Circular Business Models: Product Design and Consumer Participation*

Stefan Buehler, Rachel Chen, and Daniel Halbheer†

October 2023

Abstract

This paper develops an analytical framework to study the mechanics of circular business models in markets where consumers care about recyclability and make both a purchase decision and a disposal decision when the product reaches end-of-life. Transitioning to a circular business model allows the firm to tap into a new source of revenue by recycling end-of-life products and charge a green premium for products with higher recyclability. We show that the firm determines recyclability by balancing the marginal changes in the expected end-of-life utility of the product perceived by consumers and the unit cost net of the expected value of the recovered resources. We also show that stronger consumer concerns about recyclability and a higher market value of the recovered resources increase recyclability, but have an ambiguous impact on price, profit, and the waste footprint of the firm. In addition, we identify the conditions under which the transition from a linear to a circular business model is profitable and socially desirable, and show how policy makers can accelerate the circular transition. Finally, we show that competition has no impact on recyclability but tends to undermine the viability of circularity, and present options for policy makers to improve the performance of circular business models.

Keywords: Circular transition, end-of-life product disposal, deconsumption, waste footprint, recycling, pricing.

*The authors are grateful to Anette Boom, Christian Keuschnigg, Severin Lenhard, Wilfried Sand-Zantman, and seminar audiences at Bocconi University, CY Cergy Paris Université, HEC Paris, the Business Schools for Climate Leadership (BS4CL) initiative, the University of Giessen, the University of St. Gallen, the IO Committee of the German Economic Association, SSES 2022, EARIE 2023, and VfS 2023.

†Stefan Buehler: School of Economics and Political Science, University of St. Gallen, Varnbuelstr. 19, 9000 St. Gallen, Switzerland (email: stefan.buehler@unisg.ch). Rachel Chen: Graduate School of Management, University of California at Davis, Davis, CA 95616, United States (rachen@ucdavis.edu). Daniel Halbheer: HEC Paris, Marketing Department, 1 rue de la Libération, 78351 Jouy-en-Josas Cedex, France (halbheer@hec.fr); holder of the FII Institute Chair on “Business Models for the Circular Economy” and member of the CNRS unit GREGHEC, UMR CNRS 2959.

1 Introduction

Business leaders, consumers, and governments are increasingly becoming aware of the enormous resource and waste footprints resulting from the "take-make-dispose" approach of the *linear economy*, which extracts resources to make products that are discarded as waste when they reach end-of-life. Global circularity decreased from 9.1% in 2018 to 7.2% in 2022, which reinforces the massive circularity gap of over 90% (Circle Economy 2023). In times of increasing raw material prices, foregoing the resources embedded in end-of-life products becomes even more costly to firms and society. To tackle this double cost of waste, firms must urgently develop innovations across product design, recovery of end-of-life products, and recycling technologies that enable the transition from a linear to a *circular economy*. Stated differently, putting circularity at the core of sustainability strategies is key to reducing the resource and environmental footprints of doing business (World Business Council of Sustainable Development 2023; World Economic Forum 2023).[1]

There is evidence that consumers increasingly care about environmental sustainability. A survey among global consumers found that more than 51% of the respondents say that sustainability is more important to them today than it was a year ago (IBM Institute for Business Value 2022). More broadly, research by The Economist Intelligence Unit (2021) on global eco-awakening shows that people are getting more concerned about the natural environment, and that policymakers are reflecting those attitudes in the decisions they make. In response to stronger concerns about sustainability, many firms are beginning to embrace circular business models. For example, Nespresso offers free home pickup services to recover and recycle used coffee capsules (Nespresso 2021). Similarly, Holcim recycles construction and demolition materials into high-value products (Holcim 2023), and Apple's iPhone recycling robot Daisy can disassemble up to 1.2 million phones

[1]The foundations of the circular economy are laid out in the report "Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition" (Ellen MacArthur Foundation 2013) and Stahel (2016, 2019). Circularity has gained momentum by highlighting opportunities for green business (Accenture 2017; McKinsey 2017). For a recent practitioner article on circular business models, see Atasu, Dumas, and Van Wassenhove (2021).

each year, supporting the recovery of valuable resources via the Apple Trade In program (Apple 2022). Electric car makers around the planet are also heavily investing in circular initiatives to recover rare materials and put them into new batteries (The Economist 2022).

This paper develops an analytical framework to study the mechanics of circular business models that attempt to close the loop by recycling end-of-life products for materials recovery and thereby reduce the resource and waste footprint of the firm. The framework focuses on recycling and applies to end-of-life products that contain valuable remaining resources, including single-use plastics, one of the world's most pressing environmental threats (Reuters 2023; Wall Street Journal 2022). Importantly, consumers not only make a purchase decision but also a disposal decision when the product reaches end-of-life: return the product for recycling or dispose of it as waste. In response to the consumers' life-cycle perspective, the firm chooses the product design—recyclability and price—and decides whether or not to build a reverse supply chain to recycle end-of-life products. Specifically, recyclability captures the extent to which an end-of-life product can be recycled by the firm. Going circular creates an opportunity for the firm to tap into a new source of revenue, the size of which depends on recyclability, consumer participation in the reverse supply chain, and the market value of recovered resources. Going circular also creates an opportunity for the firm to charge a green premium because of the consumers' higher willingness to pay for products with higher recyclability.

The purpose of our paper is to gain insight into the mechanics of circular business models in a coherent analytical framework that integrates disposal decisions by consumers who care about recyclability into a model of profit-maximizing product design. The key novelty is that consumers make an endogenous disposal decision that is affected by the firm's choice of recyclability, the strength of their concerns about recyclability, and the idiosyncratic cost of returning the product for recycling, which together determine the product's end-of-life utility. Importantly, this novel feature on the demand side enters the objective function of a profit-maximizing firm via their impact on not only sales but also recycled resources, thereby affecting product-design decisions. The notion of end-of-life utility also allows us to track the waste externality created by buyers and develop a policy toolbox to design market interventions in circular industries.

Our results offer insights for firms and policy makers regarding the profitability and social desirability of circular business models when consumers care about recyclability. First, we show that the expected utility of disposing of an end-of-life product can be positive or negative depending on the costs and benefits associated with the recycling and trash disposal options, thus allowing for "deconsumption," a reduction in demand due to environmental concerns. Second, under a circular business model with a reverse supply chain, recyclability is determined by balancing the marginal changes in the expected end-of-life utility perceived by consumers and the "net unit cost" of the firm, defined as the unit production cost net of the expected value of the recovered resources. However, if the marginal increase in the expected end-of-life utility outweighs the corresponding change in net unit cost, the firm offers a fully recyclable product, and a fully circular model arises if all consumers endogenously choose to recycle the product. We also find that the standard linear business model emerges as a special case if the firm offers a non-recyclable product and hence has no incentive to build a reverse supply chain. The comparative statics show that stronger concerns about recyclability or a higher value of the resources embedded in end-of-life products (e.g., because of increasing scarcity) increase recyclability, but have an ambiguous impact on price, demand, profit, and the overall waste footprint. Third, the transition to a circular business model is profitable if the profit increase due to a green premium and the cost-dampening effect of recycling outweighs the cost of building the reverse supply chain. Because the firm ignores the impact of the product-design decisions on consumer surplus and the social cost of waste, it has an incentive to strategically distort recyclability to exploit its pricing power, which in turn stalls the circular transition. In addition, there is insufficient circularity from a societal point of view if the marginal reduction in the social cost of waste per unit of product outweighs the private marginal increase in the expected end-of-life utility.

Furthermore, we show that competition has no impact on the profit-maximizing recyclability. Therefore, competition does not induce profit-maximizing firms to offer less recyclable products (i.e., there is no race to the bottom). However, competition tends to undermine the viability of the circular business model due to lower pricing power. Finally, we examine how policy tools such as command-and-control regulation and taxation can improve recyclability. Staying in the realm of competition, we show that a deposit-refund system may reduce recyclability below the level chosen by a profit-maximizing firm. In addition, we show that product buyback is equivalent to introducing a deposit-refund system, which means that mandatory product buyback may reduce recyclability. Finally, note that a trash disposal fee may also reduce recyclability, which is certainly an unintended consequence of making consumers pay for waste.

2 Related literature

Our research is related to two main streams of the literature: the green product design literature in marketing and the closed-loop supply chains (CLSC) literature in operations. In marketing, the green product design literature focuses on the profit-maximizing choice of the environmental product attributes when consumers value green and traditional quality attributes (Bertini et al. 2022; Chen 2001; Sudhir, Shankar, and Jin 2022). We add to this stream of literature by showing how recyclability and price are endogenously determined by the interplay of consumers' concerns about recyclability, the value of the resources embedded in end-of-life products, and competitive forces. The most closely related paper to ours is Bertini et al. (2022), which studies product carbon footprinting and pricing by firms that face consumers with climate concerns. The novelty of the present paper is that consumers adopt a life cycle approach and derive a utility from making a discrete choice between recycling and trashing an end-of-life product, which may either enhance or reduce demand, thereby imposing their preferences on the firm.

Accounting for the end-of-life utility of a product allows us to extend the analysis of product design to circular business models, thereby adding to classic work on the returns on quality in linear business models (Rust, Moorman, and Dickson 2002; Rust and Zahorik 1993; Rust, Zahorik, and Keiningham 1995). The difference to a model where the firm chooses price and (environmental) quality is that consumers make both purchase *and* disposal decisions, which determine not only demand and profit, but also the firm's waste footprint and the waste externality buyers impose on society. By studying the impact of product design on the environmental footprint of the firm, we further add to the sustainability literature in marketing (Chandy et al. 2021; Cronin et al. 2011; Huang and Rust 2011; Luo and Bhattacharya 2006; Papadas, Avlonitis, and Carrigan 2017). More specifically, we show how the circular transition affects the triple bottom line of profit, people, and planet (Elkington 1999).

The closed-loop supply chains (CLSC) literature studies reverse flows in supply chains to take back products from customers and recover the embedded value (Guide and Van Wassenhove 2009; Savaskan, Bhattacharya, and Van Wassenhove 2004). So far, the vast majority of CLSC research has focused on remanufacturing, the process of restoring a used product to a common aesthetic and operating standard (Souza 2013). Critically, remanufacturing and other *re-x* strategies introduce cannibalization of new product sales by extending product life through refurbish, repair, and reuse of returned products (Atasu, Guide, and Van Wassenhove 2008; Atasu, Sarvary, and Wassenhove 2008). In contrast, we consider materials recovery through the recycling of end-of-life products. Rather than studying product differentiation through extensions of the loop in the presence of a green customer segment, we analyze how market-wide concerns about recyclability drive disposal decisions, recyclability, and the incentives of the firm to close the loop by recycling for materials recovery. A related paper is Raz and Souza (2018), where firms choose the recycling rate and materials recovery as a strategic supply source. However, in our paper firms choose recyclability in product design and consumers make an endogenous disposal decision.

Our research is closely related to product design in the CLSC literature (Atasu and Souza 2013; Raz, Druehl, and Blass 2013; Agrawal, Atasu, and Ülkü 2021; Agrawal, Atasu, and Van Wassenhove 2019). We add to this stream by considering recyclability in the product design stage and endogenizing the return probability, instead of focusing on the product quality of the remanufactured product and its implications on demand, pricing and competition with new products. Recently, Agrawal, Atasu, and Ülkü (2021) examined the impact of leasing and modularity on economic, social, and environmental outcomes in durable goods markets. In contrast, our paper analyzes the impact of recyclability as a strategy for circularity on the triple bottom line. In addition, our approach allows to track the waste externality caused by buyers, which is key for designing policies that improve the performance of circular business models.

Finally, our paper contributes to the emerging literature on the impact of morally or environmentally concerned consumers on market outcomes in economics (Dewatripont and Tirole 2023; Herweg and Schmidt 2022). We show how concerns about recyclability affect the end-of-life utility of a product, which in turn influences the firm's profit-maximizing product design. Our analysis also shows that consumer concerns about the end-of-life properties of a product force the firm to adopt a life-cycle perspective, which may induce a purely profit-maximizing firm to switch from a linear to a circular business model.

3 Analytical framework

3.1 The firm

Consider a firm that designs a product with a fixed lifetime by choosing the index of recyclability $r \in [0,1]$ and the price $p \geq 0$. The index of recyclability captures the extent to which the resources embedded in an end-of-life product can be recycled by the firm. Specifically, the product is non-recyclable if $r = 0$, partially recyclable if $r \in (0,1)$, and fully recyclable if $r = 1$. For example, Nespresso's aluminium capsules and HP's toner cartridges are fully recyclable (Nespresso 2021; HP 2022), and The Coca-Cola Company pledged to make 100% of its packaging recyclable by 2025.[2] Currently, Renault estimates that around 85% of a car is recyclable (The Economist 2022), whereas wind turbine

[2]For Coca Cola's packaging solutions for a "World Without Waste," see http://bit.ly/3iIUOmC.

blades can't be recycled (Bloomberg 2020). Throughout, we assume that recyclability r is truthfully communicated to consumers by the firm to focus on the mechanics of circular business models and avoid issues of "greenwashing," whereby firms make unsubstantiated environmental claims to affect consumer behavior (Wu, Xang, and Xie 2020).

Improving product recyclability is costly. Specifically, the unit cost of a product with recyclability index r is $c(r)$, where $c'(r) > 0$ and $c''(r) > 0$ for $r \in (0,1]$, with $c(0) \geq 0$ and $c'(0) \geq 0$. Building a reverse supply chain involves a fixed cost $K \geq 0$. Letting $\omega \geq 0$ denote the market price for the resources embedded in one unit of product, the value of a recycled product to the firm is ωr.

3.2 Consumers

Consider a market with a unit mass of consumers who evaluate the product based on the utility provided during its lifetime *and* the utility from disposal when it reaches the end of its lifetime—a life-cycle approach. Importantly, consumers not only make a purchase decision but also a disposal decision when the product reaches end-of-life: return the product for recycling or dispose of it as waste (Viscusi, Huber, and Bell 2011). Using backward induction, we first analyze the end-of-life decision and follow with the purchase decision.

3.2.1 Disposal decision

Buyers derive a benefit $b(r;\lambda) \geq 0$ from returning the product for recycling that captures the warm glow from participating in a pro-environmental action (Andreoni 1995), where $\lambda \geq 0$ indicates the strength of concerns about recyclability, a market-specific consumer attitude. The concerns for recycling should be expected to be strong in markets where the waste disposal of end-of-life products is known to be harmful to the environment (e.g, batteries, electronics, and plastics). The idiosyncratic hassle cost $\kappa \geq 0$ of returning the product for recycling is realized when the product reaches end-of-life, a natural assumption that allows for the possibility that buyers end up disposing of the product as waste even if they are likely to return it for recycling ex ante. Specifically, we assume that the hassle cost κ is distributed across consumers according to the cumulative distribution function $G(\kappa)$ with associated density $g(\kappa)$ over the interval $[0,+\infty)$, with $G(0)=0$ and $\lim_{\kappa\to\infty} G(\kappa)=1$.

