JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT **36**, 131–148 (1998)
ARTICLE NO. EE981044

Policies for Green Design[1]

Don Fullerton

Department of Economics, University of Texas at Austin, Austin, Texas 78712

and

Wenbo Wu

H. John Heinz III School of Public Policy and Management, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

Received June 18, 1997; revised June 1998

A simple general equilibrium model is used to analyze disposal-content fees, subsidies for recyclable designs, unit-pricing of household disposal, deposit-refund systems, and manufacturer ‘‘take-back’’ requirements. Firms use primary and recycled inputs to produce output that has two ‘‘attributes’’: packaging per unit output, and recyclability. If households pay the social cost of disposal, then they send the right signals to producers to reduce packaging and to design products that can more easily be recycled. If garbage is collected for free, then socially optimum attributes can still be achieved by a tax on producers' use of packaging and subsidy to recyclable designs. © 1998 Academic Press

Key Words: green design; source reduction; household waste; disposal content; deposit refund; green dot; packaging tax; recycling subsidy.

A consumer durable may be composed of a hundred different parts, each designed by a different team that selects the best type of plastic or other material for its own purpose. Assembly may use different sized bolts, or one-way fasteners. The firm does not care about disassembly because the buyer does not care; the unit can most often be discarded for free. If somebody had to worry about the social cost of disposal, however, a better solution might use a design with fewer types of plastic, and one sized bolt, for easier subsequent disassembly and recycling.

The U.S. Office of Technology Assessment [33] defines green design as a ‘‘process in which environmental attributes are treated as design objectives.’’ The purpose is to reduce pollution at its source, that is, to ‘‘avoid the generation of waste in the first place’’ [33, p. 7]. It also finds that ‘‘better product design offers new opportunities to address environmental problems, but that current governmental regulations and market practices are not sufficient to fully exploit these opportunities’’ [33, p. 3].

[1] We are grateful for financial assistance from the National Science Foundation's Grant SBR-9413334 and EPA Grant R824740-01-0, and for helpful suggestions from Bob Haveman, Arik Levinson, Wally Oates, Hilary Sigman, Lowell Taylor, Margaret Walls, anonymous referees, and various seminar participants. This paper is part of NBER's research program in Public Economics. Any opinions expressed are those of the authors and not those of the National Science Foundation, the EPA, or the National Bureau of Economic Research.

0095-0696/98 $25.00

A variety of reforms have been proposed to deal with these perceived problems, both at state and federal levels. Packaging could be subjected to standards, taxes, deposit-refund systems, or recycling requirements. Other proposals would tax toxic substances, require a minimum percentage of recycled content in certain products such as newspapers, require manufacturers to "take back" certain products such as batteries, provide tax credits for machinery used in recycling, require local governments to collect household recycling at the curb, and require households to pay a price per unit of garbage. Table I lists 34 such policy interventions, from a table in OTA [33, p. 17].

Existing studies have analyzed economic and environmental effects of selected policies, usually in partial equilibrium models, but comparison across policies is made difficult by differences in the design of those studies.[2] In this paper, we extend prior contributions by constructing a single general equilibrium model that can be used to compare virtually all of the 34 policies listed in Table I. A single framework is important, because these policies may not be consistent with each other. For example, the U.S. General Accounting Office [36] points out that a major effort to collect curbside recycling would not work in places where the recyclable materials are already diverted by a beverage container deposit-refund system.

This model has several important attributes. First, it encompasses the entire life-cycle of each product from design to production, packaging, sale, use, and disposal. Table I shows how proposed policies target different stages of this life-cycle, and our model shows how the stages are connected. Policies to affect product design will also affect product disposal, and vice versa. Another policy directed at consumers may similarly affect market prices and firm behavior.[3] Our model can be used to find the equivalence between different policies directed at producers, consumers, and waste managers.

