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The Implications of Recycling Technology Choice on Extended Producer Responsibility

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We study recycling technology choice, a critical factor that has received little attention in the context of extended producer responsibility, and its interaction with product design-for-recycling in driving the environmental benefits of recycling systems. Collective recycling systems have long been criticized for restricting the environmental benefits of extended producer responsibility because of free riding issues among producers, which can undermine incentives for product design-for-recycling. We revisit and refine this assertion by analyzing the interaction between recycling technology and product design-for-recycling choices. We develop game-theoretic models where producers and processors decide on product design-for-recycling and recycling technology choices, respectively. We then compare the equilibrium benefits of recycling in collective and individual systems. The key result in this study is that when recycling technology choice is taken into account, collective recycling systems can lead to higher environmental and economic benefits than individual recycling systems. This is because collective recycling systems provide stronger incentives for recycling technology improvements. In turn, these improvements can help overcome the drawbacks associated with inferior product design-for-recycling outcomes caused by free riding concerns among producers in collective recycling systems. In light of these results, we posit that an exclusive focus on product design-for-recycling to assess the environmental benefits of extended producer responsibility-based recycling systems may need scrutiny. Producers and policy makers may need to evaluate recycling systems with respect to the incentives they provide for both product design-for-recycling and recycling technology improvements.

Key words: recycling technology; design for environment; extended producer responsibility; game theory
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1. Introduction

Extended producer responsibility (EPR) legislation is a widely adopted policy tool around the globe that holds producers responsible for proper treatment of their end-of-life products (Kalimo et al. 2012). One of the main purposes of EPR is to provide design-for-recycling incentives for producers. However, it is often argued that many implementations of EPR legislation have created limited incentives for producers to design their products for recycling, and therefore undermined the environmental benefits potential of the policy instrument (Lifset and Lindhqvist 2008). The lack of such design incentives is largely ascribed to the collective practice of recycling, that is, processing products from multiple producers in shared recycling systems (Shao and Lee 2009) and having producers share associated costs based on their recycling volumes (Atasu and Subramanian 2012, Gui et al. 2018). Specifically, collective recycling systems are considered prone to free-riding between producers, and diluting incentives to design products for recycling. Therefore, from an environmental point of view, collective recycling systems have often been argued to be inferior to individual recycling systems where different producers' products are processed separately (Atasu and Subramanian 2012, Greenpeace 2008, Lifset and Lindhqvist 2008, Sander et al. 2007).

However, a close examination of recycling practice suggests that an environmental benefit comparison between collective and individual recycling systems purely based on the incentives they provide for product design-for-recycling should bear scrutiny. This is because the environmental benefits from recycling (e.g., increase in landfill diversion, toxicity reduction or material recovery levels) depend not only on

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product design-for-recycling choices, but also on recycling technology choices. Consider Embraco (http://www.embraco.com), a global manufacturer of compressors, which works with a recycling partner, Nat.-Genius. Embraco has largely improved the efficiency of recycling their products by leveraging the complementarity between their product design and recycling technology choices (Bosco 2018). In particular, Embraco embraces design for disassembly. For example, they design compressors with fewer screws to reduce disassembly time, avoid use of adhesives to keep components intact when disassembled, and design compressors to work without oil/lubrication to reduce contamination during disassembly and recycling. Meanwhile, Nat.Genius—Embraco's recycler—utilizes a manual recycling technology, where disassembly and separation is handled manually to leverage Embraco's specific design-for-recycling feature choices. The combination of these design features and the manual recycling process has significantly improved the efficiency of Embraco's recycling operations, and increased unit recycling profit margins by around 30% (Bosco 2018). Raul Bosco, corporate manager of Nat.Genius, estimates that the use of an industrial shredder (as opposed to manual disassembly and separation) would have capped the recycling process efficiency improvement at 5%. Similarly, it is estimated that the use of manual disassembly without the design-for-recycling features previously mentioned would have capped the same at about 10%.

This complementarity between design-for-recycling and recycling technology choices can also be observed in EPR legislation implementations, and some of those have leveraged it well to achieve higher efficiency in recycling. Cases in point are Japanese Home Appliance Recycling Law (HARL) implementations, in which significant improvements in recycling process efficiency have been reported despite their collective nature. Tojo (2004) and Dempsey et al. (2010) indicate that such improvements in HARL implementations are largely due to inputs from both product designers and recycling facility engineers, which better leverage the complementarity between product design and recycling technology improvements (DTI 2005). These examples suggest that taking into account the complementarity between product design-for-recycling and recycling technology choices is crucial in improving the environmental benefits of recycling. Similar examples can be found in other recycling contexts, such as home appliance, cell phone, carpet, plastics, textile, and mattress recycling (see Appendix A).

Accordingly, environmental benefits of recycling systems depend not only on the extent they provide incentives for product design-for-recycling, but also on how they shape recycling technology choices. To this end, the long-standing practical debate and academic research on the comparison between individual and collective recycling systems should also account for recycling technology choice along with product design-for-recycling. To the best of our knowledge, however, this key interaction has received little attention, if any, in academic research or practice. In what follows, we fill this void by formally analyzing how collective and individual recycling systems differ with respect to recycling technology choice, and how their environmental and economic benefits compare in the presence of this choice.

For this analysis, we develop stylized game-theoretic models of collective and individual recycling systems where producers and processors (i.e., recyclers) decide on design-for-recycling and recycling technology choices, respectively. We first compare these systems based on an environmental impact measure of recycling process efficiency, which captures the joint effect of product design-for-recycling and recycling technology choices (see section 3.1 for a detailed discussion). We then compare the economic benefits of recycling systems from producers' and processors' perspectives and explore the alignment between environmental and economic benefits of recycling systems.

Our analysis yields several insights. First, comparing the equilibrium recycling process efficiency of the recycling systems, we show that when recycling technology choices of processors are taken into account, a collective system (where multiple producers share a contracted recycling facility) can lead to higher environmental and economic benefits than an individual system (with either contracted or producer-owned facilities) despite being prone to free-riding among producers. This is due to the impact of horizontal pooling (i.e., recycling products of different producers together), which provides larger scale and, in turn, stronger incentives for recycling technology improvements at the shared processor. When this positive scale effect dominates the negative impact of free-riding between producers (which may hurt design-for-recycling choices), the recycling process efficiency of a collective system exceeds that of an individual system. This happens when a contracted recycling facility is shared by producers with similar recycling volumes in a collective system, and recycling technology choice has a high impact on the recycling process efficiency. In addition, individual systems with producer-owned facilities lead to higher environmental and economic benefits than individual systems with contracted facilities. This is due to the impact of vertical integration, which mitigates the free-riding between producers and processors in individual systems with contracted facilities. Furthermore, we show

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that producers' and processors' profits are higher in a collective system than in an individual system when producers' volumes are similar. This implies that when the degree of recycling volume heterogeneity is low, there is a natural alignment between the environmental and economic benefits of collective systems.

Finally, we put these insights in practical context using a case study based on regulated electronics recycling system implementations in the states of Washington and Oregon. We also generalize our model in several directions, and show that the key results are robust to producer or processor competition, the sequence in which recycling technology and product design-for-recycling choices are made, and the loss of efficiency due to mix of products in collective systems.

The rest of the study is organized as follows. We review the related literature in section 2, and present the model set-up in section 3. Our main results are presented in section 4. We provide a numerical case study based on electronics recycling programs in practice in section 5, and present several extensions of the model in section 6. We conclude with a summary of managerial insights and recommend directions for future research in section 7. Appendices to the study provide proofs and additional technical details (see Appendix A-F).

2. Literature Review

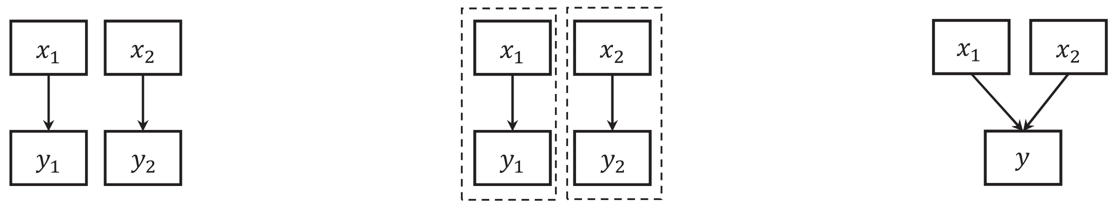
In this study, we contribute to the long-standing operations management and industrial ecology literature that studies how a choice between collective and individual recycling systems in the context of EPR affects the environmental benefits of recycling. In this context, the industrial ecology literature provides several qualitative analyses and case studies (e.g., Sander et al. 2007, Tojo 2003) that document evidence regarding free-riding (among producers in collective recycling systems), which undermines incentives for product design-for-recycling. This literature posits that either an individual recycling system or a proper allocation of recycling costs between producers (often referred to as individual producer responsibility) is crucial for providing product design-for-recycling incentives and generating the environmental benefits expected from EPR (Dempsey et al. 2010, Kalimo et al. 2012, Lifset and Lindhqvist 2008).

This study belongs to the intersection of two research streams in the recent operations management literature. One stream focuses on different EPR implementation approaches and different stakeholder perspectives (e.g., Alev et al. 2019, Atasu et al. 2013, Gui et al. 2013, Toyasaki et al. 2011). The other stream studies product design implications of EPR (e.g., Atasu and Souza 2013, Gui et al. 2018, Huang et al. 2019, Raz et al. 2013, Subramanian et al. 2009, Tian et al. 2014). Most closely related to our research, a particular set of studies analyze how collective recycling affects incentives for product design-for-recycling. Plambeck and Wang (2009) and Atasu and Subramanian (2012) study primary market competition and new product introduction choices under e-waste legislation, respectively, and find that collective recycling systems lead to inferior design incentives compared to individual recycling systems. Mazahir et al. (2019) study the impact of a collective reuse target policy based on the 2012 Recast of the WEEE Directive of the European Commission, and conclude that such a policy update may undermine electronics producers' incentives for energy efficient product designs. Esenduran and Kemahlíoğlu-Ziya (2015) and Gui et al. (2018), on the other hand, show that collective recycling systems can be designed (by appropriately choosing collection targets or cost allocation mechanisms) to create stronger incentives for product design-for-recycling.

