# Waste, Recycling, and "Design for Environment": Roles for Markets and Policy Instruments

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## Abstract

Several studies that have solved for optimal solid waste policy instruments have suggested that transaction costs may often prevent the working of recycling markets. In this paper, we explicitly incorporate such costs into a general equilibrium model of production, consumption, recycling, and disposal. Specifically, we assume that consumers have access to both recycling without payment and recycling with payment but that the latter option comes with transaction costs. Producers choose material and nonmaterial inputs to produce a consumer product, and they also choose design attributes of that product—its weight and degree of recyclability. We find that the policy instruments that yield a social optimum in this setting need to vary with the degree of recyclability of products. Moreover, they need to be set to ensure that recycling markets do *not* operate—that is, that all recycling takes place without an exchange of money between recyclers and consumers. We argue that implementing such a policy would be difficult in practice. We then solve for a simpler set of instruments that implement a constrained (second-best) optimum. We find the results in this setting more encouraging: a modest disposal fee—less than the Pigouvian fee—combined with a common deposit-refund applied to all products will yield the constrained optimum. Moreover, this set of constrained optimal instruments is robust to the possibility that consumers imperfectly sort used products into trash and recyclables.

**Key Words:** Dfe, deposit-refund, disposal fee, constrained optimum
**JEL Classification Numbers:** H21, Q28

## Contents

# Waste, Recycling, and "Design for Environment": Roles for Markets and Policy Instruments

Paul Calcott and Margaret Walls[1]

## Introduction

Several studies of solid waste policy show that a range of policy instruments can achieve a socially optimal amount of waste disposal and recycling. The simplest instrument is a Pigouvian tax on disposal. A combined output tax and recycling subsidy, usually referred to as a deposit-refund, can also achieve the first-best outcome and will be preferable if taxing disposal leads to illegal dumping (Dinan 1993; Sigman 1995; Fullerton and Kinnaman 1995; Palmer and Walls 1997).

These optimal policy instruments, however, depend on fully functioning private markets, including a fully functioning recycling market. If producers can choose product design—in particular, the degree of product recyclability—then the Pigouvian waste tax, or the deposit-refund, can achieve a first-best outcome only if recyclers pay consumers a price for their used products that depends on the degree of recyclability of the products. We showed this in an earlier paper (Calcott and Walls 2000) in which we argued that such a situation is unlikely in the real world, making the first-best outcome unattainable. We solved for the policy instruments that implement a second-best, constrained optimum assuming that recycling markets are not operating.

In reality, recycling markets operate to some extent, they just come with transaction costs. Consumers sell some used products to recyclers, but other items are simply handed over for free, often in a curbside recycling bin. In this paper, we model this reality. We assume that consumers return some products to recyclers and receive in exchange a price that depends on how valuable that product is for recycling. However, this market exchange is assumed to involve transaction costs because it is difficult for recyclers to determine the value of products for recycling and pay a price based on that value. Other items, those less valuable for recycling, are

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[1] We received helpful comments on an earlier version of this paper from Don Fullerton, Karen Palmer, and Hilary Sigman.

tossed in the curbside bin. Remaining items, on which recyclers would incur a loss, are put in the trash. We then explore how transaction costs affect the roles played by both markets and policies in achieving efficient levels of waste disposal, recycling, and product design.

Early studies of solid waste policy ignored product design issues; producers in those models made decisions about material inputs and about levels of output, but not about recyclability or other product characteristics. The issue of "design for environment" (DfE), however, is becoming increasingly important to environmentalists and to environmental policymakers. In the same way that the pollution policy focus is shifting from so-called end-of-pipe treatments to pollution prevention, solid waste policy is shifting from waste disposal concerns back upstream to product and process design issues.[2]

Fullerton and Wu (1998) were the first to address DfE in an economic model. They assumed that producers choose a degree of packaging for their products and a degree of recyclability, where recyclability is the fraction of the product that can be recycled. They then solved for optimal policies under a range of assumptions about missing markets and the feasibility of various policy instruments.[3]

In this study, we extend the work of Fullerton and Wu (1998) and Calcott and Walls (2000) in three ways. First, unlike Fullerton and Wu, we explicitly incorporate a recycling market—that is, private profit-maximizing agents who get secondary materials from consumers, process them, and resell the processed material to upstream producers.[4] Including the recycling market also allows us to have a more realistic specification of recyclability. Instead of being the fraction of a product that can be recycled, which we argue is not sensible for many products, we model recyclability as an index that affects the cost of processing the material. Second, as explained above, we include transaction costs in recycling markets. The earlier studies simply assumed that markets either work or don't work. Explicitly modeling transaction costs allows us

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[2] The producer "take-back" movement is one example of this shift. Take-back has evolved into the notion of extended producer responsibility, or EPR—making producers physically or financially responsible for products at the end of the products' useful lives (see www.epa.gov/epr/ or www.oecd.org/env/efficiency/epr.htm). EPR laws have been passed for packaging, electronics, home appliances, and automobiles in many European countries and Japan. In the United States, there are currently no EPR laws in place, but several states are considering legislation focused on electronics.

[3] Eichner and Pethig (2001) address a more limited form of product design, the "material content" of products; they also solve for policy instruments that yield a social optimum.

[4] In Fullerton and Wu, consumers return products directly to producers and there is no processing cost.

to explore the role those costs play in setting policy. And third, we allow for the possibility that materials are imperfectly sorted by consumers into recyclable and nonrecyclable items. Such imperfect sorting can occur for various reasons, as when a product is consumed someplace where recycling is inconvenient and the product therefore ends up in the trash. Allowing for this possibility in the model is another way of depicting imperfections in recycling markets.

We find that the first-best optimum is attainable with a combined output tax–recycling subsidy in which the tax and subsidy rates vary with product recyclability. This is similar to a result in Fullerton and Wu, but our findings highlight the interesting role played by transaction costs. We find that the optimal tax and subsidy rates must be set to ensure that no transaction costs are incurred—to ensure that markets do *not* operate. The intuition is this: since some recycling will take place without money changing hands between consumers and recyclers, as in the curbside bin, it is efficient to have *all* recycling take place this way to avoid the transaction costs associated with payment. Thus, to yield the socially optimal outcome, taxes must completely displace markets.

There are reasons to find that result troubling. First, it seems to be driven by an assumption that government policy is perfect but markets are not. Moreover, product-specific taxes are unlikely to be feasible in the real world, since policymakers almost certainly cannot observe the degree of recyclability of individual products. As a result, the first-best outcome can no longer be attained with realistic policy instruments. We then assume that policymakers must base instruments on a more limited set of information. In particular, we assume that they can observe whether a particular item is accepted by profit-maximizing recyclers and also whether the item is paid for by recyclers. This allows policymakers to infer whether an item meets the threshold levels of recyclability that make recycling and payment for items profitable for recyclers. We then solve for the set of policy instruments that achieve a constrained optimum in this setting.

Interestingly, we find that it is not necessary for policymakers to have even this limited set of information to reach the constrained optimum. The constrained optimum can be implemented with either (1) a modified output tax–recycling subsidy in which the output tax varies with whether a product reaches the recyclability threshold necessary to be accepted by recyclers, or (2) a combination of a disposal fee and a common output tax–recycling subsidy applied to *all* products, regardless of recyclability levels. The disposal fee in option (2) is less than the Pigouvian fee, since the output tax does some of the work of the Pigouvian fee in reducing waste. If there is imperfect sorting of materials into waste and recycling, the second set of instruments continues to yield a constrained optimum.