Second, the model can also be used to analyze the distinction in Table I between regulatory instruments and economic instruments. Since we assume perfect certainty, we can show how a behavioral mandate raises production costs and thus product prices in a way that may be equivalent to a price incentive.[4]

Third, the model includes a negative externality from total waste generation, and it specifies exactly when a particular market failure precludes exchange at an equilibrium price. This attribute is important, because many of the proposals in Table I really address different problems altogether. The goal is not recycling *per*

[2] Policy options are discussed in Miedema [16], *Project 88—Round II* [23], and the U.S. Congressional Budget Office [32]. A complete review of analytical studies is not possible here, but several are noteworthy. In a model of the toxic disposal market, Sullivan [31] finds the optimal subsidy on legal disposal and degree of enforcement against illegal disposal. Bohm [3] and Dobbs [8] avoid the problem of enforcement by finding the optimal tax on the product (deposit) and subsidy to proper disposal (refund). Sigman [27] compares policies for lead recycling, while Palmer and Walls [20] assess efficiency implications of an output tax, recycling subsidy, and recycled-content standard. Such policies are implemented numerically in Palmer, Sigman, and Walls [21] for several different materials to find specific effects on source reduction, recycling, and waste.

[3] Thus disposal charges can reduce initial demand for the product. The U.S. Environmental Protection Agency (EPA, [34]) places this kind of "source reduction" at the top of its "solid waste management hierarchy," ahead of recycling or waste-to-energy. Palmer, Sigman, and Walls [21] point out that the optimal allocation of resources probably involves an optimal *mix* of these alternatives.

[4] Weitzman [38] shows how the equivalence between quantity restrictions and price incentives depends on uncertainty, and Stavins [29] shows how it depends on transaction costs.

TABLE I
Policy Options that Could Affect Materials Flows

Life-cycle stage	Regulatory instruments	Economic instruments
Raw material extraction and processing	1. Regulate mining, oil, and gas nonhazardous solid wastes under the Resource Conservation and Recovery Act (RCRA). 2. Establish depletion quotas on extraction and import of virgin materials.	1. Eliminate special tax treatment for extraction of virgin materials, and subsidies for agriculture. 2. Tax the production of virgin materials.
Manufacturing	1. Tighten regulations under Clean Air Act, Clean Water Act, and RCRA. 2. Regulate nonhazardous industrial waste under RCRA. 3. Mandate disclosure of toxic materials use. 4. Raise corporate average Fuel Economy Standards for automobiles. 5. Mandate recycled content in products. 6. Mandate manufacturer take-back and recycling of products. 7. Regulate product composition, e.g., volatile organic compounds or heavy metal. 8. Establish requirements for product reuse, recyclability, or biodegradability. 9. Ban or phase out hazardous chemicals. 10. Mandate toxic use reduction.	1. Tax industrial emissions, effluents, and hazardous wastes. 2. Establish tradable emissions permits. 3. Tax the carbon content of fuels. 4. Establish tradable recycling credits. 5. Tax the use of virgin toxic materials. 6. Create tax credits for use of recycled materials. 7. Establish a grant fund for clean technology research.
Purchase, use, and disposal	1. Mandate consumer separation of materials for recyling.	1. Establish weight/volume-based waste disposal fees. 2. Tax hazardous or hard-to-dispose products. 3. Establish deposit-refund system for packaging, hazardous products. 4. Establish a fee/rebate system based on product energy efficiency. 5. Tax gasoline.
Waste Management	1. Tighten regulation of waste management facilities under RCRA. 2. Ban disposal of hazardous products in landfills and incinerators. 3. Mandate recycling diversion rates for various materials. 4. Exempt recylers of hazardous wastes from RCRA Subtitle C. 5. Establish a moratorium on construction of new landfills and incinerators.	1. Tax emissions or effluents from waste management facilities. 2. Establish surcharges on wastes delivered to landfills or incinerators.

SOURCE: Office of Technology Assessment [33, p. 17].

se, or even "reduction of waste," because some wastes might be too low while others are too high. If all prices for all products and all forms of disposal reflected full social costs, then markets would send the "right" signals about how to consume and how to dispose of each waste. Thus the "problem" in each case can be defined by identifying exactly where markets fail. Then a policy can be designed to correct that market failure.

In our model, firms produce output using primary resources (labor or capital) and recycled materials. They also choose an amount of packaging, and a level of "recyclability," intended to reflect the resources needed to implement a design that would allow the subsequent recycler to take apart the item more easily, separate the different types of plastic, and recycle a higher percentage of it.[5] Households in this model supply primary resources (labor or capital), retain some resources for home production or leisure, and generate amounts of garbage and recycling that depend upon the firm's choice of packaging and the firm's choice of recyclability. All markets clear, in this closed economy, so the amount of recycling generated by households must match the amount of recycling that gets reused in production. Also, the amount of garbage generated by households must match the supply of disposal services by a collection firm.