Instead, when disposing of the product as waste, buyers receive the disutility $\bar{u}(\lambda)\leq 0$ that captures the cold prickle from participating in an anti-environmental action, which generally differs from the warm glow from doing something good (Andreoni 1995; Viscusi, Huber, and Bell 2011). To put additional structure on the costs and benefits associated with the end-of-life disposal decision, we impose the following assumption.

Assumption 1 (Disposal decision)**.** *(i) The benefit of recycling $b(r;\lambda)$ satisfies $b_r(r;\lambda)\geq 0$, $b_\lambda(r;\lambda)\geq 0$, and $b_{\lambda r}(r;\lambda)\geq 0$ for all (r,λ), with $b(r;0)=0$; (ii) The disutility $\bar{u}(\lambda)$ from discarding the product as waste satisfies $\bar{u}'(\lambda)\leq 0$ for all λ, with $\bar{u}(0)=0$.*

To intuitively understand this assumption, note that part (i) requires that consumers value recyclability, that the benefit increases in concerns about recyclability, and that the marginal benefit from recyclability is non-decreasing in λ. The normalization $b(r;0)=0$ means that consumers do not derive a warm glow if they do not care about recyclability. Part (ii) states that the cold prickle is higher when consumers have stronger concerns about recyclability and zero if they do not care about recyclability.

When considering the disposal alternatives, buyers return the product for recycling if the utility from recycling $b(r;\lambda)-\kappa$ exceeds the disutility $\bar{u}(\lambda)$ of trashing the product, that is, if the hassle cost of recycling the product κ is smaller than the benefit of recycling including the averted guilt $b(r;\lambda)-\bar{u}(\lambda)$. Thus, the endogenous probability that a buyer returns the product for recycling is

$$\phi(r;\lambda)\equiv G(b(r;\lambda)-\bar{u}(\lambda)), \tag{1}$$

which satisfies $\phi_r(r;\lambda)\geq 0$ and $\phi_\lambda(r;\lambda)\geq 0$ by Assumption 1. Stated differently, higher recyclability and stronger concerns about recyclability increase the recycling probability.

Because the hassle cost is not known until the product reaches end-of-life, consumers must form an expectation of the utility from disposing of an end-of-life product when making the purchase decision, hereafter referred to as "end-of-life utility." The following result holds (for ease of exposition, all proofs are relegated to the Appendix).

Lemma 1 (End-of-life utility)**.** *When making the purchase decision, the expected utility from disposing of an end-of-life product is given by*

$$e(r;\lambda) = \int_0^{b(r;\lambda)-\bar{u}(\lambda)} G(\kappa)d\kappa + \bar{u}(\lambda) \tag{2}$$

and satisfies $e(r;\lambda) \gtrless 0$*,* $e_r(r;\lambda) \geq 0$*,* $e_\lambda(r;\lambda) \gtrless 0$*, and* $e_{r\lambda}(r;\lambda) \geq 0$*.*

Lemma 1 highlights that the end-of-life utility and its derivative with respect to λ can be positive or negative depending on the costs and benefits associated with the two disposal options. In addition, Lemma 1 shows that increasing recyclability translates into a higher end-of-life utility, and that the increase in end-of-life utility from recyclability is non-decreasing in λ.[3]

To intuitively understand Lemma 1, consider Figure 1, which dissects the end-of-life utility and the impact of a marginal change in the concerns about recyclability, respectively. Panel (a) indicates that the end-of-life utility of a product is zero if consumers do not care about its recyclability. If there is a warm glow from recycling but no guilt associated with trash disposal, then $e(r,\lambda) > 0$. Instead, if there is a cold prickle from trash disposal but no warm glow from recycling, then $e(r,\lambda) < 0$. If consumers consider both effects, then $e(r,\lambda)$ is strictly positive if the warm glow dominates the cold prickle, that is, if $\int_0^{b-\bar{u}} G(\kappa)d\kappa > -\bar{u}$ due to sufficiently high b compared to $\bar{u}$. Panel (b) highlights that a marginal change in λ may affect the warm glow from recycling or the cold prickle from trash disposal. Specifically, stronger concerns about recyclability increase the end-of-life utility if the change in the warm glow dominates the change in the cold prickle, that is,

[3]For example, if the hassle costs are uniformly distributed over the interval $[0,1]$, then $e = \frac{(b-\bar{u})^2}{2} + \bar{u}$, with $b - \bar{u} < 1$ implying trash disposal by buyers who face high realizations of hassle costs.

	$\bar{u}=0$	$\bar{u}<0$
$b=0$	$e=0$	$e<0$ cold prickle
$b>0$	$e>0$ warm glow	$e \gtrless 0$ both

(a) Two utility components

	$\bar{u}'=0$	$\bar{u}'<0$
$b_\lambda=0$	$e_\lambda=0$	$e_\lambda<0$ higher guilt
$b_\lambda>0$	$e_\lambda>0$ higher benefit	$e_\lambda \gtrless 0$ both

(b) Impact of a change in λ

Figure 1: Dissecting end-of-life utility.

if $e_\lambda(r;\lambda) = G(b-\bar{u})(b_\lambda - \bar{u}') + \bar{u}' > 0$ due to sufficiently high b_λ compared to $\bar{u}'$. On the other hand, if the marginal change in $\bar{u}$ is sufficiently strong, the impact on $e(r;\lambda)$ can be negative. Finally, it is worthwhile to highlight that both the warm glow and the cold prickle increase the recycling probability, whereas they have opposite effects on the end-of-life utility, because they not only affect the trade-off between the disposal decisions but also the utility levels associated with these options.

Note that the expected utility from disposing of an end-of-life product is not directly observable. However, its importance is revealed in real-world markets by consumers who incur the hassle cost of returning end-of-life products for recycling without compensation. For instance, Nespresso has reached a global recycling rate of 32% for its aluminum coffee capsules without compensating consumers for returning used capsules, which implies a non-zero end-of-life utility (Nespresso 2021).

3.2.2 Purchase decision

When considering whether to purchase, consumers take the intrinsic utility of the product *and* the expected end-of-life utility into account. Specifically, a consumer derives utility

$$u(r,p;\lambda) = v - p + e(r;\lambda) - E(r,p;\lambda), \tag{3}$$

from purchasing the product, where $v \in [0,\infty)$ is the valuation of the intrinsic product features, distributed across consumers according to the cumulative distribution function $F(v)$, with $F(0) = 0$, and $\lim_{v\to\infty} F(v) = 1$, and density $f(v) > 0$ for all v; $e(r;\lambda)$ is the end-of-life utility in (2); and $E(r,p;\lambda) \geq 0$ is the waste externality from product disposal, which will be derived in Section 4.3.

Normalizing the intrinsic utility of the outside option to zero, a consumer derives utility $u_0 = -E(r,p;\lambda)$ from choosing the outside option, because a single consumer has no impact on the externality (Cremer and Thisse 1999). A consumer therefore purchases the product if $v \geq p - e(r;\lambda)$, and the demand for the product is

$$D(r,p;\lambda) = 1 - F(p - e(r;\lambda)), \tag{4}$$

where $p - e(r;\lambda)$ can be interpreted as the generalized price, which can be higher or lower than p depending on whether consumers derive a positive or negative end-of-life utility. Stated differently, if $e(r;\lambda) > 0$, then the end-of-life utility is demand-enhancing because of an increase in willingness to pay, whereas it is demand-reducing if $e(r;\lambda) < 0$, a form of deconsumption due to a reduction in willingness to pay. In addition, demand has the natural properties that it decreases in price and increases in recyclability as $e_r(r;\lambda) \geq 0$. In turn, stronger concerns about recylability have an ambiguous impact on demand as $e_\lambda(r;\lambda) \gtreqless 0$. Importantly, this shows that the impact of concerns about recyclability on demand is not clear-cut and critically depends on market-specific consumer preferences.

4 The circular business model

The distinctive feature of the circular business model is that it goes beyond the point of sale and allows the firm to tap into a new source of revenue from recycling end-of-life products and exploit the consumers' higher willingness to pay for products with higher recylability. Specifically, under a circular business model, the firm's profit is given by

$$\pi(r,p;\lambda,\omega,K) = [p-c(r)]D(r,p;\lambda) + \phi(r;\lambda)\omega r D(r,p;\lambda) - K, \tag{5}$$

where $\phi(r;\lambda)\omega r$ is the expected value of a recycled product and K is the fixed cost of setting up the reverse supply chain. Note that $[p-c(r)]D(r,p;\lambda)$ is the profit contribution from sales—the standard forward supply chain—whereas $\phi(r;\lambda)\omega r D(r,p;\lambda) - K$ is the expected profit contribution from recycling—the reverse supply chain.[4]

Due to recycling, the unit cost $c(r)$ of the product is reduced to the "net unit cost" $c(r) - \phi(r;\lambda)\omega r$, which satisfies the following properties.

Lemma 2 (Net unit cost)**.** *Suppose that the unit cost $c(r)$ is sufficiently convex and that $\frac{g'(\kappa)}{g(\kappa)}$ is not too negative. Then, the net unit cost function*

$$z(r;\lambda,\omega) \equiv c(r) - \phi(r;\lambda)\omega r \tag{6}$$

satisfies the properties $z(r;\lambda,\omega) \geq 0$, $z_r(r;\lambda,\omega) \geq 0$, $z_{rr}(r;\lambda,\omega) \geq 0$, $z_\lambda(r;\lambda,\omega) \leq 0$, $z_{r\lambda}(r;\lambda,\omega) \leq 0$, $z_\omega(r;\lambda,\omega) \leq 0$, and $z_{r\omega}(r;\lambda,\omega) \leq 0$ for admissible values of (λ,ω).

Intuitively, the convexity assumption in Lemma 2 rules out a "perpetuum mobile" by ensuring that the unit cost $c(r)$ exceeds the expected value of a recycled product $\phi(r;\lambda)\omega r$ for all r. The result shows that the net unit cost function $z(r;\lambda,\omega)$ is convex in r, and that a higher λ and ω decrease both $z(r;\lambda,\omega)$ and the marginal net unit cost $z_r(r;\lambda,\omega)$. The regularity condition on the density function $g(\kappa)$ ensures that the marginal net unit cost is decreasing in λ, a natural property as the return probability $\phi(r;\lambda)$ is higher when consumers have stronger concerns about recyclability.[5] Finally, Lemma 2 shows that the marginal net unit cost is decreasing in the market value ω of the recovered resources.

[4]The collection of end-of-life products can also be outsourced to a third party (Savaskan, Bhattacharya, and Van Wassenhove 2004). However, this would not qualitatively change the analysis.

[5]This condition holds for all monotone densities with $g'(\kappa) \geq 0$, including the uniform distribution. If $g'(\kappa) < 0$, the condition requires that the share of consumers with high hassle costs is sufficiently large.

4.1 Product design

The profit-maximizing circular product design exploits the opportunities from recycling and the consumers' higher willingness to pay. Hence, the firm chooses recyclability r and price p to

$$\max_{r,p} \quad \pi(r,p;\lambda,\omega,K) \;=\; [p-z(r;\lambda,\omega)][1-F(p-e(r;\lambda))]-K \tag{7}$$
$$\text{s.t. } 0 \leq r \leq 1.$$

Assuming that the profit function is strictly concave in r and p and therefore has a unique constrained maximum, the profit-maximizing recyclability index r^* and price p^* satisfy the following necessary and sufficient first-order conditions (the multipliers $\mu_1 \geq 0$ and $\mu_2 \geq 0$ are associated with the inequality constraints):

$$-z_r(r^*;\lambda,\omega)[1-F(\cdot)]+[p^*-z(r^*;\lambda,\omega)]f(\cdot)e_r(r^*;\lambda)+\mu_1-\mu_2=0, \tag{8}$$

$$1-F(\cdot)-[p^*-z(r^*;\lambda,\omega)]f(\cdot)=0, \tag{9}$$

$$\mu_1 r^*=0 \text{ and } \mu_2(r^*-1)=0.$$

The terms in the first equation capture the marginal changes in profit due to higher net unit cost and a higher end-of-life utility, respectively, whereas the second equation determines the firm's "pricing power" captured by $p^*-z(r^*;\lambda,\omega)$. We derive the following result.

Proposition 1 (Circular design)**.** *Under the circular business model, the firm offers a non-recyclable product with* $r^*=0$ *if* $-z_r(0;\lambda,\omega)+e_r(0;\lambda)\leq 0$*, and a fully recyclable product with* $r^*=1$ *if* $-z_r(1;\lambda,\omega)+e_r(1;\lambda)\geq 0$*. Otherwise, the firm offers a partially recyclable product with* $r^*\in(0,1)$*, characterized by the condition* $-z_r(r^*;\lambda,\omega)+e_r(r^*;\lambda)=0$*. The profit-maximizing price* p^* *solves* $p^*=z(r^*;\lambda,\omega)+\frac{1-F(p^*-e(r^*;\lambda))}{f(p^*-e(r^*;\lambda))}$.

The result highlights that a profit-maximizing firm does not necessarily offer a fully recyclable product under the circular business model. Specifically, at an interior solution, the firm offers a partially recyclable product with $r^* \in (0,1)$, chosen to balance the marginal changes in net unit cost and end-of-life utility, that is $z_r(r^*;\lambda,\omega) = e_r(r^*;\lambda)$. At a corner solution with $r^* = 1$, the marginal change in net unit cost is smaller than the corresponding increase in end-of-life utility, and the firm offers a fully recyclable product. In this limiting case, a fully circular business model emerges if all consumers return the product for recycling ($\phi^* \to 1$). On the other hand, at a corner solution with $r^* = 0$, the marginal change in net unit cost is larger than the corresponding increase in end-of-life utility, and the firm offers a non-recyclable product. Irrespective of the choice of r^*, the profit-maximizing price p^* is characterized by the standard inverse-elasticity pricing rule for given net unit cost $z(r^*)$.

The next result immediately follows from Proposition 1 and shows that the circular product design with zero recyclability coincides with the product design under a linear "take-make-dispose" business model where the firm does not build a reverse supply chain and consumers have no other choice than disposing of end-of-life products as waste.