Yet, both streams of literature ignore the effect of recycling technology choice, an important decision in recycling practice, on the design of recycling systems. They consider creating incentives for product design-for-recycling as the immediate objective of EPR and do not take into account the effect of recycling technology choice on the environmental benefits of recycling. Two exceptions are Van Rossem (2008), who qualitatively recognizes the impact of recycling technology and its interaction with product design-for-recycling, and Zuidwijk and Krikke (2008), who study a recycling firm's trade-off between investing in product eco-design vs. advanced recycling technologies to reduce compliance cost under EPR. However, to the best of our knowledge, there is no research that explicitly studies the effect of recycling technology choice and its interaction with product design-for-recycling choice on the comparison between collective and individual recycling systems. We fill this gap and find that a joint evaluation of product design-for-recycling and recycling technology choices can be critical in measuring the environmental and economic benefits of recycling. More importantly, we show that collective systems can induce superior recycling technology choices and thus lead to higher environmental and economic benefits compared to individual systems.

This study is also related to the literature on the impact of environmental policy on technological development and welfare (e.g., Fischer et al. 2003, Jaffe et al. 2002). Related research in operations management studies the implications of carbon tax and cap-and-trade mechanisms on firms' incentives to adopt clean technology. These studies take into account operational factors such as production cost and quantity choices (Krass et al. 2013), location

Figure 1 The Three Recycling System Models. Arrows Indicate Recycling Facilities of Each producer's Products. Dashed Boxes Indicate Producers' Ownership of Recycling Facilities



(a) Individual Recycling System with Contracted Facilities (I)

(b) Individual Recycling System with Producer-owned Facilities (IO)

(c) Collective Recycling System (C)

choices under carbon leakage (Drake 2018, İşlegen et al. 2016), technology portfolio choice (Drake et al. 2016), dynamic capacity adjustment under uncertainty (Wang et al. 2013), and timing of clean technology adoption (Chen and Tseng 2011). Our study shares a similar spirit as the choice of recycling technology can impact the recycling process efficiency and that impact hinges on an operational factor, that is, product design. Nevertheless, our focus on the complementarity between technology and product design choices in the recycling context distinguishes our work from this literature.

3. Model

In this section, we develop stylized game-theoretic models of recycling systems, where producers and processors decide on design-for-recycling and recycling technology choices, respectively. In order to capture the fundamental trade-offs between product design and technology choices, we construct three basic recycling system models: In a *collective system*, products of multiple producers are recycled at a shared contracted recycling facility, and producers and the processor share recycling revenue (or cost savings) of all products proportionally. For instance, the Washington state E-cycle program is operated as a state-wide collective recycling system, wherein producers share the total recycling cost proportional to their sales/return volumes. In an *individual system with contracted facilities*, products of each producer are recycled separately, wherein each producer shares revenue (or cost savings) of recycling its products with the contracted processor (e.g., as in the case of Samsung (Samsung 2018)). In contrast, in an *individual system with producer-owned facilities*, products of a producer are recycled in a recycling facility that is owned by the producer (e.g., as in the case of HP (HP 2019)). In this case, the producer collects all the revenue (or cost savings) of recycling its products.[1]

In our main analysis, we represent these stylized scenarios by considering two producers, denoted by $i \in \{1,2\}$. We later extend our model and analysis to scenarios with multiple producers (see section 5). Figure 1 presents these three recycling system models (see section 3.1 for notation details). Before presenting the details of the decision-making model of producers and processors in each recycling system, we first introduce a couple of model components that capture the environmental benefit and revenue from recycling as well as the investment costs of design-for-recycling and recycling technology improvements.

3.1. Model Components

We consider a unidimensional measure for the environmental benefits of recycling that depends on both product design-for-recycling and recycling technology choices, referred to as the *recycling process efficiency*. For example, the recycling process efficiency of metal recycling (i.e., the level of valuable material recovery) depends on the material purity of products as well as the metal separation technology at the recycling facility. In the Embraco example, the recycling process efficiency of compressor disassembly (i.e., the degree to which disassembled components can be fed back to re-manufacturing or material recycling, which could effectively improve profits and reduce environmental impact of the manufacturing process) depends on both product design-for-disassembly features and the type of disassembly technology used. This measure also depends on the recycling system model, which we discuss in detail below.

Recycling Process Efficiency of Individual Systems: In individual recycling systems (with contracted and producer-owned facilities), products of each producer $i \in \{1,2\}$ are processed separately, as illustrated in Figure 1a and b. Thus, the recycling process efficiency of producer i's products (and in turn, the corresponding costs/revenue) depends only on that producer's choice of design-for-recycling, which we denote by $x_i \geq 0$, and the corresponding processor's choice of recycling technology, which we denote by $y_i \geq 0$. In order to capture the dependency between x_i and y_i, we model the recycling process efficiency of each producer with a Cobb–Douglas function:

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$$V_i(x_i, y_i) \doteq q_i x_i^{\alpha} y_i^{1-\alpha}, \tag{1}$$

in which q_i is the recycling volume of producer $i \in \{1,2\}$ for a given time period, and the exponents α and $1-\alpha$, which take values in (0,1), capture the relative impacts of product design-for-recycling and recycling technology choices on the recycling process efficiency, respectively. As shown in Equation (1), the recycling process efficiency of an individual system is determined by the joint effects of x_i and y_i, which implies a per unit environmental recycling benefit of $V_i(x_i, y_i)/q_i = x_i^{\alpha} y_i^{1-\alpha}$. The Cobb–Douglas function, while stylized, is conceptually appealing as it allows us to capture the joint outcome of two complementary inputs (i.e., product design-for-recycling and recycling technology choices). This functional form has also been widely used in the literature to capture complementary actions in other contexts (see Table A1 in Appendix B). The value of α naturally varies across product categories. For example, in the case of small electronics refurbishing, product design-for-recycling can be considered to play a more important role (Hogan 2018), which implies a large α; whereas in the case of recycling compressors, recycling technology choice can be considered to play a more important role (Bosco 2018), which implies a small α.[2]

We note that, in practice, product design and technology choices could be multi-faceted or discrete choices. In our analysis, we consider them to be unidimensional and continuous to simplify the exposition and characterize equilibrium choices in closed-form. Nonetheless, we show in Appendix F that the main insights continue to hold when we consider discrete choices. In practice, there may also exist baseline product design and recycling technology requirements for producers and processors (i.e., $x \geq x_0$ and $y \geq y_0$). For instance, these could reflect meeting certain standards mandated by law (e.g., the RoHS standards in the European Union (RoHS 2019), and the performance standards for processors mandated by the WA E-cycle program (Washington State Legislature 2013)). Since such baseline design and technology levels do not affect the insights of our analysis, we normalize them to zero (i.e., $x_0 = y_0 = 0$) for simplicity, and focus on product design-for-recycling and recycling technology choices that producers and processors voluntarily adopt on top of these baseline levels.

Recycling Process Efficiency of Collective Systems: In a collective recycling system, products of both producers are processed at a shared recycling facility, as illustrated in Figure 1c. Accordingly, the recycling process efficiency of a collective system depends on both producers' design-for-recycling choices (i.e., $\mathbf{x} = (x_1, x_2)$), and the shared processor's recycling technology choice (which we denote by $y \geq 0$). Specifically,

$$V(\mathbf{x}, y) = \sum_{i=1}^{2} V_i(x_i, y) = q_1 {x_1}^{\alpha} \cdot y^{1-\alpha} + q_2 {x_2}^{\alpha} \cdot y^{1-\alpha}, \tag{2}$$

which implies a per unit environmental recycling benefit of $V(\mathbf{x},y)/(q_1+q_2) = (\frac{q_1}{q_1+q_2}){x_1}^{\alpha} \cdot y^{1-\alpha} + (\frac{q_2}{q_1+q_2}){x_2}^{\alpha} \cdot y^{1-\alpha}$ that depends on both producers' volumes and design choices. As we explain in section 3.2 (where producers' profit functions are introduced), this is the key differentiating factor between a collective system and an individual system where a producer's benefits from recycling do not depend on the other producer's product design or volume (see the discussion after Equation (1)). We note that the model in Equation (2) represents cases where the complexity of the product mix in a collective system has a minimal impact on the recycling process efficiency. We present a detailed discussion on the effect of product mix and a generalization of our model to capture the mix effect in section 6.2.

Revenue (or Cost Savings) from Recycling: Environmental benefits associated with recycling process efficiency often translate into economic benefits in the form of cost reduction or increase in recycling revenue. For example, higher purity of recycled materials implies a higher market value, and removal of toxic materials eliminates the need for controlled hazardous substance transportation. To capture such economic benefits from recycling process efficiency improvements, as a reasonable abstraction of reality, we assume that a unit improvement in recycling process efficiency implies a monetary benefit of K (referred to as the input conversion factor in the co-development literature). Thus, the total added recycling revenue (or cost savings) of products recycled can be written as $K \cdot V_i(.)$ and $K \cdot V(.)$ in an individual and a collective system, respectively (where $V_i(.)$ and $V(.)$ are as defined in Equations (1) and (2)). Note that this formulation does not assume profitable recycling, as the recycling revenue can be interpreted as either added recycling revenue or recycling cost reduction.

Recycling Revenue Sharing: In recycling practice, contracts between producers and processors are often based on the revenue (or cost) generated from the recycling process. For example, when recycling is profitable, a processor may pay the producer of the recycled products and essentially shares the recycling revenue generated with the producer. On the other hand, when recycling is costly, the processor typically charges the producer a price that equals the recycling cost plus a margin (Gui et al. 2013). Hence, we assume that recycling cost reduction can be reflected through a price reduction charged to the producer.

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This is equivalent to the processor sharing the cost reduction with the producer. In this study, we adopt linear sharing rules under which the added recycling revenue or the recycling cost reduction is shared between producers and processors in proportions ρ (which takes values in (0,1)) and $1-\rho$, respectively. Such linear sharing rules provide the second-best solution theoretically (Bhattacharyya and Lafontaine 1995).

Design-for-Recycling and Recycling Technology Investment Costs: We assume that producers and processors incur costs for their product design-for-recycling and recycling technology choices. We model these costs as convex-quadratic and increasing functions, that is, $c(x) = c \cdot x^2$ and $d(y) = d \cdot y^2$, with $c>0$ and $d>0$. Such cost functions have been widely used in the literature (e.g., Bhaskaran and Krishnan 2009, Rahmani and Ramachandran 2020), and are consistent with empirical evidence (Cohen and Klepper 1992). We also note that the investment cost parameters are set to correspond to the same time period for which other model parameters (e.g., volumes) are defined.

3.2. Game-theoretic Models of Recycling Systems

We next describe game-theoretic models between producers and processors in the three recycling systems depicted in Figure 1 (hereafter referred to as *I*, *IO*, and *C* systems). We denote each producer's and processor's profits by $\Pi^S_{i,p}(.)$ and $\Pi^S_{i,r}(.)$ for $i \in \{1,2\}$ and $S \in \{I,C,IO\}$, respectively.

