that same level of reuse as intended through a policy $\mathtt{P}$ is obtained. $\therefore -\frac{\delta\tau c_d + \delta c_n + \delta c_{rec}\sigma\tau - \delta\tau c_d\sigma + \delta t_m + c_{rec} - c_r}{\delta(c_{rec} - 1 + \delta + c_d\tau + c_n + \tau\sigma c_{rec} - \sigma c_d\tau + t_m - c_r)} = \phi \implies t_m = \frac{\phi(1-\delta)}{1+\phi} + \frac{(c_r - c_{rec})(1+\delta\phi)}{\delta(1+\phi)} - c_n - \tau c_d - \tau\sigma c_{rec} + \tau\sigma c_d$. Plugging this value of t_m in the expressions for new and remanufactured product quantities lead us to same quantities as obtained though adjustment of collection target in proposition 7. Therefore, profit, consumer surplus as well as virgin material as well as use phase component of environmental footprint remain same as obtained through increment of collection, recycling target (stated in Proposition 8). From perspective of EOL footprint, it is straightforward that ${\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{P}} - {\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{T}} > 0$ iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}}$. **Subsidy policy** Alternatively, reuse level can also be increased by providing a subsidy on product reuse. Suppose, (s_r) is per unit subsidy on unit remanufacturing such that reuse level is equivalent to that of policy $\mathtt{P}$. In this case, $q_n^{\mathrm{T}} = \frac{1 - c_n - \tau c_d + \tau\sigma c_d - \tau\sigma c_{rec}}{2(1+\delta\phi)}, q_r^{\mathrm{T}} = \phi\Big(\frac{1 - c_n - \tau c_d + \tau\sigma c_d - \tau\sigma c_{rec}}{2(1+\delta\phi)}\Big)$. We plug these values into the expressions of components environmental footprint and subtract from the values under policy $\mathtt{P}$. ${\mathrm{E}_{\mathrm{p}}}^{\mathrm{P}} - {\mathrm{E}_{\mathrm{p}}}^{\mathrm{T}} < 0, {\mathrm{E}_{\mathrm{u}}}^{\mathrm{P}} - {\mathrm{E}_{\mathrm{u}}}^{\mathrm{T}} < 0, {\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{P}} - {\mathrm{E}_{\mathrm{EOL}}}^{\mathrm{T}} < 0$ iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}} \therefore \mathrm{E}^{\mathrm{T}} > \mathrm{E}^{\mathrm{P}}$.$S^{\mathrm{T}} - S^{\mathrm{P}} = \frac{\phi\Big(-\delta\phi(1-\delta) - (c_r - c_{rec})(1+\delta\phi) + \delta(1+\phi)(c_{rec}\sigma\tau - \tau c_d\sigma + c_n + \tau c_d)\Big)}{8(1+\delta\phi)^2(1+\delta\phi^2+2\delta\phi)} \times \Big((-2\delta^2\phi^2 - 2\delta\phi^2 - 8\delta\phi - 4)q_n^{\mathrm{R}} + (-4\delta - 4\delta^2\phi^2 - 2\delta\phi - 6\delta^2\phi)q_r^{\mathrm{R}}\Big)$. The second term is negative and the first term is also negative iff $\phi > \frac{q_r^{\mathrm{R}}}{q_n^{\mathrm{R}}} \therefore S^{\mathrm{T}} > S^{\mathrm{P}}$. Similarly, we can prove that $\Pi^{\mathrm{T}} > \Pi^{\mathrm{P}}$.

Tax/Subsidy policy Under this policy, we assume a combined system of taxation and subsidy for increasing reuse level. Furthermore, in order to draw a fair comparison with policy $\mathtt{P}$ which is cost-neutral, we assume that there is no capital injection and subsidy is provided from the collected taxes. For this policy, there are two conditions to satisfy,

$$(i) \quad \frac{q_r^{\mathrm{T}}}{q_n^{\mathrm{T}}} = \phi$$

$$(ii) \quad q_n^{\mathrm{T}} \times t_m - q_r^{\mathrm{T}} \times s_r = 0$$

The simultaneous solutions of equations (i),(ii) give optimal value of taxation and subsidy levels. We plug these values back to obtain optimal new and remanufactured product quantity and find $q_n^{\mathrm{T}} = q_n^{\mathrm{P}}$ and $q_r^{\mathrm{T}} = q_n^{\mathrm{P}}$ and all values for environmental footprint, profitability and social welfare identical. Therefore, both policies are the same.

