A Market-Based Recycling Subsidy

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Abstract

When direct taxation on waste disposal is not a feasible option, it is well established that a combination of a tax on production and a subsidy for recycling is necessary to attain efficient levels of waste disposal. We propose a new instrument that possesses some preferable properties over conventional instruments: a tax on production and a market-based subsidy for recycling. In this market, recyclers can sell credits that can be used by firms to reduce their tax base. The credit's price acts as a subsidy for recycling and efficient levels of production, recycling and waste are achieved in equilibrium. The advantages of this instrument are: (i) it gives flexibility to allow the separation of the production and recycling activities; and (ii) it lowers the financial burden on government. Additionally, we show that our proposed instrument can also provide incentives for "design for environment".

JEL classification: H21; H23; Q58.

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1 Introduction

Since Dinan (1993), solutions to reach the optimal level of production, recycling and waste generation in an economy have focused on two-part instruments. Because direct Pigouvian taxation on waste disposal — like Pay As You Throw (PAYT) pricing — give incentives to illegal disposal, authors have proposed a combination of a tax on production and a subsidy for recycling (TS). TS have at least three advantages over direct taxation on waste disposal: 1) it does not encourage illegal dumping; 2) has less monitoring costs when applied upstream; and 3) it has less evasion problems since taxes (and subsidies) are applied on sales (see Walls, 2011).

Deposit-Refund (DR) schemes are the most common application of TS-inspired policies. A DR scheme combines a tax on production or consumption ("upstream" or "downstream" applications, respectively) with a rebate when the product or its packaging is returned for recycling so the government only collects the net tax.[1] "Bottle bills" is a popular example; as of 2013, eleven states in the United States, and all but one of the Canadian provinces have bottle bills in place. Typically, retailers pay distributors a deposit for each can or bottle that is purchased. Retailers in turn, charge consumers with the deposit, which is returned if the can or bottle is brought back for recycling. This rebate is then discounted from deposits paid by the retailer to the distributor. Other relevant applications of similar DR schemes are in lead acid batteries and tires in the U.S., and motor oil in Canada and California (see Walls, 2011).

The conceptual foundation of any system that gives incentives for the optimal generation of waste is that only non-recycled units must be taxed. Noticeably, any mechanism will require government intervention, so comparisons between schemes should be done not only on the basis of the achievement of the optimal generation of waste, but also on the financial burden for the government.

In this paper, we propose a two-part instrument that is incentive-equivalent to any TS policy — maintaining the advantages over direct taxation stated above —, but that possesses some preferable properties over conventional instruments. We consider a tax on production and the creation of a related market for credits. These credits can be sold by recyclers and used by final good producers to reduce the tax base. The credit's price acts as a subsidy for recycling and in equilibrium efficient levels of production, recycling and waste are achieved.

The advantages of this instrument are: (i) it gives flexibility to allow the separation

[1] To our knowledge, there are no TS applications other than DR schemes. What is indeed common to find are subsidies for recycling that are not matched with a tax on the produced good.

of the production and recycling activities; and (ii) it lowers the financial burden on government. While in a DR scheme the government only collects taxes (does not assign monetary subsidies), a substantial part of incentives are restricted to a single actor. Taxes and the rebate (that acts as the subsidy for recycling) are subject to the same agent, typically the producer, imposing restrictions on the recycling chain. In turn, in a standard TS, when the tax and the subsidy are assigned to different agents, the government has both to collect the tax and assign the subsidy, but this allows for a separation of the production and recycling activities. Our instrument maintains the virtues of both alternatives: government only collects the net tax, does not compute and assign a subsidy, reducing the financial burden for the government, and it allows for the separation of the production and recycling activities.

We also show how the instrument can be used to provide incentives for efficient "design for environment" (DfE), a question that has been given substantial attention in the literature. Intuitively, incentives that depend on the degree of recyclability can induce proper design by correcting this externality (Fullerton and Wu, 1998; Calcott and Walls, 2000, 2005; Walls and Calcott, 2000). We show that it is possible to attain the first best results with a more general version of our mechanism that makes the percentage of the tax base that is reduced by the credit dependent on the degree of recyclability.

The remainder of the paper is organized as follows. In the next section we present a model and characterize the optimal allocation of resources in an economy where a unique final good is produced with virgin and recycled inputs. Section 3 describes our proposed instrument and in section 4 we show how the instrument can provide incentives for efficient design for environment (DfE). Conclusions are presented in section 5.