Individual Recycling System with Contracted Facilities (*I*)**:** In this system, products of each producer *i* are processed separately (i.e., by processor *i*), for $i \in \{1,2\}$, as illustrated in Figure 1a. Accordingly, the game between producer *i* and processor *i* in an individual system with contracted facilities can be modeled as follows:

$$x_i^I \doteq \arg\max_{x_i \geq 0} \ \Pi^I_{i,p}(x_i, y_i^I) \doteq \rho \cdot K \cdot V_i\left(x_i, y_i^I\right) - cx_i^2 \quad \forall i \in \{1,2\}, \tag{3}$$

$$y_i^I \doteq \arg\max_{y_i \geq 0} \ \Pi^I_{i,r}(x_i^I, y_i) \doteq (1-\rho) \cdot K \cdot V_i\left(x_i^I, y_i\right) - dy_i^2 \quad \forall i \in \{1,2\}. \tag{4}$$

As noted before, in this system, each producer gains revenue (or cost savings) associated with its products alone. The corresponding total recycling process efficiency of the individual recycling system with contracted facilities is then given by $T^I \doteq \sum_{i=1,2} V_i(x_i^I, y_i^I)$.

Individual Recycling System with Producer-owned Facilities (*IO*)**:** In this system, products of each producer are processed in a recycling facility that is owned by that producer, as illustrated in Figure 1b. Hence, each producer jointly chooses both product design-for-recycling and recycling technology choices (x_i, y_i) to maximize the total profit:

$$\left(x_i^{IO}, y_i^{IO}\right) \doteq \arg\max_{x_i \geq 0, y_i \geq 0} \Pi^{IO}_{i,p}(x_i, y_i) \doteq K \cdot V_i(x_i, y_i) - cx_i^2 - dy_i^2 \quad \forall i \in \{1,2\}. \tag{5}$$

The corresponding total recycling process efficiency of the individual recycling system with producer-owned facilities is given by $T^{IO} \doteq \sum_{i=1,2} V_i(x_i^{IO}, y_i^{IO})$.

Collective Recycling System (*C*)**:** In this system, products of the two producers are processed at a shared recycling facility, as illustrated in Figure 1c. The total recycling revenue of the collective system is shared based on ρ and $1-\rho$ proportions between the producers and the shared processor. The portion of the revenue to producers is then shared proportionally between the two producers based on their volumes, which is commonly known as the allocation by return/market share in practice (Dempsey et al. 2010, Esenduran and Kemahlíoğlu-Ziya 2015, Gui et al. 2013). Accordingly, the game between the producers and the processor in a collective system can be modeled as follows:

$$x_i^C \doteq \arg\max_{x_i \geq 0} \Pi^C_{i,p}(x_i, x^C_{-i}, y^C) \doteq \rho \cdot K \cdot \left(\frac{q_i}{q_1+q_2}\right) \cdot V\left(\left(x_i, x^C_{-i}\right), y^C\right) - cx_i^2 \quad \forall i \in \{1,2\}, \tag{6}$$

$$y^C \doteq \arg\max_{y \geq 0} \ \Pi^C_r(\mathbf{x}^C, y) \doteq (1-\rho) \cdot K \cdot V\left(\mathbf{x}^C, y\right) - dy^2. \tag{7}$$

The corresponding total recycling process efficiency of a collective system is then given by $T^C \doteq V(\mathbf{x}^C, y^C)$.

We finally note that these three stylized recycling systems are designed to capture the fundamental trade-offs between product design and technology choices in the presence of sharing revenue (or cost savings) in recycling systems. In practice, there could be scenarios that lie between the basic scenarios captured by these models. For instance, producers may not participate in a collective recycling system, but process their products in a contracted facility that also processes other producers' products. In such cases, if the producers' products are being processed separately and each producer receives revenue (cost savings) based on its own product specifications, the system would be similar

Table 1 Summary of Notation

Notation	Definition
Parameters	
q_i	Recycling volume of producer $i \in \{1,2\}$
$\gamma \doteq \frac{q_2}{q_1} \in (0,1]$	The degree of recycling volume heterogeneity between the two producers
$\rho \in (0,1)$	Each producer's share of the recycling revenue per unit product recycled
c	Design-for-recycling investment cost coefficient
d	Recycling technology investment cost coefficient
$\alpha \in (0,1)$	Impact parameter of the product design-for-recycling choice on recycling process efficiency
K	Monetary benefit associated with a unit of recycling process efficiency improvement
Variables and Functions	
(x_i^I, y_i^I)	Equilibrium choices in an individual recycling system with contracted facilities
(x_i^{IO}, y_i^{IO})	Equilibrium choices in an individual recycling system with producer-owned facilities
$(\mathbf{x}^C, y^C)$	Equilibrium choices in a collective recycling system
$V_i(.)$	Total recycling process efficiency in an individual system for producer $i \in \{1,2\}$
$V(.)$	Total recycling process efficiency in a collective system
$\Pi_{i,p}^S(.)$	Producer i's profit in a recycling system $S \in \{I,C,IO\}$
$\Pi_{i,r}^S(.)$	Processor i's profit in a recycling system $S \in \{I,C,IO\}$

to our conceptualization of an individual system with contracted facilities. However, if their products are being processed together and each producer receives revenue (cost savings) based on the overall recycling process efficiency at the processor, the system would be similar to our conceptualization of a collective system.

In the next section, we analyze the games between producers and processors in these three recycling system configurations and compare their equilibrium characteristics. Throughout our analysis, without loss of generality, we assume $q_1 \geq q_2$, and define $\gamma \doteq \frac{q_2}{q_1} \in (0,1]$ as the degree of *recycling volume heterogeneity* between the producers. Table 1 summarizes the notation used in this study. In section 6, we extend our model and analysis to cases when product design-for-recycling and recycling technology choices are made sequentially (section 6.1), when inefficiencies due to product mix are taken into account (section 6.2), when the recycling volumes are endogenized (i.e., determined based on design choices or competition) and vary between individual and collective recycling systems (section 6.3), and when processors compete in winning producers' recycling volumes (section 6.4).

4. A Comparison between Collective and Individual Recycling Systems

The next proposition characterizes the equilibrium product design-for-recycling and recycling technology choices in the three recycling system configurations we model.

Proposition 1. (Equilibrium Choices). *In each recycling system, there exists a strictly positive equilibrium (i.e., x_i, y_i or $y>0$ for $i \in \{1,2\}$) that is Pareto-dominant. Specifically,*

(*i*) *The positive equilibrium outcomes for an individual recycling system with contracted facilities are as follows:*

$$x_i^I = \left(\frac{q_i K}{2}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{\frac{1-\alpha}{2}}\left(\frac{\alpha\rho}{c}\right)^{\frac{1+\alpha}{2}}, \tag{8}$$

$$y_i^I = \left(\frac{q_i K}{2}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{1-\frac{\alpha}{2}}\left(\frac{\alpha\rho}{c}\right)^{\frac{\alpha}{2}}. \tag{9}$$

(*ii*) *The positive equilibrium outcomes for an individual recycling system with producer-owned facilities are as follows:*

$$x_i^{IO} = \left(\frac{q_i K}{2}\right)\left(\frac{1-\alpha}{d}\right)^{\frac{1-\alpha}{2}}\left(\frac{\alpha}{c}\right)^{\frac{1+\alpha}{2}}, \tag{10}$$

$$y_i^{IO} = \left(\frac{q_i K}{2}\right)\left(\frac{1-\alpha}{d}\right)^{1-\frac{\alpha}{2}}\left(\frac{\alpha}{c}\right)^{\frac{\alpha}{2}}. \tag{11}$$

(*iii*) *The positive equilibrium outcomes for a collective recycling system are as follows:*

$$x_i^C = \left(\frac{K}{2}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{\frac{1-\alpha}{2}}\left(\frac{\alpha\rho}{c}\right)^{\frac{1+\alpha}{2}}(q_1+q_2)^{\frac{-1-\alpha}{2}} \left(q_1^{\frac{2+\alpha}{2-\alpha}}+q_2^{\frac{2+\alpha}{2-\alpha}}\right)^{\frac{1-\alpha}{2}} \cdot q_i^{\frac{2}{2-\alpha}}, \tag{12}$$

$$y^C = \left(\frac{K}{2}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{1-\frac{\alpha}{2}}\left(\frac{\alpha\rho}{c}\right)^{\frac{\alpha}{2}}(q_1+q_2)^{-\frac{\alpha}{2}} \left(q_1^{\frac{2+\alpha}{2-\alpha}}+q_2^{\frac{2+\alpha}{2-\alpha}}\right)^{1-\frac{\alpha}{2}}. \tag{13}$$

As shown in Proposition 1, in each recycling system configuration, there exists a strictly positive equilibrium. In addition to that, there is an equilibrium with which neither producers nor processors improve their design and technology (i.e., $x_i = 0$, $y_i = 0$, and $y = 0$). However, as we show in Proposition 1, the strictly positive equilibrium is Pareto-dominant. This implies that, in equilibrium, both producers and processors find it optimal to improve their product design and recycling technology choices to enhance the recycling process efficiency. However, the magnitude of their improvements vary depending on the recycling system, which we analyze in detail in

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section 4.2. Before that, in 4.1, we first compare the total recycling process efficiency of the three recycling systems with the equilibrium design-for-recycling and recycling technology choices.

4.1. When Does a Collective Recycling System Improve Recycling Process Efficiency?

Replacing the producers' and processors' equilibrium choices characterized in Proposition 1 into the total recycling process efficiency of individual and collective systems (i.e., T^I, T^{IO}, and T^C, as defined in section 3.2), we obtain

$$T^I = K^2\left(\frac{q_1q_2}{2\gamma}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{1-\alpha}\left(\frac{\alpha\rho}{c}\right)^{\alpha}(1+\gamma^2), \tag{14}$$

$$T^{IO} = K^2\left(\frac{q_1q_2}{2\gamma}\right)\left(\frac{1-\alpha}{d}\right)^{1-\alpha}\left(\frac{\alpha}{c}\right)^{\alpha}(1+\gamma^2), \tag{15}$$

$$T^C = K^2\left(\frac{q_1q_2}{2\gamma}\right)\left(\frac{(1-\alpha)(1-\rho)}{d}\right)^{1-\alpha}\left(\frac{\alpha\rho}{c}\right)^{\alpha}(1+\gamma)^{-\alpha} \cdot \left(1+\gamma^{\frac{2+\alpha}{2-\alpha}}\right)^{2-\alpha}. \tag{16}$$

The next proposition characterizes when a collective system improves the recycling process efficiency as compared to an individual system (with contracted or producer-owned facilities). Recall that γ is defined as the degree of volume heterogeneity between the two producers.