In contrast to the first-best outcome, in the world of constrained policy instruments, markets should not be displaced. In providing incentives for DfE, markets and taxes are now complements rather than substitutes. It is also interesting that a simple deposit-refund remains a preferred instrument, even with imperfectly functioning recycling markets and imperfect recycling behavior on the part of consumers. As we stated at the start of this paper, several studies have advocated the deposit-refund option, but those studies ignored the product design issue and assumed perfectly functioning markets. We find that the deposit-refund still has much to recommend it, even when recycling markets do not work perfectly and when encouraging DfE is an important part of the policy prescription.

Another interesting finding of this paper is the role played by markets, even poorly functioning ones. All other studies assume that markets either work or fail. By explicitly incorporating transaction costs, we allow markets to work to some extent. And we find that markets play an important role in encouraging DfE. The taxes and subsidies set by government provide incentives to producers to make products sufficiently recyclable to justify a favorable tax and subsidy status. But it is the existence of markets that provides incentives for producers to make goods with higher levels of recyclability. Above some threshold, improving recyclability has value to recyclers and to consumers, and this can be reflected in product prices.

In section II, we present a general equilibrium model and characterize the private market equilibrium and social optimum. Section III analyzes the choice of policy instruments, first under the assumption that product-specific taxes are feasible and then under the assumption that they are not. The last part of section III incorporates imperfect sorting of materials into recycling and disposal. Section IV includes some discussion of the results and extensions of the model, and section V provides concluding remarks.

## 2. The General Model

### *2.1 The basic theoretical framework*

We develop a simple general equilibrium model that incorporates five stages in the product life cycle: extraction of virgin materials, production, consumption, recycling, and disposal. In the "upstream" production stage, firms use material and nonmaterial inputs to produce a material output that has two environmentally important design attributes, weight and degree of recyclability. In the "downstream" stage, consumed products are either recycled or sent to a landfill.

Because of the focus on recyclability, we simplify the characterization of both virgin material extraction and waste disposal. The technology for the extraction of virgin materials is assumed to have constant returns to scale, with a unit extraction cost of $\gamma_1$. Private waste collection and disposal costs per unit are also constant and equal to $\gamma_2$. In addition, all markets are assumed to be competitive and without preexisting distortions from income or other taxes.

We adopt a simple and general characterization of product recyclability. The degree of recyclability of product *i* is represented with the scalar index $\rho_i$, which determines the cost of recycling the product. This treatment of recyclability follows Calcott and Walls (2000) but differs from that of Fullerton and Wu (1998), who interpret recyclability as the proportion of a product that can be recycled.[5] Although neither interpretation is strictly correct for all products, we believe that the cost approach is more realistic for many goods. Almost any product is technically recyclable, but many products are prohibitively costly to recycle. And most changes that producers can make to a product do not increase the proportion of an individual product that is recycled but rather lower the cost of recycling the product. These changes vary widely. For example, the cost of recycling plastic packaging is lower if contaminants that cannot be readily separated from the packaging are avoided, if particular types of plastics are avoided, and if particular production methods are used. Electronic products can be designed to ease disassembly, and suitable labeling of materials can also make recycling easier and less costly.[6] A wide range of these activities is allowed for in our model.

We assume a composite material input and a composite nonmaterial input. Consequently, some increases in recyclability that result from using more environmentally friendly inputs will not be explicit in the model. In Appendix B, we present an extension that allows for multiple types of material inputs. Our basic findings continue to hold, however, and because the model with multiple inputs is significantly more complicated to present, we limit it to Appendix B and to a discussion of the results in section IV.

We assume that each product is either fully recycled or not recycled at all. In addition, virgin and secondary raw material inputs are perfect substitutes in production, and no waste by-

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[5] Producers are homogeneous in the model constructed by Fullerton and Wu. And as we stated above, they provide no explicit treatment of the role of recyclers or of recycling costs. Eichner and Pethig (2001) model recycling costs but treat recyclability as a proportion, in this case the proportion of a product's material content that is of a particular type.

[6] For a good discussion of these issues and more about DfE, see Fiksel (1996, especially chapter 8), U.S. Congress Office of Technology Assessment (1992), and American Plastics Council (2001).

products are generated during production.[7] This leads to a materials balance condition given by $v_i+r_i=\alpha_i q_i$, where $v_i$ is the amount of virgin materials and $r_i$ the amount of recycled materials used in production by firm *i* (with both inputs measured in mass units, such as pounds), $q_i$ is the units of output produced, and $\alpha_i$ is the weight of the product, in pounds per unit. Finally, we assume that all items received from households for recycling are used again by producers as inputs to production.[8]

Figure 1 gives an illustration of the model. The direction of the arrows indicates the flow of materials, and the price in each of the markets is shown along the arrows. Recyclers are assumed to be profit-maximizing firms. They collect some items for recycling without reimbursing consumers but may also pay consumers $p_r^i(\rho_i)$ for some items.[9] In either case, they incur some processing costs, resell to producers, and may receive a subsidy from the government. There is an additional transaction cost, *T*, associated with payment to consumers, free or collection of trash. For simplicity, we assume that this transaction cost is borne directly by the consumer. However, little would change if both parties to the transaction bore a share of which is above and beyond any transaction costs associated with collection of recyclables for the costs.[10] Consumers pay price $P_q^i$ per unit of good *i*, and that price depends on recyclability, $\rho_i$, and product weight, $\alpha_i$. Waste disposal from product *i* is denoted by $w_i$.

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[7] These assumptions could be relaxed, but that would not change our basic results and it would only clutter the model. Palmer and Walls (1997) and Walls and Palmer (2001) allow for a manufacturing by-product; Walls and Palmer (2001) also consider the case of some air or water pollution generated during the production process. Neither paper considers product design.

[8] We abstract from dynamic considerations in the model and assume that products last only one period or that we are in a steady-state.

[9] Consumers may receive payment from reverse vending machines (for drink containers), at recycling centers, and via the Internet, which is increasingly used to find markets for materials and products such as computers and other electronics (see http://www.wasteclick.com/exchange/, for example).

[10] We assume that consumers are willing to recycle even when disposal fees are zero. The high participation rates in curbside recycling programs suggest that this is a reasonable assumption where such programs are offered (Jenkins et al. 1999).

