Policies to Encourage Recycling and "Design for Environment": What to Do When Markets are Missing

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Abstract

Several studies have shown the efficiency of both a Pigovian tax on waste disposal and a deposit-refund instrument, that is a combined output tax and recycling subsidy. The efficiency of these instruments, however, critically depends on households being paid for recycling. In reality, although most households have access to curbside recycling services, they are not paid for the items they set out at the curb. All items placed in a recycling bin are thus of equal value to a household, and there is no incentive for producers to make their products any more recyclable than what is necessary to be eligible for the bin. This paper characterizes the constrained (second-best) optimum that exists with the missing recycling market and solves for a modified deposit-refund instrument that will achieve the constrained optimum.

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Paul Calcott and Margaret Walls[1]

1. Introduction

Recent studies have shown that waste disposal externalities can be addressed in a variety of ways. If illegal dumping is not a concern, then an obvious remedy is a charge for disposal, namely, a standard Pigovian tax. Alternatively, a tax on output combined with a subsidy for recycling, commonly referred to as a deposit-refund, can achieve the same outcome as a disposal charge and may be called for when there is a potential for dumping.[2]

Disposal taxes and deposit-refunds give producers incentives to make efficient design choices as well (Fullerton and Wu, 1998). Such design choices can include changing the weight of a product or the degree of packaging that comes with it, and making a product easier and less costly to recycle. "Design for environment" (DfE) activities of this type can help to achieve cost-effective reductions in waste disposal, and policymakers have focused on them in recent years.[3]

The efficiency of the Pigovian tax and deposit-refund options, however, depends critically on households being paid for recycling. In reality, households have access to curbside recycling for certain materials but they do not receive payment for the items they set out at the curb. The costs of making such payments would be prohibitively high.

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[2] For discussions of the merits of disposal charges, usually referred to as "unit-based pricing (UBP)" of waste disposal, see Repetto, et al. (1992) and Skumatz (1993). Studies that derive optimal alternative policies are Dinan (1993), Sigman (1995), Fullerton and Kinnaman (1995), Palmer and Walls (1997), Fullerton and Wu (1998), and Choe and Fraser (1999).

[3] DfE is the impetus for manufacturer "take-back" requirements such as those in Germany's well-known packaging law. See www.oecd.org/env/efficiency/eprworkprogr.htm for updates on a series of OECD workshops on the broader topic of "extended producer responsibility."

Fullerton and Wu (1998) consider the possibility that there is no recycling market and find that a social optimum can still be reached with a direct subsidy to enhance product "recyclability" combined with an output tax and a tax on packaging. All of the instruments depend on production function parameters; thus if producers are heterogeneous, tax rates in the Fullerton and Wu model would need to differ by producer. Moreover, recyclability is impossible to observe and measure for purposes of making a subsidy payment.

In this paper, we argue that such policy options are unrealistic and show that without them, and in the absence of a fully functioning recycling market, a first-best outcome can no longer be reached. We solve for the constrained (second-best) optimum that exists in this case and describe policy options that would yield this constrained optimum.

Our policy results in this second-best setting are encouraging. Although we find that a disposal fee by itself cannot implement the constrained optimum, a modified deposit-refund instrument can. The deposit depends on whether or not a product is eligible for recycling—that is, whether it reaches the threshold level of recyclability necessary for recyclers to be willing to collect the product from households. Producers of products that are recycled pay a tax up-front that is equivalent to the refund received by recyclers. Producers of products that are not recycled pay an "advance disposal fee," namely a tax equal to the marginal social cost of disposal.

Our results lend further support to the "two-part instrument" (2PI) idea advanced by Fullerton and Wolverton (2000) and the suggestion by Palmer, Sigman, and Walls (1997) that a deposit-refund be placed "upstream" to avoid the transaction costs of dealing with households. In our model, the deposits are paid by producers, and the refunds are paid to recyclers; households "downstream" are not directly taxed or subsidized. As pointed out by Fullerton and Wolverton (2000), the deposit and refund do not necessarily need to equal one another, nor do they need to be placed on the same actors in the marketplace. The value of the findings in our paper lie in the fact that we reach similar policy conclusions in a second-best setting, that is, even when the first-best setting is unattainable with available instruments, a deposit-refund still seems to perform well. This finding is important because the constrained setting is a more realistic representation of how solid waste and recycling markets function.

Section 2 briefly describes the theoretical framework. Section 3 characterizes the social optimum and demonstrates how it can be implemented in a first-best world. We show that either a Pigovian tax on disposal or a deposit-refund will move private markets to the first-best, if there are functioning markets for recyclables. Without such markets, product-specific taxes and recycling subsidies can implement the first-best, but we argue that these options are not feasible. In Section 4, we derive a set of policy instruments that get private markets to the constrained optimal outcome. Section 5 deals with some extensions to the model and Section 6 offers some concluding remarks.