2 The Model

The economy consists of three representative agents: A consumer, a producer and a recycler.[2] The consumer derives utility $U(q, m) = m + V(q)$ from q units of a final good — with price p — and m units of a numeraire good. We assume $V(q)$ is strictly concave and an initial endowment M of the numeraire good. The consumer maximizes utility by choosing the consumption bundle subject to the budget constraint $pq + m \leq M$.

The firm uses two imperfect substitutes (both measured in tons) as inputs: virgin material (x) and recycled material (r), to produce $f(x, r, \theta) = \alpha q$ tons of the final good with a strictly concave production function. The weight per unit is $\alpha > 0$ and $\theta \in [\underline{\theta}, \bar{\theta}]$ is its degree of recyclability. It is useful to think of the latter as a summary measure of

[2]A similar approach can be found in Calcott and Walls (2000).

the product's design characteristics that make it more or less difficult to recycle.[3]

The firm incurs both direct and indirect costs when choosing to employ more environmentally friendly product design. Direct costs are design activities, represented by a strictly convex design cost function $g(\theta)$. Indirect costs — including lower production and marginal productivity of inputs — also increase when the designer factors in recyclability in the making of the product. These arise from the requirement for a more sophisticated technology in production that diverts resources from production.

The recycler collects and processes tons of residual (r) that results from consumption and sell them back to the firm at a price z per ton.[4] The cost of recycling is $c(r, \theta)$, that is increasing and strictly convex in r and decreasing in the degree of recyclability.

The amount of waste (in tons) that is disposed in the landfill is $W = \alpha q - r$. Each ton imposes a social external cost of $\beta \geq 0$, which is borne by the social planner. The price of virgin material inputs is exogenous and equal to $v > 0$.

3 The Instrument - Taxes and credits market.

We first describe the benchmark equilibrium without considering design for environment — when the degree of recyclability of the final good is not a choice variable — and traditional approaches that aim to achieve it. This is for illustrative purposes as the simplified model clarifies the intuition behind the proposed instrument. In section 4, we solve a more general case where the firm chooses the degree of recyclability, and we study how it may be adapted to induce proper incentives for DfE.

3.1 Social optimum benchmark

We solve the problem of the social planner who chooses production levels, specifies use of inputs and assigns consumption bundles subject to the aggregate resource (M) and the technology restrictions of the economy. The planner solves:

$$\begin{aligned} \max_{\{q,m,x,r\}} \quad & m + V(q) - \beta(\alpha q - r) && (\mathrm{P}_1) \\ \text{s.t.} \quad & m + vx + c(r,\theta) + g(\theta) \leq M \\ & \alpha q = f(x, r, \theta) \end{aligned}$$

[3]Examples include the number of different types of materials, wrapping and disassembly characteristics or information on material contents.

[4]Our results can be extended to the case where recycled inputs do not have re-use at all (e.g batteries), or when they are used in the production of a different final good. Recycled tires, for example, may be re-used to build roads or sports facilities.

The sufficient first order conditions for maximization are:[5]

$$[x]: \quad v + \beta f_x = \frac{f_x V'(q)}{\alpha} \tag{1}$$

$$[r]: \quad c_r + \beta f_r = \frac{f_r V'(q)}{\alpha} + \beta \tag{2}$$

The social marginal cost of the use of each input must equal its marginal benefit to society. In addition to the cost upon purchase, each input contributes to the production of goods that end up in the landfill with an additional associated cost of β. The use of recycled materials therefore has a social benefit β for each ton that is diverted from the landfill. Conditions 1 and 2 determine conditional inputs use. Plugging them in the production function we can find the social optimum final good production level. We will refer to the solution of P_1 — $\{q^*, m^*, x^*, r^*\}$ — as the social optimum.[6]

Figure (1) shows two known alternative instruments to achieve first best results to the social planner problem. The first is a PAYT that charges a tax τ for each ton of waste deposited in the landfill. The second is a TS instrument consisting of: (i) A tax t per ton of the final good production such that $p' - p = t$, where p' and p are the demand and supply final good prices; (ii) A subsidy s for recyclers such that $z - z' = s$ where z' and z are the demand and supply price of recycled material.