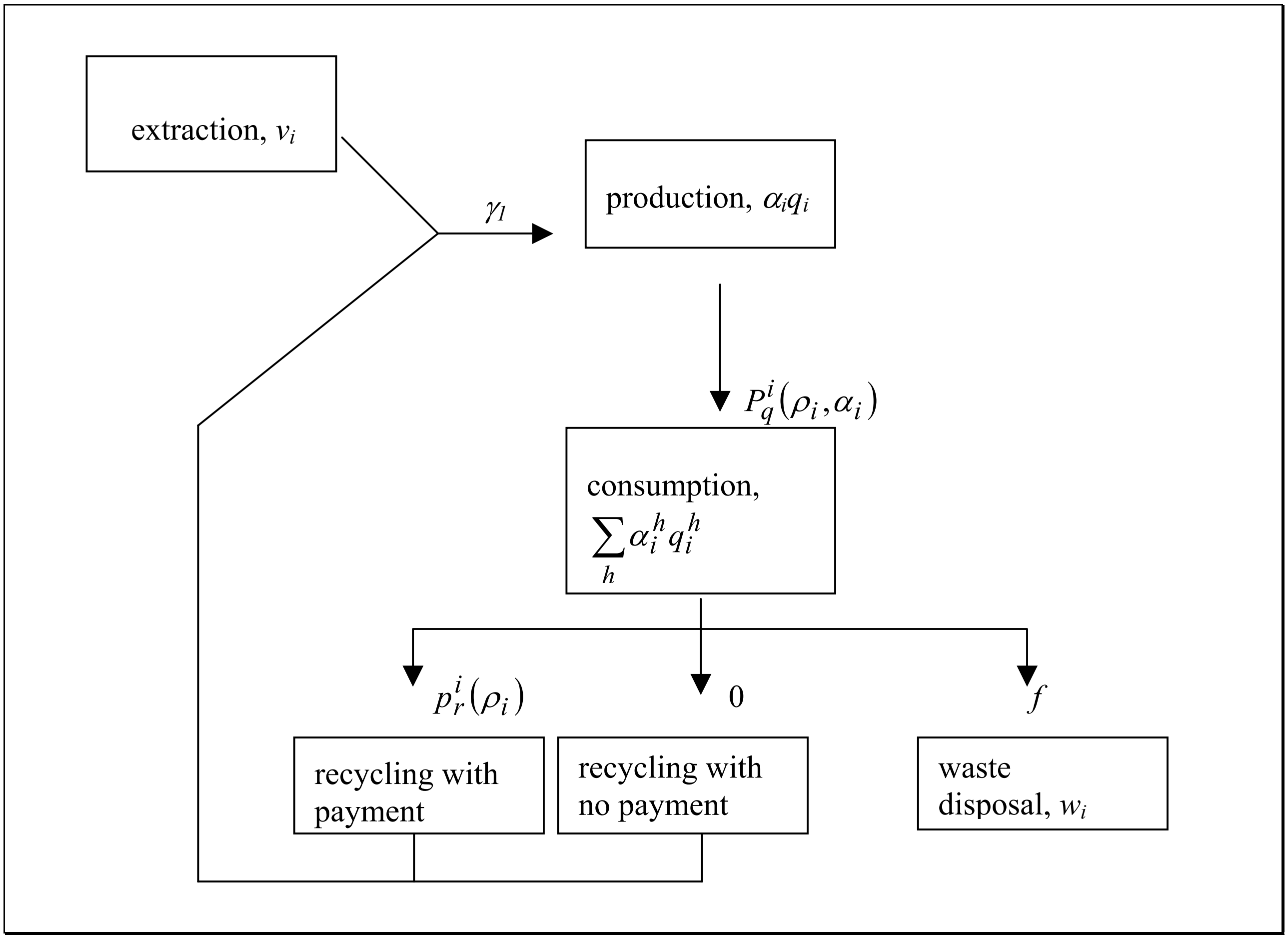

**Figure 1. The product life cycle, materials balance, and prices.**

## *2.2. The private market equilibrium*

Consumers choose how much and which variety of product to consume, to maximize utility subject to a budget constraint. We assume there are $h=1,\ldots,H$ consumers with quasi-linear utility functions:

(1) $V^h(q^h, W) + m^h$

where $V^h$ is strictly concave in $q^h$ for every $h$, $q^h = \sum_i q_i^h$ is total consumption of $q$ by consumer $h$, $W$ is aggregate solid waste generated by all consumers, measured in mass units, and $m^h$ is $h$'s consumption of a composite numeraire good. Aggregate waste disposal, $W$, has a negative effect on utility. Varieties of $q$ differ only in their degree of recyclability, $\rho_i$, and their weight, $\alpha_i$. Although these two characteristics do not enter the utility function directly, they can affect the consumer's budget constraint. This constraint is

$$(2)\; y^h \geq m^h + \sum_i P_q^i(\rho_i,\alpha_i)q_i^h + \sum_i \alpha_i q_i^h PRC(\rho_i)$$

where $y^h$ is $h$'s wealth, and PRC is the (per pound) net "private removal cost" of a product incurred by the consumer at end of product life. If the product is thrown away, PRC is equal to the disposal fee, *f;* if the product is collected for recycling without payment, PRC is equal to zero; and if payment occurs, PRC equals the transaction cost less the price paid by the recycler, $T$- $p_r^i$.

Substituting a consumer's budget constraint into her utility function, we can write her maximization problem as

$$(3)\, \max V^h\left(q^h, W\right) + y^h - \sum_i P_q^i\left(\rho_i,\alpha_i\right)q_i^h - \sum_i \alpha_i q_i^h PRC(\rho_i)\,.$$

The first-order conditions for $q_i^h, \alpha_i$, and $\rho_i$ imply that the (inverse) demand for product $i$ is given by

$$(4) \qquad P_q^i(\rho_i,\alpha_i) = \overline{V}_q - \alpha_i PRC(\rho_i)\,,$$

where $\overline{V}_q = \partial V^h(q^h *) / \partial q^h$ is the willingness to pay for another unit of consumption. Since $\overline{V}_q$ is the same across all products, equation (4) says that the effective price—that is, the explicit price paid for the product at time of purchase, $P_q^i$, plus the removal cost—is the same for all products. The $h$ superscript on $V$ is dropped because all consumers face the same effective price, and thus the marginal willingness to pay must be the same across all consumers.

Each producer, $i=1,\ldots,n$, pays for its raw material inputs and also incurs some nonmaterial costs of production, $C^i(\alpha_i,\rho_i,q_i)$. We allow cost functions to differ among firms, which leads to a range of products in the marketplace with varying weights and degrees of recyclability.[11] Increasing the amount of output or the degree of recyclability, all else equal, increases nonmaterial costs, and reducing product weight, all else equal, increases nonmaterial costs. Thus, $C^i_q > 0$, $C^i_\rho > 0$, and $C^i_\alpha < 0$, where subscripts denote first partial derivatives.[12]

Each individual producer receives price, $P^i_q$ for its output and $\gamma_1$ for its raw material inputs, and may pay a tax, $t_i$, per pound of output produced. The producer chooses the output quantity and the two product attributes, $\rho_i$ and $\alpha_i$, to maximize profits (note that $q_i = \sum_h q_i^h$ ):

$$(5)\ P^i_q(\rho_i,\alpha_i)q_i - C^i(\rho_i,\alpha_i,q_i) - \gamma_1\alpha_i q_i - \alpha_i q_i t_i$$

Substitution of equation (4), the inverse demand function, into equation (5), the producer's profits, yields

$$\overline{V}_q q_i - \alpha_i q_i[\gamma_1 + t_i + PRC(\rho_i)] - C^i(\rho_i,\alpha_i,q_i).$$

To simplify notation, let $\gamma_1+t_i+PRC(\rho_i)$ be the "producer's material cost" (PMC). Then profits can be written in the following simple form:

$$(6)\ \overline{V}_q q_i - \alpha_i q_i PMC(\rho_i) - C^i(\rho_i,\alpha_i,q_i).$$

### *2.3 The social optimum*

The social planner maximizes the sum of consumers' utility functions:[13]

$$(7) \sum_h V^h(q^h,W) + \sum_h m^h$$

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[11] In the special case in which all firms have access to the same technology, there may still be a range of product characteristics in the marketplace, as the profit-maximizing design may not be unique.

[12] Reducing product weight, $\alpha$, will decrease material costs, but that is reflected elsewhere in the model. Nonmaterial costs rise as product weight is reduced because it is assumed to be more difficult to produce a lighter-weight product.