2. The Basic Theoretical Framework

The model takes a simple general equilibrium approach, incorporating 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.

The model has three decisionmakers: producers, consumers, and recyclers. There are $i=1,...,n$ heterogeneous producers; this leads to a distribution of products in the marketplace with varying weights and degrees of recyclability. Each product is either fully recycled or not recycled.[4] The degree of recyclability of a product, ρ_i, is assumed to be an unobservable (to policymakers) index that varies across products and determines the cost of recycling the product. This way of treating recyclability is different from that of Fullerton and Wu (1998), who do not explicitly address recycling costs and treat recyclability as the proportion of a product that is capable of being recycled.[5]

Although neither model is strictly correct for all products, we feel 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 are wide-ranging. For example, the cost of recycling plastic packaging is lower if contaminants that cannot be readily separated from the packaging are avoided, particular types of plastics are avoided, and particular production methods are used. Electronic products can be designed to ease disassembly; this generally means that access to components is improved, and component interfaces and the overall design of the product are simplified. Enhanced labelling of materials can also make recycling easier and less costly. All of these activities are allowed for in our model by representing recyclability as an index that varies across products and determines the cost of recycling.[6]

All markets are assumed to be competitive, and there are no pre-existing distortions from income or other taxes. Since we focus our attention on producers' choices regarding recyclability and weight, we simplify the characterization of both virgin material extraction and waste disposal. Virgin material extraction is assumed to take place under constant returns to scale technology, with unit extraction cost of γ_1. Private waste collection and disposal costs per unit are also constant and equal to γ_2. We

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[4] We view a product and any packaging that might come with it as a single item characterized by its overall weight and degree of recyclability. For example, we consider the soft drink and the plastic bottle or aluminum can it comes in as a single product. Fullerton and Wu's (1998) model has a recyclable product that comes with some packaging, which is not recyclable. Product weight is not a variable in their model, but firms choose the amount of packaging and this is similar to, though not exactly the same as, the choice of product weight in our model.

[5] Producers are homogeneous in the Fullerton and Wu model, thus there is a single product type. Also, there is no explicit treatment of the role of recyclers as in our model.

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

assume that virgin and secondary raw material inputs are perfect substitutes in production and there are no waste by-products 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 α_i is the weight of the product, in pounds per unit. Finally, we assume that all items collected 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. We consider two sets of assumptions about the market for recyclables: consumers are either paid price p_r^i per pound of product i collected by recyclers, and that price depends on the recyclability of the product, ρ_i, or they are paid nothing – i.e., $p_r^i = 0$. The latter assumption is more in keeping with the way markets for waste and recycling currently work. Recyclers collect items from households, incur some processing costs, resell to producers, and may receive a subsidy from the government. Based on their revenues and costs, recyclers decide which items they will collect from households. Households place their refuse in two bins, a waste disposal bin and a recycling bin. Households may or may not pay for disposal, and we denote that fee as f. Consumers pay price P_q^i per unit of good i and that price depends on recyclability, ρ_i, and product weight, α_i. Aggregate waste disposal is denoted by W.

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[7] These assumptions could be relaxed, but it would not change our basic results and only serve to clutter the model. Palmer and Walls (1997) and Walls and Palmer (1999) allow for a manufacturing by-product; Walls and Palmer (1999) also consider the case of some air or water pollution generated during the production process. Neither paper considers DfE issues.