PROPOSITION 2. (COMPARISON OF RECYCLING PROCESS EFFICIENCY). *There exist unique thresholds $\underline{\gamma}$ and $\overline{\gamma}$ (with $\underline{\gamma} \leq \overline{\gamma}$) such that*

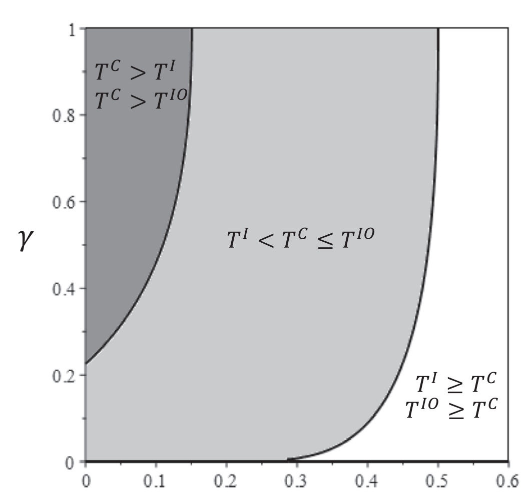
(*i*) *A collective system leads to a higher recycling process efficiency than an individual system with contracted facilities (i.e., $T^C > T^I$) if and only if $\gamma > \underline{\gamma}$.*
(*ii*) *A collective system leads to a higher recycling process efficiency than an individual system with producer-owned facilities (i.e., $T^C > T^{IO}$) if and only if $\gamma > \overline{\gamma}$.*
(*iii*) *An individual system with producer-owned facilities always leads to a higher recycling process efficiency than an individual system with contracted facilities (i.e., $T^{IO} > T^I$).*

Moreover, $\overline{\gamma}$ and $\underline{\gamma}$ are non-decreasing in α for $\alpha \in (0,1)$.

Figure 2 illustrates the results in Proposition 2. The results show that, when recycling technology choices of processors are taken into account, a collective system can lead to a higher recycling process efficiency (and in turn, higher environmental benefits) than an individual system with contracted or producer-owned facilities. On one hand, a collective system leads to free-riding between producers. On the other hand, it provides higher incentives for recycling technology improvement as well as for producers to align their product design choices to maximize the benefits of shared recycling. The superior performance of the collective system is determined by the trade-off between these two effects, which we discuss in detail in section 4.2. We note that while the impact of collective system on free-riding between producers is well-established in the literature and practice, capturing the effect of that on aligning producers' choices requires consideration of endogenous recycling technology choice, which has not been studied in prior research.

Proposition 2 also indicates that a collective system leads to a higher recycling process efficiency when the degree of volume heterogeneity between producers is low (i.e., γ is high). This is because the collective system provides higher incentives to producers to align their choices when γ is high. This, combined with the fact that product design and technology choices are complementary, results in a superior performance of the collective system. This effect also gets stronger when the relative impact of technology choice on recycling process efficiency is high (i.e., α is small). We provide an intuitive understanding of these effects in section 4.2 where we compare the equilibrium product design-for-recycling and recycling technology choices among the three recycling systems. Proposition 2 further states that an individual system with producer-owned facilities is always

Figure 2 When Does Collective Recycling System Improve Recycling Process Efficiency? γ Captures the Degree of Recycling Volume Heterogeneity Between the Two Producers, and α Captures the Relative Impact of Product Design-for-Recycling Choices on Recycling Process Efficiency. Parameter: ρ = 0.3



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superior to an individual system with contracted facilities (i.e., $T^{IO} > T^{I}$). This is due to the benefits of vertical integration that eliminates the free-riding between producers and processors, which we discuss in more detail in section 4.2.

4.2. Why Does a Collective Recycling System Improve Recycling Process Efficiency?

In this section, we turn our attention to why collective recycling systems can lead to higher recycling process efficiency. To this end, we compare producers' and processors' equilibrium choices under the three recycling systems.

PROPOSITION 3. (COMPARISON OF PRODUCT DESIGN CHOICES).

(*i*) *The design-for-recycling choices of both producers are always lower in a collective system than in an individual system with contracted facilities* (*i.e.,* $x_i^C \leq x_i^I$ *for* $i \in \{1,2\}$) *or producer-owned facilities* (*i.e.,* $x_i^C \leq x_i^{IO}$ *for* $i \in \{1,2\}$).

(*ii*) *The design-for-recycling choices of both producers are always lower in an individual system with contracted facilities than in an individual system with producer-owned facilities* (*i.e.,* $x_i^I \leq x_i^{IO}$ *for* $i \in \{1,2\}$).

Proposition 3 shows that producers always choose inferior design-for-recycling in a collective system than in an individual system (with contracted or producer-owned facilities), which is consistent with the general understanding in the literature and practice (e.g., Atasu and Subramanian 2012, Sander et al. 2007). This is due to the *free-riding* between producers in a collective system. That is, because producers share the recycling revenue (cost savings) in a collective system, each producer has an incentive to free-ride by investing less in its product design-for-recycling with the hope of benefiting from the other producer's product design (Kandel and Lazear 1992). This effect does not arise in an individual system, because each producer's products are processed separately, which eliminates the need for sharing their recycling revenue (cost savings).

The proposition further states that producers always choose superior design-for-recycling in an individual system with producer-owned facilities than with contracted facilities. This is due to the free-riding between a producer and a processor in an individual system with contracted facilities. In such a system, because a producer and a processor share the recycling revenue (cost savings), they both have incentives to free-ride in choosing their product design and recycling technology, respectively. The vertical integration of an individual system with producer-owned facilities mitigates this free-riding and results in superior equilibrium choices. This contributes to the higher recycling process efficiency of an individual system with producer-owned facilities as compared to an individual system with contracted facilities. These findings follow traditional results in the co-development literature that show an integrated system (i.e., the first-best solution) results in better outcomes than a decentralized system (e.g., Bhattacharyya and Lafontaine 1995, Rahmani et al. 2017, Roels et al. 2010).

Overall, these results indicate that the product design-for-recycling choices are diminished in a collective recycling system. The question then is, how does the collective system lead to a higher recycling process efficiency? We next answer this question by comparing recycling technology choices in situations where the collective system is superior to individual systems.

PROPOSITION 4. (COMPARISON OF RECYCLING TECHNOLOGY CHOICES).

(*i*) *When* $T^C > T^I$ (*i.e.,* $\gamma > \underline{\gamma}$, *as shown in Proposition* 2), *the recycling technology choice of the shared processor is higher than those of both processors in an individual system with contracted facilities* (*i.e.,* $y^C \geq y_1^I$ *and* $y^C \geq y_2^I$).

(*ii*) *When* $T^C > T^{IO}$ (*i.e.,* $\gamma > \bar{\gamma}$, *as shown in Proposition* 2), *the recycling technology choice of the shared processor is higher than that of processor* 2 (*with a smaller recycling volume*) *in an individual system with producer-owned facilities* (*i.e.,* $y^C \geq y_2^{IO}$). *In addition, there exists a threshold* $\bar{\gamma}_1$ *such that the recycling technology choice of the shared processor is higher than that of processor* 1 (*with a larger recycling volume*) *in an individual system with producer-owned facilities* (*i.e.,* $y^C \geq y_1^{IO}$) *if and only if* $\gamma \geq \bar{\gamma}_1$.

(*iii*) *The recycling technology choices of both processors are always higher in an individual system with producer-owned facilities than in an individual system with contracted facilities, that is,* $y_1^{IO} \geq y_1^I$ *and* $y_2^{IO} \geq y_2^I$.

Proposition 4 shows that a collective system can provide an incentive for the shared processor to improve its recycling technology more than each of the processors in an individual system (with contracted or producer-owned facilities). This is due to the effect of horizontal pooling (i.e., recycling products of different producers together), which provides higher recycling volumes to the shared processor than each of the processors in an individual recycling system. This *scale* effect justifies a larger investment in recycling technology improvement by the shared processor, and is the main driver of the superior recycling process efficiency of a collective system compared to individual systems. Specifically, a collective system leads to a higher recycling process efficiency when its positive scale effect on recycling technology choice (Proposition 4) outweighs its negative free-riding effect on producers' product design-for-recycling choices (Proposition 3).

The above findings help us explain why the superior performance of a collective system arises when γ is large and α is small (as shown in Proposition 2 and Figure 2). When the degree of volume heterogeneity between producers is low ($\gamma \rightarrow 1$), producers' design choices are similar (i.e., $x_1^S/x_2^S \rightarrow 1$ for $S \in \{I,IO,C\}$). In a collective system, this alignment of producers' choices enhances the shared processor's incentive to improve its recycling technology, because the benefits of such improvements can be better realized (recall that, in a collective system, the revenue (cost savings) of producers and the shared processor depend on the additional profit achieved through the recycling process efficiency improvement of both producers' products). However, in individual systems, the alignment between producers' design choices does not impact each processor's choice of technology (recall that, in an individual system, revenue (cost savings) of each producer and its dedicated processor only depends on that producer's products). In contrast, when the degree of volume heterogeneity between producers is high ($\gamma \rightarrow 0$), producers' design choices vary significantly (i.e., $x_1^S/x_2^S \gg 1$ for $S \in \{I,IO,C\}$). This misalignment of producers' choices represses the shared processor's incentive to improve its recycling technology. As such, the positive scale effect of a collective system is more pronounced when γ is large. In addition, since the higher efficiency of a collective system is driven by the positive effect of that on the recycling technology choice of the shared processor, the benefits of that can be realized only when the recycling technology choice has high impact on the recycling process efficiency (i.e., α is small).

Finally, Proposition 4 shows that recycling technology choices are always higher in an individual system with producer-owned facilities than in an individual system with contracted facilities. As we discussed after Proposition 3, this is due to the fact that the vertical integration of producers and processors mitigates the issue of free-riding among them and leads to higher equilibrium choices, and in turn, a higher recycling process efficiency. This again follows traditional results in the co-development literature which shows that an integrated system (i.e., the first-best solution) results in better outcomes than a decentralized system (e.g., Bhattacharyya and Lafontaine 1995, Rahmani et al. 2017, Roels et al. 2010). This result also provides an intuitive understanding for the magnitude of thresholds in Proposition 2. That is, because an individual system with producer-owned facilities is superior to an individual system with contracted facilities, the threshold above which a collective system is superior to an individual system with producer-owned facilities is larger than the same for an individual system with contracted facilities (i.e., $\bar{\gamma} \geq \underline{\gamma}$).