[13] Because utility functions are quasi-linear and no costs of redistribution are assumed, any efficient allocation in which $m^h>0$, $\forall h$, will maximize the sum of utility functions.

subject to the resource constraints. There are resource constraints associated with both material and nonmaterial goods (such as labor and capital services). The resource constraint for materials is the mass balance condition that was given above. The nonmaterial resource constraint states that the total amount of these goods must be no greater than the total endowment, R. Nonmaterial goods are used in the extraction of virgin materials, in the production of output, for consumption, and in removal of consumed products, either as waste disposal or as recycling. Let the (per pound) "social removal cost" of good *i* (including waste transport and recycling costs) be SRC($\rho_i$).[14]

$$(8)\, SRC(\rho_i) = \begin{cases} \gamma_2 & for \quad waste\ disposal \\ k(\rho_i) & for \quad recycling\ without\ payment \\ k(\rho_i) + T & for \quad recycling\ with\ payment \end{cases}$$

Consequently, the nonmaterial resource constraint is

$$(9)\ R = \gamma_1 \sum_i v_i + \sum_i C^i(\alpha_i, \rho_i, q_i) + \sum_h m^h + \sum_i \alpha_i q_i SRC(\rho_i).$$

Because of the materials balance condition, the amount of virgin materials used in production is equal to the amount, in pounds, of waste disposal, $\sum_i v_i = W = \sum_i w_i$, where $w_i$ is equal to $\alpha_i q_i$ if the product is landfilled and zero otherwise. Substituting these conditions into (9), and then using $\sum_h m^h$ to substitute this constraint into the objective function, equation (7), yields the following objective for the social planner:

$$(10)\ \sum_h V^h(q^h, W) + R - \sum_i C^i(\alpha_i, \rho_i, q_i) - \gamma_1 \sum_i w_i - \sum_i \alpha_i q_i SRC(\rho_i).$$

Equivalently, the objective function can be written as

$$(11)\ \sum_i \left[\overline{V}_q q_i - \alpha_i q_i SMC(\rho_i) - C^i(\alpha_i, \rho_i, q_i)\right].$$[15]

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[14] SRC excludes the externalities from waste allowed for in equation (7). These will be incorporated below.

[15] We obtain this expression by substituting a first-order Taylor series expansion for the first term in equation (10) and combining part of that Taylor series expansion into the SMC term, which is defined below.

The social planner chooses $\{q_i, \alpha_i, \rho_i\}$ to maximize this function and to ensure that $\partial V^h(q^h*)/\partial q^h = \overline{V}_q$ for every $h$. SMC stands for (per pound) "social material cost," which includes the externalities from waste disposal as well as social removal costs:

$$(12)\; SMC(\rho_i) = \begin{cases} SRC(\rho_i) + \gamma_1 - \sum_h V_W^h & \textit{for products destined for waste disposal} \\ SRC(\rho_i) & \textit{for products destined for recycling} \end{cases}$$

The private market outcome is represented with solutions to equation (6), the social optimum by solutions to equation (11). The two will be equivalent if PMC is equated to SMC. In the following section, we solve for policy instruments that accomplish this objective. Part A deals with the case in which the government can observe product recyclability and set product-specific taxes and subsidies. In part B, we assume that product-specific taxes and subsidies are infeasible. This means that a social optimum can no longer be reached. A constrained optimum can be attained, however; we show how PMC and SMC are altered slightly in this case and then solve for policy instruments that bring the two expressions in line—that is, that implement the constrained optimum. In part C, we consider imperfect sorting of materials.

## 3. The Choice of Policy Instruments

### *3.1 The case in which product-specific taxes and subsidies are feasible*

In section II, we showed that a producer's material cost (PMC) is equal to $\gamma_1 + t_i + PRC(\rho_i)$. In this section, we assume that it is feasible to levy different taxes on products with different levels of recyclability. Therefore, one component of PMC is the per pound tax $t_i = t(\rho_i)$. Another component is the consumer's removal cost (PRC), and this depends on recycling decisions. Those decisions depend, in turn, on the functioning of the recycling market.

We assume that recyclers are private agents. The government in our model sets policy instruments, such as product taxes, recycling subsidies, and disposal fees, but does not otherwise intervene in the recycling market. In particular, there is no government provision of recycling services.[16] A recycler is assumed to incur a constant cost per pound, $k(\rho_i)$, in the recycling process, where $k'(\rho_i) < 0$ and $k''(\rho_i) > 0$. That is, increasing the recyclability of a product reduces the costs of recycling, but at a declining rate. A recycler is paid $\gamma_1$ per pound by producers (the same amount paid for virgin materials) and may receive a subsidy, $s(\rho_i)$ per pound, from the government.

Consider recyclable materials that recyclers pay for, such as those brought to reverse vending machines or recycling centers. Recyclers pay consumers $p_r^i$ for each pound of product *i*. In this setting, a recycler makes a net gain of $\gamma_1 - k(\rho_i) - p_r^i(\rho_i) + s(\rho_i)$ on every pound of product *i* recycled. If we assume that recyclers are perfectly competitive and have no fixed costs, each recycler will make zero profits on each purchase. This means that the equilibrium price that consumers receive is

(13) $p_r^i(\rho_i) = \gamma_1 - k(\rho_i) + s(\rho_i)$.

Equation (13) can be incorporated into the expression for the consumer's removal cost, PRC.

$$PRC(\rho_i) = \begin{cases} f & \text{if} \quad \text{thrown away} \\ 0 & \text{if} \quad \text{recycled without payment} \\ T - (\gamma_1 - k(\rho_i) + s(\rho_i)) & \text{if} \quad \text{recycled with payment} \end{cases}$$

Consumers will choose the least expensive way to get rid of waste products. As long as $f \geq 0$, it will be cheaper to leave a product to be collected for recycling (without payment) than to leave it for the refuse collection. However, a product will be accepted for recycling only if a recycler will not incur a loss, even when paying a price of zero. This will be so only for products with a level of recyclability, $\rho_i$, for which $\gamma_1 - k(\rho_i) + s(\rho_i) \geq 0$. Let $\underline{\rho}$ be this threshold level of recyclability, below which products will not be collected for recycling.

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[16] In the real world, a variety of market arrangements exist (Walls et al. 2002). Local government employees sometimes collect recyclables from households, operate processing centers, and/or sell processed secondary materials. However, often one or all of these operations are contracted out to private firms. And sometimes the government intervenes only by licensing firms to collect materials from households, with processing undertaken by private firms (Hall 1998). The purpose of this paper is to examine the prospects for decentralized design and recycling decisions.