At this point, the model allows for various possible market failures. In Case A, private collection firms charge a price per unit of disposal that reflects the private cost of disposal but not negative externalities. A landfill imposes aesthetic or health costs on neighbors, an incinerator generates air pollution and hazardous residue, and collection trucks create noise, odor, and litter. In Case B, the collection of a price or tax per bag of garbage is not possible at all, either because it would cause difficulties of administration, costs of compliance, or an overabundance of illegal dumping on the back roads or vacant lots.[6] Indeed, most local governments collect garbage for free.[7] This zero price can avoid illegal dumping and administrative cost, but it leaves households with insufficient incentive to reduce waste by demanding that firms design and produce goods with less packaging and greater recyclability. In this case, government policy can be used to present firms directly with the right incentives to reduce packaging and to increase recyclability. Thus, different policy packages can be used to induce the same socially optimum outcome. Cases C and D involve a failure in the recycling market, and Case E considers a manufacturer "take-back" requirement. In Case F, where a subsidy to the firm's choice of "recyclability" is not feasible, we show that again the same optimum can be achieved with a tax on packaging and subsidy to the consumer's choice of recycling. The choice among these alternative but equivalent policy packages can depend on their relative administrative feasibilities.

[5] The idea of design for recyclability appears in Henstock [12], and modifications to packaging are suggested in Stilwell *et al*. [30]. Further discussion appears in Denison and Ruston [6]. As described below, we model the choice among existing designs with different degrees of recyclability, not the uncertain process of research to develop new designs.

[6] Jenkins [14] and Repetto *et al*. [25] indicate that illegal dumping can be addressed by other policies, and they calculate the welfare gain from charging a curbside fee equal to the marginal social cost of disposal. When illegal dumping is a problem, however, Fullerton and Kinnaman [10] show that the optimal curbside fee may be close to zero. In a case study of an actual curbside fee program, Fullerton and Kinnaman [11] provide evidence on the amount of dumping, and show that administrative cost may outweigh any gain in efficiency from charging a price equal to the social cost of disposal.

[7] Sixteen towns with unit pricing are studied in EPA [35]. Recent empirical work on unit pricing includes Jenkins [14], Hong, Adams, and Love [13], Reschovsky and Stone [24], and Miranda *et al*. [17]. The great majority of towns still charge no price per bag of garbage.

We analyze enough of the policies listed in Table I to clarify how the model would be used to analyze any of them. For each market failure, we show how alternative policies can correct it. In a later section, we extend the model to consider heterogeneous goods with different degrees of packaging, recyclability, and toxicity. The model could also be extended to consider trade between jurisdictions with different disposal costs, or households with different incomes.

I. A SIMPLE GENERAL EQUILIBRIUM MODEL

The model in this paper is designed to convey basic intuition about materials flows in general equilibrium from the producer to the household and possibly back to the producer before disposal or reuse in production. Initially, therefore, we build a simple static model with one type of household and one commodity.[8]

A. Model Assumptions

Our simple economy has n identical individuals or households that buy a single composite commodity q. This product possesses two "attributes": a degree of recyclability ρ and a packaging rate θ. We can interpret ρ as the fraction of the weight of the product that can be recycled at the end of its useful life, and θ as the weight of the box and other protection that accompanies each unit of the product. In order to focus on the recycling of the product itself, we assume that the packaging cannot be recycled.

Households dispose of solid waste either in the form of garbage collection g or in the form of recycling r. The generation of g is given by the household's technology:

$$g = g(q, \rho, \theta), \tag{1}$$

where $g(.,.,.)$ is continuous and quasi-concave, with first derivatives $g_q > 0$, $g_\rho < 0$, and $g_\theta > 0$. That is, garbage collection g increases with the quantity of consumption q, all else equal. Garbage would decrease if the product had more recyclability ρ, or increase if it had more packaging θ. The generation of recycling is given by:[9]

$$r = r(q, \rho), \tag{2}$$

where $r(.,.)$ is continuous and quasi-concave, with first derivatives $r_q > 0$, $r_\rho > 0$. All else equal, recycling increases with the quantity q and increases with recyclability ρ.

[8] Smith [28] presents a dynamic model where disposal creates a stock externality. Our model here is similar to one in Fullerton and Kinnaman [10], but we add the two attributes as well as other contributions listed above. The model has only one period, but more "recyclability" could be interpreted as more "durability": a product that lasts longer will generate less disposal per period. To put it another way, longer continued use is like recycling and reusing the product.