Corollary 1 (Linear design)**.** *If $r^* = 0$, then the profit-maximizing product design (r^*, p^*) under the circular business model coincides with the product design $(\hat{r}, \hat{p})$ under the linear business model*

$$\hat{r} = 0 \text{ and } \hat{p} = c(0) + \frac{1 - F(\hat{p} - \bar{u}(\lambda))}{f(\hat{p} - \bar{u}(\lambda))},$$

with corresponding profit $\pi(0, \hat{p}; \lambda) = [\hat{p} - c(0)][1 - F(\hat{p} - \bar{u}(\lambda))]$.

4.2 Impact of a changing market environment

Understanding the impact of a changing market environment is key to adapt the product design. Our next result shows how stronger concerns about recyclability λ and a higher market value ω of the resources embedded in end-of-life products affect the firm.

Proposition 2 (Impact on firm)**.** *If the firm offers a partially recyclable product, then stronger concerns about recyclability λ increase the recyclability index r^*. In addition, they decrease demand and profit if $e_\lambda(r^*;\lambda) < z_\lambda(r^*;\lambda,\omega)$, and increase demand and* *profit if the inequality is reversed. A higher market value ω of the recovered resources increases the recyclability index r^*, demand, and profit. The impact of changes in λ and ω on pricing is ambiguous.*

Proposition 2 establishes the intuitive result that a profit-maximizing firm increases recyclability in response to stronger concerns about recyclability, while the impact on price is ambiguous. More interestingly, the proposition shows that the impact of stronger concerns about recyclability on demand and profit is market-specific and depends on the particular changes in end-of-life utility and net unit cost. The impact on demand and profit is negative if stronger concerns about recycling have a large negative effect on end-of-life utility (i.e., if they strongly increase the guilt from throwing away the product). Conversely, the impact on demand and profit is positive if stronger concerns about recycling increase end-of-life utility (i.e., if the increase in the warm glow dominates the increase in the cold prickle). Finally, while the impact of a higher value of recovered resources on price is generally ambiguous, the impact on demand and profit is always positive. The reason is that the firm cannot lose from recycling end-of-life products that become more valuable.

4.3 Waste footprint and externality

The waste footprint of the firm measures the amount of resources going to waste, either through the trash disposal of products or through the recycling of products that are not fully recyclable. Without loss of generality, we normalize the amount of resources embedded in an end-of-life product to unity and assume that the resources cannot be recovered from waste. Then, the expected waste footprint per unit of product is $w(r;\lambda) = 1 - \phi(r;\lambda)r$, with $w_r(r;\lambda) \leq 0$ and $w_\lambda(r;\lambda) \leq 0$, which means that the waste footprint per unit of product decreases in recyclability r and concerns about recyclability λ. Note that $\phi(r;\lambda)r$ can be interpreted as the expected recycling rate.

The firm's waste footprint results from adding up the per-unit waste footprint $w(r;\lambda)$ across buyers:

$$\Phi(r, p;\lambda) = [1 - \phi(r;\lambda)r]D(r, p;\lambda). \tag{10}$$

Importantly, the waste footprint is zero if and only if both the return probability and the index of recyclability are equal to unity.

Proposition 3 (Impact on waste footprint)**.** *If the firm offers a partially recyclable product with* $r^* \in (0,1)$*, then stronger concerns about recyclability* λ *reduce the waste footprint per unit of product,* $w(r^*;\lambda) = 1 - \phi(r^*;\lambda)r^*$*. If* $e_\lambda(r^*;\lambda) < z_\lambda(r^*;\lambda,\omega)$*, then the overall waste footprint* $\Phi(r^*, p^*;\lambda) = w(r^*;\lambda)D(r^*, p^*;\lambda)$ *decreases; otherwise the overall waste footprint may increase. The impact of a higher market value* ω *of recovered resources on the overall waste footprint is generally ambiguous.*

The result shows that stronger concerns about recyclability unambiguously reduce the waste footprint per unit of product. Intuitively, the result follows from the associated increases in recyclability and the probability of recycling. The impact on the overall waste footprint, in turn, is market-specific and depends on the impact on demand. If demand decreases (because the impact on end-of-life utility is negative, see Proposition 2), the impact on the overall waste footprint is negative. However, if demand increases, the impact on the overall waste footprint may be positive—a rebound effect (Alcott 2005; Raz, Druehl, and Blass 2013). Similarly, the impact of a higher market value of the recycled resources is ambiguous due to a positive demand effect.

With the definition of the waste footprint in mind, we now derive the externality buyers impose on society if they do not fully account for the environmental damage caused by product disposal. Assuming that one unit of waste causes an environmental damage $\delta \geq 0$ in monetary terms, a consumer should internalize the amount $-\delta w(r;\lambda)$ when purchasing the product. However, a buyer accounts for the end-of-life utility $e(r,\lambda)$ and thus creates a negative externality whenever $e(r;\lambda) > -\delta w(r;\lambda)$. Stated differently, the non-internalized environmental cost of waste per unit of product is $e(r;\lambda) + \delta w(r;\lambda)$. The waste externality can therefore be calculated by summing up the non-internalized environmental cost of waste across buyers:

$$E(r, p;\lambda) = [e(r;\lambda) + \delta w(r;\lambda)]D(r, p;\lambda). \tag{11}$$

Note that the waste externality equals the environmental cost of the firm's waste footprint $\delta\Phi(r,p;\lambda)$ if consumers do not care about recyclability, in which case the end-of-life utility $e(r;\lambda)$ is zero.

5 The circular transition

Tackling the circularity gap is key to reducing the resource and environmental footprints of doing business. In this section, we compare the market outcomes under the linear and the circular business model, and derive conditions under which the circular transition is profitable and socially desirable. Moreover, we derive the socially optimal product design and discuss policies that help to accelerate the circular transition. Throughout this section, we focus on the interesting case of partial recyclability $r^* \in (0,1)$ under a circular business model.

5.1 Profit perspective

The circular business model is viable if $\pi(r^*, p^*; \lambda, \omega, K) \geq 0$ but not necessarily the best choice when considering the linear alternative. The next result shows that the firm charges a green premium under the circular business model and characterizes the condition under which the transition to the circular business model is profitable.

Proposition 4 (Green premium). *Under a circular business model, the firm charges a green premium $p^* - \hat{p} > 0$. The transition to the circular business model increases profit if and only if $K < K^*$, where K^* is defined by the condition $\pi(r^*, p^*; \lambda, \omega, K^*) - \pi(0, \hat{p}; \lambda) = 0$, that is, if the extra profit resulting from the change in product design exceeds the cost of building the reverse supply chain.*

The result highlights that the transition to the circular business model allows the firm to charge a green premium for a recyclable product. However, the profit increase from the change in product design may be outweighed by the cost of building the reverse supply chain, in which case the transition to the circular business model is not profitable. A higher market value ω of recovered resources facilitates the circular transition as it increases the profit gap $\pi(r^*, p^*; \lambda, \omega, K) - \pi(0, \hat{p}; \lambda)$ by Proposition 2 and thus the threshold level K^*. Stronger concerns about recyclability, in turn, do not not necessarily facilitate the circular transition, even though they reduce the profitability of the linear business model.

5.2 Triple bottom line perspective

From a policy perspective, it is key to understand the conditions under which the circular transition would be desirable from a welfare perspective but is not undertaken by the firm because of profitability considerations. Following convention, we define welfare as the sum of profit and utilities that accrue to buyers and non-buyers,

$$\begin{aligned} W(r,p;\lambda,\omega,K) &= \pi(r,p;\lambda,\omega,K) + \int_{p-e(r;\lambda)}^{\infty} [v - p + e(r;\lambda) - E(r,p;\lambda)] dF(v) \\ &\quad + \int_0^{p-e(r;\lambda)} [-E(r,p;\lambda)] dF(v), \end{aligned} \tag{12}$$

where $E(r,p;\lambda)$ is the waste externality that affects buyers and non-buyers. By rearranging terms, welfare can equivalently be written as the triple bottom line of profit, people, and planet (Bertini et al. 2022; Elkington 1999):

$$W(r,p;\lambda,\omega,K) = \pi(r,p;\lambda,\omega,K) + S(r,p;\lambda) - \delta\Phi(r,p;\lambda), \tag{13}$$

where $S(r,p;\lambda) \equiv \int_{p-e(r;\lambda)}^{\infty} v dF(v) - pD(r,p;\lambda)$ is the standard consumer surplus absent the externality and $\delta\Phi(r,p;\lambda)$ is the environmental cost of waste. This decomposition captures the notion of "sustainability," an umbrella term generally viewed as comprising economic profitability, social justice, and respect for the environment (Boyd 2001; Huang and Rust 2011; Johnson 2009). Specifically, the triple bottom line reveals that society is confronted with a cost of waste that is ignored under a profit perspective. In addition, it shows that the waste externality is welfare-neutral as it only has a distributional effect. The discrepancy between the profit and welfare perspective leads to the following result.

Proposition 5 (Insufficient circularity)**.** *Under the circular business model, the socially optimal recycling rate r^w is characterized by the condition $-z_r(r^w;\lambda,\omega)-\delta w_r(r^w;\lambda)=0$, and the corresponding socially optimal price is $p^w=z(r^w,\lambda,\omega)+e(r^w;\lambda)+\delta w(r^w;\lambda)$. If $e_r(r;\lambda)+\delta w_r(r;\lambda)<0$, then a profit-maximizing firm provides insufficient recyclability, that is, $r^*<r^w$. The distorted product design stalls the circular transition for $K^*<K<\bar{K}$, where $\bar{K}$ is defined by the condition $W(r^*,p^*;\lambda,\omega,\bar{K})-W(0,\hat{p};\lambda)=0$.*

Proposition 5 shows that a profit-maximizing firm underprovides recyclability if the non-internalized cost of waste $e(r;\lambda)+\delta w(r;\lambda)$ is decreasing in recyclability. Intuitively, this condition holds if the marginal reduction in the social cost of waste per unit of product outweighs the private marginal increase in end-of-life utility. The result also shows that the socially optimal price is equal to the net unit cost plus the non-internalized cost of waste, the social cost of producing the product. Finally, Proposition 5 shows that ignoring the impact on people and planet may prevent the firm from making the circular transition, even though it is desirable from a social point of view. The misalignment of private and social interests is partly driven by the classical result that the firm has an incentive to strategically distort quality in order to exploit its pricing power by raising price above cost (Spence 1975). However, the novelty is that the inefficient choice of recyclability not only affects consumer surplus but also the cost of waste. Thus, $\bar{K}>K^*$ whenever the welfare gain from the change in consumer surplus and the overall environmental damage dominate the welfare loss from the profit reduction due to a higher cost of the reverse supply chain.

5.3 Accelerating the transition

Policy makers can accelerate the circular transition in various ways. First, an obvious policy is to subsidize investments in reverse supply chains whenever the circular transition is socially desirable but not profitable. In effect, this amounts to redistributing welfare gains to the firm by a "green subsidy." Second, policy makers can increase the value of recovered resources ω to the firm. This can be done, for instance, by prioritizing the use of recycled resources (European Commission 2020). Third, policy makers can take measures

Outcome Variable	Circular Model		Linear Model		Δ
Recyclability	r^*	0.1793	$\hat{r}$	0	0.1793
Price	p^*	0.4654	$\hat{p}$	0.2979	0.1676
Demand	D^*	0.3594	$\hat{D}$	0.2979	0.0615
Profit	π^*	0.1091	$\hat{\pi}$	0.0887	0.0204
Consumer surplus	S^*	0.0646	$\hat{S}$	0.0444	0.0202
Waste footprint	Φ^*	0.3026	$\hat{\Phi}$	0.2979	0.0048
Welfare	W^*	0.0466	$\hat{W}$	0.0080	0.0386
Thresholds	K^*	0.0404			
	$\bar{K}$	0.0586			

Table 1: Comparing the linear and the circular model for $\lambda = 0.75$, $\bar{u}_0 = 0.75$, $\alpha = 0.3$, $\omega = 0.15$, $K = 0.02$, and $\delta = 0.42$.

to raise concerns about recyclability through environmental campaigns. Even though the impact of changes in λ on $\pi(r^*, p^*; \lambda, \omega, K^*) - \pi(0, \hat{p}; \lambda)$ is generally ambiguous, such campaigns provide incentives to go circular in markets where stronger concerns about recyclability increase the value of the product in the eyes of the consumers (i.e., if $e_\lambda > 0$).

5.4 A numerical example

Assume that the benefit from recycling is $b(r;\lambda) = \lambda\sqrt{r}$, that the guilt from trashing the product is $\bar{u}(\lambda) = -\lambda\bar{u}_0$, with $\bar{u}_0 \geq 0$, and that the unit cost is $c(r) = (\alpha + \sqrt{r})r$, with $\alpha > 0$. Further, suppose that the hassle cost κ and product valuation v are drawn from uniform distributions over the interval $[0, 1]$. Demand therefore becomes $D(r, p; \lambda) = 1 - p + e(r;\lambda)$, with $e(r;\lambda) = \frac{\lambda^2}{2}(\bar{u}_0 + \sqrt{r})^2 - \lambda\bar{u}_0$. The net unit cost can be derived as $z(r;\lambda,\omega) = c(r) - \lambda(\bar{u}_0 + \sqrt{r})\omega r$, with $\phi(r;\lambda) = \lambda(\bar{u}_0 + \sqrt{r})$. To simplify exposition, we assume specific parameter values to solve the model and report the results in Table 1.

The numerical results illustrate several of our key findings above. First, the transition from the linear to the circular business model increases recyclability ($r^* > 0$) and allows the firm to charge a green premium ($p^* > \hat{p}$). Second, the change in product design increases demand ($D^* > \hat{D}$) and profit ($\pi^* > \hat{\pi}$), but the circular transition is profitable if and only if the cost of setting up the reverse supply chain is sufficiently small (specifically, $K < K^* = 0.0404$). Third, the circular transition increases consumer surplus ($S^* > \hat{S}$) and the overall waste footprint ($\Phi^* > \hat{\Phi}$) due to the increase in demand—a rebound effect. Finally, the circular transaction increases welfare ($W^* > \hat{W}$), and there may be insufficient circularity (as $K^* < \bar{K}$).

6 Competition

We now extend our analysis to markets in which firms compete for consumers under circular business models. The main objective is to study how competition affects the way in which profit-maximizing firms decide about recyclability and price.