[8] We abstract from dynamic considerations in the model and assume that products last only one period or that we are looking at a steady-state.
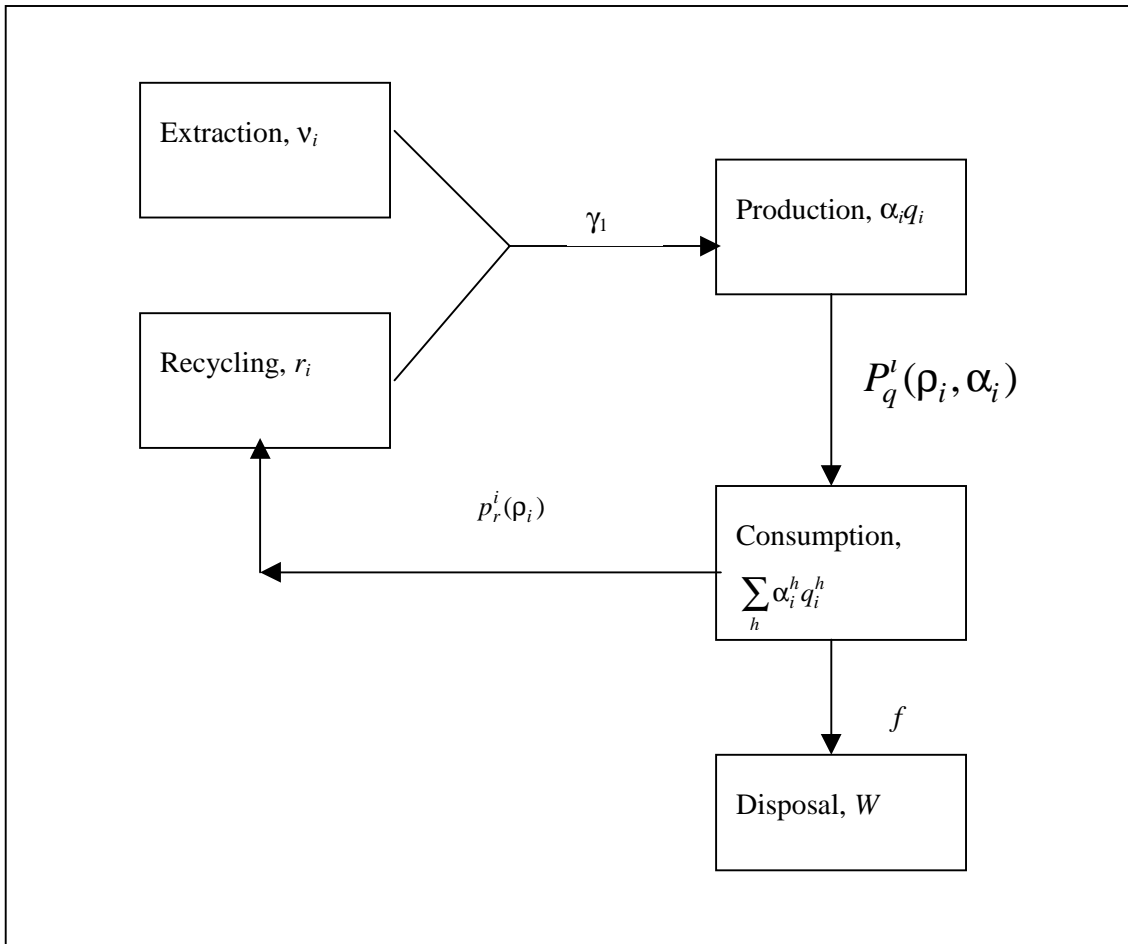
Figure 1. The product life-cycle, materials balance, and prices.

3. The Unconstrained Social Optimum

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,...,H* identical consumers with quasi-linear utility functions:

$$V\left(q^h, W\right) + m^h$$

where *V* is strictly concave, $q^h = \sum_i q_i^h$ 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 ρ_i and their weight α. Although these two characteristics do not enter the utility function directly, they can affect the consumer's budget constraint, which is given as:

$$(2)\ y^h + \sum_i p_r^i(\rho_i)I_i\alpha_i q_i^h \geq m^h + \sum_i P_q^i(\rho_i,\alpha_i)q_i^h + \sum_i (1-I_i)f\alpha_i q_i^h$$

where y^h is h's wealth, and I_i is an indicator function that is equal to one if product i is recycled and zero otherwise. For each pound of i's output, a consumer can obtain p_r^i if she sells it to a recycler—i.e., those items for which $I_i=1$ – or can alternatively pay a disposal fee of f on those items that are not recycled ($I_i=0$).

Substituting the budget constraint into the utility function, we can write the representative consumer's maximization problem as:

$$(3)\ \max V\left(q^h,W\right) + y^h + \sum_i p_r^i(\rho_i)I_i\alpha_i q_i^h - \sum_i P_q^i(\rho_i,\alpha_i)q_i^h - \sum_i (1-I_i)f\alpha_i q_i^h.$$

The first-order conditions for q_i^h, α_i, and ρ_i imply that the (inverse) demand for product i is given by:

$$(4)\ P_q^i(\rho_i,\alpha_i) = V_q + \alpha_i\left((p_r^i(\rho_i)+f)I_i - f\right).$$

Since utility is quasi-linear, V_q is the marginal rate of substitution between q and the numeraire good, m. It is also the marginal willingness to pay by a given consumer for an increase in consumption of any firm's product (since from a utility perspective, all products are identical). Therefore, equation (4) states that, for any good i, the marginal willingness to pay should be equal to the effective price. The effective price is the explicit price paid up-front, less the refund from recyclers on the items recycled, plus the disposal fee paid on the items thrown away. Since V_q is the same across products, the effective price is the same across products, even though explicit prices may vary.