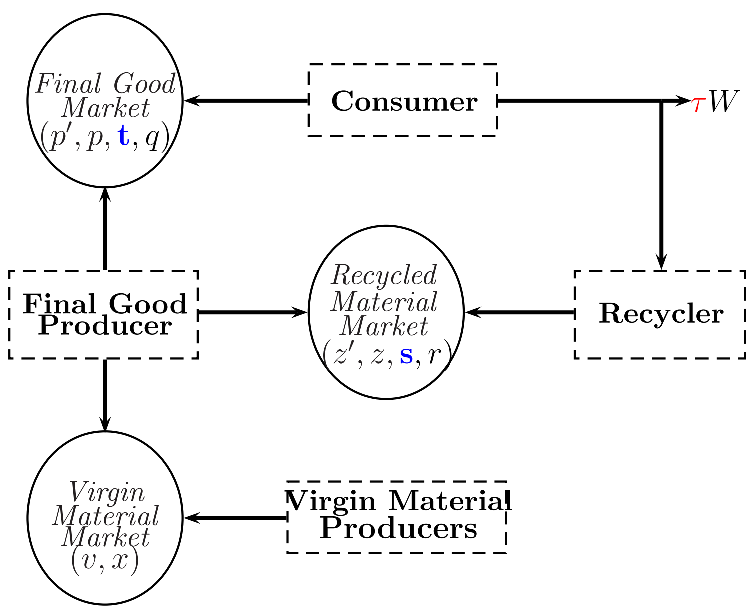

Figure 1: Markets and alternatives for regulation: *PAYT* tax (red) and *TS* (blue)

[5] We use Theorem 1 in Arrow and Enthoven (1961), that provides a result for the first order conditions in a constrained maximization problem to be sufficient for a maximum.

[6] It can be shown that given our assumptions made about preferences and technology this solution is unique. Inada conditions on the production function are sufficient conditions for a unique maximum.

Direct Pigouvian taxation (PAYT) is considered to be impractical as it gives incentives to illegal disposal of waste. In turn, there is a financial burden associated with assigning a subsidy as part of a TS scheme. Consequently, it is worth studying alternatives that can provide the same incentives for optimal levels of recycling and waste disposal at lower costs for the government. Deposit Refund schemes go a long way in this direction. In this case, the government does not actually assign a direct monetary subsidy, but it acts indirectly through the rebate. This is an interesting feature, but it is achieved at the cost of forcing the producer to be part of the recycling chain. Only when he receives the product back for recycling he is able to discount it from the total tax to be paid. In the next section we describe our proposed instrument. Its most important feature is that it maintains the indirect subsidy of DR schemes without the cost of forcing the producer to be part of the recycling chain.

3.2 The Proposed Instrument

We propose a new instrument that has relevant policy advantages over the alternatives discussed above. It can be considered as an amended TS that maintains its successful features (optimal production, recycling and waste generation without illegal disposal) while reducing government intervention.

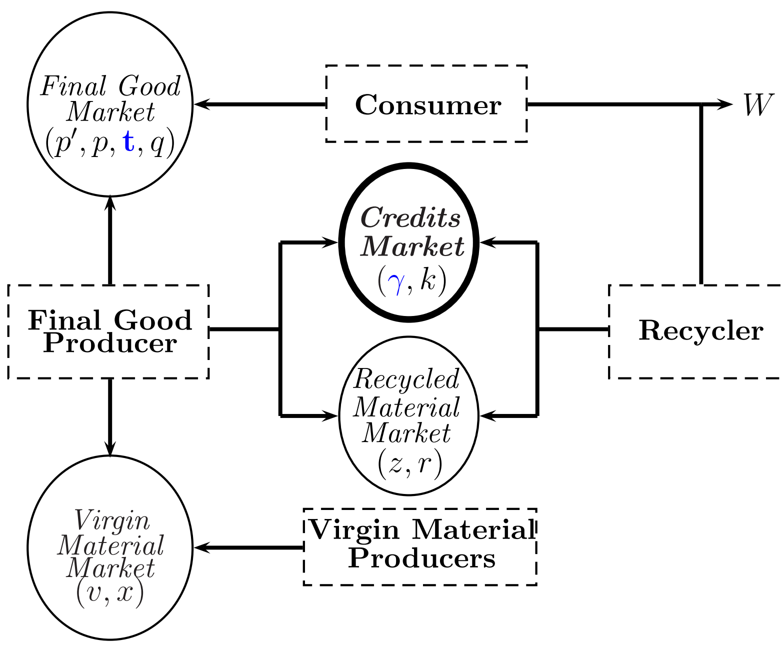

Figure 2: The Proposed Instrument I=$\langle t, \rho\rangle$

We consider an instrument I=$\langle t, \rho\rangle$ consisting of a per-ton tax t on production and a credit issued by the recycler that allows the firm to reduce the tax base by $\rho > 0$. This instrument works as depicted in Figure (2): The recycler collects and sells residuals and sells credits with the regulatory restriction that the amount of credits can not exceed the total tonnage recycled (i.e $k \leq r$). The firm is taxed by an amount t per ton of production and buys credits from the recycler. Therefore, if the firm produces αq tons and buys k credits at a price γ each, then it pays $t(\alpha q - \rho k)$ in taxes and γk for the credits. Thus, when facing prices (z, v, γ), the firm solves:

$$\begin{aligned} \max_{\{q,r,x,k\}} \quad & \Pi^P = pq - zr - vx - g(\theta) - t\left(\alpha q - \rho k\right) - \gamma k \\ \text{s.t.} \quad & \alpha q = f(x, r, \theta) \end{aligned}$$

Note that if $t\rho > \gamma$ the objective function is increasing in k. For this reason, demand for credits k^D is:

$$k^D = \begin{cases} 0 & \text{if } \gamma > t\rho \\ (0, \infty) & \text{if } \gamma = t\rho \\ \infty & \text{if } \gamma < t\rho \end{cases} \tag{3}$$

Since this is a concave optimization problem, the first order conditions are sufficient for a maximum. Hence, the maximization conditions for the firm are:

$$[x]: \quad v + tf_x = \frac{f_x p}{\alpha} \tag{4}$$

$$[r]: \quad z + tf_r = \frac{f_r p}{\alpha} \tag{5}$$

The recycler, in turn, maximizes profits subject to two constraints. The first is related to the feasibility of the recycling process, namely the recycler can only obtain strictly less tons of recycled material than available tons of waste. The second is the regulatory restriction described previously.

$$\begin{aligned} \max_{\{r,k\}} \quad & \Pi^R = zr + \gamma k - c(r, \theta) \\ \text{s.t.} \quad & r \leq \alpha q \\ & k \leq r \end{aligned}$$

The objective function is strictly increasing in k for any $\gamma > 0$, so the supply of credits is $k^S = r$ and the implicit price per ton of recycled material is $z + \gamma$. Since this is again a concave maximization problem with linear constraints, the first order conditions are sufficient for a maximum:

$$[r]: \quad z + \gamma = c_r \tag{6}$$

The first order condition above determines the supply of recycled material. Figure (3) shows the markets for both credits and recycled materials. In the former market the demand is infinitely elastic, whereas supply is perfectly inelastic. Notice that the credit supply will be endogenously determined by the equilibrium quantity of recycled material. In the recycled material market, the demand has a negative slope whereas supply is upward-sloping.

From (3), the unique equilibrium price for credits is $\gamma^* = t\rho$. Equations (4)-(5) are the demands for inputs; the demand for recycled material (resp. virgin material) represents the net marginal benefit that results from f_r/α (resp. f_x/α) more units sold at a price p and a cost that includes, in addition to the price z, the tax t on those f_r (resp. f_x) extra tons produced.