[9] The amount of packaging θ could easily enter the recycling generation function, since people reuse boxes for storing or shipping other items and brown paper bags for wrapping postal packages. This added realism would come at the expense of some added clutter, however, and it would not change the basic insights below. We focus on how disposal costs affect recycling of the product, and the amount of packaging, without mixing the two concepts together.

Household utility then depends on the amount of this good, q, purchased in the market, and on the amount of another good, h, produced and consumed at home. In order to capture the possibility of a negative externality from others' garbage, we assume that each household's utility also depends on $G = ng$, the total amount of garbage generated in the economy. Utility then is

$$u = u(q, h, G), \tag{3}$$

with first derivatives $u_q > 0$, $u_h > 0$, $u_G \leq 0$. Later, with heterogeneous commodities, we can include different externalities from hazardous and nonhazardous wastes. In this formulation, households do not care about recyclability or packaging *per se*. Instead, those attributes affect waste generation (through Eqs. (1) and (2)) and thus disposal costs. In other words, ρ and θ do not affect households directly through the utility function but indirectly through the resource constraint.[10]

Competitive firms produce output q under conditions of constant returns to scale, using inputs of resources k_q and recycled materials r. In equilibrium, the firm's use of r must match the household's generation of it. In its production decision, the firm also chooses the product's recyclability ρ and packaging rate θ. We could think of production with three outputs (q, ρ, θ) as a function of two inputs (k_q, r). Instead, we just move the two attributes over to the other side of the equation. Thus the production function is[11]

$$q = f(k_q, r, \rho, \theta), \tag{4}$$

where some first derivatives are $f_k > 0$, $f_r > 0$, $f_\rho < 0$. As usual, output increases with greater use of either input k_q or r. In order to make the output more recyclable, however, the firm needs to use up some inputs. Given a total use of k_q and r, therefore, more ρ implies less output q. With regard to θ, we consider the cost of producing and distributing the product safely to the consumer. At low levels of packaging, the firm might need to replace broken units or pay for damages resulting from impurities. Thus more packaging can free inputs for use in producing output ($f_\theta > 0$). At higher levels of θ, on the other hand, more packaging can use up resources unnecessarily ($f_\theta < 0$). Thus we assume that production cost is minimized at a point θ^* where $f_\theta = 0$, as shown in Fig. 1.

In the garbage collection industry, firms use resources k_g as the only input, with constant returns to scale, so the production function is linear:

$$g = \gamma k_g. \tag{5}$$

[10] In general, packaging may serve as a form of advertising and promotion, as well as protection and transportation. Packaging θ could enter the demand for q, or directly into utility. Also, recycling itself could provide utility, as in Mrozek [19]. Instead we focus on incentives. These suggestions would introduce extra terms into results below but would not alter our basic insights.

[11] Three comments about this formulation. First, production does not directly generate any solid wastes, air pollution, or liquid effluents. Those topics are thoroughly treated elsewhere, as in Baumol and Oates [2]. The concern here is with post-consumption waste and disposal. In some ways, however, θ can be viewed as direct waste, skipping the rest of the product life-cycle through the consumer. Second, Fullerton and Kinnaman [10] consider extraction of virgin materials and associated externalities, but these are omitted here to avoid clutter. A straightforward extension of this model could integrate the extraction phase of the product life-cycle. Third, although we omit transactions costs *per se*, we do not omit the recyclers' costs of collection, sorting, cleaning, and other processing. These activities are incorporated in the production function f which specifies the transformation of r into q.

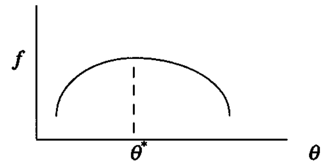

FIG. 1. The effect on net output (f) from packaging (θ).

The good h is produced from home use of time and resource, k_h:

$$h = k_h, \tag{6}$$

which can be interpreted as leisure. Finally, the model is closed by the resource constraint:[12]

$$k = k_q + k_g + k_h, \tag{7}$$

where k denotes a fixed total resource such as capital, labor, or land. No distinction between labor and capital is necessary to obtain our results below about optimal policies toward households or firms regarding garbage, recycling, packaging, or recyclability.