There is also a second threshold that relates to the decision by consumers to sell recyclables rather than leave them for curbside collection. Products must meet a higher level of recyclability before consumers will find it worthwhile to incur the transaction cost *T*, to receive payment. Let the threshold level of recyclability for receiving payment be $\overline{\rho}$; then, given the expression for $p_r^i$ in equation (13), this threshold is where $\gamma_1 - k(\rho_i) + s(\rho_i) = T$. We can now characterize PMC. Again assuming that $f \geq 0$,

$$(14)\, PMC(\rho_i) = \begin{cases} \gamma_1 + t(\rho_i) + f & \text{if} \quad \rho_i < \underline{\rho} \\ \gamma_1 + t(\rho_i) & \text{if} \quad \underline{\rho} \leq \rho_i < \overline{\rho} \\ t(\rho_i) - s(\rho_i) + k(\rho_i) + T & \text{if} \quad \overline{\rho} \leq \rho_i, \end{cases}$$

where

$$(15)\ \underline{\rho} = \min\{\rho \mid k(\rho) - \gamma_1 \leq s(\rho)\} \text{ and } \overline{\rho} = \min\{\rho \mid k(\rho) - \gamma_1 \leq s(\rho) - T\}.$$

To reach the social optimum, we need to equate private and social costs of using materials. The social material cost was characterized in equation (12). Continuing to use $\underline{\rho}$ and $\overline{\rho}$ as the thresholds for recycling with and without payment, we can restate equation (12) as

$$(16)\, SMC(\rho_i) = \begin{cases} \gamma_1 + \gamma_2 - \sum_h V_W^h & \text{for} \quad \rho_i < \underline{\rho} \\ k(\rho_i) & \text{for} \quad \underline{\rho} \leq \rho_i < \overline{\rho}. \\ k(\rho_i) + T & \text{for} \quad \overline{\rho} \leq \rho_i \end{cases}$$

The socially optimal value of the first threshold, $\underline{\rho}$, is where recycling has the same social cost as waste disposal; every product with a recyclability level below that threshold should be thrown away. The optimal value of the second threshold, however, is not well defined. From the perspective of the social optimum, *all* recycling should be conducted without incurring transaction costs. Thus, it is better to have consumers put all their recyclables in their curbside recycling bins than for them to take some to a recycling center or reverse vending machine for payment. This means that for a social optimum, the following conditions must hold:

$$(17)\, \underline{\rho} = \min\{\rho \mid k(\rho) - \gamma_1 \leq \gamma_2 - \sum_h V_W^h\} \text{ and } \rho_i < \overline{\rho}, \ \forall i.$$

The private market outcome will be the same as the socially optimal outcome if the profit-maximizing values of $q_i$, $\alpha_i$ and $\rho_i$ are those that also maximize social welfare—that is, if equations (14) and (15) are equivalent to equations (16) and (17). Also, to ensure that $\rho_i < \overline{\rho}$ for all *i*, we need $T > p_r^i$ for all *i*. Substituting for $p_r^i$, this means that we need to choose the subsidy such that $s(\rho_i) < k(\rho_i) - \gamma_1 + T$.

A range of settings for the policy instruments will achieve the desired outcome. One notable example sets the disposal fee, *f*, to zero, and applies the following two-part instrument:

$$t(\rho_i) = \begin{cases} \gamma_2 - \sum_h V_W^h & if \quad \rho_i < \underline{\rho} \\ k(\rho_i) - \gamma_1 & if \quad \underline{\rho} \leq \rho_i \end{cases} \quad s(\rho_i) = \begin{cases} 0 & if \quad \rho_i < \underline{\rho} \\ k(\rho_i) - \gamma_1 & if \quad \underline{\rho} \leq \rho_i \end{cases}$$

All products are subject to output taxes. Products that end up in the landfill are subject to a tax equal to the full social costs of disposal—the direct costs plus the externality costs, $\gamma_2 - \sum_h V_W^h$. This tax is often referred to as an advance disposal fee (Florida Conservation Foundation 1993). Products that are sufficiently recyclable—that is, products that meet or exceed the threshold, $\underline{\rho}$—are subject to a tax equal to the difference between recycling costs and virgin material costs, $k(\rho_i)-\gamma_1$. These same products receive a subsidy when they are recycled; the subsidy is equal to the tax that was paid up front. Thus, recyclable products are subject to what is often referred to as a deposit-refund.

For products that are only moderately recyclable, such as those that would not be collected without a subsidy, $k(\rho_i)-\gamma_1$ is positive, meaning that the tax is indeed a tax and the recycling subsidy, a subsidy. For highly recyclable products, however, the expression is likely to be negative, meaning that some products receive an *output subsidy* and a *recycling tax*. These items are the ones that are very valuable for recycling: their processing costs are low relative to the price that recyclers receive for the material after processing. Recyclers are willing to pay consumers for these items, but from the standpoint of the social optimum, we do not want consumers incurring transaction costs to receive payment. The recycling tax helps prevent this. It is set high enough to ensure that recyclers will not pay consumers for the item but not so high that recyclers will not accept it in the free curbside collection program. The output subsidy provides incentives for production of these highly recyclable items.

Those results suggest that markets and taxes are substitutes for each another in providing incentives for DfE, and that taxes should be set in such a way as to drive out markets. Markets come with transaction costs but taxes do not. This may appear to give an unfair advantage to taxes. Moreover, in practice, it is probably not reasonable to expect the government to have enough information about the recyclability of each individual product to accurately assign product-specific tax and subsidy rates. As explained at the beginning of section II, recyclability takes different forms for different products, and recyclability can be improved with a variety of changes.[17] In addition, there are other drawbacks to levying different taxes on each product. The costs of administering a complex array of tax rates and of monitoring compliance may be prohibitive. Consequently, the policy instruments derived in this section are likely to be impractical. In part B below, we deal with simpler policy proposals.

### *3.2 The case in which recyclability is unobservable*[18]

We now assume that output taxes can not vary continuously with $\rho_i$. We assume that the social planner cannot observe $\rho_i$, but she can observe the decisions that recyclers make—decisions that depend on $\rho_i$. Because of this, we allow policy instruments to depend on whether a product is accepted for recycling without payment (say, in a curbside program) and whether it is paid for (say, at recycling centers). Equation (18) below is a revised version of equation (14), the expression for the producer's material cost, where $s(\rho_i)$ has been replaced by $s_1$ and $s_2$, the (per pound) subsidies for recycling without and with payment to consumers, respectively. In addition, $t(\rho_i)$ has been replaced by $t_0$,, $t_1$ and $t_2$, the tax per pound assessed on products that are collected as refuse, collected for curbside recycling, and paid for at centers, respectively.[19] [is the second sentence in FN 19 a complete sentence? should it be, "*since* s1 > s2 etc"?]

$$(18)\, PMC(\rho_i) = \begin{cases} \gamma_1 + t_0 + f & \text{if} \quad \rho_i < \underline{\rho} \\ \gamma_1 + t_1 & \text{if} \quad \underline{\rho} \le \rho_i < \overline{\rho} \\ t_2 - s_2 + k(\rho_i) + T & \text{if} \quad \overline{\rho} \le \rho_i \end{cases}$$

---

[17] The optimal tax plus subsidy is equal to $k(\rho_i)-\gamma_1$, which is the negative of the amount that recyclers would be willing to pay (per pound) if there were no subsidy (see equation (13) above). This means that to fix the level of the tax and subsidy, the policymaker may not need to observe $\rho_i$ but needs to know only the recyclers' willingness to pay . Unfortunately, however, there is no market price to observe at the optimum, since our instruments are set to ensure that payment does not take place, so this information problem for policymakers is equally daunting.

[18] The results in this section could be regarded as second-best, but we limit our use of this term here since it is often (particularly in the environmental literature) associated with a situation in which there are preexisting distortionary taxes—something we do not consider in this paper (see Bovenberg and de Mooij 1994). Furthermore, we do not examine mechanisms by which producers might be induced to reveal information about their products' recyclability. Instead we deal with robust instruments that are not sensitive to small changes in information about individual products.