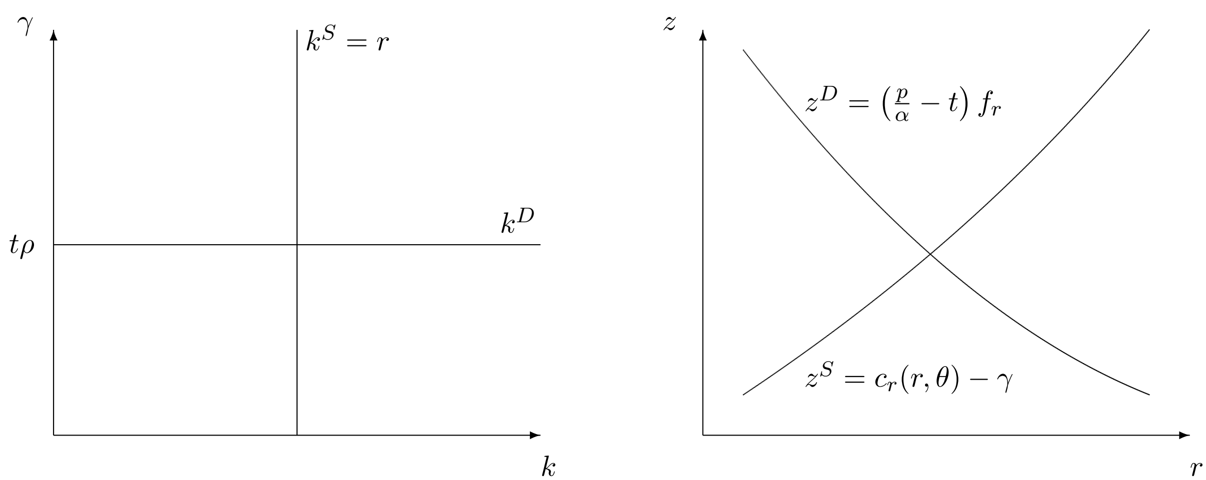

Figure 3: Equilibrium in Credits Market & Recycled Material

The consumer optimization condition equates the price to the marginal utility so $V'(q) = p$. Combining this with (3)-(5) and (6) we have:

$$[x]: \quad v + tf_x = \frac{f_x V'(q)}{\alpha} \tag{7}$$

$$[r]: \quad c_r + tf_r = \frac{f_r V'(q)}{\alpha} + \gamma^* \tag{8}$$

Now that we have solved both the social optimum benchmark and the decentralized model, we can clearly identify the conditions required to decentralize the former equilibrium. Since ours is a general equilibrium model, we need one condition per market.

(i) Credits Market Equilibrium $\gamma^* = t\rho$.

(ii) Virgin Material $t = \beta$ so that condition (7) replicates (1).

(iii) Recycled Material $t = \gamma^* = \beta$ so that condition (8) replicates (2).

Notice that equations (1) and (2) determine the equilibrium use of inputs. Plugging them in the production function we can find the final good production. To clear this market we use $V'(q) = p$ to find the market clearing price. Clearly, if $\rho = 1$ and $t = \beta$ then our proposed instrument replicates the social optimum. The instrument is incentive equivalent to a TS; marginal benefits for the recycler are increased by an amount equal to the social cost of waste. That is the social optimum and the traditional result of the literature (Dinan, 1993). The difference here is that the subsidy is determined by the equilibrium price $\gamma^* = \beta$ and is assigned to recyclers by producers, not by the government.[7]

Nonetheless, the proposed instrument outperforms known applications of TS in two ways. First, the instrument gives correct incentives to recycle at a reduced financial burden. Because the subsidy is endogenously determined by the market, transactions with the government are limited to the collection of taxes on produced units that are not recycled and there is no need to actually assign a monetary subsidy.

Second, DR can actually attain the results stated above, but at a cost: only the agent who is charged the tax is allowed to receive the subsidy. For example, consider bottle bills; producers are mandated to accept returned containers in exchange for a refund to consumers and are finally taxed only for non-returned items. One can notice that only non-returned units are finally taxed, which ensures that incentives are aligned. However, even if the government does not assign a subsidy, it is forced to make producers part of the recycling chain, which may be an inefficient solution. The instrument we propose allows for the separation of the recycling and production activities, while at the same time eliminates the need to assign a monetary subsidy.

[7] The multiplier ρ, acts simply as a unit convertor that should balanced in the market. If the firm is allowed to discount two tons for each credit bought in the market, in order to replicate the first best results, recyclers should be allowed to generate only half a credit for each ton they produce. This condition should hold in order to not over-incentivize recycling.

4 Incentives for DfE

Incentives for environmentally friendly design have been actively discussed in the literature, with much of the focus on the degree of recyclability as the DfE decision variable for producers. If consumers could sell their residuals to recyclers, firms will may have incentives to produce more environmentally friendly designs since consumers would be willing to pay more for goods that are more valuable to recyclers (Fullerton and Wu (1998)). In more realistic settings with transaction costs that prevent the existence of these markets, subsidies to recyclability can induce proper design (Fullerton and Wu, 1998; Calcott and Walls, 2000; Walls and Calcott, 2000).

When the degree of recyclability is a decision variable, there is a "new" social optimum benchmark that considers the benefits and costs of the final good's design properties. In the next section, we state the conditions of this new social optimum and show how our proposed instrument can be adapted to achieve it.