Each producer pays for its raw material inputs and also incurs some nonmaterial costs of production, $C^i(\alpha_i,\rho_i,q_i)$. Increasing the amount of output or the degree of recyclability, with all else equal, increases nonmaterial costs; reducing product weight, with all else equal, also increases nonmaterial costs. Thus, $C_q^i > 0$, $C_\rho^i > 0$, and $C_\alpha^i < 0$, where subscripts denote first partial derivatives.[9]

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[9] Reducing product weight should 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.

Each producer receives price, P_q^i, for its output and pays price, γ_1, for its raw material inputs. Taking this price as given, each producer may pay a tax per pound of output produced that depends on whether the product is eligible for recycling, t_1, or not eligible, t_0. In other words, if the product is permitted in the household's recycling bin, it may be subject to tax t_1; if the product is not permitted, then it may be subject to t_0. Each producer chooses its level of output and the two product attributes, ρ_i and α_i, to maximize profits (note that $q_i = \sum_h q_i^h$):

(5) $\max P_q^i(\rho_i, \alpha_i)q_i - C^i(\rho_i, \alpha_i, q_i) - \gamma_1 \alpha_i q_i - t_1 I_i \alpha_i q_i - t_0(1 - I_i)\alpha_i q_i$.

Substitution of (4), the inverse demand function, into (5) yields:

(6) $\max V_q q_i - \alpha_i q_i\left[(f + \gamma_1 + t_0)(1 - I_i) + (\gamma_1 - p_r^i(\rho_i) + t_1)I_i\right] - C^i(\rho_i, \alpha_i, q_i)$.

The equilibrium values of q_i, α_i and ρ_i will maximize equation (6). However, this depends on the determination of p_r^i and I_i, and thus on the functioning of the recycling market. We assume that a recycler incurs 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 recyclability of a product reduces the costs of recycling, but at a declining rate. A recycler receives γ_1 per pound from producers and may receive a subsidy, s, per pound from the government.

Consider the case in which there is a functioning market for recyclables, and recyclers pay consumers p_r^i for each pound of product i. In this setting, a recycler makes a net gain of

$\gamma_1 - k(\rho_i) - p_r^i(\rho_i) + s$ 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 in equilibrium. Consequently, the equilibrium price that consumers receive from recyclers is:

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

The consumer makes a rational choice between disposal and recycling each product. Utility is maximized with respect to I_i, with the result that product i is recycled (i.e., I_i is set equal to one) if $p_r^i \geq -f$ —i.e., if the gain from recycling is at least as great as that from disposal. This means that product i is recycled if $\gamma_1 - k(\rho_i) + s + f \geq 0$. Therefore, I_i is characterized by the following expression:

(8) $I_i = I(\gamma_1 - k(\rho_i) + s + f)$.

If there is not a functioning market for recyclables, recyclers will earn $\gamma_1 - k(\rho_i) + s$ on every pound of product i recycled. Consumers will send an item back for recycling as long as the disposal

fee is nonnegative, and recyclers will accept the product as long as $\gamma_1 - k(\rho_i) + s \geq 0$.[10] The missing market for recyclables means that:

$$(9)\ I_i = I\big(\gamma_1 - k(\rho_i) + s\big)$$

The Social Optimum

The social planner maximizes the sum of consumers' utility functions:[11]

$$(10)\ \sum_h V\big(q^h, W\big) + \sum_h m^h$$

subject to the resource constraints. There are resource constraints associated with both material and nonmaterial goods. The materials balance condition was given in section 2. The resource constraint for nonmaterial goods (such as labor and capital services) states that no more of these goods can be used than the total endowment in the economy, R. Nonmaterial goods are used in the extraction of virgin materials, in the production of output, for consumption, in recycling, and in waste disposal. Total recycling costs in the economy are given by $\sum_i k(\rho_i) I_i \alpha_i q_i$. Consequently, the nonmaterial resource constraint is:

$$(11)\ \ R = \gamma_1 \sum_i v_i + \sum_i C^i(\alpha_i, \rho_i, q_i) + \sum_h m^h + \sum_i k(\rho_i) I_i \alpha_i q_i + \gamma_2 W.$$

Because all nonrecycled items end up as waste in the landfill, the total amount landfilled is given by $W = \sum_i (1 - I_i)\alpha_i q_i$. Furthermore, because of the materials balance condition, the quantity of virgin materials used in production is equal to the quantity of waste landfilled $\sum_i v_i = \sum_i (1 - I_i)\alpha_i q_i$.