6.1 Setup

Consider a market with a unit it mass of consumers who make a discrete choice among n differentiated products offered by single-product firms indexed by $i = 1, ..., n$, and an outside option indexed by 0. Each firm i designs its product by choosing recyclability r_i and price p_i. In line with our above analysis, the end-of-life utility provided by product i is

$$e_i(r_i;\lambda) = \int_0^{b_i(r_i;\lambda)-\bar{u}(\lambda)} G(\kappa)d\kappa + \bar{u}(\lambda),$$

where $b_i(r_i;\lambda)$ denotes the benefit from returning product i for recycling and $\bar{u}(\lambda)$ is the guilt cost from trashing the product. Consumer l derives utility

$$u_{il}(r_i, p_i;\lambda) = \varepsilon_{il} - p_i + e_i(r_i;\lambda) - E, \quad i = 1, ..., n, \tag{14}$$

from purchasing product i, where ε_{il} can be interpreted as the match value between consumer l and product i, p_i is the price of product i, $e_i(r_i;\lambda)$ is the end-of-life utility provided by product i, and E is the environmental externality. Normalizing the intrinsic utility to zero, consumer l derives utility $u_{0l} = \varepsilon_{0l} - E$ from choosing the outside option, where ε_{0l} is the corresponding match value.[6] Building on standard discrete choice theory (Anderson, de Palma, and Thisse 1992), we assume that the match values $\{\varepsilon_{il}\}_{i=0,\dots,n}$ are independently and identically distributed across products and consumers according to some smooth joint distribution.

To simplify exposition, we let $\tilde{p}_i \equiv p_i - e_i(r_i;\lambda)$ denote the generalized price of firm i. Using the vector of generalized prices $\tilde{\mathbf{p}} = (\tilde{p}_1, \dots, \tilde{p}_n)$, the firm-specific demand functions generated from the discrete choice model can be written as $D_i(\tilde{\mathbf{p}})$, $i = 1, \dots, n$ (Anderson, de Palma, and Thisse 1992; Dewatripont and Tirole 2023). Equivalently, we can write firm-specific demand as $D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i})$, where $\tilde{\mathbf{p}}_{-i}$ is the vector of all generalized prices except for $\tilde{p}_i$.[7]

6.2 Invariance of recyclability

Under a circular business model, each firm $i = 1, \dots, n$ chooses the recyclability index r_i and the price p_i to solve

$$\max_{r_i, p_i} \quad \pi_i(r_i, p_i, \tilde{\mathbf{p}}_{-i}; \lambda, \omega, K_i) = [p_i - z_i(r_i;\lambda,\omega)] D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i}) - K_i \qquad (15)$$
$$\text{s.t. } 0 \le r_i \le 1,$$

where $z_i(r_i;\lambda,\omega) \equiv c_i(r_i) - \phi_i(r_i;\omega)\omega r_i$ is firm i's net unit cost function, with $\phi_i(r_i;\lambda) \equiv G(b_i(r_i;\lambda) - \bar{u}(\lambda))$ denoting the product-specific share of returned products, and K_i is the

[6] The monopoly considered above is a special case of this model. To see this, suppose that only one product, say product 1, is available and define $v \equiv \varepsilon_{1l} - \varepsilon_{0l}$. Then, the purchase condition boils down to $v \ge p_1 - e_1(r_1;\lambda)$, and demand is $D_1(\tilde{p}_1) = 1 - F(p_1 - e_1(r_1;\lambda))$ for some cumulative distribution $F(v)$.

[7] A widely used specification in marketing and economics is logit demand, which takes the form

$$D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i}) = \frac{\exp(-\tilde{p}_i/\mu)}{1 + \sum_{k=1}^{n} \exp(-\tilde{p}_k/\mu)}, \quad i = 1, \dots, n,$$

if the match values are distributed according to the double exponential with zero mean and standard deviation proportional to $\mu > 0$, which can be interpreted as the degree of horizontal consumer/product heterogeneity (Anderson and de Palma 2001; Anderson, de Palma, and Thisse 1992).

fixed cost of setting up a reverse supply chain for product i. In line with our above analysis, we assume that firm i's net unit cost function satisfies $z_i(r_i;\lambda,\omega) \geq 0$ and is convex in r_i.

Assuming that the profit function is strictly concave in r_i and p_i, the profit-maximizing index of recyclability r_i^* and price p_i^* of firm i, $i = 1,...n$, satisfy the following necessary and sufficient first-order conditions (where the arguments are suppressed for simplicity):

$$-\frac{\partial z_i}{\partial r_i}D_i - [p_i^* - z_i]\frac{\partial D_i}{\partial \tilde{p}_i}\frac{\partial e_i}{\partial r_i} + \mu_1 - \mu_2 = 0, \tag{16}$$

$$D_i + [p_i^* - z_i]\frac{\partial D_i}{\partial \tilde{p}_i} = 0, \tag{17}$$

$$\mu_1 r_i^* = 0 \text{ and } \mu_2(r_i^* - 1) = 0.$$

Similar to the monopoly case, the first equation characterizes the marginal change in profit due to a marginal change in r_i^*, whereas the second equation determines the firm's "pricing power" captured by $p_i^* - z_i$. We derive the following result.

Proposition 6 (Competitive product design)**.** *The profit-maximizing recyclability index r_i^* of product i is determined by the firm-specific incentive $\partial e_i(r_i^*;\lambda)/\partial r_i - \partial z_i(r_i^*;\lambda,\omega)/\partial r_i$, for $i = 1,...,n$, independent of the number of firms n in the industry and the prices $p_1^*,...,p_n^*$ set under competition. The recyclability index r_i^* increases in the concerns about recyclability λ and the market value ω of recycled resources.*

The result shows that the way in which the profit-maximizing recyclability of a product is determined under monopoly naturally carries over to competition: each firm i considers the firm-specific marginal changes in net unit cost and end-of-life utility, and chooses r_i^* accordingly, independent of the competitors' decisions about recyclability. In addition, the comparative statics of recyclability are unaffected, and therefore robust across market structures. Proposition 6 implies, in particular, that competition does *not* induce profit-maximizing firms to offer products that are less recyclable (i.e., there is no race to the bottom). Intuitively, the result follows from the simultaneous determination of recyclability and price (Dasgupta and Stiglitz 1982) and the additive separability of the utility function (14) in recyclability and price. It is reminiscent of the "irrelevance result" by Dewatripont and Tirole (2023), which shows that competition does not affect the "ethical behavior" of firms that maximize a weighted average of profit and welfare.

The equilibrium prices, in turn, are determined by simultaneously solving the firm-specific inverse-elasticity pricing rules for given recyclability indices $r_1^*, \ldots, r_n^*$, accounting for the outside option. If increasing the number of firms decreases equilibrium prices and profits, then competition undermines the viability of the circular business model as it becomes increasingly difficult for a firm to recover the cost of setting up the reverse supply chain.[8] This provides a rationale for policy makers to foster industry-wide reverse supply chains to avoid the replication of fixed costs.

7 The policy toolbox for circularity

This section studies how different policy tools help increase recyclability when firms compete for consumers under circular business models, as profit-maximizing firms tend to provide insufficient recyclability from a societal perspective. First, we examine the impact of regulation aimed at improving consumer participation, considering mandatory deposit-refund systems (DRS) and product-buyback policies. Next, we study the impact of an obligation to retain product ownership (RPO) that eliminates "leakage" from consumers who would otherwise trash the product. Finally, we examine how different taxes and fees that put a price on waste affect equilibrium recyclability. Throughout, we focus on the interesting case of partial recyclability and assume that each firm builds its own reverse supply chain.

7.1 Deposit fee and product buyback

Under a mandatory deposit-refund system, each firm i collects a deposit $d_i > 0$ from buyers as a surcharge at the time of purchase that is refunded when the product is returned for

[8] For example, in a model with logit demand, prices and profits in a symmetric equilibrium are decreasing functions of n (Anderson, de Palma, and Thisse 1992).

recycling, a financial incentive commonly used for beverage containers, lead-acid batteries, motor oil, tires, various hazardous materials, and consumer electronics (Fullerton and Wolverton 2000; Walls 2011). Using the superscript D to index the relevant expressions under a deposit-refund system, firm i chooses the deposit d_i, as well as the index of recyclability r_i and the purchase price p_i to

$$\begin{aligned} \max_{d_i,r_i,p_i} \quad \pi_i^D &= [p_i + d_i - z_i^D(r_i, d_i; \lambda, \omega)] D_i(\tilde{p}_i + d_i, \tilde{\mathbf{p}}_{-i} + \mathbf{d}_{-i}) \\ &\quad - \phi_i^D(r_i, d_i; \lambda) d_i D_i(\tilde{p}_i + d_i, \tilde{\mathbf{p}}_{-i} + \mathbf{d}_{-i}) - K_i \end{aligned} \tag{18}$$

where $z_i^D(r_i, d_i; \lambda, \omega) \equiv c_i(r) - \phi_i^D(r_i, d_i; \lambda)\omega r_i$ is the net unit cost, $\phi_i^D(r_i, d_i; \lambda) d_i$ is the expected refund, and $\tilde{\mathbf{p}}_{-i} + \mathbf{d}_{-i}$ denotes the vector of all deposit-adjusted generalized prices except for product i. A deposit-refund system makes $e_i^D(r_i, d_i; \lambda)$ as well as the return probability $\phi_i^D(r_i, d_i; \lambda)$ dependent on d_i because consumers receive $b_i(r_i; \lambda) + d_i$ when recycling the product.

Proposition 7 (Deposit refund)**.** *The profit-maximizing deposit for product $i = 1, \ldots, n$, equals the value of a recovered product, $d_i^D = \omega r_i^D$. Coupling a circular business model with a deposit-refund system increases recyclability to $r_i^D > r_i^*$ only if the additional number of consumers who recycle the product is sufficiently large.*

This result first shows that the profit-maximizing deposit corresponds to the value of the resources embedded in an end-of-life product. Intuitively, firm i overpays for the value of the resources if $d_i > d_i^D$ and underpays if the inequality is reversed. Second, the result shows that a deposit-refund system does not necessarily increase recyclability. The reason is that raising recyclability beyond r_i^* is profitable only if the benefit (a higher value of the recovered resource and a higher marginal end-of-life utility) exceeds the additional cost (a higher expected refund due the higher probability of recycling), a condition that is satisfied if the deposit induces a sufficiently large number of additional consumers to recycle the product. Importantly, the deposit-refund system implements ex-post price discrimination, as non-recyclers forego the deposit refund and therefore pay a higher transaction price than buyers who recycle the product.

Another way to implement ex-post price discrimination is to mandate the repurchase of end-of-life products from buyers (without collecting a deposit at the time of purchase).[9] Letting the superscript B index the variables under buyback, with s_i^B denoting the repurchase price determined by firm i, the next result establishes that it does not matter for the market outcome whether the policy maker mandates a buyback policy or a deposit-refund system.

Proposition 8 (Product buyback)**.** *Coupling a circular business model with a buyback policy is equivalent to introducing a deposit-refund system with $r_i^B = r_i^D$, $p_i^B = p_i^D + d_i^D$, and $s_i^B = \omega r_i^B$ for all i.*

This result shows that the product design in terms of recyclability and the transaction price are the same under a deposit-refund system and a buyback strategy. That is, price partitioning plays no role because the buyback price can be viewed as an implicit deposit that is collected upfront. The result also shows that the buyback price should be set equal to the deposit refund. Intuitively, it does not matter whether a buyer foregoes the deposit or the buyback price when disposing of the product as waste.

7.2 Retaining product ownership

Deposit-refund systems and buyback strategies create "leakage" because consumers do not necessarily return the product for recycling. In contrast, an obligation to retain product ownership (RPO) ensures that all products being sold can be recovered for recycling. Typical examples of RPO strategies include rentals and leasing—the idea of "product as a service." Note that RPO can be viewed as a form of Extended Producer Responsibility (EPR) that has the objective of making producers responsible for the environmental impact

[9]Voluntary product-buyback policies are often used in trade-in program and refurbishing markets. For example, the Apple Trade In program offers credit toward the next purchase, and Back Market buys back electronics devices from consumers to sell them on their marketplace of refurbished electronics.

of their products across the life cycle (OECD 2016, 2018).[10] Using the superscript O to index the variables under an RPO strategy, firm i chooses the index of recyclability r_i and the purchase price p_i to

$$\max_{r_i,p_i} \quad \pi_i^O \quad = \quad [p_i - z_i^O(r_i;\omega)]D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i}) - K_i, \tag{19}$$

where $e_i^O(r_i;\lambda) = b_i(r_i;\lambda) - E[\kappa]$ is end-of-life utility in the presence of a contractual obligation to return the product and $E[\kappa] = \int_0^\infty \kappa dG(\kappa) > 0$ denotes the corresponding expected hassle cost. As $\phi_i^O(r_i;\lambda) = 1$ by construction, the net unit cost $z_i^O(r_i;\omega)$ is independent of λ. We derive the following result.

Proposition 9 (Product Ownership)**.** *Coupling a circular business model with an RPO strategy increases recyclability.*

This result shows that introducing an RPO policy unambiguously leads to better recyclable products. By eliminating leakage on the part of consumers, an RPO strategy automatically creates a fully circular business model whenever $r^O = 1$.

7.3 Waste taxes and disposal fees

We now consider different taxes and fees that put a price on waste. To make firms pay for the cost of waste, the policy maker can either use a firm-specific lump-sum tax $T_i > 0$ or a per-unit waste tax $t > 0$. Instead, to make consumers pay, the policy maker can either use an advanced disposal fee $\varphi_i > 0$ or a trash disposal fee $\gamma > 0$.[11] The following result holds.

[10]RPO has been used as a voluntary strategy by firms in the past. For example, Xerox has for a long time leased its printers and photocopiers to corporate customers, Michelin Fleet Solutions proposes tire lease programs with fixed price per mile rates, and On's running shoe made from the oil of castor beans is available on subscription only "to ensure your old pair of Cyclons goes back to the company, so that the recycling loop actually works."

[11]In contrast to the deposit-refund system, the two types of fees considered here are beyond the control of the firm and need to be paid by all buyers and non-recyclers, respectively. See, for example, Plambeck and Wang (2009) for an application of "fee-upon-sales" and "fee-upon-disposal" in e-waste regulation.

Proposition 10 (Pricing waste)**.** *The lump-sum tax $T_i^* = \delta\Phi_i^*$ makes firm i pay for the cost of waste but does not affect recyclability, whereas a per-unit waste tax $t > 0$ increases r_i^*. The advanced disposal fee $\varphi_i^*(r_i^*;\lambda) = e_i(r_i^*;\lambda) + \delta w_i(r_i^*;\lambda)$ makes buyers pay for the non-internalized cost of waste but does not affect recyclability, whereas a trash disposal fee γ imposed on non-recyclers has an ambiguous impact on r_i^*.*

To put the result into perspective, recall from the triple bottom line approach that profit-maximizing firms do not account for the impact of their choices on consumer surplus and the environmental damage of waste. To make firm i pay for the cost of waste, the policy maker can impose a lump sum tax $T_i^* = \delta\Phi_i^*$, a transfer from the firm to society that leaves product design and welfare unaffected. Imposing a lump-sum tax can be viewed as an EPR policy: Firms not only pay for the cost of the reverse supply chain but also for the cost of the remaining waste, thereby making them responsible for the product along the entire life cycle. Instead, by imposing a unit waste tax $t > 0$ on the firm, the policy maker provides an incentive to improve recyclability. To see this, note that the waste tax adds $tw_i(r_i;\lambda)$ to the net unit cost $z_i(r_i;\lambda)$ but leaves the end-of-life utility $e_i(r_i;\lambda)$ unaffected, which results in higher recyclability as $\partial w_i(r_i;\lambda)/\partial r_i \leq 0$. Clearly, if the tax fully reflects the cost of waste (i.e., $t = \delta$), then firm i pays for the cost of waste but passes part of the tax burden on to consumers.