Product Specific versus Category based Targets

For this case, we use the optimization problem and the set of constraints as presented in equation (8).

Proof of Corollary 3

We start from the policy C^P that represents existing version of the take back scheme. The optimization problem is given as:

$$\max_{q_n, q_N, q_r, q_R} \Pi = q_n(p_n - c_n) + q_r(p_r - c_r) + q_N(p_N - c_N) + q_R(p_R - c_R) - (1 - \sigma)\tau(q_n + q_N)c_d - q_{rec} \times c_{rec}$$

If q_n is high in comparison with q_N then the entire recycling quota can be satisfied through increased recycling of P_1. In this case $(q_{rec} \geq \sigma\tau(q_n + q_N) - q_r - q_R)$ and $q_{REC} = 0$ as specified in part 1 of Corollary 3.

However, if q_N is high enough then the recycling quota can not be satisfied through P_1 alone. The firm may start to recycle P_2 or increase its reuse. The constraint is given as $\sigma\tau(q_n + q_N) \geq q_n$ which suggests that recycling quota can not be satisfied even if all items from P_1 are collected back.In this case, $q_{rec} = q_n - q_r$ and the recycling quantity for P_2 is given as $q_{REC} = \sigma\tau(q_n + q_N) - q_n - q_R$. Plugging back these constraints in the optimization problem presented, we solve for the respective quantity decisions. We plug back the quantity values in $q_{REC} = \sigma\tau(q_n + q_N) - q_n - q_R > 0$ and solve for (c_{REC}). We obtain $\bar{c}_{REC}^P$ given in part 2 of corollary. If the recycling cost of P_2 is below this threshold then $q_{REC} > 0$. Otherwise, $q_{REC} = 0$ and the firm increases q_R to satisfy the mandated recycling quota.

A similar approach is used to obtain the respective threshold for policy C^F.

Proof of Proposition 10

We study a case where a firm offers two products in the markets and compare two different policy schemes. policy $\mathcal{S}$, which implements collection and recycling targets and requires individual compliance for each product placed in market. policy C enforces more parameters i.e., a reuse target in addition to collection and recycling targets. The firm profit maximization problem is given in equation 8 along with the set of constraints for policy $\mathcal{S}$ and C are presented respectively. We consider that these products have their distinct markets and therefore, there is no market interaction between P_1 and P_2. We study the case where products are not differentiated with respect to their recycling and disposal cost $c_{rec} = c_{REC} = c_{rec}$ and $c_d = c_D = c_d$. If P_2 is not conducive for remanufacturing i.e., $q_R = 0$, with policy C, all mandatory remanufacturing has to come from $P1$ i.e., $q_r \geq \phi(q_n + q_N)$. With policy $\mathcal{S}$, there is no obligation for remanufacturing and the firm will just comply with product specific obligations presented in equation 8. The optimal product quantities are given as $q_n^{\mathcal{S}} = \dfrac{1 - \delta - c_n + c_r - c_{rec} - \tau\sigma c_{rec} + \tau\sigma c_d}{2(1 - \delta)}$, $q_N^{\mathcal{S}} = \dfrac{1 - c_R - \tau c_d - \tau\sigma c_{rec} + \tau\sigma c_d}{2}$ and $q_r^{\mathcal{S}} = \dfrac{\delta c_n - c_r + c_{rec} + \tau\delta c_d + \tau\sigma\delta c_{rec} - \tau\sigma\delta c_d}{2\delta_1(1 - \delta_1)}$.Similarly, $q_n^C = \dfrac{(1 - \delta\phi_C)(1 - c_N - \tau\sigma c_{rec} + \tau\sigma c_d + \tau c_d + \phi_C c_{rec} - \phi_C c_r + \delta\phi) + (1 + \delta\phi_C^2)(c_N - c_n)}{2(1 - \phi_C^2\delta^2 + 2\delta\phi_C + 2\delta\phi_C^2)}$
$q_N^C = \dfrac{-(1 + \delta\phi_C)(1 - c_N - \tau\sigma c_{rec} + \tau\sigma c_d + \tau c_d + \phi_r c_{rec} - \phi_C c_r + \delta\phi_C) + \delta\phi_C(1 + \phi_C)(c_N - c_n)}{2(1 - \phi_C^2\delta^2 + 2\delta\phi_C + 2\delta\phi_C^2)}$ and $q_r^C = \phi_C(q_n^C + q_N^C)$.
Observe that the implementation of reuse target has enforced interaction between all three products.