This expression is not increasing in $\rho_i$, except for (1) increases in $\rho_i$ that change the method of removal, and (2) those increases where the level of $\rho_i$ is above $\overline{\rho}$. This means that the only levels of recyclability that might ever be chosen by producers are (1) zero, (2) the threshold level that makes the product acceptable for recycling $(\underline{\rho})$, and (3) levels over the threshold for taking recyclables to be sold $(\rho_i \geq \overline{\rho})$.[20]

Note the critical difference between this case and the case considered in part A. When output taxes can vary continuously with recyclability, producers can be induced to make products with recyclability levels above $\underline{\rho}$ and below $\overline{\rho}$. This is no longer possible; only zero, $\underline{\rho}$, and values of $\rho_i \geq \overline{\rho}$ will be chosen. This means that we can rewrite equation (18) to incorporate the constraints on the implementable values of $\rho_i$:

$$(19)\, PMC(\rho_i) = \begin{cases} \gamma_1 + t_0 + f & \text{if} \quad \rho_i = 0 \\ \gamma_1 + t_1 & \text{if} \quad \rho_i = \underline{\rho} \\ t_2 - s_2 + k(\rho_i) + T & \text{if} \quad \overline{\rho} \leq \rho_i \end{cases}$$

We now consider the social planner's problem. The planner faces two constraints that did not appear in the previous section. The first is that, as argued above, not all levels of $\rho_i$ can be implemented. This is because it is infeasible to set taxes and subsidies that vary continuously with $\rho_i$. The second constraint is that levels of $\rho_i$ above $\overline{\rho}$ can be implemented only by harnessing the incentives provided by explicit markets for recyclables and hence by incurring transaction costs. In the previous section, when taxes and subsidies could be functions of $\rho_i$, those instruments could be set such that transaction costs were circumvented. In the constrained optimum, this is no longer the case. We incorporate these two constraints to the social planner's problem by amending equation (16), the expression for the social material cost, SMC.

$$(20)\, SMC(\rho_i) = \begin{cases} \gamma_1 + \gamma_2 - \sum_h V_W^h & \text{if} \quad \rho_i = 0 \\ k(\underline{\rho}) & \text{if} \quad \rho_i = \underline{\rho} \\ k(\rho_i) + T & \text{if} \quad \overline{\rho} \leq \rho_i \end{cases}$$

---

[19] Like equation (14), equation (18) is constructed under the assumption that $f \geq 0$. In addition, it is now assumed that $s_1 > s_2 - T$, that is, the subsidy on curbside collection is greater than the subsidy at recycling centers less transaction costs.

The social planner needs to choose $\alpha_i$, $q_i$, and $\rho_i$ to maximize the objective function, equation (11), given the characterization of SMC in equation (20). It is also necessary to choose the levels of the two thresholds, $\underline{\rho}$ and $\overline{\rho}$. In Appendix A, we show how the two thresholds are chosen. Here, we show how instruments can be set to yield the constrained optimal values for $\alpha_i$, $q_i$, and $\rho_i$, for given levels of the thresholds.[21]

There is a range of policy settings that reconcile the equilibrium, equation (19), with the (constrained) optimum, equation (20). One natural approach is to modify the policy proposals of the previous subsection, by substituting in $\underline{\rho}$ for $\rho_i$:

$$\begin{array}{lll} t_0 = & \gamma_2 - \sum_h V_w^h & \text{if} \quad \textit{not recyclable} \\ t_1 = t_2 = & k(\underline{\rho}) - \gamma_1 & \text{if} \quad \textit{recyclable} \end{array} \qquad s_1 = s_2 = k(\underline{\rho}) - \gamma_1$$

According to this proposal, all products classified as recyclable are given the same tax and subsidy status, whether they are paid for or not. Analogous to the results in part A, recyclable products face an output tax equal to the difference between the recycling costs (this time, at the first threshold, $\underline{\rho}$) and virgin material costs. Those products then receive an equivalent subsidy when they are recycled. Products that are not classified as recyclable are discouraged with a tax, $t_0$, which reflects the full social costs of waste disposal.

Although this proposal has a similar form to that suggested in part A above, it embodies a profound simplification for the policymaker. Instead of observing the degree of recyclability of each recyclable product and setting tax rates that vary with recyclability, she need only make a single distinction between recyclable and nonrecyclable products—and this can be inferred from recyclers' behavior. Even though, at the beginning of this section, we allowed for the possibility of setting separate taxes and subsidies on recyclable products collected for free and those that are paid for, it turns out that separate instruments are not needed.

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[20] These are the only viable solutions to the maximization problem described in equation (6) with PMC as outlined in (18). Otherwise, an interior solution would require $-C_\rho^i = 0$, but this is ruled out by the assumption that $C_\rho^i > 0$.

[21] The government does not set the thresholds and force private markets to meet them; it chooses taxes and subsidies that simultaneously yield the constrained optimal choices of $\alpha_i$, $\rho_i$, $q_i$, and the two thresholds. Even if the thresholds are not set at the ideal levels, the settings of policy instruments shown below will still be constrained optimal, whatever thresholds are chosen.

It is notable that this proposal is the same as that derived in Calcott and Walls (2000), whose model did not incorporate transaction costs but simply assumed there was no payment for recyclables. In that model, producers had no incentive to make products with recyclability levels above the threshold, $\underline{\rho}$. Here, the tax-subsidy can still correct the "market" without a price—recycling collection without payment—just as it did in our earlier study. But it has no effect on the market with a competitive price. In that market, the tax and subsidy effectively cancel each other out. It is the market itself that provides producers with incentives to design products with recyclability levels greater than $\overline{\rho}$.

Interestingly, there is an alternative policy setting that also equates PMC with SMC but requires only a single tax rate applied to *all* products, recyclable and nonrecyclable alike:

$$f = (\gamma_2 - \sum_h V_w^h) - (k(\underline{\rho}) - \gamma_1)$$

$$t_0 = t_1 = t_2 = k(\underline{\rho}) - \gamma_1 \qquad s = k(\underline{\rho}) - \gamma_1$$

In this case, all products face an output tax equal to the difference between recycling costs (at the first threshold) and virgin material costs and receive an equivalent subsidy when recycled. A disposal fee is also necessary to fully implement the constrained optimum, and that fee is equal to the social costs of disposal less the difference between recycling costs (at the threshold) and virgin material costs. Since the second component of the disposal fee should be positive—recycling costs are greater than virgin material costs at the lower threshold, $\underline{\rho}$—this constrained optimal disposal fee is less than the social costs of disposal, $\gamma_2 - \sum_h V_w^h$. This result makes sense, since all products, both those that will end up being recycled and those that will be thrown away, are already assessed a tax up front.

In our view, this set of constrained optimal instruments has some advantages over the first set. First, it is administratively easier for the government to set a single output tax rate than to impose two rates. Second, a "modest" disposal fee—something less than the marginal social costs of disposal—may have some merit. It could provide incentives for low-cost waste-reduction activities by households, such as leaving grass clippings on the lawn and composting yard waste, while not creating big incentives for illegal dumping.

The solutions in this section include relatively simple policy instruments because markets are allowed to do some of the work of providing incentives for DfE. The tax, subsidy, and disposal fee encourage producers to make products sufficiently recyclable to justify their tax and subsidy status, but the incentive to make products with higher levels of recyclability comes from the existence of markets.