4.1 New Social Optimum Benchmark

When the degree of recyclability is a decision variable, the modified social planner's problem is:

$$\begin{aligned} \max_{\{q,m,x,r,\theta\}} \quad & m + V(q) - \beta(\alpha q - r) \\ \text{s.t.} \quad & m + vx + c(r,\theta) + g(\theta) \leq M \\ & \alpha q = f(x,r,\theta) \end{aligned} \tag{P$_2$}$$

The following first order conditions characterize the new social optimum:

$$[x]: \quad v + \beta f_x = \frac{f_x V'(q)}{\alpha} \tag{9}$$

$$[r]: \quad c_r + \beta f_r = \frac{f_r V'(q)}{\alpha} + \beta \tag{10}$$

$$[\theta]: \quad g_\theta - v\frac{f_\theta}{f_x} = -c_\theta \tag{11}$$

Equations (9) and (10) are the same first order conditions as in the problem with exogenous DfE. Condition (11) in turn equates the marginal benefit of increasing the degree of recyclability, which is given by the cost reduction for the recycler ($-c_\theta$), with its marginal cost, which is given by the increase in design costs for the producer (g_θ) and the value of the reduction in production, which is vf_θ/f_x.

We will refer to this new social optimum benchmark as $\{q^\star, m^\star, x^\star, r^\star, \theta^\star\}$, which is the solution to P_2. Notice that the private solution for the degree of recyclability is $\theta = \underline{\theta}$ since higher θ only increases design costs by g_θ and reduces the value of the reduction in production given by vf_θ/f_x. This is clearly different from the social optimum that involves $\theta^\star > \underline{\theta}$. There is clearly a positive design externality from the firm to the recycler.

4.2 The Proposed Instrument with DfE

The proposed instrument, when producers make DfE decisions, is again a two-part instrument that maintains the tax and the market for credits. The adaptation of the mechanism depends heavily on the observability of θ. We assume that the degree of recyclability is not only observable but also that the firm can commit to their decisions regarding θ, so there is no reason to monitor it. We later discuss how the instrument could work without this observability/commitment assumption. The producer is offered a menu of tax base reductions that depend on the degree of recyclability $\rho(\theta)$. The firm solves:

$$\begin{aligned} \max_{\{q,r,x,k,\theta\}} \quad & \Pi^P = pq - zr - vx - g(\theta) - t\left(\alpha q - \rho(\theta)k\right) - \gamma k \\ \text{s.t.} \quad & \alpha q = f(x, r, \theta) \end{aligned}$$

As in the previous case, the unique equilibrium price for the credit is $\gamma^\star = t\rho(\theta^\star)$. However, the producer has incentives to increase θ in order to reduce the tax base. The first order conditions are:

$$\begin{aligned} [x]: \quad & v + tf_x = \frac{pf_x}{\alpha} \\ [r]: \quad & z + tf_r = \frac{pf_r}{\alpha} \\ [\theta]: \quad & g_\theta - p\frac{f_\theta}{\alpha} = -t\left(f_\theta - k\rho_\theta(\theta)\right) \end{aligned}$$

The recycler's problem remains the same, so the optimization condition is still given by (6). Combining the optimization conditions of all agents yields:

$$[x]: \quad v + tf_x = \frac{f_x V'(q)}{\alpha} \tag{12}$$

$$[r]: \quad c_r + tf_r = \frac{f_r V'(q)}{\alpha} + \gamma^\star \tag{13}$$

$$[\theta]: \quad g_\theta - f_\theta \left(\frac{V'(q)}{\alpha} - t \right) = tk\rho_\theta \tag{14}$$

The difference now is that there is an extra condition that we need to replicate for the degree of recyclability. Thus, to replicate the social optimum we need:

(i) Credits Market Equilibrium: $\gamma^\star = t\rho(\theta^\star)$.

(ii) Virgin Material: $t = \beta$ so that condition (12) replicates (9).

(iii) Recycled Material: $t = \gamma^\star = \beta$ so that condition (13) replicates (10).

(iv) Degree of Recyclability: Condition (14) replicates (11) if:

$$\rho_\theta = \frac{-c_\theta(r^\star, \theta)}{tk^\star} = \frac{-c_\theta(r^\star, \theta)}{tr^\star}$$

It follows from (i)-(iii) that we still need $\rho(\theta^\star) = 1$ and $t = \beta$. Integrating the condition in (iv) and using $\rho(\theta^\star) = 1$ we have:

$$\rho(\theta) = 1 + \frac{[c(r^\star, \theta^\star) - c(r^\star, \theta)]}{\beta r^\star} \tag{15}$$

This describes the menu of tax base discounts depicted in Figure (4) that the planner could offer to the producer as a function of the product's degree of recyclability.