Substituting these conditions into (11), and then using $\sum_h m^h$ to substitute this constraint into the objective function, equation (10), yields the following objective for the social planner:

$$(12)\ \sum_h V\big(q^h, W\big) + R - \sum_i C^i(\alpha_i, \rho_i, q_i) - (\gamma_1 + \gamma_2)\left[\sum_i (1 - I_i)\alpha_i q_i\right] - \sum_i k(\rho_i) I_i \alpha_i q_i$$

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[10] We assume that consumers have no significant costs of recycling and thus will recycle even when disposal fees are zero. The high participation rates in curbside recycling programs suggest that this is a reasonable assumption (Jenkins, et al., 1999).

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

The social planner chooses q_i^h, α_i, ρ_i, and I_i to maximize equation (12). Rather than take first-order conditions, we choose to apply a partial linearization to equation (12) and then compare the resulting social planner's objective function to the firm's private profit maximization problem given in equation (7).[12] A first order Taylor series expansion can be substituted for the first terms in equation (12):[13]

$$(13) \sum_h V\left(q^h, W\right) \cong \sum_i \left(V_q + V_W H(1 - I_i)\alpha_i\right)q_i + \text{a constant}$$

Substituting this expression into equation (12) yields (ignoring the constant terms):

$$(14) \quad \sum_i \left[V_q q_i - \alpha_i q_i \left((\gamma_1 + \gamma_2 - V_W H)(1 - I_i) + k(\rho_i)I_i\right) - C^i\left(\alpha_i, \rho_i, q_i\right)\right]$$

which should be maximized with respect to I_i, q_i, α_i and ρ_i. If it is maximized with respect to I_i, for given values of q_i, α_i and ρ_i, then I_i will be set to one if $\gamma_1 + \gamma_2 - V_W H - k(\rho_i) \geq 0$, and zero otherwise. Therefore,

$$(15) I_i = I\left(\gamma_1 + \gamma_2 - V_W H - k(\rho_i)\right).$$

The private market outcome will be the same as the socially optimal outcome if the profit maximizing values of q_i, α_i and ρ_i are those that also maximize equation (14); and the products that end up recycled are the ones that accord with equation (15)—that is, the private market recycles a product (I_i=1) when $\gamma_1 + \gamma_2 - V_W H - k(\rho_i) \geq 0$. The policy instruments that implement such an outcome will depend on whether a functioning recycling market exists. Recall that if such a market exists, then $p_r^i(\rho_i)$ is given by equation (7) and equilibrium recycling decisions are characterized by equation (8). A range of settings for the policy instruments will lead to the efficient outcome. Two notable examples are:

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[12] We adopt this procedure because of the irregular nature of the objective function. This irregularity is a more pressing concern in the constrained environment described later in this paper; there, the choice of ρ_i is never characterized as a differentiable turning point. This procedure also allows us to treat the discrete variable, I_i as an explicit choice of the social planner.

[13] The Taylor series expansion reduces to an expression without h superscripts because any i firm's product is the same from a utility perspective – i.e., $q^h = \sum_i q_i^h$ in each h consumer's utility function. Consequently, the social planner does not need to worry about allocating particular products to particular consumers, only about total output produced by each i firm, q_i.

Option 1:   Option 2:

$$f = \gamma_2 - V_W H \qquad\qquad t_0 = t_1 = s = \gamma_2 - V_W H$$
$$t_0 = t_1 = s = 0 \qquad\qquad f = 0$$

Option 1 is the standard Pigovian approach: a disposal fee is set to the full social cost of disposal, which is the sum of the private collection and disposal costs, γ_2, and the externality, $-V_W H$. Option 2 calls for a tax on output and an equivalent subsidy on recycling equal to the full social cost of disposal. The tax rate is the same whether products are recycled or not ($t_0 = t_1$). This deposit-refund approach may be preferable if a positive disposal fee will lead to illegal dumping.

These results have been reached in other models that do not incorporate DfE. In particular, several studies have shown the efficiency of the deposit-refund (Dinan, 1993; Sigman, 1995; Fullerton and Kinnaman, 1995). Fullerton and Wu (1998), who have the only model that explicitly incorporates producers' choices of product recyclability, also find that a disposal fee can generate the social optimum. A deposit-refund instrument by itself, however, cannot reach the full social optimum in their model but must be coupled with a tax on packaging. This result comes from the assumption that packaging is not recyclable. Fullerton and Wu derive several other policies that generate the social optimum, many of which include a subsidy on recyclability.