B. Outcome in the Social Planning Model

The social planner's goal is to maximize utility of a representative household Eq. (3), subject to the resource constraint Eq. (7), production functions Eq. (4–6), and waste generation technologies Eq. (1–2). We maximize the appropriate Lagrangian and use first-order conditions to show:[13]

$$\frac{u_q}{u_h} = \frac{1}{f_k} + \left(\frac{1}{\gamma} - \frac{nu_G}{u_h}\right) g_q + \left(-\frac{f_r}{f_k}\right) r_q, \tag{8a}$$

$$-\frac{f_\rho}{f_k} + \left(\frac{1}{\gamma} - \frac{nu_G}{u_h}\right) g_\rho + \left(-\frac{f_r}{f_k}\right) r_\rho = 0, \tag{8b}$$

$$-\frac{f_\theta}{f_k} + \left(\frac{1}{\gamma} - \frac{nu_G}{u_h}\right) g_\theta = 0. \tag{8c}$$

All of these expressions employ the marginal social cost per unit of garbage, which we call MSC_g, defined to include both the direct resource cost $(1/\gamma)$ and the external cost $(-nu_G/u_h)$. This external cost includes the negative externality $(u_G < 0)$ on all n households. We will use these equations below, but the first just says that the marginal utility from another unit of q would equal the marginal

[12] Also, we could have said that household recycling activities require some time and resources for handling and storage, as in Wertz [37], Morris and Holthausen [18], or Choe and Fraser [4]. Then k_r could enter the resource constraint Eq. (7) and the recycling function Eq. (2). Again, however, this variation does not alter the basic insights below. In any case, these costs are similar in nature to costs of transactions in any market: time to get to the store to buy q, or time needed to dispose of g.

[13] We assume convexity, with no corner solutions, for a unique global optimum.

social cost of producing *and* disposing of it. The second condition says that recyclability ρ should increase until its marginal resource cost offsets the savings in disposal costs. Similarly, Eq. (8c) says that society cannot gain from alterations in packaging θ. Note that f_θ must be positive, along the upward sloping portion of the curve in Fig. 1. That is, optimal packaging is below the point that minimizes production cost, to account for disposal cost.

This model captures a full general equilibrium, since prices and quantities are determined using demand and supply simultaneously for several different "goods" including recyclability ρ, and packaging θ, as well as garbage collection g, recycling r, and output q. An extension below considers many outputs q_i where $i = 1, \dots, m$. It is a "first-best" model, however, because it does not incorporate any other distorting taxes on labor supply or capital. To achieve this social optimum in the decentralized economy described next, the government can use lump sum taxes to raise any revenue needed to pay for subsidies to garbage collection or recycling.[14] Similarly, any revenue from a tax on packaging or on garbage disposal is returned to consumers in lump sum form. This assumption considerably simplifies the analysis, because we do not need to keep track of those lump sum taxes or transfers: any exogenous change to income of the consumer will affect the quantities demanded, and the *values* of the marginal utilities (such as u_q or u_h), but do not affect the appearance of the first-order conditions. Each of these equations simply states that the marginal benefits of having more of the good equals the marginal cost, and such an equation still holds with any lump sum tax or transfer.

While we do not include distorting taxes, we do include a simple treatment of other possible market failures due to illegal dumping, transactions costs, enforcement problems, or the administrative cost of trying to collect a tax on a tax-base that is difficult to measure. For simplicity, we consider only two extremes: the sum of these costs in a particular market is either zero or prohibitive. Thus, we do not specify a particular form for these costs. In one case we assume "perfect markets" in the sense that the firm can charge a price and the government can charge a tax per unit of garbage collection, with no administrative cost. In other cases the collection of that price or tax is impossible, and we do not need to specify whether it is because of transactions costs, fear of illegal dumping, or administrative costs. We then find alternative policies that can restore the first-best allocation (Eqs. (8)). Note that when the market "fails" in this sense, and the price or tax per unit of garbage is not collected, then illegal dumping and administrative costs are again zero.

C. *Outcome in the Decentralized Model*

Now we turn to the case of private markets, where government can provide various tax incentives to households or firms. In particular, the household budget is affected by a tax or subsidy on each good:

$$(k - k_h) + (p_r - t_r)r = (p_q + t_q)q + (p_g + t_g)g. \tag{9}$$

[14] Many "second-best" general equilibrium models assume that lump sum taxes are not available, and that government must use distorting taxes to meet an explicit revenue requirement. A review of this large literature appears in Auerbach [1].