4.3. Producer and Processor Perspectives

In this section, we examine whether producers' and processors' perspectives are aligned with the environmental benefits of collective recycling systems. Specifically, we answer the following question: Will profit-focused producers and processors be willing to participate in a collective system when it is environmentally superior? To address this question, we compare the producers' and processors' profits under collective and individual recycling systems. Since we cannot partition the producer's and processor's profits in vertically integrated systems, we focus this analysis on the comparison of the producers' and processors' profits between a collective system and an individual system with contracted facilities.[3]

PROPOSITION 5. (COMPARISON OF PRODUCERS' AND PROCESSORS' PROFITS). *When a collective system leads to a higher recycling process efficiency than an individual system with contracted facilities, that is,* $T^C > T^I$ *(which is equivalent to* $\gamma > \underline{\gamma}$*, as shown in Proposition* 2),

(*i*) *The shared processor's profit in a collective system is higher than the sum of the two processors' profits in an individual system with contracted facilities (i.e.,* $\Pi_r^C > \Pi_{1,r}^I + \Pi_{2,r}^I$*).*
(*ii*) *There exists a threshold* $\underline{\gamma}_1 \geq \underline{\gamma}$ *such that producer 1's profit is higher in a collective system than in an individual system with contracted facilities (i.e.,* $\Pi_{1,p}^C > \Pi_{1,p}^I$*) if and only if* $\gamma > \underline{\gamma}_1$.
(*iii*) *Producer 2's profit is higher in a collective system than in an individual system with contracted facilities (i.e.,* $\Pi_{2,p}^C > \Pi_{2,p}^I$*).*

Proposition 5 shows that when a collective system improves recycling process efficiency, the shared processor's profit in a collective system is higher than the sum of the two processor's profits in an individual system with contracted facilities. The reason is that a collective system allows the shared processor to achieve economies of scale. Accordingly, the shared processor's choice of recycling technology is higher than each of the processor's choice in an individual recycling system (Proposition 4).

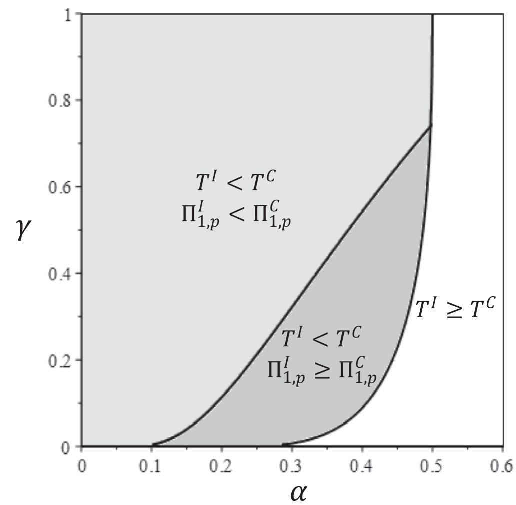
However, from the producers' perspectives, the benefits of collective recycling depend on recycling volumes. The proposition shows that the smaller volume producer's profit is always higher in a collective system than in an individual system with contracted facilities. However, the larger volume producer's profit is higher in a collective system only when the degree of recycling volume heterogeneity is low (i.e., γ is large). The reason is that, when γ is small, on one hand, the shared processor's choice of recycling technology is just marginally higher than the larger processor's choice of recycling technology in an individual system (i.e., y^C/y_1^I is close to one); on the other hand, the larger producer's incentives to improve design-for-recycling is undermined in the collective system due to free riding concerns. Combining these two effects leads to a lower profit for the larger producer in a collective system compared to an individual system. However, producer 2's profit remains higher in a collective system than in an individual system even when the degree of recycling volume heterogeneity is high. The reason is that, when γ is small, the shared processor's choice of recycling technology is significantly higher than the smaller processor's choice of recycling technology in an individual system (i.e., $y^C \gg y_2^I$), making it worthwhile for producer 2 to share its recycling revenue in a collective system. Figure 3 illustrates these findings.

These results have implications for recycling practice: When the degree of recycling volume heterogeneity is low, there is a natural alignment between environmental and economic benefits of collective system. In contrast, when the degree of recycling volume heterogeneity is high, there can be a misalignment between environmental and economic benefits, suggesting that policy makers may consider providing additional incentives to larger producers to promote the implementation of collective recycling.

5. An Illustrative Case Study based on Electronics Recycling Programs in Washington and Oregon States

In this section, we provide a case study based on the E-cycle program implementations in the states of Washington and Oregon to illustrate how our results elaborated so far relate to practice. Since both the Washington and the Oregon state programs are based on contracted processors, in this section, we focus on comparing collective systems and individual systems with contracted facilities. We also focus on demonstrating the environmental benefit (i.e., the recycling process efficiency) implications of collective recycling in this case study. Moreover, since these practical programs involve more than two producers, we first explain how our model can be generalized to the case with multiple producers in section 5.1. We then estimate values for model parameters and present our

Figure 3 When Does Collective Recycling System Lead to Higher Environmental and Economic benefits? Note that $\Pi_r^C > \Pi_{1,r}^I + \Pi_{2,r}^I$ and $\Pi_{2,p}^C > \Pi_{2,p}^I$ in the Region Where $T^C > T^I$



findings for the E-cycle program implementations in section 5.2.

5.1. Generalized Model of Recycling Systems with Multiple Producers

In this section, we present generalized models and analysis corresponding to the case where there are more than two producers participating in a recycling system. Let $N = \{1,2,\ldots,n\}$ be the set of producers. Similar to formula (2), we model the recycling process efficiency of a collective system with multiple producers as follows:

$$V(\mathbf{x}, y) = \sum_{i=1}^{n} V_i(x_i, y) = \sum_{i=1}^{n} q_i {x_i}^{\alpha} \cdot y^{1-\alpha}. \tag{17}$$

Then, the game between n producers (each of which chooses its design-for-recycling x_i^C) and a shared processor (who chooses its recycling technology y^C) in a collective system can be modeled as follows:

$$x_i^C = \arg\max_{x_i \geq 0} \quad \left(\frac{q_i}{\sum_{i=1}^{n} q_i}\right) \cdot \rho \cdot K \cdot V(x_i, \mathbf{x}_{-i}^C, y^C) - c x_i^2 \quad \forall i = 1, 2, \ldots, n \tag{18}$$

$$y^C = \arg\max_{y \geq 0} \quad (1-\rho) \cdot K \cdot V(\mathbf{x}^C, y) - d y^2 \tag{19}$$

where $-i \doteq N \setminus \{i\}$ denotes the set of producers other than i. Accordingly, we define $T_n^C \doteq V(\mathbf{x}^C, y^C)$. The individual recycling system with multiple producers can be modeled in the same way as in the model introduced in section 3.2, and we define $T_n^I \doteq \sum_{i \in N} V_i(x_i^I, y_i^I)$.

We present the equilibrium design-for-recycling and recycling technology choices in recycling systems with multiple producers in Lemma A3 in the appendix. The next proposition compares the recycling process efficiency of collective and individual systems with multiple producers. To simply capture the effect of the number of producers on the efficiency of recycling systems, here, we consider identical producers (i.e., $q_i = q$ for all $i \in N$). Additional analysis shows that the result can be structurally extended to when producers' recycling volumes are different, as we demonstrate by the numerical case study in section 5.2.

PROPOSITION 6. (COMPARISON OF RECYCLING SYSTEMS WITH MULTIPLE PRODUCERS). *Suppose $q_i = q$ for all $i \in N$. Then,*

(*i*) *The collective recycling system leads to a higher recycling process efficiency than an individual recycling system if and only if $\alpha < 1/2$.*
(*ii*) *The ratio of the total recycling process efficiency of a collective system to an individual system with contracted facilities (i.e., T_n^C/T_n^I) is increasing in n when the collective system leads to a higher recycling process efficiency, and it is decreasing in n otherwise.*

Proposition 6 shows that, irrespective of the number of producers, the collective system (with homogeneous producers) improves the recycling process efficiency when the relative recycling process efficiency impact of technology choice is high (i.e., α is small), which is consistent with our results in Proposition 2. In such situations, the recycling process efficiency of a collective system relative to an individual system increases as the number of producers that share the recycling facility increases. The intuition behind this result is as follows: In a collective system, producers' incentives to design for recycling diminish as the number of producers increases (i.e., x_i^C is decreasing in n). However, the shared processor's incentive to improve the recycling technology enhances as n increases (i.e., y^C is increasing in n). When the recycling technology has a higher impact on recycling process efficiency (i.e., α is small), the positive effect of a collective system on recycling technology choice outweighs its negative effect on product design-for-recycling choices much faster.

5.2. Comparison between Collective and Individual Recycling Systems based on the Washington and Oregon States Programs

The E-cycle programs in the states of Washington and Oregon focus mainly on recycling TVs, computers, monitors and other peripherals. While the two programs are similar in nature due to geographical proximity and product coverage, certain differences between them allow us to effectively illustrate our key results regarding collective EPR implementations. Specifically, the Washington state program is operated as a state-wide collective recycling system. All producers selling designated electronics in the state participate in this plan, which is operated by the Washington Materials Management & Financing Authority (Department of Ecology 2019), and share the costs of recycling based on their recycling volumes (see details in Gui et al. (2013)). The collective recycling system considered in this study mimics the Washington state implementation.

The Oregon implementation, on the other hand, is operated through a combination of independent recycling alliances and a state-organized program (Department of Environmental Quality 2014). To-date, three recycling systems emerged in the Oregon recycling implementation. The first is the Manufacturers' Group Plan (MGP) which is run by the Reverse Logistics Group Americas (Reverse Logistics Group Americas 2019) and includes major producers such as Acer (Acer 2019) and Lenovo (Lenovo 2019). The second is the Manufacturers Recycling Management (MRM) system that consists of twenty-two producers including Sony, Panasonic, Philips and Toshiba (MRM 2019). The third is the state contractor system, which is run by the National Center for Electronics Recycling (National Center for Electronics Recycling 2019) and covers all producers that do not participate in the first two systems.

All three systems in the Oregon implementation operate independently based on contracted recycling facilities. However, different from the collective and individual system models we utilize, each program in the Oregon implementation consists of multiple producers sharing costs according to recycling volumes (Department of Environmental Quality 2019). This fragmented recycling system structure is effectively a hybrid between the collective and the individual recycling systems considered in this study, for which our model and results can be generalized straightforwardly (see Appendix D.1).