Alternatively, the policy maker can make buyers pay for the cost of waste by mandating firms to collect an advanced disposal fee. Importantly, this fee does not affect the disposal decisions of buyers as it is sunk when the product reaches end-of-life, and therefore has no impact on recyclability. The advanced disposal fee $\varphi_i^*(r_i^*;\lambda) = e_i(r_i^*;\lambda) + \delta w_i(r_i^*;\lambda)$ makes buyers pay for the non-internalized cost of waste and thereby eliminates the externality, similar to a Pigou tax that corrects for under-priced externalities (Pigou 1932). Alternatively, the policy maker can impose a trash disposal fee on non-recyclers. The impact of a such a fee on recylability is ambiguous because it reduces both the end-of-life utility and the net unit cost of a product through a higher return probability. Overall, whereas a lump-sum tax on the firm and an advanced disposal fee for buyers only have distributional effects, a per-unit waste tax imposed on the firm is the only policy tool considered here that necessarily increases recyclability.

8 Discussion

This paper developed an analytical framework to gain insight into the mechanics of circular business models in markets where consumers care about recyclability. The key novelty is that consumers make an endogenous disposal decision that is affected by the firm's choice of recyclability, the strength of their concerns about recyclability, and the idiosyncratic cost of returning the product for recycling. The concerns about recyclability drive both the benefit from returning the product for recycling and the guilt associated with trash disposal, and their relative importance drives demand, profit, and the waste footprint. Importantly, the consumers' end-of-life decision about product disposal enters the objective function of a profit-maximizing firm via their impact on sales and recycled resources, thereby affecting product-design decisions with respect to price and recyclability.

We derived three key results. First, the end-of-life utility of a product can be positive or negative depending on the market-specific costs and benefits associated with the recycling and trash disposal options, thereby allowing for the possibility of demand expansion or deconsumption. Second, under a circular business model, recyclability is determined by balancing the marginal changes in the expected end-of-life utility perceived by consumers and the net-unit cost of the firm, which highlights that a profit-maximizing firm does not necessarily offer a fully recyclable product. Third, a linear firm transitions to a circular business model if the profit increase due to a green premium and the cost-dampening effect of recycling outweighs the cost of building the reverse supply chain.

In addition, we show that competition has no impact on the profit-maximizing choice of recyclability at the level of the firm. An important implication of this result is that competition does not undermine recyclability but makes the circular business model less profitable due to the reduced pricing power. Finally, staying in the realm of imperfectly competitive markets, we show how policy tools such as regulation and taxation can improve recyclability and eliminate waste externalities in circular business models.

8.1 Implications for firms

The consumers' concerns about recyclability offer new opportunities for firms: They may not only benefit from a higher willingness to pay for products with better recyclability, but also tap into a new source of revenue from recycling end-of-life products. However, to seize these opportunities, firms must invest in a reverse supply chain. A key driver of the circular transition is the ability of the firm to charge a green premium for better recyclable products. Another important driver of the circular transition is to reduce the hassle costs for consumers to return the product for recycling, for example through higher investments in the reverse supply chain, such as free home pick-up services.

Once the firm has shifted to a circular business model, a higher market value of the recovered resources reinforces the benefits from circularity. However, the impact of stronger concerns about recyclability is market-specific and depends on the relative change of the warm glow from recycling and the cold prickle from trash disposal. In particular, if the guilt from trash disposal strongly increases due to stronger concerns about recylability, then firms may suffer from deconsumption. On the other hand, if the benefit from recycling strongly increases, a firm's overall waste footprint may increase due to higher demand. At a deeper level, distinguishing the warm glow and the cold prickle allows managers to understand how the perceived benefit from recycling and the guilt from trash disposal affect product design, profit, and the environmental impact of the firm.

There are indications that the circular business model will become more profitable in the near future. Increasing prices of raw materials and more intense competition over rare earth materials suggest that recycling end-of-life products becomes more attractive. In addition, policies that raise consumer awareness, such as the European Union's Circular Economy Action Plan (European Commission 2020), might lead to deconsumption for non-recyclable products as consumers increasingly dread the prospect of having to trash end-of-life products. Finally, it seems plausible that technological progress will render circular supply chains more profitable. Innovation reduces not only the cost of setting up reverse supply chains, but also the buyers' hassle cost of returning the product for recycling (e.g., through curbside pickup).

8.2 Implications for policy makers

There are many ways in which policy makers can support the transition to a circular economy: regulation, taxation, and "realpolitik." Common policy objectives are to increase recyclability, reduce the waste footprint, and introduce the polluter-pays-principle for the environmental damage. Other industrial policies include subsidizing reverse supply chains, fostering industry-wide supply chains in competitive markets, and creating well-functioning markets for secondary raw materials.

An important insight is that competition has no impact on recyclability. However, it undermines the viability of the circular business model if it exerts downward pressure on price, which naturally calls for joint ventures in reverse supply chains to avoid duplication of fixed costs. The policy toolbox offers two instruments that increase recyclability: a per-unit waste tax imposed on the firm, and retaining product ownership as a form of extended producer responsibility. On the other hand, policy instruments such as mandatory deposit fees, product buyback, or trash disposal fees may even hurt recylability. Finally, a lump-sum waste tax imposed on the firm or an advanced disposal fee paid does not affect recyclability but eliminates the externality by shifting the cost of waste on the polluters.

Regarding recent realpolitik, the European Commission (2019, 2020) and the Chinese National Development and Reform Commission (NDRC 2021) have proposed several measures to accelerate the circular transition of the economy.[12] The Circular Economy Action Plan adopted in March 2020, one of the main building blocks of the European Green Deal (European Commission 2019), targets how products are designed. One of the policy levers is to impose a minimum level of recyclability, which necessarily increases

[12]For an overview of the circular economy in China, see Bleischwitz et al. (2022).

recyclability but has a cost to the firm by placing an additional restriction on the profit maximization problem. The policy action mainly focuses on resource-intensive sectors such as textiles, construction, electronics and plastics. Likewise, China's development plan (NDRC 2021) focuses on recycling for materials recovery, and will make circular economy a national priority.

8.3 Implications for consumers

Consumer concerns about recyclability enter the objective function of a profit-maximizing firm via their impact on the revenues from sales and recycled resources, respectively, thereby affecting the product design decisions regarding recyclability and price. In other words, consumers can impose their environmental preferences even on firms that narrowly focus on profit maximization.

Yet, consumers should be aware that their choices not only affect the firm's profit but also impose a negative externality on society if they do not fully account for the cost of waste caused by their purchase decisions. Full internalization requires that the cold prickle from throwing away an end-of-life product offsets the waste footprint and the warm glow from participating in the recycling system, or that an advanced disposal fee makes up for any difference. Otherwise, the expected end-of-life utility is "too large," which results in an excessively high demand and overall waste footprint. To introduce the polluter-pays-principle and make buyers pay for the cost of waste, non-buyers can lobby for an advanced disposal fee. Similarly, consumers can lobby for the lump-sum taxation of polluting firms, thereby making them pay for the cost of waste to society.

8.4 Limitations and future research

Our general framework offers several avenues for future research. First, one could study how different ways of building dynamics into the model affect product design and market outcomes. For example, one could consider asymmetric industry structures in which one firm has an initial competitive advantage, either in the cost of delivering recyclability or the cost of operating the reverse supply chain. An interesting question in such a dynamic setting could be whether linear and circular firms can coexist in equilibrium. Alternatively, one could study how firms can go beyond recycling by extending the loop through additional "R-levers" including reuse, repair, and remanufacture to further reduce resource extraction and waste production. However, the dynamics in such a setting critically depend on the decisions of buyers to participate in the reverse supply chain (e.g., incur the cost to repair a product). Another fruitful avenue could be to explore how new products with uncertain recyclability, such as electric cars or wind turbines, are perceived by consumers, and how the uncertainty affects product design and market outcomes.

Second, it would be important to develop a better understanding of how consumers value recyclability. An immediate step could be to empirically quantify the warm glow from participating in recycling and the cold prickle from trash disposal, and how stronger concerns about recyclability affect these quantities. Another avenue could be to explore the potential for greenwashing when consumers care about product recyclability. We assumed that consumers take recyclability claims made by firms at face value. However, firms may be tempted to make unsubstantiated green claims to affect consumer behavior, and it would therefore be interesting to examine the conditions under which greenwashing can prevail in market equilibrium. Thus, there are several directions which research could take to tackle the "circularity gap" and align business models with planetary boundaries.

References

Accenture (2017), "Waste to Wealth: Creating Advantage in a Circular Economy" (accessed December 14, 2022), `https://bit.ly/3YoefRB`.

Agrawal, Vishal, Atalay Atasu, and Sezer Ülkü (2021), "Leasing, Modularity, and the Circular Economy," *Management Science*, 67(11), 6782–6802.

Agrawal, Vishal V., Atalay Atasu, and Luk N. Van Wassenhove (2019), "OM Forum—New Opportunities for Operations Management Research in Sustainability," *Manufacturing & Service Operations Management*, 21(1), 1–12.

Alcott, Blake (2005), "Jevons' Paradox," *Ecological Economics*, 54(1), 9–21.

Anderson, Simon P., and André de Palma (2001), "Product Diversity in Asymmetric Oligopoly: Is the Quality of Consumer Goods Too Low?" *Journal of Industrial Economics*, 49, 113–135.

Anderson, Simon P., André de Palma, and Jean-François Thisse (1992), *Discrete Choice Theory of Product Differentiation*, MIT Press.

Andreoni, James (1995), "Warm-Glow Versus Cold-Prickle: The Effects of Positive and Negative Framing on Cooperation in Experiments," *Quarterly Journal of Economics*, 110(1), 1–21.

Apple (April 19, 2022), "Apple Expands the Use of Recycled Materials Across Its Products" (accessed December 15, 2022), `https://bit.ly/3j1Yek9`.

Atasu, Atalay, V. Daniel R. Guide Jr., and Luk N. Van Wassenhove (2008), "Product Reuse Economics in Closed-Loop Supply Chain Research," *Production and Operations Management*, 17(5), 483–496.

Atasu, Atalay, Céline Dumas, and Luk N. Van Wassenhove (2021), "The Circular Business Model," *Harvard Business Review*, 99(4), 72–81.

Atasu, Atalay, Miklos Sarvary, and Luk N. Van Wassenhove (2008), "Remanufacturing as a Marketing Strategy," *Management Science*, 54(10), 1731–1746.

Atasu, Atalay, and Gilvan C. Souza, (2013), "How Does Product Recovery Affect Quality Choice?" *Production and Operations Management*, 22(4), 991–1010.

Bertini, Marco, Stefan Buehler, Daniel Halbheer, and Donald R. Lehmann (2022), "Carbon Footprinting and Pricing Under Climate Concerns," *Journal of Marketing* 86(2), 186–201.

Bleischwitz, Raimund, Miying Yang, Beijia Huang, X.U. Xiaozhen, Jie Zhou, Will McDowall, Philip Andrews-Speed, Zhe Liu, and Geng Yong (2022), "The Circular Economy in China: Achievements, Challenges and Potential Implications for Decarbonisation," *Resources, Conservation and Recycling*, 183, 106350, `https://bit.ly/3WpPjaF`.

Bloomberg (February 5, 2020), "Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills" (accessed January 16, 2023), `http://bit.ly/3QQOV59`.

Boyd, Chris (2001), "Sustainability is Good Business," *OECD Observer*, 228 (September).

Chandy, Rajesh K., Gita Venkataramani Johar, Christine Moorman, and John H. Roberts (2021), "Better Marketing for a Better World," *Journal of Marketing*, 85(3), 1–9.

Chen, Chialin (2001), "Design for the Environment: A Quality-Based Model for Green Product Development," *Management Science*, 47(2), 250–263.

Circle Economy (2023), *The Circularity Gap Report 2023*. Amsterdam: Circle Economy.

Cremer, Helmut and Jean-Jacques Thisse (1999), "On the Taxation of Polluting Products in a Differentiated Industry," *European Economic Review*, 43(3), 575–594.

Cronin, Jr., J. Joseph, Jeffery S. Smith, Mark R. Gleim, Edward Ramirez, and Jennifer Dawn Martinez (2011), "Green Marketing Strategies: An Examination of Stakeholders and the Opportunities They Present," *Journal of the Academy of Marketing Science*, 39(1), 158–174.

Dasgupta, Partha and Joseph Stiglitz (1980), "Industrial Structure and the Nature of Innovative Activity," *Economic Journal*, 90(358), 266–293.

Dewatripont, Mathias, and Jean Tirole (2023), "The Morality of Markets," *ECARES Working Paper 2022-35*, https://bit.ly/3sQsjrZ.

Elkington, John (1999), "Triple Bottom-Line Reporting: Looking For Balance," *Australian CPA* 69, 18-21.

Ellen MacArthur Foundation (2013), "Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition" (accessed December 14, 2022), https://bit.ly/3OCN4h4.

European Commission (2020), "A New Circular Economy Action Plan For a Cleaner and More Competitive Europe," https://bit.ly/3WaqPm4.

European Commission (2019), "The European Green Deal," https://bit.ly/3YAYMOM.

Fullerton, Don, and Ann Wolverton (2000), "Two Generalizations of a Deposit-Refund Systems," *American Economic Review*, 90(2), 238–242.

Geng, Yong, Joseph Sarkis, and Raimund Bleischwitz (2019), "How to Globalize the Circular Economy," *Nature*, 565, 153–155.

Gui, Luyi, Atalay Atasu, Özlem Ergun, and L. Beril Toktay (2016), "Efficient Implementation of Collective Extended Producer Responsibility Legislation, *Management Science*, 62(4), 1098–1123.

Guide Jr, V. Daniel R., and Luk N. Van Wassenhove (2009), "OR FORUM—The Evolution of Closed-Loop Supply Chain Research," *Operations Research*, 57(1), 10–18.

Herweg, Fabian, and Klaus M. Schmidt (2022), "How to Regulate Carbon Emissions With Climate-Conscious Consumers," *The Economic Journal*, 132(648), 2992–3019.