The household owns k of resources and sells $(k - k_h)$ to the market at a price of one (since k is numeraire). The household earns p_r for each unit of recycling, which might be taxed at rate t_r per unit. Any tax rate may be positive or negative. With this income, the household can buy the consumption good at price p_q with per-unit tax rate t_q. For each unit of garbage, the household might have to pay price p_g and tax t_g.

Firms' decisions are also affected by taxes. Producers of q maximize profits:

$$\pi = p_q q - p_r r - k_q - q\rho t_\rho - q\theta t_\theta, \tag{10}$$

where t_θ is the tax per unit of packaging, on a measure such as weight, and t_ρ is the tax per unit of recyclability. This tax may be difficult to implement, as discussed more below, but could apply to the percentage of the weight of the item that satisfies prespecified criteria for recyclability.[15] To investigate permit requirements or other quantity restrictions, such as a recycled content standard, Eq. (10) would be maximized subject to a constraint on r per unit production of q.

Individual firms are price-takers, but in the aggregate they face "demand" schedules for ρ and θ that are reflected in the price p_q that consumers are willing to pay. If consumers have to pay for garbage disposal, then they will be willing to pay more for a product with greater recyclability $(\partial p_q / \partial \rho \geq 0)$ or for a product with less packaging $(\partial p_q / \partial \theta \leq 0)$. We undertake the appropriate maximization and use first-order conditions to show

$$p_q = \frac{1}{f_k} + \rho t_\rho + \theta t_\theta, \tag{11}$$

$$p_r = \frac{f_r}{f_k}, \tag{12}$$

$$\frac{\partial p_q}{\partial \rho} \cdot q = q t_\rho - \frac{f_\rho}{f_k}, \tag{13}$$

$$\frac{\partial p_q}{\partial \theta} \cdot q = q t_\theta - \frac{f_\theta}{f_k}. \tag{14}$$

With competition, the sales price just covers resource cost plus taxes per unit of output. Firms use more r until its marginal product is offset by its cost to the firm.

In the garbage collection industry, competitive firms maximize profits $(p_g g - p_k k_g)$, where $g = \gamma k_g$ and $p_k = 1$, so $p_g = 1/\gamma$. This price just covers cost.

In this decentralized economy, the household maximizes utility in Eq. (3) subject to budget constraint Eq. (9) by choosing h, q, and attributes ρ and θ (which together determine g and r). These choices are available because competing firms offer different designs (even though the equilibrium with identical households will

[15] For example, the electronic news service *Greenwire* (May 3, 1995) reports that "cars built before the 1995 model year are about 75% recyclable; the remaining 25% is sent to landfills. New cars such as the Ford Contour and the Chrysler Cirrus are 80% recyclable, and the goal is to make all vehicles built by the year 2000 85% recyclable."

involve a single outcome for attributes ρ and θ).[16] Individual consumers are price-takers, but in the aggregate they face "supply" schedules for ρ and θ that are reflected in the price p_q for which firms are willing to sell. If firms devote more resources to "green design," then they will have to charge more for a product with greater recyclability or for a product with better packaging. Also, the household's optimization ignores the impact of its own g on the utility of others through the increment to total G.

Maximization of the appropriate Lagrangian yields first-order conditions in terms of the prices and tax rates faced by households, but we use Eqs. (11)–(14) above to replace each price with the corresponding cost of production:

$$\frac{u_q}{u_h} = \frac{1}{f_k} + \rho t_\rho + \theta t_\theta + t_q + \left(\frac{1}{\gamma} + t_g\right) g_q + \left(-\frac{f_r}{f_k} + t_r\right) r_q, \tag{15a}$$

$$q t_\rho - \frac{f_\rho}{f_k} + \left(\frac{1}{\gamma} + t_g\right) g_\rho + \left(-\frac{f_r}{f_k} + t_r\right) r_\rho = 0, \tag{15b}$$

$$q t_\theta - \frac{f_\theta}{f_k} + \left(\frac{1}{\gamma} + t_g\right) g_\theta = 0. \tag{15c}$$

These expressions reflect a general equilibrium where all firms are on their supply curves and all households are on their demand curves for each commodity and attribute. The first condition says that marginal utility is set equal to the "full effective price" of consumption. For each unit of q the consumer must pay the firm's cost in terms of resources and taxes, plus the private cost of disposal.