In light of these observations, we develop three example settings for our case study: (i) a collective recycling system representing the Washington implementation, (ii) a fragmented/hybrid recycling system representing the Oregon implementation, and (iii) a hypothetical individual recycling system (as a benchmark) representing situations where each producer can act independently. See Appendix D for the detailed construction of these examples. In particular, we utilize the recycling volume data of producers in the Washington state in 2015, which is publicly available (Department of Ecology 2015), and focus on the top 45 producers (denoted by $N = \{1,2,\ldots,45\}$) whose

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shares of recycling volumes are greater than or equal to 0.05%. This dataset covers more than 90% of the total return volume in the Washington state in 2015. For the fragmented system based on the implementation in Oregon, we consider the same set of producers N. To reflect the three parallel programs in Oregon, we partition N into three subsets of N_1, N_2, and N_3, where $N_1 = \{1,2\}$ represents the MGP system (with producers 1 and 2 corresponding to Acer and Lenovo), $N_2 = \{3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18\}$ represents the MRM system (with producers 3, 4, 5, and 6 corresponding to Sony, Panasonic, Philips, and Toshiba), and $N_3 = N \setminus (N_1 \cap N_2)$ represents the state contractor system.

We evaluate recycling volumes of producers (i.e., q_i $\forall i \in \mathcal{N}$) based on each producer's share of recycling volume and the total recycling volume data in the Washington state implementation (Department of Ecology 2015, Department of Energy 2018). In particular, since TVs and monitors dominate the recycling return volumes in the state of Washington (e.g., they constituted 91.4% of the total recycling volume of electronics in 2018 (Department of Energy 2018)), we focus on this product category and calculate each q_i using the following formula:

$$q_i = \frac{\text{Share of recycling volume of producer } i}{\sum_{i=1}^{45} \text{Share of recycling volume of producer } i} \times \text{total recycling volume of TVs/monitors} \tag{20}$$

We estimate the remaining model parameters based on LCD TV/monitor disassembly data. We note that there are many parts to a recycling process, from collection to transportation, and disassembly to smelting or disposal, all of which entail different product design and processing technology choice options in order to improve the process efficiency in different industrial contexts. However, due to data availability limitations, we focus on the disassembly process just for the purpose of illustrating how the model parameters can be estimated. A more advanced empirical assessment of model parameters requires micro-level and industry-specific data, and is beyond the scope of this analysis.

Specifically, we focus on an example of Active Disassembly with Smart Materials (ADSM), which is a well-known design-for-disassembly approach for LCD TVs and monitors (Chiodo and Jones 2012, Peeters et al. 2012). The ADSM design replaces traditional screws and connectors with shape memory polymers or alloys that self-separate under proper thermal or other stimuli. These design features imply faster and more efficient disassembly, and in turn, lower recycling costs and more effective material recovery. The benefits of ADSM can be better leveraged if more of such polymers/alloys are used in the screws or connectors and the recycling facility has an efficient technology that provides the self-separation stimuli required (DTI 2005). For illustration purposes, we capture continuum in the design and the technology choices by the percentage of shape memory polymers components in a product, and the energy efficiency of the heating technology used to provide the self-separation stimuli, respectively. Available technical data based on ADSM experiments and industry reports allow us to estimate the parameter α for the use of ADSM in LCD TVs to be in the range of [0.46,0.54], K = \$361, and d = \$2000 (see Appendix D.2). We present our analysis under ρ = 0.5 and c = 500, and note that similar results can be obtained for other values of ρ and c.

To highlight the impact of taking into account recycling technology choices on the efficiency of collective recycling systems in the context of TV/monitor recycling with ADSM, we conduct two numerical analyses. First, we consider a scenario in which processors utilize an existing recycling technology with relatively low energy efficiency to provide the self-separation stimuli, without investing in improving this technology. Therefore, the only means for recycling process efficiency improvement in this scenario is changing product designs towards ADSM. Given this scenario, we analyze how the status quo Washington and Oregon state recycling implementations, as well as the hypothetical individual recycling system would compare in terms of their overall recycling process efficiency. In particular, we calculate the percentage recycling process efficiency difference between the collective system example vs. the fragmented and the individual system examples as follows: $\delta_F^C \doteq \frac{T^C - T^F}{T^F} \times 100$ and $\delta_I^C \doteq \frac{T^C - T^I}{T^I} \times 100$.

We find that when the recycling technology is exogenous, the collective recycling system example is environmentally inferior compared to the other two systems and provides a recycling process efficiency that is up to 24.5% lower relative to the fragmented recycling system example and up to 62.8% lower relative to the individual recycling system example. This scenario is illustrated in Figure 4a. Overall, these observations are consistent with the general understanding of design implications of collective recycling systems in the literature, that is, when recycling technology choice is not taken into account, collective recycling systems suffer from free riding concerns that hurt producers' design incentives, and thus lead to lower recycling process efficiency.

Next, we take endogenous recycling technology choice into account, that is, we assume that processors can choose to improve their ADSM recycling technology efficiency. In this case, we find that the collective recycling system example performs significantly

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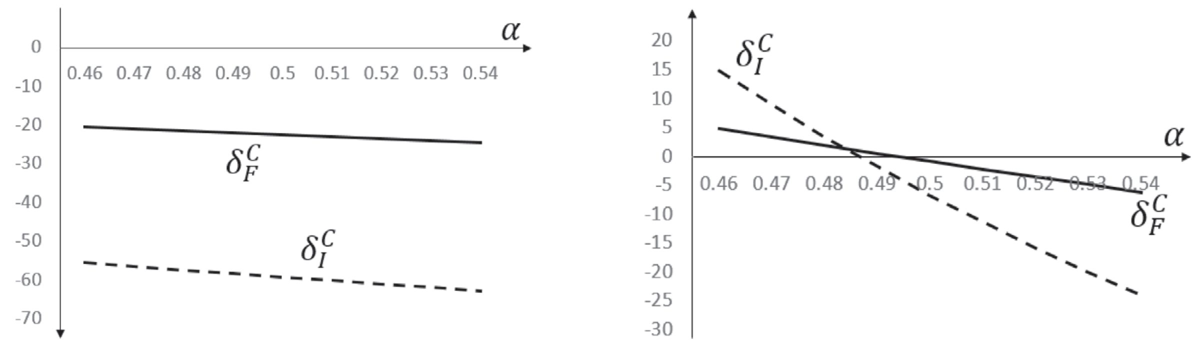
Figure 4 The Percentage Recycling Process Efficiency Difference Between the Collective System Example vs. the Fragmented and the Individual System Examples (denoted by δ_F^C and δ_I^C, respectively) with K = \$361, ρ = 0.5, d = \$2000, c = \$500, and the Recycling Volume Data in Table A3 in Appendix D.2



(a) With exogenous recycling technology choice. **(b)** With endogenous recycling technology choice.

better compared to the previous scenario. In particular, Figure 4b shows the percentage recycling process efficiency difference between the collective system example vs. the fragmented and the individual system examples (i.e., δ_F^C and δ_I^C defined above) in this case. Different from the previous scenario, we observe that the collective recycling system example can improve recycling process efficiency, and in turn the benefits of recycling, by up to 14.8% compared to the individual recycling system example, and up to 4.8% compared to the fragmented recycling system example. In both cases, the percentage difference declines as α increases, and it becomes negative when α is above 0.49, an observation that follows directly from Proposition 6. This effect is more pronounced when comparing the performance of the collective system example against that of the individual system example than the fragmented system example, because intuitively the former represents a larger impact of collective recycling than the latter.

Overall, comparing these two scenarios demonstrates that the economic and environmental benefits potential of collective recycling systems can be significantly underestimated in practice when recycling technology choice and its interaction with product design-for-recycling are ignored. Nevertheless, we note in closing that this case study is a very stylized representation of practice focused only on disassembly with a specific recycling approach (ADSM) and it is based on a calibrated numerical analysis leveraging a limited data set that we could gather. From that point of view, this case study can only serve to illustrate possible implications of our results in a relevant contextual example without immediate policy implications.

6. Extensions

In this section, we extend our model and analyses in several directions to demonstrate the robustness of our main insights. To simplify the exposition, we focus on comparing a collective system with an individual system with contracted facilities in terms of recycling process efficiency. We expect similar insights continue to hold when comparing it with an individual system with producer-owned facilities or when considering profits. All technical details regarding these extensions are relegated to Appendix E for brevity.

6.1. Sequential Product Design-for-Recycling and Recycling Technology Choices

In our main analysis, we focused on situations where producers and processors determine their product design-for-recycling and recycling technology choices simultaneously. In this section, we extend our model and analysis to cases where these decisions are made in sequence. In practice, the recycling technology choice may proceed the product design-for-recycling choice for products with long life cycle (e.g., large appliances), and vice versa for products with short life cycle (e.g., small electronics). We denote the sequence in which producers' decisions on product design-for-recycling are being made prior (subsequent) to the processors' decisions on recycling technology by *Seq*:*P*−*R* (*Seq*:*R*−*P*). We characterize the equilibrium choices of producers and processors under both sequences, and compare them with those under simultaneous decision-making. For brevity, the details of this analysis are presented in Appendix E.1.

We first find that, compared to simultaneous decision-making, sequential decision-making leads to better product design and technology choices and therefore higher recycling process efficiency. We also find that the magnitude of the increase in recycling process efficiency depends on the specific sequence: When α is large, the equilibrium recycling process efficiency is higher when recycling technology choice is made before the product design-for-recycling

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choice. The opposite holds true when α is small. This is because the sequential decision-making motivates producers and processors to make larger investments, especially for the one that makes the first decision.

We next analyze whether and how these decision sequences affect our key insights. The next proposition compares the process efficiency of the collective and individual recycling systems and shows that the main insights from section 4.1 continue to hold under both sequences.

PROPOSITION 7. (COMPARISON OF RECYCLING SYSTEMS WITH SEQUENTIAL DECISION-MAKING). *The ratio of the total recycling process efficiency of a collective system to that of an individual system with contracted facilities is the same under simultaneous, P−R, and R−P sequence of decision-making:*

$$\frac{T^C(Seq:P-R)}{T^I(Seq:P-R)} = \frac{T^C(Seq:R-P)}{T^I(Seq:R-P)} = \frac{T^C}{T^I}, \qquad (21)$$

where T^C and T^I are as presented in Equations (14) and (16).