Holcim (2023), "Ecocycle® Enables the World's First Fully Recycled Concrete Building" (accessed September 10, 2023), https://bit.ly/3Ew7Yus.

HP (April 2022), "Closed-Loop Recycling (accessed December 19, 2022), https://bit.ly/3BL6Imf.

Huang, Ming-Hui, and Roland T. Rust (2011), “Sustainability and Consumption,” *Journal of the Academy of Marketing Science*, 39(1), 40–54.

Huang, Ximin (Natalie), Atalay Atasu, and L. Beril Toktay (2019), “Design Implications of Extended Producer Responsibility for Durable Products,” *Management Science*, 65(6), 2573–2590.

IBM Institute for Business Value (2022), “Balancing Sustainability and Profitability” (accessed December 16, 2022), `https://bit.ly/3PtWkFf`.

Johnson, Robert L. (2009), “Organizational Motivations for Going Green or Profitability Versus Sustainability,” *The Business Review*, 13(1), 22–28.

Luo, Xueming, and C. B. Bhattacharya (2006), “Corporate Social Responsibility, Customer Satisfaction, and Market Value,” *Journal of Marketing*, 70(4), 1–18.

McKinsey Quarterly (2017), “Mapping the Benefits of a Circular Economy” (accessed December 14, 2022), `https://bit.ly/3BwDhUQ`.

Moorthy, K., Sridhar (1984), “Market Segmentation, Self-Selection, and Product Line Design,” *Marketing Science*, 3(4), 228–307.

NDRC People’s Republic of China (2021), “Action Plan for Carbon Dioxide Peaking Before 2030” (accessed January 11, 2023) `https://bit.ly/3hFDPBe`.

Nespresso (2021), “The Positive Cup” (accessed January 10, 2023), `https://bit.ly/3X1lwAs`.

OECD (2018), “Business Models for the Circular Economy: Opportunities and Challenges from a Policy Perspective,” OECD Publishing, Paris.

OECD (2016), “Extended Producer Responsibility: Updated Guidance for Efficient Waste Management,” OECD Publishing, Paris.

Papadas, Karolos-Konstantinos, George J. Avlonitis, and Marylyn Carrigan (2017), “Green Marketing Orientation: Conceptualization, Scale Development and Validation,” *Journal of Business Research*, 80, 236–246.

Pigou, Arthur C. (1932), *The Economics of Welfare*, 4th edition, London, Macmillan.

Plambeck, Erica, and Qiong Wang (2009), “Effects of E-waste Regulation on New Product Introduction,” *Management Science*, 55(3), 333–347.

Raz, Gal, Cheryl T. Druehl, and Vered Blass (2013), “Design for the Environment: Life-Cycle Approach Using a Newsvendor Model,” *Production and Operations Management*, 22(4), 940–957.

Raz, Gal, and Gilvan C. Souza (2018), “Recycling as a Strategic Supply Source,” *Production and Operations Management*, 27(5), 902–916.

Reuters (February 6, 2023), “Single-Use Plastic Production Rose Between 2019 and 2021 Despite Pledges” (accessed September 19, 2023), `https://bit.ly/3PooMsd`.

Rust, Roland T., Christine Moorman, and Peter R. Dickson (2002), “Getting Return on Quality: Revenue Expansion, Cost Reduction, or Both?” *Journal of Marketing*, 66(4), 7–24.

Rust, Roland T., and Anthony J. Zahorik (1993), “Customer Satisfaction, Customer Retention, and Market Share,” *Journal of Retailing*, 69(2), 193–215.

Rust, Roland T., Anthony J. Zahorik, and Timothy L. Keiningham (1995), “Return on Quality (ROQ): Making Service Quality Financially Accountable,” *Journal of Marketing*, 59(2), 58–70.

Santibanez Gonzalez, Ernesto D.R., Lenny Koh, and Janny Leung (2019), “Towards a Circular Economy Production System: Trends and Challenges for Operations Management,” *International Journal of Production Research*, 57(23), 7209–7218.

Savaskan, R. Canan, Shantanu Bhattacharya, and Luk N. Van Wassenhove (2004), "Closed-Loop Supply Chain Models With Product Remanufacturing," *Management Science*, 50(2), 239–252.

Souza, Gilvan C. (2013), "Closed-Loop Supply Chains: A Critical Review, and Future Research," *Decision Sciences*, 44(1), 7–38.

Stahel, Walter R. (2019), The Circular Economy: A User's Guide. *Routledge*.

Stahel, Walter R. (2016), The Circular Economy, *Nature*, 531, 435–438.

Sudhir, K., Ramesh Shankar, and Yuan Jin (2022), "Consumer Guilt and Sustainable Choice: Environmental Impact of Durable Goods Innovation," *Cowles Foundation Discussion Paper No. 2320*.

The Economist (October 27, 2022), "Battery-Makers Are Powering a Circular Economy" (accessed September 20, 2023), `https://bit.ly/3ZnkllH`.

The Economist Intelligence Unit (2021), "An Eco-Wakening: Measuring Global Awareness, Engagement and Action for Nature" (accessed December 15, 2022), `https://bit.ly/3Hzv3iF`.

Viscusi, W. Kip, Joel Huber, and Jason Bell (2011), "Promoting Recycling: Private Values, Social Norms, and Economic Incentives," *American Economic Review*, 101(3), 65–70.

Walls, Margaret (2011), "Deposit-Refund Systems in Practice and Theory," *Resources for the Future Discussion Paper No. 11-47*.

Wall Street Journal (May 5, 2022), "U.S. Recycles 5% of Plastic Waste, Studies Show," `https://bit.ly/3PJDH1B`.

World Business Council for Sustainable Development (2023), "Circular Transition Indicators v4.0: Metrics for Business, by Business" (accessed September 10, 2023), `https://bit.ly/3ZdBwq7`.

World Economic Forum (2023), "Circular Transformation of Industries: Unlocking New Value in a Resource-Constrained World" (accessed September 13, 2023), `https://bit.ly/3RkUTMa`.

Wu, Yue, Kaifu Zhang, and Jinhong Xie (2020), "Bad Greenwashing, Good Greenwashing: Corporate Social Responsibility and Information Transparency," *Management Science*, 66(7), 3095–3112.

Appendix

Proof of Lemma 1. To establish (2), note that

$$\begin{aligned} e(r;\lambda) &= \int_0^{b-\bar{u}} (b-\kappa)\, g(\kappa) d\kappa + \int_{b-\bar{u}}^{\infty} \bar{u} g(\kappa) d\kappa \\ &= \int_0^{b-\bar{u}} (b-\kappa)\, g(\kappa) d\kappa + \bar{u}\,(1-G(b-\bar{u}))\,, \end{aligned}$$

where the arguments of $b(r;\lambda)$ and $\bar{u}(\lambda)$ are suppressed for ease of exposition. Defining $h(\kappa) \equiv b-\kappa$ and using integration by parts, we obtain

$$\begin{aligned} e(r;\lambda) &= h(\kappa)G(\kappa)|_0^{b-\bar{u}} - \int_0^{b-\bar{u}} h'(\kappa)G(\kappa)d\kappa + \bar{u}\,(1-G(b-\bar{u})) \\ &= h(b-\bar{u})G(b-\bar{u}) - h(0)G(0) + \int_0^{b-\bar{u}} G(\kappa)d\kappa + \bar{u}\,(1-G(b-\bar{u})) \\ &= \int_0^{b-\bar{u}} G(\kappa)d\kappa + \bar{u} \gtrless 0. \end{aligned}$$

Using Leibniz's rule, the following properties hold:

$$e_r(r;\lambda) = G(b-\bar{u})b_r \geq 0 \tag{A.1}$$

$$e_{r\lambda}(r;\lambda) = G(b-\bar{u})b_{r\lambda} + g(b-\bar{u})\left(b_\lambda - \bar{u}'\right) b_r \geq 0, \tag{A.2}$$

where these inequalities follow from Assumption 1 and the properties of G. Finally, the impact of a higher λ on $e(r;\lambda)$ is ambiguous as $e_\lambda(r;\lambda) = G(b-\bar{u})(b_\lambda - \bar{u}') + \bar{u}'$ is the sum of a positive and a negative term. □

Proof of Lemma 2. Recall that $z(0;\lambda,\omega) = c(0) \geq 0$ by our assumptions on the unit cost function. Suppressing the arguments of the benefit function, differentiating $z(r;\lambda,\omega)$ and imposing that $c(r)$ is sufficiently convex in r yields

$$\begin{aligned} z_r(r;\lambda,\omega) &= c'(r) - \omega[\phi_r(r;\lambda)r + \phi(r;\lambda)] \\ &= c'(r) - \omega[g(b-\bar{u})b_r r + G(b-\bar{u})] \geq 0 \end{aligned} \tag{A.3}$$

and

$$\begin{aligned} z_{rr}(r;\lambda,\omega) &= c''(r) - \omega[\phi_{rr}(r;\lambda)r + 2\phi_r(r;\lambda)] \\ &= c''(r) - \omega[(g'(b-\bar{u})b_r^2 + g(b-\bar{u})b_{rr})r + 2g(b-\bar{u})b_r] \geq 0, \end{aligned} \tag{A.4}$$

where the properties of the benefit function are given in Assumption 1 and the properties of $\phi(r;\lambda)$ are derived from (1). Also, because $z(0;\lambda,\omega) \geq 0$ and $z_r(r;\lambda,\omega) \geq 0$, the net unit cost function satisfies $z(r;\lambda,\omega) \geq 0$ for admissible values of (λ,ω). Further,

$$\begin{aligned} z_\lambda(r;\lambda,\omega) &= -\phi_\lambda(r;\lambda)\omega r \\ &= -g(b-\bar{u})(b_\lambda - \bar{u}')\omega r \leq 0, \end{aligned} \tag{A.5}$$

and the impact of a higher λ on the marginal net unit cost $z_r(r;\lambda,\omega)$ is given by

$$\begin{aligned} z_{r\lambda}(r;\lambda,\omega) &= -\omega[\phi_{r\lambda}(r;\lambda)r + \phi_\lambda(r;\lambda)] \\ &= -\omega[(g'(\cdot)(b_\lambda - \bar{u}')b_r + g(\cdot)b_{r\lambda})r + g(\cdot)(b_\lambda - \bar{u}')] \leq 0, \end{aligned} \tag{A.6}$$

where the inequality holds if and only if

$$\frac{g'(\cdot)}{g(\cdot)} \geq -\frac{1}{b_r}\left(\frac{b_{r\lambda}}{b_\lambda - \bar{u}'} + \frac{1}{r}\right).$$

Finally,

$$z_\omega(r;\lambda,\omega) = -G(b-\bar{u})r \leq 0 \tag{A.7}$$

and

$$z_{r\omega}(r;\lambda,\omega) = -[g(b-\bar{u})b_r r + G(b-\bar{u})] \leq 0, \tag{A.8}$$

as $b_r \geq 0$ from Assumption 1. □

Proof of Proposition 1. Substituting (9) into (8) yields

$$-z_r(r^*;\lambda,\omega) + e_r(r^*;\lambda) + \frac{\mu_1 - \mu_2}{1 - F(\cdot)} = 0, \tag{A.9}$$

where $e_r(r;\lambda)$ and $z_r(r;\lambda,\omega)$ are stated in model primitives in (A.1) and (A.3), respectively. If $-z_r(0;\lambda,\omega) + e_r(0;\lambda) \leq 0$, then there is a corner solution with $r^* = 0$. Instead, if $-z_r(1;\lambda,\omega) + e_r(1;\lambda) \geq 0$, then there is a corner solution with $r^* = 1$. At an interior solution, $\mu_1 = \mu_2 = 0$, and r^* is implicitly defined by the condition

$$-z_r(r^*;\lambda,\omega) + e_r(r^*;\lambda) = 0. \tag{A.10}$$

Solving (9), the optimal price p^* is given by

$$p^* = z(r^*;\lambda,\omega) + \frac{1 - F(p^* - e(r^*;\lambda))}{f(p^* - e(r^*;\lambda))}, \tag{A.11}$$

the quality-adjusted inverse-elasticity pricing rule. □

Proof of Proposition 2. The profit function $\pi(r,p)$ is strictly concave in (r,p) if and only if $\pi_{rr} < 0$, $\pi_{pp} < 0$ and $\pi_{rr}\pi_{pp} - (\pi_{pr})^2 > 0$. These partial derivatives can be derived as

$$\begin{aligned}
\pi_{rr} &= -z_{rr}[1-F(\cdot)] - 2z_r f(\cdot)e_r - [p-z(r)][f'(\cdot)e_r^2 - f(\cdot)e_{rr}] \\
\pi_{pp} &= -2f(\cdot) - [p-z(r)]f'(\cdot) \\
\pi_{pr} &= \pi_{rp} = f(\cdot)z_r + f(\cdot)e_r + [p-z(r)]f'(\cdot)e_r.
\end{aligned}$$

For later reference, we now evaluate these derivatives at the interior optimizer (r^*, p^*). First, π_{rr} can be written as

$$\begin{aligned}
\pi_{rr} &= -z_{rr}[1-F(\cdot)] - 2z_r f(\cdot)e_r - [p^*-z(r^*)][f'(\cdot)e_r^2 - f(\cdot)e_{rr}] \\
&= -(z_{rr}-e_{rr})[1-F(\cdot)] + \pi_{pp}e_r^2.
\end{aligned}$$

Second, π_{pp} reduces to

$$\begin{aligned}
\pi_{pp} &= -2f(\cdot) - \frac{1-F(\cdot)}{f(\cdot)}f'(\cdot) \\
&= -\frac{1}{f(\cdot)}(2[f(\cdot)]^2 + [1-F(\cdot)]f'),
\end{aligned}$$

whereas π_{pr} boils down to

$$\begin{aligned}
\pi_{pr} &= f(\cdot)z_r + f(\cdot)e_r + [p^*-z(r^*)]f'(\cdot)e_r \\
&= [2f(\cdot) + [p^*-z(r^*)]f'(\cdot)]e_r \\
&= \frac{1}{f(\cdot)}[2[f(\cdot)]^2 + [1-F(\cdot)]f'(\cdot)]e_r \\
&= -\pi_{pp}e_r. \qquad \text{(A.12)}
\end{aligned}$$

Finally, the determinant of the Hessian matrix can be calculated as

$$\begin{aligned}\pi_{pp}\pi_{rr}-(\pi_{pr})^2 &= \pi_{pp}(-(z_{rr}-e_{rr})[1-F(\cdot)]+\pi_{pp}e_r^2)-(-\pi_{pp}e_r)^2 \\ &= -\pi_{pp}(z_{rr}-e_{rr})[1-F(\cdot)], \qquad \text{(A.13)}\end{aligned}$$

which requires that $z_{rr}-e_{rr}>0$ at (r^*,p^*).