Now consider the case without a functioning market for recyclables. In this case, $p_r^i(\rho_i) = 0$ and equilibrium recycling decisions are characterized by equation (9). Again, a range of settings for the policy instruments will lead to the efficient outcome. Two possibilities are:[14]

Option 1:   Option 2:

$$f = \gamma_2 - V_W H \qquad\qquad f = 0$$
$$s = k(\rho_i) - \gamma_1 \qquad\qquad s = k(\rho_i) - \gamma_1$$
$$t_1 = k(\rho_i) - \gamma_1 \qquad\qquad t_1 = k(\rho_i) - \gamma_1$$
$$t_0 = 0 \qquad\qquad\qquad t_0 = \gamma_2 - V_W H$$

In option 1, the disposal fee is set according to the Pigovian approach. However, unlike results above, it is now necessary to supplement the disposal fee with other instruments. This is because of the second market failure, the missing recycling market. Option 2 is in the spirit of the deposit-refund

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[14] There are other possibilities. For example, it is possible to have one output tax rate that applies to all products, along with a disposal fee and recycling subsidy, but both the output tax and disposal fee would depend on ρ_i.

proposed above: producers pay a tax up-front and recyclers receive a refund.[15] However, t_0 no longer equals t_1. Products that are recycled are subject to a tax, t_1, equal to the difference between recycling costs and virgin material costs; this tax equals the recycling subsidy, s. Products that end up in the landfill are subject to a tax, t_0, equal to the marginal social cost of disposal, γ_2-V_WH. This tax is often referred to as an "advance disposal fee" (Florida Conservation Foundation, 1993).

Unfortunately, these instruments are not practicable. In particular, it is not reasonable to expect that the government can determine *ex ante* the level of recyclability of an output for purposes of assigning tax and subsidy rates to individual products. Even if it could observe *ex post* the cost of recycling, it would be infeasible to set separate tax and subsidy rates for individual products. It might be possible to mandate a manufacturer "take-back" requirement so that each individual producer was forced to collect from consumers and reuse its own product again at end-of-life. But the administrative and transactions costs of such an approach would be prohibitively high. In Germany, where there is a take-back mandate for packaging, producers have joined a consortium that hires a third party to collect members' waste—marked with a green dot—and recycle it. Individual producers do not collect and reuse their own products again at end-of-life.[16] In the following section, we examine the outcome when policymakers lack options that could implement the first-best outcome.

4. The Constrained Social Optimum[17]

We continue the assumption of no functioning market for recyclables, but we now assume that output taxes can depend only on I_i and not on ρ_i. Then, producers maximize the profit function, equation (6), subject to equation (9). This problem is rewritten here as:

$$\max V_q q_i - \alpha_i q_i \left[(f + \gamma_1 + t_0)(1 - I_i) + (\gamma_1 + t_1) I_i \right] - C^i (\rho_i, \alpha_i, q_i)$$

$$\text{s.t.} \, I_i = I(\gamma_1 - k(\rho_i) + s), \, \forall i \, .$$

In this situation, producers will not be rewarded for increasing recyclability above the threshold at which recyclers accept the product. This threshold is where $\gamma_1 - k(\rho_i) + s = 0$ and the net gain to

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[15] The refund, s, given in both options ensures that the conditions for I_i in equilibrium match those in equation (15), the first-best social optimum – i.e., ensures that the "right" products get recycled – *and* yields zero profits for recyclers in equilibrium.

[16] See OECD (1998) for a discussion of the German program.

[17] The results in this section are 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 pre-existing distortionary taxes, something we do not consider in this paper (see Fullerton and Wolverton, 2000, for an example).

recyclers is zero.[18] Therefore ρ_i will take one of two possible values, zero or the threshold, $\tilde{\rho}(s) = \{\rho_i \mid \gamma_1 - k(\rho_i) + s = 0\}$.[19] This result for ρ_i is a key difference between the constrained and unconstrained cases. The unconstrained case also has a threshold level of recyclability—that is, a level below which recyclers will not accept a product—but producers have the incentive to make products with recyclability levels above the threshold because they can get a higher price from consumers when they do. Consumers will pay more because they can get a higher payment from recyclers at the other end. Receiving payment is no longer possible in the constrained (second-best) setting.

We now consider the social planner's problem. Like the producers, the planner needs to choose α_i, q_i, and $\rho_i \in \{0, \tilde{\rho}\}$, but the planner has an extra choice to make, the choice of the recyclability threshold, $\tilde{\rho}$. For convenience, we consider this choice of $\tilde{\rho}$ separately. If the other three choices are made so as to yield the constrained optimum, then $\tilde{\rho}$ should be chosen to maximize the following expression:

(17)
$$\sum_i \max \left\{ \max_{q_i,\alpha_i} \left(V_q q_i - \alpha_i q_i (\gamma_1 + \gamma_2 - V_W H) - C^i(0,\alpha_i,q_i) \right), \max_{q_i,\alpha_i} \left(V_q q_i - \alpha_i q_i k(\tilde{\rho}) - C^i(\tilde{\rho},\alpha_i,q_i) \right) \right\}$$