Comparison of Environmental Footprint

Virgin Material usage $\left(e_m q_n^C + e_M q_N^C\right) - \left(e_m q_n^S + e_M q_N^S\right) < 0$ iff $\phi_C > \frac{-\delta_1 c_n - \delta c_{rec}\sigma\tau + \delta c_d\sigma\tau - \delta c_d\tau + c_r - c_{rec}}{\delta(-\delta c_N + 2\delta - \delta c_{rec}\sigma\tau - \delta c_d\tau + \delta c_d\sigma\tau - 2 + c_{rec} + c_N - c_r + c_n + 2c_{rec}\sigma\tau - 2c_d\sigma\tau + 2c_d\tau)}$ which is true as long as ϕ_C is binding $\therefore \mathrm{E_p}^S > \mathrm{E_p}^C$. Similarly, it can be proven that $\mathrm{E_u}^S < \mathrm{E_u}^C$ and $\mathrm{E_{EOL}}^S < \mathrm{E_{EOL}}^C$ as long as ϕ is binding. We solve $\mathrm{E_p}^C + \mathrm{E_u}^C + \mathrm{E_{EOL}}^C < \mathrm{E_p}^S + \mathrm{E_u}^S + \mathrm{E_{EOL}}^S$ for e_m given by $\bar{\mathrm{e}}_m = \overbrace{\tau(\hat{e}_d - e_d + \sigma e_d) + \frac{1-\delta}{\delta(1+\phi_C)}(\hat{e}_d + e_u)}^{=\bar{\bar{e}}_m} - \hat{e}_d \frac{1+\delta\phi_C}{\delta(1+\phi_C)} - \frac{\phi_C(1-\delta)(e_U + e_M + \hat{e}_D - \tau\hat{e}_D + e_D\tau - \sigma\tau e_D)}{(1+\phi_C)}$. Therefore, $\bar{\mathrm{e}}_m < \bar{\bar{e}}_m$. In other words, when reuse target is environmentally dominant than category based targets with reuse lead to better outcomes.

In order to prove the case 2 of proposition 10, we solve for the optimal quantities for all sub-cases i.e.,(i) when all recycling come from P_1, (ii) when $q_{REC} > 0$ and (iii when $q_{REC} = 0$ but firm increases remanufacturing of P_2. Note that corollary 3 characterize these cases. We plug the respective values of product quantity into the environmental footprint function and compare for product specific schemes versus category based schemes. The respective thresholds can be obtained by comparison as presented in proposition 10 and appendix A-1.

Appendix: A3 Calculation of Environmental Footprint

This section presents a non-exhaustive list of methods that are generally used to measure the environmental footprint associated with product life-cycle. We explain how these methods can be integrated into our model.

Let there are N environmental criteria that form the basis of the evaluation for total environmental footprint where $i \in \{1...N\}$. And α_i denotes the environmental footprint associated with a criterion i. The life-cycle assessment based studies obtain this value by measuring the footprint associated with life-cycle stages.We consider three different life-cycle stages, however, effects from other stages can also be associated with one of these stages. Let us consider P_i,U_i denote the environmental footprint for a criterion i from manufacturing and use phase of the product life-cycle.Similarly, the environmental footprint associated with end-of-life phases are given as, eol_i and EOL_i respectively. Therefore,

$$\alpha_i = \mathrm{P}_i + \mathrm{U}_i + \mathrm{eol}_i + \mathrm{EOL}_i \qquad \text{Eqn(A)}$$

The total environmental footprint can be obtained by combining the footprints from all criteria. In the following paragraph, we present some methods:

Cost Monetization

Much of the literature in environmental economics and sustainable operations assume that the environmental cost can be translated into a monetary value. This assumption is necessary to conduct social welfare analysis. Let us consider γ_i a cost monetization factor that converts the environmental footprint from a criterion i to respective monetary value. In this case,

$$\sum_{i=1}^{N} \gamma_i \alpha_i = \sum_{i=1}^{N} \gamma_i \left(\mathrm{P}_i + \mathrm{U}_i + \mathrm{eol}_i + \mathrm{EOL}_i\right) \qquad \text{A-1}$$

$$= \sum_{i=1}^{N} \gamma_i \mathrm{P}_i + \sum_{i=1}^{N} \gamma_i \mathrm{U}_i + \sum_{i=1}^{N} \gamma_i \mathrm{eol}_i + \sum_{i=1}^{N} \gamma_i \mathrm{EOL}_i \qquad \text{A-2}$$