Proposition 7 shows that although sequential decision-making increases recycling process efficiency, this increase is uniform between collective and individual systems. Hence, the ratio of the total recycling process efficiency of individual and collective systems remains the same for all cases. This implies that our main results regarding the comparison between recycling process efficiency in collective system vs. individual system with contracted facilities continue to hold regardless of the decision-making sequence.

6.2. Loss of Recycling Process Efficiency due to Product Mix

An important feature of a collective recycling system is that products of different producers can be recycled in a mix, which can limit the benefits of design-for-recycling, especially when design choices of producers vary (Gutowski and Dahmus 2005). For example, in glass recycling, clear glass has a higher recycling value as it is more versatile than colored glass (Envirothink 2012). However, the value of producing clear glass will be lost if it is recycled in a mixed batch with colored glass as the output materials will be tinted (Vedantam et al. 2016). We refer to this loss of recycling process efficiency due to product mix as the *mix-driven value loss*.

In order to model the mix-driven value loss in collective recycling systems, we introduce a new measure, the *effective design-for-recycling*, denoted by $f_r(x_1, x_2)$. This measure needs to replace the design variable $\mathbf{x}$ in the recycling process efficiency function and effectively represent how variations in producers' design choices and the mix in the collective system affect recycling process efficiency. To this end, a generalized mean function (Hardy et al. 1952) provides a natural representation of the effective design-for-recycling measure, which depends on producers' design-for-recycling choices and recycling volumes as follows:

$$f_r(x_1, x_2) \doteq \left(\frac{q_1 x_1^r + q_2 x_2^r}{q_1 + q_2}\right)^{\frac{1}{r}} \qquad (22)$$

This generalized mean function (commonly referred to as a CES function) is widely used in the literature to model an aggregate and quantifiable output of a mix of inputs in various economic contexts (e.g., Adams 2006, Bonatti and Horner 2011, Roels 2014, and Rahmani et al. 2018. Also, see details in Appendix B). Given this effective design-for-recycling measure, the corresponding recycling process efficiency in a collective system can be written as:

$$V(f_r(x_1, x_2), y) = (q_1 + q_2) \cdot f_r(x_1, x_2)^{\alpha} \cdot y^{1-\alpha}. \qquad (23)$$

In this specification, the parameter $r \in (-\infty, \alpha)$ represents the degree of mix-driven value loss and captures a spectrum of the same that can be observed in practice. Specifically, since $f_r(x_1, x_2)$ increases in r, a higher value of parameter r implies a smaller degree of mix-driven value loss. For example, the case of $r = \alpha$ represents a scenario where there is no mix-driven value loss as in Equation (2). The case of $r \to -\infty$, on the other hand, represents the other extreme scenario with the highest level of mix-driven value loss. In this case, the function $f_r(x_1, x_2)$ reduces to the Leontief production function, that is, $\lim_{r \to -\infty} f_r(x_1, x_2) = \min\{x_1, x_2\}$ (Arrow et al. 1961). This indicates that only the worst design-for-recycling choice between the two products effectively contributes to the recycling process efficiency of the collective system, and the value of any additional design investment for the other product is lost. This case represents scenarios where design-for-recycling focuses on material purity improvement in the recycling output, similar to the glass recycling example discussed above.

PROPOSITION 8. (COMPARISON OF RECYCLING SYSTEMS WITH MIX-DRIVEN VALUE LOSS). *In the presence of the mix-driven value loss, there exists a unique threshold $\underline{\gamma}_r$ such that a collective system leads to a higher recycling process efficiency than an individual system with contracted facilities (i.e., $T^C > T^I$) if and only if $\gamma > \underline{\gamma}_r$. In addition, $\underline{\gamma}_r$ is non-increasing in r.*

Proposition 8 shows that the efficiency of a collective system is higher when the mix-driven value loss is small (i.e., r is large). Figure 5 illustrates these

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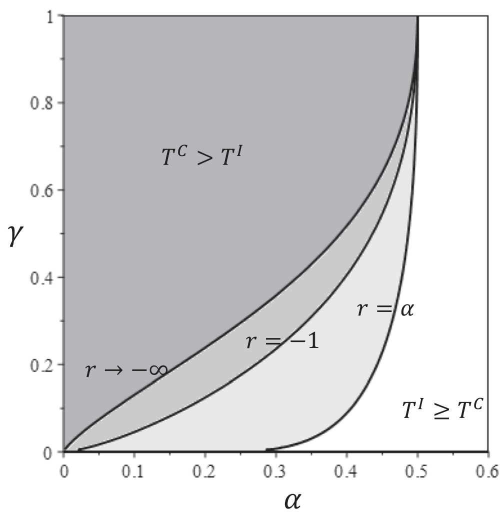
Figure 5 The Effect of Mix-driven Value Loss on Recycling Process Efficiency



results. It can be seen that even when the mix-driven value loss is at its maximum (i.e., when $r \to -\infty$), a collective system can lead to a higher recycling process efficiency than an individual system with contracted facilities. This indicates that the recycling process efficiency advantage of collective systems is preserved even in the worst case scenario regarding the mix of products.

6.3. Endogenous Recycling Volumes

So far, we have considered exogenous recycling volumes and showed that recycling volume heterogeneity plays an important role in determining the environmental benefits of collective recycling systems. In this section, we extend our model to consider endogenous recycling volumes that depend on product design-for-recycling (section 6.3.1) or producer market competition (section 6.3.2).

6.3.1 Product Design Dependent Recycling Volumes. Improvements in product design-for-recycling can impact recycling volumes in different ways. On one hand, a producer who improves its product design-for-recycling can use such design improvements (e.g., reduction of hazardous chemicals, ease of disassembly, etc.) to induce a higher market share for its product. Such an increase in the sales volume can then lead to an increase in recycling volume. On the other hand, a product with better design-for-recycling can naturally become more attractive to independent for-profit third-party recyclers (Esenduran et al. 2018, Vedantam and Iyer 2018). In that case, a producer's access to recyclable products decreases due to third-party recycling, implying lower recycling volumes. These two scenarios imply that improvements in product design-for-recycling can increase or decrease recycling volumes of producers.

To capture these possible scenarios, we extend our main model to situations where recycling volumes of producers are functions of their design-for-recycling choices, denoted by $q_i(x_i)$ for $i \in \{1{,}2\}$, which can be increasing or decreasing in x_i. In particular, for analytical tractability, we consider a functional form of $q_i(x_i) = q_i \cdot (1 + x_i)^a$ with $a \in [-1{,}1]$. This function is increasing (decreasing) in x_i when a is positive (negative). We replace the q_i parameter with $q_i(x_i)$ in our main models, and then compare the resulting total recycling process efficiency of the modified collective and individual recycling systems. The details of this analysis are presented in Appendix E.3.1.

This analysis suggests that the main insights from section 4.1 continue to hold in this setting. However, the parametric region in which the collective system leads to a higher recycling process efficiency is enlarged (diminished) when a is positive (negative), indicating that the benefits of collective recycling system increases (decreases) when improvements in product design-for-recycling lead to an increase (a decrease) in recycling volumes. The intuition behind this result is that an increase in recycling volumes motivates both producers and processors to improve their product design-for-recycling and recycling technology, respectively. As a result, when a is positive (negative), the process efficiency of both collective and individual recycling systems increase (decrease). However, this effect is stronger in a collective system than in an individual system, because a larger (smaller) total recycling volume enhances (reduces) the positive effect of the collective system on the recycling technology choice.

6.3.2 Producer Market Competition. We next extend our model and analysis to a competitive product market, under which recycling volumes endogenously emerge, and then compare the resulting collective and individual systems. To this end, we consider two producers engaged in price competition in a vertically differentiated duopoly. Without loss of generality, we assume that producer 1 sells a high-end product and producer 2 sells a low-end product. The producers face heterogeneous consumers whose valuations for the high-end product are uniformly distributed in [0,1]. For the low-end product, consumer valuations are discounted by a factor $\delta < 1$; the lower the δ, the more differentiated the two producers (see Esenduran et al. 2017, Ferguson and Toktay 2006, Ferrer and Swaminathan 2006 for similar models.) In this game, producers determine their sales prices as well as product design to maximize their profits, which determine the producers' recycling volumes

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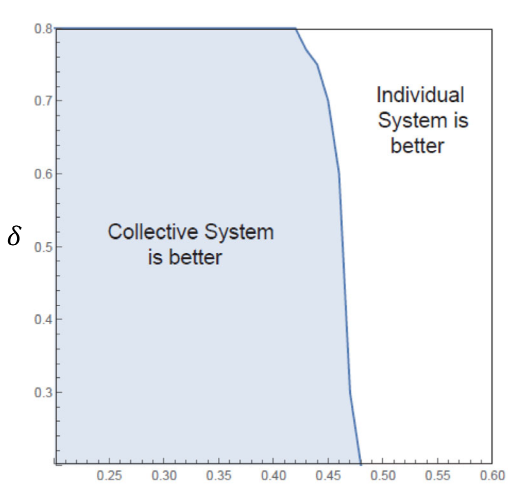
assuming all products sold will eventually be returned for recycling.

We then characterize the equilibrium price, product design, and recycling technology choices in this game for collective and individual systems. Given that different systems lead to different recycling volumes in equilibrium, we compare the average recycling process efficiency per unit between the collective and individual systems. For brevity, the details of this analysis are presented in Appendix E.3.2. Results from this analysis suggest that a collective system leads to a higher per-unit average recycling process efficiency than an individual system when α and δ are low. Figure 6 illustrates these results.

The above results are in line with the analysis in section 4, suggesting that our main insights are robust to producer competition. The only notable exception from this analysis is that volume heterogeneity is now measured with respect to the vertical differentiation parameter δ (as opposed to γ in section 4). Note, however, that there is a one-to-one correspondence between δ and γ. In particular, γ in the competitive equilibrium decreases in δ. That is, the more differentiated the two producers are (i.e., lower δ), the lower the volume heterogeneity in equilibrium (i.e., higher γ). While this observation is counter-intuitive at first, it can be explained by the strategic choices of the two differentiated producers. The high-end producer is at an advantage under price competition, and can improve its margins by a higher sales price. The low-end producer, being at a disadvantage under price competition, chooses to improve its margins mainly from recycling. It is therefore in the low-end producer's best interest to reduce its price to increase its sales volume so that investments in product design-for-recycling lead to higher recycling profits. This effect is more pronounced when δ is lower, which explains the correspondence between γ and δ under producer competition.