### 3.3 The case in which recyclability is unobservable and consumers imperfectly sort products

In the real world, some items that would be accepted by recyclers end up being thrown away. This can occur when, for example, consumption takes place away from home and no recycling bin is nearby, or it can happen simply by accident or through forgetfulness. In this section, we modify the model of part B to account for imperfect sorting. We do so by introducing some uncertainty, at the time of purchase, about the eventual destination of a product. A consumer may buy a highly recyclable item in the expectation that it will be recycled, but contingencies may arise that make it more convenient to dispose of it as trash. Let $\theta$ be the probability that an item will be recycled. This probability may depend on the price that the item would receive from recyclers:[22]

$$(21)\ \theta = \begin{cases} \theta_0 & if \quad T > p_r^i \\ \theta(p_r^i) & if \quad T \le p_r^i \end{cases}$$

The expression in equation (21) says that the probability that an item will be recycled is a constant, $\theta_0$, where $0<\theta_0<1$, as long as the item's recyclability level is low enough that the transaction costs of taking it in for payment are greater than the price received. When the price covers the transaction costs, we assume that the probability that the item is recycled is a function of the price (where $\theta' \geq 0$). As the product becomes increasingly valuable, it becomes less likely that the consumer will neglect to recycle it.

At the time of purchase, the consumer's expected removal costs are

$$(22)\ PRC(\rho_i) = \begin{cases} f & if \quad \rho_i = 0 \\ (1-\theta_0)f & if \quad \rho_i = \underline{\rho} \\ \theta(p_r^i)(T - p_r^i) + (1-\theta(p_r^i))f & if \quad \overline{\rho} \le \rho_i \end{cases}$$

---

[22] One way to motivate this assumption is by introducing an additional cost, the cost to the consumer of recycling relative to waste disposal. Let the cost of getting rid of a product be $\eta$. It is equal to $\eta_0$ if the product is left as trash; its value if the product is to be recycled is unknown at the time of purchase, but it is drawn from the distribution $F$. Then $\theta_0=F(\eta_0)$ and $\theta(p_r^i)=F(\eta_0-T-p_r^i)$.

This expression for removal costs implies the following revision to the producer's material cost, equation (19):

$$(23)\; PMC(\rho_i) = \begin{cases} f + \gamma_1 + t_0 & if \quad \rho_i = 0 \\ \gamma_1 + t_1 + (1-\theta_0)f & if \quad \rho_i = \underline{\rho} \\ \gamma_1 + t_2 + f + \theta(p_r^i)\left(T - p_r^i - f\right) & if \quad \bar{\rho} \le \rho_i \end{cases}$$

Social material costs are also affected by incomplete sorting. Since all recyclable products have a chance of being thrown away, the social costs of recyclable products are higher than they were in the case with perfect sorting. Equation (20), the social material cost expression, is amended to the following:

$$(24)\; SMC(\rho_i) = \begin{cases} \gamma_1 + \gamma_2 - \sum_h V_W^h & if \quad \rho_i = 0 \\ \theta_0 k(\underline{\rho}) + (1-\theta_0)\left(\gamma_1 + \gamma_2 - \sum_h V_W^h\right) & if \quad \rho_i = \underline{\rho} \\ \theta(p_r^i)\left(k(\underline{\rho}) + T\right) + \left(1 - \theta(p_r^i)\right)\left(\gamma_1 + \gamma_2 - \sum_h V_W^h\right) & if \quad \bar{\rho} \le \rho_i \end{cases}$$

Again the task of the social planner is to reconcile SMC and PMC.[23] This will not be achieved if our first policy proposal in part B is adopted, but it will be achieved with the second proposal, in which the output tax and recycling subsidy are equal to $k(\underline{\rho}) - \gamma_1$ per pound on every product and the disposal fee is set to $(\gamma_2 - \sum_h V_w^h) - (k(\underline{\rho}) - \gamma_1)$.

The reason that these instruments continue to implement the constrained optimum is that the social cost of a product's chance of becoming refuse is accounted for with the disposal fee. The disposal fee is applied to everything that is thrown away, including those items that should have been recycled. Consequently, this proposal is robust to the possibility that some recyclables end up being thrown away by mistake. Furthermore, since output taxes should be set at the same levels, irrespective of the ultimate destination of a product, no difficulty is introduced by uncertainty about a product's eventual destination.

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[23] The recyclability thresholds, $\underline{\rho}$ and $\bar{\rho}$, are unchanged from part B for both the private market and the social optimum. The lower threshold is determined by the per pound profits of private recyclers and the costs of recycling, $k(\rho_i)$. These are not affected by imperfect sorting. The higher threshold is unchanged, since it concerns the decision between the two types of recycling transactions, not the choice about whether to recycle.

Including the possibility that consumers mistakenly throw recyclable products in the trash affects neither our (second set of) constrained optimal policy instruments nor the functioning of the recycling market. This is yet another factor in favor of the second set of instruments derived above, the modest disposal fee coupled with a common output tax and recycling subsidy applied to all products.

## 4. Discussion and Extensions

In section III, we showed that when recycling markets include transaction costs, efficient DfE is attainable only with taxes and subsidies that vary with products' degrees of recyclability. We argued that these instruments were infeasible and thus turned to policy instruments that would not require so much information. Although we believe that this argument is reasonable, we make two qualifications. First, we consider the information that is required to set the thresholds to implement the constrained optimum. Second, we consider the possibility that an intermediate amount of information might be used—less information than that required to implement the first-best outcome but more than we allowed for in considering the constrained optimum.

Both sets of constrained optimal policy instruments depend on the first recyclability threshold, $\underline{\rho}$. To determine that threshold, the policymaker needs to know the average value of the increase in production costs due to an increase in $\rho$ (see Appendix A). This is a far cry from knowing the level of recyclability of individual products, but it may still be a significant information requirement.

A wider range of information than we considered here could be available for heterogeneous products, and some of that information might be useful for setting policies. A policymaker might gain some information about recyclability, for example, by observing the quantities of different types of material inputs.[24] In the model above, we assumed only a single composite material, but in Appendix B we present a more general and more complicated model with multiple materials. In that model, we continue to assume that recyclability also depends on design features that may differ across products.[25] As a consequence, we find that taxes would

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[24] Improved recyclability sometimes requires producers to change the mix of materials used in production—making a container out of glass rather than plastic, for example, or out of a single plastic resin rather than a mix of resins.

[25] Eichner and Pethig (2001) consider different material types but do not also incorporate product design. They derive material input taxes that can implement a first-best outcome.

still need to vary with design as well as with input quantities, if they are to implement first-best DfE.

In general, policymakers' decisions about the complexity of policy instruments will depend on the relative costs and benefits of obtaining and using information about products. Some aspects of recyclability of some kinds of goods are more straightforward to determine than other aspects and other goods. For example, the recyclability of a newspaper is relatively easier to discern than the recyclability of a computer monitor. We have not explicitly modeled the costs of using information in setting taxes; instead, we have assumed that only a modest amount of firm-specific information can be used. Future work could explore the optimal level of complexity for policy instruments. One possible approach is to explicitly model information costs to policymakers and producers in assessing how recyclable a product is (Kaplow 1995).

There may be alternative proposals with intermediate levels of complexity that would be preferable to our suggestion and to the first-best instruments. Furthermore, we cannot judge the size of the welfare loss from trying to use first-best instruments in a constrained best world. We know that there would be benefits in improved incentives for DfE, but we cannot compare them with the costs of increased complexity.

## 5. Conclusion

Decentralized decisions by producers and consumers usually rely on markets to transmit incentives. If recycling markets work—if recyclers pay consumers for recyclable items and pay higher prices for items with higher value—then consumers would be willing to pay more up front for products designed to be recyclable. But in fact, most recycling is collected without payment, and so this transmission of incentives tends not to occur. In this paper, we explicitly model an explanation for these "missing prices"—the explanation that has been suggested informally by previous authors: that they are precluded by transaction costs.