In the curly brackets in equation (17), there are two terms: the first term is the contribution to social welfare made by product i when that product is not recyclable –namely, when $\rho_i = 0$; and the second term is the contribution to social welfare when the product is recyclable – i.e., meets the threshold, $\tilde{\rho}$. Equation (17) thus says that α_i and q_i should be chosen to maximize these contributions to social welfare and then the maximum of these two terms should be chosen to determine whether each i product should meet the recyclability threshold or not. Finally, the social planner chooses $\tilde{\rho}$, the threshold recyclability level, to maximize the sum of these expressions for all i products.

The first-order condition of equation (17) with respect to $\tilde{\rho}$ is:

$$(18) \sum_i I_i (C_\rho^i - k'(\tilde{\rho})\alpha_i q_i) = 0$$

This means that the optimal threshold level of recyclability, $\tilde{\rho}$, is where the average increase in production costs from an increase in $\tilde{\rho}$, per pound of output produced, just equals the marginal reduction in recycling costs.

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[18] This is the only viable interior solution to the maximization problem in (16). Otherwise, an interior solution would require $-C_\rho^i = 0$, but this is ruled out by the assumption that $C_\rho^i > 0$. A corner solution exists where $\rho_i = 0$.

[19] Equivalently, $\tilde{\rho}(s) = k^{-1}(\gamma_1 + s)$, where k^{-1} is the inverse of the k function.

The recycling subsidy, s, is the policy instrument that generates this choice of recyclability. At any threshold, the subsidy is equal to $k(\rho_i)-\gamma_1$, since this yields zero profits; equation (18) ensures the s that is chosen generates the constrained optimal threshold.

In characterizing the constrained optimal level of $\tilde{\rho}$, we assumed that the other variables could be set at their constrained optimal levels. This means that profit maximization (equation (16)) is consistent with the social planner's remaining choices. We write the social planner problem as in equation (14) but subject to the constraints that $\rho_i \in \{0, \tilde{\rho}\}$ and $I_i = I(\gamma_1 - k(\rho_i) + s)$:

(19)   max wrt $q_i \in R_+$, $\alpha_i \in R_+$, $\rho_i \in \{0, \tilde{\rho}\}$ $\forall i$,

$$\sum_i \left[V_q q_i - \alpha_i q_i \left((\gamma_1 + \gamma_2 - V_W H)(1 - I_i) + k(\rho_i) I_i \right) - C^i(\rho_i, \alpha_i, q_i) \right]$$

subject to $I_i = I(\gamma_1 - k(\rho_i) + s)$, $\forall i$.

We now compare equation (19) with equation (16), the profit maximization problem in the constrained case. The two equations are the same when

$$(1 - I_i)(\gamma_2 - V_W H) + (k(\tilde{\rho}) - \gamma_1) I_i = (1 - I_i)(f + t_0) + t_1 I_i$$

Either of the following two sets of instruments will satisfy the required condition and achieve the constrained optimal recyclability threshold, $\tilde{\rho}$:

Option 1:

$f = \gamma_2 - V_W H$
$s = k(\tilde{\rho}) - \gamma_1$
$t_1 = k(\tilde{\rho}) - \gamma_1$
$t_0 = 0$

Option 2:

$f = 0$
$s = k(\tilde{\rho}) - \gamma_1$
$t_1 = k(\tilde{\rho}) - \gamma_1$
$t_0 = \gamma_2 - V_W H$

Except for the tilde on $\tilde{\rho}$, these options look the same as those suggested in the previous section, where it was assumed that output taxes could depend on ρ_i. The current instruments do not achieve the first-best outcome but are implementable because they do not require output taxes or recycling subsidies to vary continuously with recyclability. Instead, they depend only on whether output meets the recyclability threshold or not – i.e., whether $I_i = 1$ or $I_i = 0$.

As in the previous section, a disposal fee alone is not sufficient to encourage DfE. The lack of a functioning recycling market is a second market failure in addition to the externality associated with waste disposal. Consequently, policy instruments need to be targeted at both disposal and recycling. Unlike the disposal fee, a deposit-refund can target both classes of output, that which is recyclable and that which is not.