Figure 6 When Does Collective Recycling System Improve Recycling Process Efficiency with Producer Market Competition? δ Captures the Vertical Differentiation Between the Two Producers. Parameters: $K = c = d = 1$ and $\rho = 0.5$ [Color figure can be viewed at wileyonlinelibrary.com]



We further note that while our focus in this analysis has been on recycling technology and product design improvements that focus on end-of-life cost reduction of products, one could also consider accounting for consumer valuations being higher due to increased efficiency in the recycling process. In that context, one would intuitively expect that recycling process efficiency improvements that also increase consumer valuations would favor a collective system more to the extent that they close the perceived value gap between the high-end and low-end products. We expect this to be the case when δ is low, in which case both producers find higher incentives to improve product designs and in turn the processor also improves the corresponding technology choice. In contrast, when δ is high, we expect this effect to get weaker and the relative value added of a collective system be lower. However, a complete investigation of those effects is tedious and intractable in our setting, which we therefore leave for future research.

6.4. Processor Competition

In our main analysis, we compared the efficiency of individual and collective recycling systems where the pairing between producers and processors was exogenous to the model. However, in practice, producers' selection of processors can depend on processors' technology choices. In particular, a processor that adopts a more advanced recycling technology can be more competitive in winning producers' recycling volumes. In this section, we generalize our model and analysis to scenarios where there is competition between processors in an individual recycling system.

We therefore construct an *endogenous* individual recycling system where producers' selection of processors depends on processors' technology choices. We then compare the total recycling process efficiency of the endogenous individual recycling system with that of a collective recycling system. To do so, we consider two models of processor competition: In the first model, we focus on processor competition on recycling technology, that is, producers choose the processor to work with based on the processors' recycling technology choices. In the second model, we incorporate a price competition to the first model. That is, the two competing processors not only strategically choose their recycling technologies, but also their prices for use of their recycling facilities. The detailed setup and analysis of these two models are presented in Appendix E.4.

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We first find that the competition between processors creates incentives for processors to improve their recycling technologies, which consequently leads to an increase in producers' deign-for-recycling choices (due to complementarity), and thus a higher recycling process efficiency under the endogenous individual system. Nevertheless, under both models, a collective system can still lead to a higher recycling process efficiency than that attainable in an endogenous individual system in equilibrium. In particular, with both models, a collective system leads to a higher recycling process efficiency when α is low and γ is high, which are consistent with our results in Proposition 2.

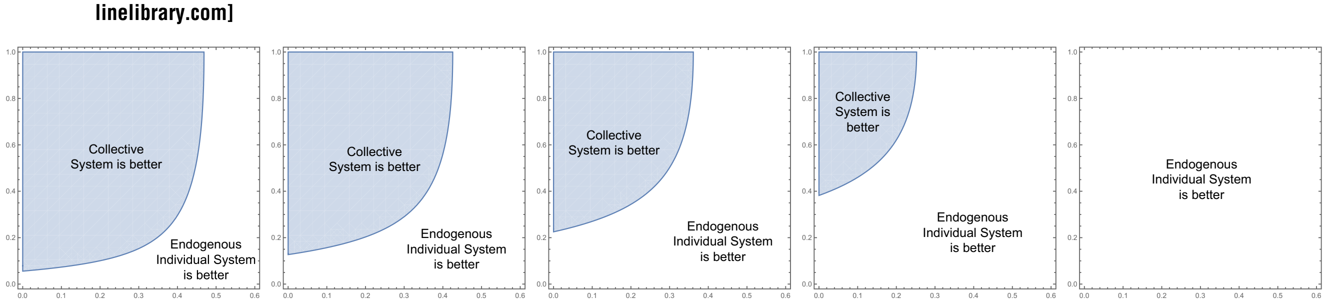
Moreover, in the second model with both price and technology competition, we show that the efficiency of a collective system increases as the revenue sharing parameter (ρ) decreases. Figure 7 illustrates the effect of ρ on the efficiency of a collective system as compared to the endogenous individual system with both price and technology competition. This effect is due to the fact that, under both price and recycling technology competition, a processor that has adopted a better recycling technology can charge a higher price due to its higher recycling cost efficiency. It can be shown that this pricing advantage depends on producers' benefits from using that recycling technology. This benefit is increasing in ρ; that is, when the producer obtains a higher share of the recycling revenue, it receives a higher benefit from working with a processor with a better recycling technology, and therefore that processor may charge a higher price. This leads to a higher recycling technology improvement by processors and thus a higher recycling process efficiency of an endogenous individual system. In contrast, when processors obtain larger revenue shares (i.e., when ρ is relatively small), the effectiveness of price competition in enhancing processors' choices of recycling technology in an individual system weakens, and that leads to a higher recycling process efficiency of a collective system.

7. Conclusions

This study examines studies the effect of recycling technology choice on the design of recycling systems. Motivated by our experience and interactions with recycling practice, we posit that recycling policy may need to take producer and processor perspectives into account altogether, and a joint evaluation of product design-for-recycling and recycling technology choices is important in measuring the environmental and economic benefits of recycling systems. More specifically, we posit that the perspective that the benefits of recycling should be measured based on the incentives they create for product design-for-recycling may be incomplete, and need an adjustment. That is, what should matter from an environmental or economic point of view is the consequential output of the recycling process, for example, whether and to what extent recycling leads to an increase in landfill diversion, toxicity reduction, material recovery levels, or cost savings. Accordingly, policy implementation choices regarding recycling systems may need to consider comprehensive measures that quantify how the combination of product design-for-recycling and recycling technology choices affect recycling process efficiency and the associated environmental and economic outcomes.

This new perspective allows us to contribute to a long-standing practical debate on the choice between collective and individual recycling systems. It has long been argued that collective recycling systems are environmentally inferior to individual recycling systems, which is largely ascribed to the lack of product design-for-recycling incentives in collective systems. Our results can help this assertion by positing that collective systems can lead to higher environmental benefits than individual systems by inducing superior recycling technology choices. When complementary with product design-for-recycling, such recycling technology improvements can also help

Figure 7 The Effect of Processors Competition on Recycling Process Efficiency. Parameters: $K = c = d = 1$ [Color figure can be viewed at wileyonlinelibrary.com]



(a) When $\rho = 0.1$ **(b)** When $\rho = 0.2$ **(c)** When $\rho = 0.3$ **(d)** When $\rho = 0.4$ **(e)** When $\rho \geq 0.5$

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improve product design-for-recycling incentives and lead to higher environmental benefits in collective systems.

A numerical case study based on electronics recycling in the states of Washington and Oregon helps illustrate how the above insights can relate to practice. We further show that these advantages of collective recycling systems are robust to producer or processor competition, the loss of recycling process efficiency due to a mix of products, and the sequence in which recycling technology and product design choices are made. We believe that these insights can help identify an environmental rationale for collective recycling system implementations observed in practice, and can be useful for an understanding of how recycling systems can be organized for superior environmental and economic benefits.

7.1. Limitations and Future Research Directions

Overall, the key contribution of this study regards the observation that recycling technology choices by processors can make a significant impact in the economics of a recycling system. That is, a collective system seeing larger recycling volumes may lead to more efficient processing technology choices, which in turn could lead to improvements in complementary product designs, effectively increasing the attractiveness of collective systems. However, we acknowledge that our study has several limitations that imply a number of opportunities for future research. First, we consider unidimensional and continuous product design and recycling technology choices, but these choices could be multi-faceted and discrete in practice (e.g., choosing between different paths for improving design or technology). Future research can build on this study to refine our insights by focusing on more specific interactions between product design and technology that are applicable in different industrial contexts. Indeed, the most fruitful and promising research direction could involve an empirical assessment of the impacts of design-for-recycling and recycling technology improvement on recycling process efficiency in different industries, and identifying industry characteristics that would serve as a proxy to distinguish the relative impacts of product design and technology choices for recycling. Second, we consider cases where the environmental and economic benefits of recycling are aligned. Investigating situations where there is a misalignment between environmental and economic impacts of recycling process efficiency improvement could be an interesting research direction especially from a policy perspective. Third, we consider situations where the monetary benefit associated with a unit of recycling process efficiency improvement is the same under collective and individual recycling systems. However, it is possible that an individual recycling system (especially with producer-owned facilities) yields a higher monetary benefit (e.g., when a producer can loop back recycling materials into its supply chain). While preliminary analyses show that our key insights remain robust to such modifications of the model, it may be worthwhile to investigate such scenarios in further details. Fourth, we note that global recycling policies such as China's recycling ban can shift recycling volumes to different locations, creating scale volatility as well as affecting commodity prices, which in turn influence recycling process efficiency. Studying the implications of such policy changes on product design and technology choices for recycling can be an insightful research direction. Fifth, since our focus was on the impact of recycling technology choice, we considered only one market and one product type. However, it is possible for multi-national producers to leverage their global presence to achieve better scale in recycling. For instance, a producer in Europe can achieve pan-European economies of scale by collecting and treating its own waste from many different locations. Future research can build on our model to examine the impact of recycling technology choice on shared recycling systems when there are multiple products and markets (e.g., product-based or market-based recycling as introduced by Tian et al. (2019)). Sixth, it would be worthwhile to investigate a cooperative game setting that determines cost allocations in collective systems with endogenous product design and technology choices. Finally, exploring product design and end-of-life recycling technology strategies that also influence consumer choices and product market competition and how those could affect the relative performance of collective vs. individual systems can also be an interesting direction to explore.

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Notes

[1]In practice, recycling system configurations may involve other features that our stylized models may not capture. These basic models allow us to analyze and compare the effects of facility and revenue (or cost savings) sharing in collective systems, and the effect of facility ownership in individual systems.

[2]The exact estimation of α requires empirical investigation with industry-specific data, which is outside of the scope of this study. In order to illustrate how one can estimate this parameter in a stylized setting with unidimensional and continuous design and technology choices, we provide basic analysis by focusing on LCD TV disassembly in Appendix D.2.

[3]A comparison of the total surplus (i.e., the sum of producers' and processors' profits) in a collective system and an individual system with producer-owned facilities shows that a collective system leads to a higher total surplus when γ is large and α is small, which is consistent with our results in Propositions 2 and 5. This indicates that there is a natural alignment between environmental and economic benefits of collective recycling in terms of total surplus.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix A: Additional Examples of Complementary Recycling Technology and Product Design-for-recycling Choices.
Appendix B: Use of Cobb-Douglas and CES Functions.
Appendix C: Proofs and Technical Details of §4.
Appendix D: Technical Details of §5: An Illustrative Case Study.
Appendix E: Proofs and Technical Details of §6: Extensions.
Appendix F: Additional Robustness Analysis: Discrete Product Design and Recycling Technology Choices.

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