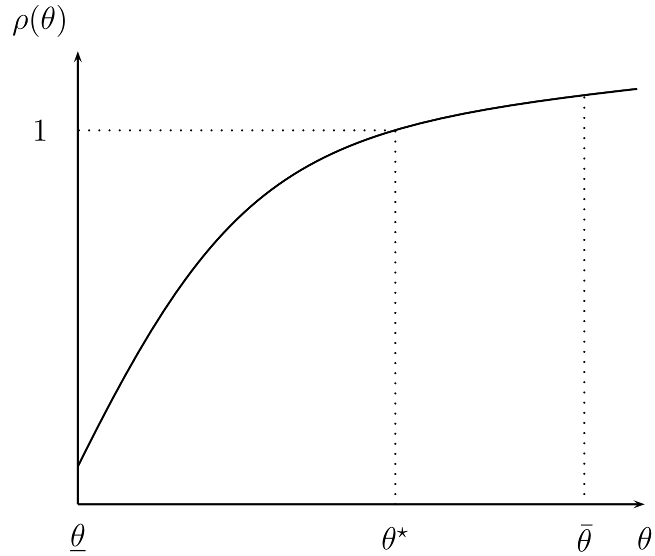

Figure 4: Menu of Discounts $\rho(\theta)$

Notice that $r^\star$ and $\theta^\star$ are known for the planner so our proposed instrument is $I(\theta) = \langle \beta, \rho(\theta) \rangle$ with $\rho(\theta)$ satisfying (15), which has been shown to achieve the social optimum in the DfE setting.

4.3 Observability of θ and Implementation

Suppose now that the degree of recyclability is difficult or costly for the authority to observe. For example, the firm's efforts with regards to DfE may take many different forms and the authority's capabilities and resources to evaluate them may be very limited. Once θ is observed by the authority and the credits granted, the firm would have little incentive to continue producing under θ if there is no effective enforcement. These two more realistic assumptions would suggest that the proposed instrument would fail to achieve the first best result under DfE. However with minor changes it is still possible to obtain the benefit of this market-based recycling subsidy system.

This problem is based on the fact that DfE is costly to observe and monitor. However if the authority focus its efforts in determining and developing capabilities to enforce just $\theta^\star$, then it is possible to achieve the first best at minimum cost for the government, by offering an even simpler menu $\hat{\rho}(\theta)$, where

$$\hat{\rho}(\theta) = \begin{cases} 1 & \text{if } \theta = \theta^\star \\ 0 & ow. \end{cases}$$

If the planner offers the instrument $\hat{I}(\theta) = \langle \hat{\rho}(\theta), \beta \rangle$, for fixed equilibrium prices

$\{p^\star, z^\star, v^\star, \gamma^\star\}$ the firm solves:

$$\max_{\{q,r,x,k,\theta\}} \quad \Pi^P = p^\star q - z^\star r - v^\star x - g(\theta) - \beta\left(\alpha q - \hat{\rho}(\theta)k\right) - \beta\hat{\rho}(\theta)k$$
$$\text{s.t.} \quad \alpha q = f(x, r, \theta)$$

One way to interpret this menu is to identify $\theta^\star$ as a production standard defined and easily observable by the regulator.[8] Then the firm has to decide whether or not to implement the minimum standard and enable the use of credits to reduce its tax base. In fact, in a more general way, we can consider a set of finite standards S. As long as $S \subset [\underline{\theta}, \bar{\theta}]$ and there is one standard equal to $\theta^\star$, our proposed instrument with standards also achieves the first best outcome.[9]

5 Conclusions

When direct taxation is not a feasible option because of incentives for illegal disposal, a tax on production and a subsidy for recycling (TS) are preferable to achieve the social optimum levels of production, recycling and waste.

We propose a new two-part instrument that is incentive-equivalent to any TS policy, but that possesses some relevant policy advantages over traditional instruments. This instrument maintains the tax on production, but creates a market for recycling credits that can be used by the firm to reduce the tax base. The credit's price acts as a market-based recycling subsidy and efficient levels of production, recycling and waste are achieved in equilibrium. The advantages of this instrument are: (i) it gives flexibility to allow the separation of the production and recycling activities; and (ii) it lowers the financial burden on government. This instrument is a welfare enhancing alternative if the costs of managing the market for credits are smaller than the costs of assigning the monetary subsidy, provided the efficiency gains of the separation of the production and the recycling activities are exploited.

When we consider design for environment decisions, our instrument offers a menu of tax base reductions to the producer, which depend on the product's degree of recyclability. In this case the relevant social optimum can also be achieved.