To derive the comparative statics results, we rewrite (8) and (9) in reduced form as

$$\begin{aligned}\pi_r(r^*(x),p^*(x),x) &= 0 \\ \pi_p(r^*(x),p^*(x),x) &= 0,\end{aligned}$$

where $x\in\{\lambda,\omega\}$. Implicit differentiation of the first-order conditions with respect to x yields the system

$$\begin{bmatrix}\pi_{rr} & \pi_{pr} \\ \pi_{pr} & \pi_{pp}\end{bmatrix}\begin{bmatrix}\frac{dr^*(x)}{dx} \\ \frac{dp^*(x)}{dx}\end{bmatrix}=-\begin{bmatrix}\pi_{rx} \\ \pi_{px}\end{bmatrix},$$

which can be solved using Cramer's rule:

$$\begin{aligned}\frac{dr^*}{dx} &= -\frac{\pi_{rx}\pi_{pp}-\pi_{pr}\pi_{px}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2} \\ \frac{dp^*}{dx} &= -\frac{\pi_{rr}\pi_{px}-\pi_{rx}\pi_{pr}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2}.\end{aligned}$$

Using the previous results, these expressions boil down to

$$\begin{aligned}\frac{dr^*}{dx} &= -\frac{\pi_{rx}\pi_{pp}-\pi_{pr}\pi_{px}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2} \\ &= \frac{\pi_{rx}+e_r\pi_{px}}{(z_{rr}-e_{rr})[1-F(\cdot)]} \qquad \text{(A.14)}\end{aligned}$$

and

$$\begin{aligned}
\frac{dp^*}{dx} &= -\frac{\pi_{rr}\pi_{px}-\pi_{rx}\pi_{pr}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2} \\
&= \frac{[-(z_{rr}-e_{rr})[1-F(\cdot)]+\pi_{pp}e_r^2]\pi_{px}+\pi_{rx}\pi_{pp}e_r}{\pi_{pp}(z_{rr}-e_{rr})[1-F(\cdot)]} \\
&= -\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{e_r\pi_{px}+\pi_{rx}}{(z_{rr}-e_{rr})[1-F(\cdot)]} \\
&= -\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{dr^*}{dx}. \qquad \text{(A.15)}
\end{aligned}$$

The impact of a higher x on demand $D^* = D(p^*, r^*)$ is given by

$$\begin{aligned}
\frac{dD^*}{dx} &= -f(\cdot)\left[\frac{dp^*}{dx}-e_r\frac{dr^*}{dx}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right] \\
&= -f(\cdot)\left[-\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{dr^*}{dx}-e_r\frac{dr^*}{dx}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right] \\
&= -f(\cdot)\left[-\frac{\pi_{px}}{\pi_{pp}}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right] \qquad \text{(A.16)}
\end{aligned}$$

where the last equality uses (A.10). Finally, to calculate these comparative statics effects, it is useful to note that

$$\begin{aligned}
\pi_{r\lambda} &= -z_{r\lambda}[1-F(\cdot)]-z_r f(\cdot)e_\lambda-z_\lambda f(\cdot)e_r \\
&+ [p-z(r)][f'(\cdot)(-e_\lambda)e_r+f(\cdot)e_{r\lambda}] \qquad \text{(A.17)} \\
\pi_{p\lambda} &= f(\cdot)e_\lambda+z_\lambda f(\cdot)+[p-z(r)]f'(\cdot)e_\lambda. \qquad \text{(A.18)}
\end{aligned}$$

Similarly, it is straightforward to show that

$$\begin{aligned}
\pi_{r\omega} &= -z_{r\omega}[1-F(\cdot)]-z_\omega f(\cdot)e_r \qquad \text{(A.19)} \\
\pi_{p\omega} &= z_\omega f(\cdot). \qquad \text{(A.20)}
\end{aligned}$$

Impact on recyclability. Using (A.14),

$$\frac{dr^*}{d\lambda} = \frac{\pi_{r\lambda} + e_r \pi_{p\lambda}}{(z_{rr} - e_{rr})[1 - F(\cdot)]} = \frac{e_{r\lambda} - z_{r\lambda}}{z_{rr} - e_{rr}}, \tag{A.21}$$

where the second equality uses that, at the optimum, $\pi_{r\lambda} + e_r \pi_{p\lambda} = (e_{r\lambda} - z_{r\lambda})[1 - F(\cdot)]$ from (A.17) and (A.18). By concavity, the denominator of (A.21) is strictly positive, and $e_{r\lambda} \geq 0$ and $z_{r\lambda} \leq 0$ by (A.2) and (A.6), respectively, which implies that $\frac{dr^*}{d\lambda} \geq 0$. Similarly, it follows from (A.19) and (A.20) that

$$\frac{dr^*}{d\omega} = \frac{\pi_{r\omega} + e_r \pi_{p\omega}}{(z_{rr} - e_{rr})[1 - F(\cdot)]} = -\frac{z_{r\omega}}{z_{rr} - e_{rr}} \geq 0, \tag{A.22}$$

as $z_{r\omega}(r; \lambda, \omega) \leq 0$ by Lemma 2.

Impact on price. Using (A.15) and suppressing the arguments of F and its derivatives for convenience,

$$\frac{dp^*}{d\lambda} = -\frac{\pi_{p\lambda}}{\pi_{pp}} + z_r \frac{dr^*(\lambda)}{d\lambda} = \frac{[f^2 + (1-F)f']e_\lambda + f^2 z_\lambda}{2f^2 + [1-F]f'} + z_r \frac{dr^*}{d\lambda},$$

where the second equality follows by substitution. Because the sign of e_λ is ambiguous and $z_\lambda(r; \lambda, \omega) \leq 0$, the impact of stronger concerns about recyclability λ on p^* is ambiguous. Similarly, because $\pi_{p\omega} = z_\omega f \leq 0$ at an interior solution for r,

$$\frac{dp^*}{d\omega} = -\frac{\pi_{p\omega}}{\pi_{pp}} + z_r \frac{dr^*}{d\omega},$$

the overall impact of a higher ω on p^* is ambiguous.

Impact on demand. Using (A.16),

$$\begin{aligned}\frac{dD(p^*,r^*)}{d\lambda} &= -f\left[-\frac{\pi_{p\lambda}}{\pi_{pp}}-e_\lambda\right]\\ &= -f\left[\frac{[f^2+(1-F)f']e_\lambda+f^2z_\lambda}{2f^2+[1-F]f'}-e_\lambda\right]\\ &= f^3\left[\frac{e_\lambda-z_\lambda}{2f^2+[1-F]f'}\right],\end{aligned}$$

which is negative if $e_\lambda < z_\lambda$ and positive if the inequality is reversed. Next,

$$\begin{aligned}\frac{dD^*}{d\omega} &= -f\left[-\frac{\pi_{p\omega}}{\pi_{pp}}\right]\\ &= f^2\left[\frac{z_\omega}{\pi_{pp}}\right] \geq 0.\end{aligned}$$

Impact on profit. Applying the envelope theorem to the optimized profit function $\pi^* = \pi(p^*,r^*)$ yields

$$\begin{aligned}\frac{d\pi^*}{d\lambda} &= -z_\lambda[1-F]+[p-z](-f)(-e_\lambda)\\ &= -z_\lambda[1-F]+\frac{1-F}{f}fe_\lambda\\ &= (e_\lambda-z_\lambda)[1-F],\end{aligned}$$

which is negative if $e_\lambda < z_\lambda$ and positive if the inequality is reversed. Finally,

$$\frac{d\pi^*}{d\omega} = -z_\omega[1-F] \geq 0.$$

□

Proof of Proposition 3. The impact of a higher x on the effective waste footprint per unit of product $1-\phi r^*$ is

$$\frac{d}{dx}[1-\phi r^*] = -\left[(\phi_r\frac{dr^*}{dx}+\phi_x)r^*+\phi\frac{dr^*}{dx}\right] \leq 0,$$

whereas the impact on the waste footprint of the firm as a whole is

$$\begin{aligned}\frac{d\Phi^*}{dx} &= -[(\phi_r \frac{dr^*}{dx} + \phi_x)r^* + \phi \frac{dr^*}{dx}]D^* + [1 - \phi r^*]\frac{dD^*}{dx} \\ &= -[(\phi_r r^* + \phi)\frac{dr^*}{dx} + \phi_x r^*]D^* + [1 - \phi r^*]\frac{dD^*}{dx}. \qquad (A.23)\end{aligned}$$

By substitution,

$$\frac{d\Phi^*}{d\lambda} = -\left[[\phi_r r^* + \phi]\frac{dr^*}{d\lambda} + \phi_\lambda r^*\right]D^* + [1 - \phi r^*]\frac{dD^*}{d\lambda}.$$

Using the results from Proposition 2, the sign of $\frac{d\Phi^*}{d\lambda}$ is generally ambiguous. However, if $\frac{dD^*}{d\lambda} < 0$, then $\frac{d\Phi^*}{d\lambda} < 0$. Similarly, the impact of ω on Φ^* is ambiguous as

$$\frac{d\Phi^*}{d\omega} = -[\phi_r r^* + \phi]\frac{dr^*}{d\omega}D^* + [1 - \phi r^*]\frac{dD^*}{d\omega}.$$

□

Proof of Proposition 4. We know from Proposition 1 and Corollary 1 that $r^* > \hat{r} = 0$ if $-z_r(0;\lambda,\omega) + e_r(0;\lambda) > 0$. Because the profit-maximizing price $p^*(r)$ defined in (9) is a smooth function of the recyclability index r, the change in prices across business models is given by

$$p^* - \hat{p} = \int_0^{r^*}\left[\frac{dp^*(r)}{dr}\right]dr > 0,$$

where

$$\begin{aligned}\frac{dp^*(r)}{dr} &= -\frac{\pi_{rp}(p^*(r),r)}{\pi_{pp}(p^*(r),r)} \\ &= \frac{f(\cdot)z_r + [f(\cdot) + (p^* - z(r))f'(\cdot)]e_r}{2f(\cdot) + [p^* - z(r)]f'(\cdot)} > 0\end{aligned}$$

by invoking the concavity of the profit function, with $p^*(r^*) = p^*$ and $p^*(0) = \hat{p}$. For the profit comparison, note that $\pi(r^*, p^*; \lambda, \omega, K) - \pi(0, \hat{p}; \lambda)$ can be decomposed as

$$\pi(r^*, p^*; \lambda, \omega, K) - \pi(0, \hat{p}; \lambda) = \pi(r^*, p^*; \lambda, \omega, 0) - \pi(0, \hat{p}; \lambda) - K.$$

Going circular is therefore profitable if the extra profit resulting from the change in product design exceeds the cost of building the reverse supply chain. □

Proof of Proposition 5. For ease of exposition, we suppress the arguments of some functions. Differentiating (13) with respect to p yields

$$\frac{\partial W}{\partial p} = \frac{\partial \pi}{\partial p} + \frac{\partial S}{\partial p} - \delta \frac{\partial \Phi}{\partial p},$$

where the first term on the right-hand side is given in (9). Next, using standard analysis, we obtain $\frac{\partial S}{\partial p} = -(p-e)f(\cdot) - D - pD_p$ and $\frac{\partial \Phi}{\partial p} = wD_p$, so that the first-order condition for p boils down to

$$1 - F(\cdot) - (p-z)f(\cdot) - (p-e)f(\cdot) - D - pD_p - \delta w D_p = 0.$$

As $D = 1 - F(\cdot)$ and $D_p = -f(\cdot)$, it immediately follows that welfare-maximizing price is given by $p^w = z + e + \delta w$.

Differentiating (13) with respect to r yields

$$\frac{\partial W}{\partial r} = \frac{\partial \pi}{\partial r} + \frac{\partial S}{\partial r} - \delta \frac{\partial \Phi}{\partial r},$$

where the first term on the right-hand side is given in (8). Next, using that $\frac{\partial S}{\partial r} = -ef(\cdot)e_r$ and $\frac{\partial \Phi}{\partial r} = w_r D + wf(p-e)e_r$, the first-order condition for r at an interior solution reduces to

$$-z_r[1 - F(\cdot)] + [p-z]f(\cdot)e_r - ef(\cdot)e_r - \delta[w_r D + wf(\cdot)e_r] = 0.$$

Substituting $p^w = z + e + \delta w$ and simplifying immediately yields that the welfare-maximizing recyclability solves the condition $z_r + \delta w_r = 0$.

Recalling from Proposition 1 that $-z_r + e_r = 0$ at an interior solution, rewriting $z_r = e_r - (e_r + \delta w_r)$ establishes that $r^w > r^*$ whenever $e_r + \delta w_r < 0$. Finally, the change in welfare from going circular can be decomposed into changes in profit, standard consumer surplus, and the firm's waste footprint in monetary terms:

$$\begin{aligned} W(r^*, p^*; \lambda, \omega, K) - W(0, \hat{p}; \lambda) &= [\pi(r^*, p^*; \lambda, \omega, K) - \pi(0, \hat{p}; \lambda)] \\ &\quad + [S(r^*, p^*; \lambda) - S(0, \hat{p}; \lambda)] \\ &\quad - \delta\,[\Phi(r^*, p^*; \lambda) - \Phi(0, \hat{p}; \lambda)]. \end{aligned}$$

We know from Proposition 1 and Corollary 1 that $r^* > \hat{r} = 0$ whenever $-z_r(0; \lambda, \omega) + e_r(0; \lambda) > 0$. Therefore, going circular is socially desirable if and only if $K < \bar{K}$, where $\bar{K}$ is defined by the condition $W(r^*, p^*; \lambda, \omega, \bar{K}) - W(0, \hat{p}; \lambda) = 0$. □

Proof of Proposition 6. Substituting (17) into (16) yields

$$-\frac{\partial z_i(r_i^*; \lambda, \omega)}{\partial r_i} + \frac{\partial e_i(r_i^*; \lambda)}{\partial r_i} + \frac{\mu_1 - \mu_2}{D_i(\tilde{\mathbf{p}})} = 0, \quad i = 1, ..., n. \tag{A.24}$$

We distinguish three cases. If $-\frac{\partial z_i(0;\lambda,\omega)}{\partial r_i} + \frac{\partial e_i(0;\lambda)}{\partial r_i} \leq 0$, then there is a corner solution with $r_i^* = 0$. Instead, if $-\frac{\partial z_i(1;\lambda,\omega)}{\partial r_i} + \frac{\partial e_i(1;\lambda)}{\partial r_i} \geq 0$, then there is a corner solution with $r_i^* = 1$. At an interior solution, $\mu_1 = \mu_2 = 0$ and r_i^* is implicitly defined by the condition

$$-\frac{\partial z_i(r_i^*; \lambda, \omega)}{\partial r_i} + \frac{\partial e_i(r_i^*; \lambda)}{\partial r_i} = 0 \tag{A.25}$$

Therefore, in all three cases, the profit-maximizing index of recyclability r_i^* is determined independent of the prices $p_1^*, ..., p_n^*$ set under competition according to (17). Similar to the proof of Proposition 2, the comparative statics immediately follow from an application of the implicit function theorem. □

Proof of Proposition 7. For ease of exposition, the arguments of some functions are suppressed. The end-of-life utility of firm i is given by

$$e_i^D(r_i, d_i; \lambda) = \int_0^{b_i(r_i;\lambda)+d_i-\bar{u}(\lambda)} G(\kappa)d\kappa + \bar{u}(\lambda),$$

with $\partial e_i^D/\partial r_i = G(b_i + d_i - \bar{u})\,(\partial b_i/\partial r_i) \geq 0$ and $\partial e_i^D/\partial d_i = G(b_i + d_i - \bar{u}) \geq 0$. The return probability is $\phi_i^D(r_i, d_i; \lambda) = G(b_i + d_i - \bar{u})$, with $\partial \phi_i^D/\partial d_i = g(b_i + d_i - \bar{u}) \geq 0$. Consequently, $\partial e_i^D/\partial d_i = \phi_i^D(r_i, d_i; \lambda)$, a result that we will use below. Further, note that the net unit cost $z_i^D(r_i, d_i; \lambda, \omega)$ depends on d_i through its impact on ϕ_i^D. Specifically, $\partial z_i^D/\partial d_i = -(\partial \phi_i^D/\partial d_i)\omega r_i$.