5. Discussion and Extensions

Our primary objective in this paper is to capture some realistic features of household waste and recycling markets that have been ignored in other studies. These realistic features are: households recycle but are not paid for doing so, and products cannot be distinguished by their degree of recyclability. Some discussion of these two points seems in order. First, although households are not currently paid for the materials they set out at curbside, it is possible that they would be under some conditions. We have not considered that possibility here; we have simply compared the outcome when there is a working recycling market to one when prices are zero. A more complete model might explicitly model transaction costs in recycling markets and explore how such costs affect policy choices.[20]

Second, we have argued that it is only feasible to have policy instruments depend on whether a product actually is recycled, not on the product's degree of recyclability. Although we feel that this distinction is reasonable, a wider range of information is available about heterogeneous products and some of that information might be useful for setting policies. In general, it will be costly to collect such information and decide how to use it for the purposes of encouraging recyclability. Future work that explored such issues might be useful.

In the model, we have assumed that all recyclable products are recycled. In reality, some products that are eligible for the recycling bin will not make their way into the bin. In an earlier version of the model, we allowed for this by having a recycling "compliance rate" less than one. The basic outcome in the constrained setting—that producers choose a recyclability level of either zero or the threshold—was not altered by this modification to the model. Our basic policy conclusions did not change either, though the tax and subsidy rates varied with the compliance rate. If recycling compliance varies among product types, location, or some other consumer characteristic, however, there could be implications for policy. The constrained optimal output taxes might vary by more than just whether a product meets the recyclability threshold.

The recycling compliance issue is one facet of consumer heterogeneity, which we have ignored by assuming a representative consumer. Most of the ways in which consumers could differ do not affect our results. The most important concern is whether consumers differ in their propensities to recycle; although this could introduce complications for policymaking, it still would not significantly affect the basic model outcome. As long as markets remain competitive, firms will continue to face an inverse demand curve for their products that reflect the costs of recycling and disposal. They would still design their products to be either totally unrecyclable or to just meet the recyclability threshold. And it would still be possible to implement the constrained optimum with a modified deposit-refund scheme of the type we have derived in this paper.

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[20] The oil industry in western Canada runs a deposit-refund program for motor oil, oil filters, and oil containers. New products are subject to a tax and collectors of used oil, filters, and containers receive a refund (called a "return incentive") when they return the used products for recycling or reuse. On their own initiative, collectors are passing on a portion of the refund to households. Collectors receive from 8 to 10 cents/litre as a refund for used oil and are currently paying households about 3 cents/litre (McCormack, 2000). For a discussion of the used oil program, see http://www.usedoilrecycling.com/.

Real-world recycling deals with a variety of materials and production processes. These variables are ruled out in our model because we assume that a single type of material is used to produce the consumer product and that production costs monotonically rise with increases in recyclability. For some products, however, minimum production costs might be incurred at recyclability levels greater than zero (but below the threshold). This complicates the analysis and the determination of the constrained optimal level of the recyclability threshold, but it does not alter our basic conclusion that output taxes should differ between products that meet the threshold and those that do not.

In a recent model, Choe and Fraser (1999) allow for the possibility of illegal dumping and what they refer to as waste reduction efforts on the part of the household—activities such as composting, leaving lawn clippings on the lawn, donating to charity, and so forth. We have ignored such options here; if they are important, then optimal behavior might not be induced by output taxes alone. For example, a disposal fee would encourage a household to leave lawn clippings on the lawn, but it is difficult to think of an output tax that would bring about similar behavior. This might be an important issue for policymakers, but one that we ignore since our focus is on identifying policies that induce efficient DfE.

6. Conclusion

Producers receive inadequate signals from consumers to undertake DfE when consumers are not paid for their recyclables. Even a tax on disposal does not get around this problem. It encourages recycling, but all products that are tossed in the recycling bin—namely, those that meet a certain threshold level of recyclability—are of equal value from the consumer's perspective. Consumers will not pay a premium for aluminum cans over plastic bottles or for certain types of easily recycled plastics over less easily recycled ones, as long as all of these materials are accepted by recyclers. If the government can set output taxes and recycling subsidies that vary with product recyclability, the problem can be overcome, but this would require designation of a single, identifiable measure of recyclability, something that would be virtually impossible in practice. Setting different tax and subsidy rates for different products would be an administratively costly and politically infeasible alternative.

We argue that there are no feasible policy instruments to generate the first-best outcome in this case. Instead, we focus on a constrained (second-best) optimum in which consumers are not paid for recycling and output taxes cannot depend on recyclability. The best outcome that can be reached in this setting is one in which all products that are recycled meet the same recyclability threshold. This constrained optimal threshold balances the increase in production costs incurred when product recyclability is increased with the savings in recycling costs. This constrained optimal outcome can be implemented with fairly straightforward policy instruments. In particular, a deposit-refund continues to be the instrument of choice, as it is in a first-best setting. Here, we show that with two different rates for the deposit, one that applies to recyclable products and one that applies to nonrecyclable products, the deposit-refund will yield the constrained optimum.

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