[8] This approach using standards has been studied before by Palmer and Walls (1997) and Ino (2011).

[9] Formally, since $(x^\star, r^\star, \theta^\star) = \arg\max_{(x,r,\theta)\in\mathbb{R}^2_+\times[\underline{\theta},\bar{\theta}]} \Pi^P(x, r, \theta)$ then $(x^\star, r^\star, \theta^\star) = \arg\max_{(x,r,\theta)\in\mathbb{R}^2_+\times S} \Pi^P(x, r, \theta)$, the social optimum is the same.

6 Appendix

A. The Social Planner Problem without *DfE*: Rewrite the social planner as

$$\begin{aligned}\max_{\{q,m,x,r\}} \quad & m + V(q) - \beta(\alpha q - r) \\ \text{s.t.} \quad & M - m - vx - c(r,\theta) - g(\theta) \geq 0 \\ & f(x,r,\theta) - \alpha q = 0\end{aligned}$$

Since $V(q)$ is strictly concave in q and all other terms are linear, the objective function is concave in (q, m, x, r). In addition, since $c(r, \theta)$ is a convex function and the production function is concave, all of the restrictions in the maximization problem are concave functions. Since concavity implies quasi-concavity, the social planner problem is one of maximizing a concave function subject to quasi-concave restrictions. We now use Theorem 1 in Arrow and Enthoven (1961) that guarantees that first order conditions are sufficient for a maximum. Thus

$$\mathcal{L} = V(q) + m - \beta(\alpha q - r) + \lambda_1[M - m - vx - c(r,\theta) - g(\theta)] + \lambda_2[f(x,r,\theta) - \alpha q]$$

The first order conditions are: $[q] : V'(q) - \beta\alpha - \lambda_2\alpha = 0; [m] : 1 = \lambda_1; [x] : \lambda_2 f_x = \lambda_1 v; [r] : \beta + \lambda_2 f_r = c_r; [\lambda_1] : M - m - vx - c(r,\theta) - g(\theta) = 0; [\lambda_2] : f(x,r,\theta) - \alpha q = 0$ This can be reduced to:

$$\begin{aligned} v + \beta f_x &= \frac{f_x V'(q)}{\alpha} \\ c_r + \beta f_r &= \frac{f_r V'(q)}{\alpha} + \beta \end{aligned}$$

Which are the conditions (1) and (2) for the first best benchmark without *DfE*.

B. The Social Planner Problem with DfE: The social planner maximizes the same problem as before but here chooses (q, m, x, r, θ). Since $g(\theta)$ is a convex function, all of the restrictions in the maximization problem are concave functions. Thus, we can use Theorem 1 in Arrow and Enthoven (1961) that guarantees that first order conditions are sufficient for a maximum. All first order conditions are the same except for an additional one with respect to θ:

$$[\theta] : \quad - c_\theta - g_\theta + \lambda_2 f_\theta = 0$$

Boundary conditions $g_\theta(\theta = \underline{\theta}) = -f_\theta(x, r, \theta = \underline{\theta}) = 0$ guarantee the solution to be unique. Thus, the first best benchmark with DfE requires

$$\begin{aligned} v + f_x\beta &= \frac{V'(q) f_x}{\alpha} \\ c_r + \beta f_r &= \frac{V'(q) f_r}{\alpha} + \beta \\ g_\theta - \frac{v f_\theta}{f_x} &= -c_\theta \end{aligned}$$

Which are conditions (9)-(11) for the first best benchmark in a context with DfE.

C. Recyclers Problem: To solve the recycler's problem we set up a Lagrangean and maximize with respect to $\{r, k\}$ as follows:

$$\mathcal{L} = zr + \gamma k - c(r, \theta) + \delta_1[\alpha q - r] + \delta_2[r - k]$$

The first order conditions are $[r] : z - c_r - \delta_1 + \delta_2 = 0; [k] : \gamma - \delta_2 = 0; [\delta_1] : \alpha q - r > 0, \delta_1[\alpha q - r] = 0$ and $\delta_1 = 0; [\delta_2] : r - k \geq 0, \delta_2[r - k] = 0$ and $\delta_2 \geq 0$. This can be reduced to the following first order conditions are:

$$\begin{aligned} [r] &: \quad z + \gamma = c_r \\ [\delta_1] &: \quad \alpha q - r > 0 \\ [\delta_2] &: \quad r = k \end{aligned}$$

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