To simplify exposition, let $m_i^D \equiv p_i - z_i^D(r_i, d_i; \lambda, \omega) + (1 - \phi_i^D(r_i, d_i; \lambda))d_i$ denote the margin of firm i. We can then write the partial derivatives of the profit function in (18) with respect to the choice variables as follows:

$$\frac{\partial \pi_i^D(r_i, \lambda)}{\partial r_i} = \left[-\frac{\partial \phi_i}{\partial r_i} d_i - \frac{\partial z_i}{\partial r_i}\right] D_i + m_i^D \frac{\partial D_i}{\partial \tilde{p}_i}\left[-\frac{\partial e_i}{\partial r_i}\right] \tag{A.26}$$

$$\frac{\partial \pi_i^D(r_i, \lambda)}{\partial p_i} = D_i + m_i^D \frac{\partial D_i}{\partial \tilde{p}_i} \tag{A.27}$$

$$\frac{\partial \pi_i^D(r_i, \lambda)}{\partial d_i} = \left[-\frac{\partial \phi_i^D}{\partial d_i} d_i + (1 - \phi_i^D) - \frac{\partial z_i^D}{\partial d_i}\right] D_i + m_i^D \frac{\partial D_i}{\partial \tilde{p}_i}\left[-\frac{\partial e_i^D}{\partial d_i} + 1\right]. \tag{A.28}$$

At an interior solution for p_i, we have $m_i^D \frac{\partial D_i}{\partial \tilde{p}_i} = -D_i$, which we can substitute into the first-order condition for d_i to obtain

$$\begin{aligned}
\frac{\partial \pi_i(r_i, \lambda)}{\partial d_i} &= \left[-\frac{\partial \phi_i^D}{\partial d_i} d_i + (1 - \phi_i^D) - \frac{\partial z_i^D}{\partial d_i} + \frac{\partial e_i^D}{\partial d_i} - 1\right] D_i \\
&= \left[-\frac{\partial \phi_i^D}{\partial d_i} d_i - \frac{\partial z_i^D}{\partial d_i}\right] D_i \\
&= \frac{\partial \phi_i^D}{\partial d_i}\left[\omega r_i - d_i\right] D_i,
\end{aligned}$$

where the second equality exploits that $\partial e_i^D/\partial d_i = \phi_i^D$ and the third equality makes us of $\partial z_i^D/\partial d_i = -(\partial \phi_i^D/\partial d_i)\omega r_i$. Hence, the profit-maximizing deposit fee satisfies $d_i = \omega r_i$, which corresponds to the value of a recovered product to firm i.

Using a similar approach, the first-order condition for the profit-maximizing index of recyclability r_i^D simplifies to

$$\begin{aligned}\frac{\partial \pi_i(r_i,\lambda)}{\partial r_i} &= \left[-\frac{\partial \phi_i^D}{\partial r_i} d_i - \frac{\partial z_i^D}{\partial r_i}\right] D_i + [-D_i]\left[-\frac{\partial e_i^D}{\partial r_i}\right] \\ &= \left[-\frac{\partial z_i^D}{\partial r_i} - \frac{\partial \phi_i^D}{\partial r_i} d_i + \frac{\partial e_i^D}{\partial r_i}\right] D_i.\end{aligned}$$

Noting that $d_i = \omega r_i$ at an interior solution, the profit-maximizing index of recyclability r_i^D is characterized by the condition $\frac{\partial z_i^D}{\partial r_i} + \frac{\partial \phi_i^D}{\partial r_i}\omega r_i = \frac{\partial e_i^D}{\partial r_i}$, which equates the marginal increase in net unit cost plus the increase in the expected refund with the marginal increase in the end-of-life utility. Further, using that

$$\begin{aligned}\frac{\partial z_i^D}{\partial r_i} + \frac{\partial \phi_i^D}{\partial r_i}\omega r_i &= c_i'(r_i) - \omega\left(\frac{\partial \phi_i^D}{\partial r_i} r_i + \phi_i^D\right) + \frac{\partial \phi_i^D}{\partial r_i}\omega r_i \\ &= c_i'(r_i) - \omega\left(\frac{\partial \phi_i}{\partial r_i} r_i + \phi_i\right) + \omega\left(\frac{\partial \phi_i}{\partial r_i} r_i + \phi_i\right) - \omega \phi_i^D \\ &= \frac{\partial z_i}{\partial r_i} - \omega(\phi_i^D - \phi_i) + \omega \frac{\partial \phi_i}{\partial r_i} r_i,\end{aligned}$$

evaluating the derivative of the profit function with respect to r_i at r_i^* yields

$$\begin{aligned}\left.\frac{\partial \pi_i(r_i,\lambda)}{\partial r_i}\right|_{r_i=r_i^*} &= \left[-\frac{\partial z_i^D}{\partial r_i} - \frac{\partial \phi_i^D}{\partial r_i} d_i + \frac{\partial e_i^D}{\partial r_i}\right] D_i \\ &= \left[-\frac{\partial z_i}{\partial r_i} + \omega(\phi_i^D - \phi_i) - \omega\frac{\partial \phi_i}{\partial r_i} r_i^* + \frac{\partial e_i^D}{\partial r_i}\right] D_i \\ &= \left[-\frac{\partial z_i}{\partial r_i} + \frac{\partial e_i}{\partial r_i} + \omega(\phi_i^D - \phi_i) - \omega\frac{\partial \phi_i}{\partial r_i} r_i^* + \frac{\partial e_i^D}{\partial r_i} - \frac{\partial e_i}{\partial r_i}\right] D_i,\end{aligned}$$

where $-\frac{\partial z_i}{\partial r_i} + \frac{\partial e_i}{\partial r_i} = 0$ in an interior solution by Proposition 6. Hence, from the first-order condition, $r_i^D > r_i^*$ only if $\omega(\phi_i^D - \phi_i) + \left(\frac{\partial e_i^D}{\partial r_i} - \frac{\partial e_i}{\partial r_i}\right) > \omega \frac{\partial \phi_i}{\partial r_i} r_i^*$, that is, if the additional benefit from marginally raising recyclability (a higher value of the recovered resource and a higher marginal end-of-life utility) exceeds the additional cost (a higher expected refund). Using that $\phi_i^D - \phi_i = \int_{b_i-\bar{u}}^{b_i+d_i-\bar{u}} g(\kappa)d\kappa$ and $\frac{\partial e_i^D}{\partial r_i} - \frac{\partial e_i}{\partial r_i} = \frac{\partial b_i}{\partial r_i}\int_{b_i-\bar{u}}^{b_i+d_i-\bar{u}} g(\kappa)d\kappa$, the condition under which $r_i^D > r_i^*$ can be written as

$$\frac{\int_{b_i-\bar{u}}^{b_i+d_i-\bar{u}} g(\kappa)d\kappa}{g(b_i-\bar{u})} > \frac{\omega\frac{\partial b_i}{\partial r_i}r_i^*}{\omega+\frac{\partial b_i}{\partial r_i}},$$

where $\frac{\partial \phi_i}{\partial r_i} = g(b_i-\bar{u})\frac{\partial b_i}{\partial r_i}$. Intuitively, this condition holds if introducing a deposit-refund system induces a sufficiently large number of additional buyers to recycle the product. □

Proof of Proposition 8. Under a buyback strategy, firm i chooses the buyback price s_i, as well as the index of recyclability r_i and the purchase price p_i to

$$\max_{s_i,r_i,p_i} \quad \pi_i^B = [p_i - z_i^B(r_i,s_i;\lambda,\omega) - \phi_i^B(r_i,s_i;\lambda)s_i]D_i(\tilde{p}_i,\tilde{\mathbf{p}}_{-i}) - K_i \quad \text{s.t. } 0 \le r_i \le 1, \tag{A.29}$$

where $z_i^B(r_i,s_i;\lambda,\omega) \equiv c_i(r) - \phi_i^B(r,s;\lambda)\omega r_i$ is the net unit cost, $\phi_i^B(r_i,s_i;\lambda)s_i$ is the expected payment for recovering a product, and $e_i^B(r_i,s_i;\lambda)$ is the end-of-life utility. Denoting the deposit-adjusted generalized prices under the deposit-refund system by $\hat{p}_i \equiv \tilde{p}_i + d_i$, the profit function of firm i under the deposit-refund system in (18) can be written as

$$\pi_i^D = [\hat{p}_i - z_i^D(r_i,d_i;\lambda,\omega) - \phi_i^D(r_i,d_i;\lambda)d_i]D(\hat{p}_i,\hat{\mathbf{p}}_{-i}),$$

which is equivalent to the profit function under the buyback strategy in (A.29). Hence, the outcome under a buyback strategy is equivalent to the outcome under a deposit-refund system, which implies that $r_i^B = r_i^D$, $p_i^B = p_i^D + d_i^D$, and $s_i^B = \omega r_i^B$ for all i. □

Proof of Proposition 9. Let $m_i^O \equiv p_i - z_i^O(r_i;\omega)$ denote the margin under RPO. From the first-order condition for the price p_i, we know that $m_i^O = D_i/(\partial D_i/\partial \tilde{p}_i)$. Then derivative of the profit function with respect to the index of recyclability r_i boils down to

$$\frac{\partial \pi_i^O}{\partial r_i} = \left[-\frac{\partial z_i(r_i;\omega)}{\partial r_i} + \frac{\partial e_i(r_i;\lambda)}{\partial r_i}\right] D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i}).$$

This implies that firm i offers a nonrecyclable product if $\frac{\partial b_i(0;\lambda)}{\partial r_i} \le c_i'(0) - \omega$, a fully recyclable product if $\frac{\partial b_i(1;\lambda)}{\partial r_i} \ge c_i'(1) - \omega$, and a partially recyclable product with r^O being characterized by the condition $\frac{\partial b_i(r_i^O;\lambda)}{\partial r_i} = c_i'(r_i^O) - \omega$ otherwise.

Compared to the circular model absent RPO, because $\phi_i(r_i;\lambda) = 1$, the marginal net unit cost is lower (because $z_i^O(r_i;\omega) \le z(r_i;\lambda,\omega)$ for any r_i) and the marginal end-of-life benefit is higher for any r_i. As a result, $r_i^O \ge r_i^*$. □

Proof of Proposition 10. Using the triple bottom line decomposition of welfare in (13) and conveniently suppressing the arguments of the functions, welfare under competition can be written as $W = \sum_i(\pi_i + S_i - \delta\Phi_i)$. Imposing a lump-sum tax $T_i = \delta\Phi_i$ puts a fixed cost of waste on each firm i, and hence does not affect product design. Welfare neutrality holds as $W = \sum_i[(\pi_i - T_i) + S_i + (T_i - \delta\Phi_i)]$, where $\pi_i - T_i$ is the profit of the firm after the tax and $\sum_i(T_i - \delta\Phi_i)$ can be interpreted as the government budget.

Under a unit waste t, each firm i solves

$$\max_{r_i, p_i} \quad \pi_i(r_i, p_i) = [p_i - z_i(r_i) - t w_i(r_i)] D_i(\tilde{p}_i, \tilde{\mathbf{p}}_{-i}),$$

where $w_i = 1 - \phi_i r_i$ is the waste footprint per unit, with $\partial w_i(r_i)/\partial r_i < 0$ at an interior solution. Using the same logic as in the proof of Proposition 6, the profit-maximizing recyclability $r_i^*(t)$ solves $\partial z_i/\partial r_i + t(\partial w_i/\partial r_i) = \partial e_i/\partial r_i$. Because the tax leaves $\partial e_i/\partial r_i$ unaffected and results in $\partial z_i/\partial r_i + t(\partial w_i/\partial r_i) < \partial z_i/\partial r_i$, it follows that $r_i^*(t) > r_i^*(0)$.

The socially optimal advanced disposal fee (ADF) eliminates the externality and hence must satisfy $\varphi_i = e_i + \delta w_i$. With an ADF, adapting the utility function in (14), consumer l

derives utility $u_{il} = \varepsilon_{il} - p_i + e_i - \varphi_i = \varepsilon_{il} - p_i - \delta w_i$ from purchasing product i, and hence fully internalizes the cost of waste.

With a trash disposal fee $\gamma \geq 0$, the end-of-life utility becomes

$$e_i(r_i;\lambda,\gamma) = \int_0^{b_i(r_i;\lambda)-\bar{u}(\lambda)+\gamma} G(\kappa)d\kappa + \bar{u}(\lambda) - \gamma,$$

with $\partial e_i(r_i;\lambda,\gamma)/\partial\gamma < 0$. In addition, the trash disposal fee γ affects the net unit cost through its impact on $\phi(r;\gamma,\omega)$. Using the proof of Proposition 6, the profit-maximizing recyclability $r_i^*(\gamma)$ satisfies $\partial z_i/\partial r_i = \partial e_i/\partial r_i$. Applying the implicit function theorem to the first-order condition immediately shows that the impact of a higher γ on recyclability $r_i^*(\gamma)$ is generally ambiguous. □