We can obtain respective values of e_m,e_u, e_{eol} and e_{EOL}

$$e_m = \sum_{i=1}^{N} \gamma_i \mathrm{P}_i \quad e_u = \sum_{i=1}^{N} \gamma_i \mathrm{U}_i \quad e_d = \sum_{i=1}^{N} \gamma_i \mathrm{eol}_i \quad \hat{e}_d = \sum_{i=1}^{N} \gamma_i \mathrm{EOL}_i \qquad \text{A-3}$$

Aggregate Panel Weightage Method

If the monetization factor for all criteria of the footprint is not available, aggregate or panel weight based methods can be used. For any criterion *i*,

$$\frac{\mathrm{P}_i}{\alpha_i}+\frac{\mathrm{U}_i}{\alpha_i}+\frac{\mathrm{eol}_i}{\alpha_i}+\frac{\mathrm{EOL}_i}{\alpha_i} \qquad \text{A-4}$$

This method gives a normalized score and allows us to identify the more dominating stages of the product life-cycle.

Two methods can be used to combine the effects from product life-cycle.

Aggregate Weighting

If all the environmental criteria are equally important, their normalized scores can be summed up and is given as:

$$\frac{1}{N}\sum_{i=1}^{N}\Big(\frac{\mathrm{P}_i}{\alpha_i}+\frac{\mathrm{U}_i}{\alpha_i}+\frac{\mathrm{eol}_i}{\alpha_i}+\frac{\mathrm{EOL}_i}{\alpha_i}\Big) \qquad \text{Footprint from Product}$$

$$e_m=\frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{P}_i}{\alpha_i} \quad e_u=\frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{U}_i}{\alpha_i} \quad e_d=\frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{eol}_i}{\alpha_i} \quad \hat{e}_d=\frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{EOL}_i}{\alpha_i} \qquad \text{A-5}$$

Panel Weighting

Naturally, one may argue that all environmental criteria are not equally critical and much depends on the preferences of the environmentalists and policymaking circles within the boundary. For example, for agriculture based economy or where people rely on underground water resources, terrestrial toxicity becomes key parameter in comparison with the others. In such cases, a panel of policy makers and experts are asked to identify the most critical criterion. They are later asked to rank the criticality of each of the considered criteria in comparison with this criteria. A score β_i can be obtained for each criterion and the environmental footprint can be computed as:

$$\frac{1}{N}\sum_{i=1}^{N}\beta_i\Big(\frac{\mathrm{P}_i}{\alpha_i}+\frac{\mathrm{U}_i}{\alpha_i}+\frac{\mathrm{eol}_i}{\alpha_i}+\frac{\mathrm{EOL}_i}{\alpha_i}\Big)$$

$$e_m=\frac{1}{N}\sum_{i=1}^{N}\frac{\beta_i\mathrm{P}_i}{\alpha_i} \quad e_u=\frac{1}{N}\sum_{i=1}^{N}\frac{\beta_i\mathrm{U}_i}{\alpha_i} \quad e_d=\frac{1}{N}\sum_{i=1}^{N}\frac{\beta_i\mathrm{eol}_i}{\alpha_i} \quad \hat{e}_d=\frac{1}{N}\sum_{i=1}^{N}\frac{\beta_i\mathrm{EOL}_i}{\alpha_i} \qquad \text{A-6}$$

Eco-Indicator99

Eco-Indicator99 is an accepted method of measuring environmental footprint. We present, how our model can also be integrated with this method. In this method, the environmental footprint from each criteria is evaluated based on its impact of (i) Human health (ii) Damage to Eco System Quality (iii) Resource Depletion. We recommend the curious readers to(Goedkoop et al. 1998) for more details. Human Health is typically measured with Disability Adjusted Life Years (DALY); the damage to Eco System Quality can be measured with loss of species over a certain area, during a certain time and damage to resources is measured with surplus energy for future extractions. Note that, it is relatively simple to convert these three metrics into monetary values. This method can also be incorporated into our model. Let us consider $\mathcal{H}_i$, $\mathcal{D}_i$ and $\mathcal{R}_i$. So the environmental footprint can be given as:

$\mathcal{H}_i\mathrm{P}_i+\mathcal{H}_i\mathrm{U}_i+\mathcal{H}_i\mathrm{eol}_i+\mathcal{H}_i\mathrm{EOL}_i$ (Health Effects)

$\mathcal{D}_i\mathrm{P}_i+\mathcal{D}_i\mathrm{U}_i+\mathcal{D}_i\mathrm{eol}_i+\mathcal{D}_i\mathrm{EOL}_i$ (Damage to Eco System)

$\mathcal{R}_i\mathrm{P}_i+\mathcal{R}_i\mathrm{U}_i+\mathcal{R}_i\mathrm{eol}_i+\mathcal{R}_i\mathrm{EOL}_i$ (Damage to Resources)

These values can be added and summed across all the criteria as well as a weighting based system can also be used.

Consider $\mathcal{A}$ is weight from health, $\mathcal{B}$ for Eco System damage and $1-\mathcal{A}-\mathcal{B}$
$\mathcal{A}\sum_{i=1}^{N}\mathcal{H}_i(\mathrm{P}_i+\mathrm{U}_i+\mathrm{eol}_i+\mathrm{EOL}_i)+\mathcal{B}\sum_{i=1}^{N}\mathcal{D}_i(\mathrm{P}_i+\mathrm{U}_i+\mathrm{eol}_i+\mathrm{EOL}_i)+\mathcal{C}\sum_{i=1}^{N}\mathcal{R}_i(\mathrm{P}_i+\mathrm{U}_i+\mathrm{eol}_i+\mathrm{EOL}_i)$ The respective values of e_m,e_u,e_d and $\hat{e}_d$ are given as:

$$e_m=\mathcal{A}\sum_{i=1}^{N}\mathcal{H}_i\mathrm{P}_i+\mathcal{B}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{P}_i+\mathcal{C}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{P}_i \quad e_u=\mathcal{A}\sum_{i=1}^{N}\mathcal{H}_i\mathrm{U}_i+\mathcal{B}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{U}_i+\mathcal{C}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{U}_i$$

$$e_d=\mathcal{A}\sum_{i=1}^{N}\mathcal{H}_i\mathrm{eol}_i+\mathcal{B}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{eol}_i+\mathcal{C}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{eol}_i \quad \hat{e}_d=\mathcal{A}\sum_{i=1}^{N}\mathcal{H}_i\mathrm{EOL}_i+\mathcal{B}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{EOL}_i+\mathcal{C}\sum_{i=1}^{N}\mathcal{D}_i\mathrm{EOL}_i$$

Appendix A-4: Targets include Remanufactured products

Although the scope of WEEE legislations is confined only to the new products introduced by the firm. However, the scope may be expanded to include the remanufactured products. In this section, we analyze the case where remanufactured products are also subjected to collection and recycling obligations. For this problem, two cases are possible; one where remanufactured products are considered towards recycling target and the other where they are not considered into recycling obligation. We call these as Policies $\tilde{\mathtt{R}}$ and $\tilde{\mathtt{O}}$ respectively. The firm's profit problem along with set of constraints are given as:

$$\Pi^{\tilde{\mathtt{O}}}=q_n(p_n-c_n)+q_r(p_r-c_r)-\sigma\tau(q_n+q_r)c_{rec}-((1-\sigma)\tau(q_n+q_r)-q_r)c_d \quad (\tilde{\mathtt{O}})$$

$$\Pi^{\tilde{\mathtt{O}}}=q_n(p_n-c_n)+q_r(p_r-c_r)-(\sigma\tau(q_n+q_r)-q_r)c_{rec}-\tau(1-\sigma)(q_n+q_r)c_d \quad (\tilde{\mathtt{R}})$$

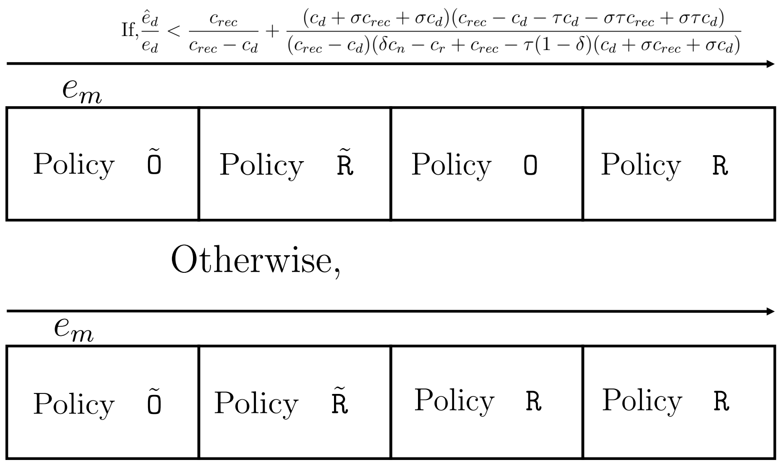
The environmental footprint for the two is given as:

$$E^{\tilde{\mathtt{O}}}=e_mq_n+e_u(q_n+q_r)+((1-\sigma)\tau(q_n+q_r)-q_r)e_d+(1-\tau)(q_n+q_r)\hat{e}_d \quad (\tilde{\mathtt{O}})$$

$$E^{\tilde{\mathtt{R}}}=e_mq_n+e_u(q_n+q_r)+\tau(1-\sigma)(q_n+q_r)e_d+(1-\tau)(q_n+q_r)\hat{e}_d \quad (\tilde{\mathtt{R}})$$

Note that the respective values for q_n and q_r are different for both policies. We solve for equation $E^{\tilde{\mathtt{R}}}=E^{\tilde{\mathtt{O}}}$ for e_m. We call this threshold value $e_m^{\tilde{\mathtt{R}},\tilde{\mathtt{O}}}$. It is straightforward to see $e_m^{\tilde{\mathtt{R}},\tilde{\mathtt{O}}}<\bar{e}_m$ (recall proposition 2). It basically suggests that for products where recast policy $\mathtt{R}$ is preferable to $\mathtt{O}$, then policy $\mathtt{R}$ is also preferable to a policy where targets apply on both products and remanufacturing is not considered into recycling. Similarly, we solve $E^{O}=E^{\tilde{\mathtt{R}}}$ for e_m and obtain threshold $e_m^{\mathtt{O},\tilde{\mathtt{R}}}$. Comparing these threshold values i.e., $\bar{e}_m$, $e_m^{\mathtt{O},\tilde{\mathtt{R}}}$ and $e_m^{\tilde{\mathtt{R}},\tilde{\mathtt{O}}}$.

By comparing and analyzing these threshold values, we obtain the preference structure for the policy choices. We find that there exists a range of e_m of products, for which a unique policy is preferable. If
$\dfrac{\hat{e}_d}{e_d}<\dfrac{c_{rec}}{c_{rec}-c_d}+\dfrac{(c_d+\sigma c_{rec}+\sigma c_d)(c_{rec}-c_d-\tau c_d-\sigma\tau c_{rec}+\sigma\tau c_d)}{(c_{rec}-c_d)(\delta c_n-c_r+c_{rec}-\tau(1-\delta)(c_d+\sigma c_{rec}+\sigma c_d)}$,
Policy $\tilde{\mathtt{O}}$ performs better. For a bit higher values of e_m, Policy $\tilde{\mathtt{R}}$ becomes policy choice. For products with higher values than that, Policy $\mathtt{O}$ become preferable and for products with even higher values of e_m, Policy $\mathtt{R}$ is the preferred choice. Similarly, if $\dfrac{\hat{e}_d}{e_d}$ is higher than the threshold specified above then Policy $\mathtt{R}$ is the preferred choice for higher values of e_m. Policy $\tilde{\mathtt{R}}$ becomes preferable for moderate values of e_m while Policy $\tilde{\mathtt{O}}$ suit products with lower e_m. Note that policy $\mathtt{O}$ no longer remains a preferred choice in this case.


If, $\frac{\hat{e}_d}{e_d} < \frac{c_{rec}}{c_{rec} - c_d} + \frac{(c_d + \sigma c_{rec} + \sigma c_d)(c_{rec} - c_d - \tau c_d - \sigma\tau c_{rec} + \sigma\tau c_d)}{(c_{rec} - c_d)(\delta c_n - c_r + c_{rec} - \tau(1-\delta)(c_d + \sigma c_{rec} + \sigma c_d)}$
e_m
Policy $\tilde{\mathtt{O}}$
Policy $\tilde{\mathtt{R}}$
Policy $\mathtt{O}$
Policy $\mathtt{R}$
Otherwise,
e_m
Policy $\tilde{\mathtt{O}}$
Policy $\tilde{\mathtt{R}}$
Policy $\mathtt{R}$
Policy $\mathtt{R}$