We find that policymakers can overcome the transaction costs and implement a socially optimal level of product recyclability *if* they can tax products according to the products' recyclability levels. Such taxes would provide the incentives that markets either fail to provide or provide at a cost. It seems implausible to us, however, that the government would really be able to impose such taxes. We take this limitation into account and require policy instruments to have a reasonably simple structure. There are both negative and positive consequences of this requirement. The negative consequence is that the first-best is no longer attainable. The positive consequence is that once we limit ourselves to the constrained optimum that is attainable, policy instruments can be further simplified without any further loss in efficiency. In particular, the constrained optimal outcome can be implemented with an output tax, at the same rate per pound for every good, combined with a subsidy on recycling at the same rate, and a rather modest disposal fee. In addition, we find that this policy option is robust to the possibility that some recyclables are mistakenly disposed of as trash.

In attaining the constrained optimum, we find a role for both taxes and markets in encouraging “design for environment.” Unlike the product-specific taxes necessary to implement the first-best, taxes and subsidies in the constrained optimum do not perform the function that prices would otherwise carry out—rewarding producers for all design changes. Taxes are not flexible enough to do that. Instead, they determine which items recyclers pay for, ideally those for which the benefits from higher levels of DfE outweigh the extra transaction costs.

We find it interesting that a modest disposal fee—one that is less than the full social cost of disposal—is part of the set of constrained optimal policy instruments. Although a disposal fee can create incentives for illegal disposal, it can also create incentives for a range of household-based waste-reduction activities, such as composting—activities that are difficult if not impossible to encourage with output taxes (Choe and Fraser 1999). And pricing household waste collection and disposal through what are often referred to as user fees, unit-based pricing, or pay-as-you-throw programs, are becoming increasingly common across the United States (Miranda et al. 1994, 1998).

Our results also lend further support to the two-part instrument (2PI) idea advanced by Fullerton and Wolverton (1999). They suggest the 2PI—a presumptive tax on all output combined with a subsidy for the use of “clean” inputs—in place of Pigouvian taxes in situations in which either illegal disposal is a possibility or monitoring and enforcement are difficult.[26] A product tax combined with a subsidy for recycling—a type of 2PI—is part of our set of constrained optimal instruments, and thus we find support for it in a setting in which transaction costs lead to poorly functioning recycling markets and policymakers are prohibited from setting product-specific taxes.

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[26] See also Eskeland and Devarajan (1996) for a similar recommendation.

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## Appendix A: The choice of the thresholds in the constrained optimum

If the other policy instruments are chosen, as suggested in section III.B, the thresholds sshould be chosen to maximize the following expression:

$$
\text{(A1)} \qquad
\begin{aligned}
\sum_i \max\Big\{ & \max_{q_i,\alpha_i}\big(V_q q_i - \alpha_i q_i(\gamma_1 + \gamma_2 - V_W H) - C^i(0,\alpha_i,q_i)\big), \\
& \max_{q_i,\alpha_i}\big(V_q q_i - \alpha_i q_i k(\underline{\rho}) - C^i(\underline{\rho},\alpha_i,q_i)\big), \qquad s \\
& \max_{\rho\geq\overline{\rho}_i,q_i,\alpha_i}\big(V_q q_i - \alpha_i q_i\big(k(\rho_i)+T\big) - C^i(\rho_i,\alpha_i,q_i)\big)\Big\}.
\end{aligned}
$$

The three parts of (A1) reflect the three possible destinations for each product. The optimal design and output may depend on whether or how a product is to be recycled. Equation (A1) is maximized with respect to $\underline{\rho}$ when

$$\sum_{i\ni\rho_i=\underline{\rho}}(C^i_\rho - k'(\underline{\rho})\alpha_i q_i) = 0$$

This means that the per pound increase in production costs due to an increase in ρ (over all products with $\rho_i = \underline{\rho}$) is set equal to the marginal reduction in recycling costs (at $\rho_i = \underline{\rho}$). There is not a unique value of $\overline{\rho}$ for which (A1) is maximized. Any value is optimal as long as it is below all values of ρi for which

$$
\text{(A2)} \qquad
\begin{aligned}
& \max_{q_i,\alpha_i}\big(V_q q_i - \alpha_i q_i k(\underline{\rho}) - C^i(\underline{\rho},\alpha_i,q_i)\big) \leq \\
& \qquad \max_{q_i,\alpha_i}\big(V_q q_i - \alpha_i q_i\big(k(\rho_i)+T\big) - C^i(\rho_i,\alpha_i,q_i)\big)
\end{aligned}
$$

for any producer *i.* This means that if a producer designs a product with $\rho_i \notin \{0,\underline{\rho}\}$, then we can be confident that a consumer would rather sell this product to a recycler than put it in the trash. But if policy instruments are chosen as suggested in section III.B, then the consumer will make this choice whenever k(ρi)+T≤k($\underline{\rho}$). And any value of $\overline{\rho}$ that satisfies (A2) will also satisfy this condition. Hence, the second threshold will be set optimally.

## Appendix B: A general model with explicit multiple material inputs

Define $\beta_i^j$ as the proportion of $\alpha_i q_i$ that is made up of input *j*. Recyclabilty is now determined by $\rho_i$ and the proportions of each material input. The nonmaterial cost function is $C^i(\alpha_i, q_i, \rho_i, \beta_i^1, ..\beta_i^M)$, as the costs of attaining particular levels of weight and recyclability may depend on the mix of material inputs. The producer maximizes the following generalization of (6)

(B1) $\overline{V}_q q_i - \alpha_i q_i PMC(\rho_i, \beta_i^1, .., \beta_i^M) - C^i(\alpha_i, q_i, \rho_i, \beta_i^1, ..\beta_i^M)$,

subject to the constraint that $\sum_j \beta_i^j = 1$, where PMC is now equal to $PRC(\rho_i, \beta_i^1, .., \beta_i^M) + t_i + \sum_j \gamma_1^j \beta_i^j$. The social planner's problem is also amended. Equation (11) becomes

(B2) $\sum_i \left(\overline{V}_q q_i - \alpha_i q_i SMC(\rho_i, \beta_i^1, .., \beta_i^M) - C^i(\alpha_i, q_i, \rho_i, \beta_i^1, ..\beta_i^M)\right)$.

High levels of recyclability are represented as high values of the function

$$g(\rho_i, \beta_i^1, .., \beta_i^M) = \sum_j \gamma_1^j \beta_i^j - k(\rho_i, \beta_i^1, .., \beta_i^M),$$

rather than of the variable $\rho_i$. The analog to the threshold $\underline{\rho}$ in section III is represented as $\underline{g}$. The first-best outcome can be implemented with the following taxes and subsidies.

$$t(\rho_i, \beta_i^1, .., \beta_i^M) = s(\rho_i, \beta_i^1, .., \beta_i^M) = \begin{cases} \gamma_2 - \sum_h V_W^h & \text{if } g(\rho_i, \beta_i^1, .., \beta_i^M) < \underline{g} \\ -g(\rho_i, \beta_i^1, .., \beta_i^M) & \text{if } g(\rho_i, \beta_i^1, .., \beta_i^M) \geq \underline{g} \end{cases}$$

The constrained best outcome can be implemented with a simple two-part instrument, $t = s = -\underline{g}$, and a disposal fee equal to $\gamma_2 - \sum_h V_W^h + \underline{g}$.