Expressions (15) are written in a form comparable to the social optimum conditions in Eqs. (8). To check on efficiency of private markets with no government interference, suppose that tax rates in Eqs. (15) were all set to zero. In this case, it is easy to see that the private market does not yield the social optimum, because the externality u_G appears in the social conditions Eqs. (8) but not in the market conditions Eqs. (15). In addition, private firms might not be able to charge a price for garbage collection at all, if transactions costs are high or households can avoid the charges by dumping in commercial dumpsters or vacant lots. If local governments must provide collection for free, then households face neither the direct cost $(1/\gamma)$ nor the external cost $(-nu_G/u_h)$.

II. MARKET FAILURES AND CORRECTIONS

In this section, we consider several possible market failures. In each case, we solve for the tax rates of Pigou [22] that induce private behavior in Eqs. (15) to match the social optimum in Eqs. (8). Assuming this optimum is unique, it might be achieved using several different combinations of taxes and subsidies.

Case A: Negative Externality with Unit-Pricing of Garbage

In the simplest case, suppose that competitive waste disposal firms just break even, so, $p_g = 1/\gamma$, and that consumers pay $(p_g + t_g)$ per unit of garbage col-

[16] An important assumption is full information. Direct regulations might be proposed by those who would not rely on consumers to know product characteristics and to signal their preferences.

lected. Then Eq. (15c) can be made to match Eq. (8c) if $t_g = -nu_G/u_h$ and $t_\theta = 0$. Next, Eq. (15b) matches Eq. (8b) if $t - \rho$ and t_r are zero. Finally, Eq. (15a) matches Eq. (8a) if $t_q = 0$ as well. In other words, if consumers have to pay the full marginal social cost of disposal MSC_g, then they will induce firms to design products with the right combinations of ρ and θ. In this case the government does not do anything about household recycling, or consumption, or about the producer's choice of inputs. The tax on garbage corrects for the only externality.

Case B: *Free Garbage Collection*

Because of illegal dumping, or tax collection costs, many communities do not or cannot charge for garbage collection. We therefore consider the case where $p_g + t_g = 0$. Free garbage collection means that collection firms are receiving a per-unit subsidy equal to the price. In this case the consumer does not care about disposal cost and is *not* willing to pay any extra for greater recyclability or for green design of packaging. Manufacturers do not receive those market signals from consumers, but they can still be given the right signals by appropriate taxes and subsidies. Eq. (15c) will match Eq. (8c) if the tax rate on packaging is $t_\theta = (1/\gamma - nu_G/u_h)g_\theta/q$. This tax is $MSC_g \cdot g_\theta/q$, the marginal disposal cost per unit of output from a change in θ. This tax is positive, to induce firms to reduce packaging which contributes to direct resource costs and external costs of disposal. Then Eq. (15b) will match Eq. (8b) if $t_r = 0$ and $t_\rho = (1/\gamma - nu_G/u_h)g_\rho/q = MSC_q \cdot g_\rho/q$. This tax rate is negative and reflects the cost *savings* from a change in ρ that reduces disposal costs per unit of output.

Finally, Eq. (15a) matches Eq. (8a) if

$$t_q = \left(\frac{1}{\gamma} - \frac{nu_G}{u_h}\right)\left(g_q - \frac{\rho g_\rho + \theta g_\theta}{q}\right),$$

which equals $MSC_g \cdot g_q - \rho t_\rho - \theta t_\theta$. The first term looks a lot like the proposal for "disposal-content charges"[17] since it collects the cost of disposal of the extra g from an extra q. The other terms correct for the effects of other instruments on the price of output. The subsidy t_π is intended to increase ρ, but it also would reduce the cost of production, reduce output price, and increase the quantity demanded. Thus the output tax takes back that implicit subsidy per unit of output. Similarly, in the final term, the output tax gives back the effect of the packaging tax on the output price. The result is a system that just discourages packaging, and not output generally. The sign of the overall tax rate depends on the relative size of the recyclability and packaging parameters.

This case where consumers pay nothing for disposal provides a coherent rationale for a tax on packaging and a subsidy to designs that improve recyclability.[18] It does not include a subsidy to recycling, since recycling has no externality (but see

[17] See, for example, Menell [15]. In this case, the output tax is combined with a subsidy to recyclability, an example of what Fullerton [9] calls a "two-part instrument."

[18] These policies directed at the firm are enough to reach the social optimum in this model, because the firm chooses packaging and recyclability. If household garbage and recycling also depended on effort at the household level, as in Choe and Fraser [4], then an additional instrument would have to be directed at the behavior of those households.

Case F below). This "upstream" policy package involves three different instruments (t_θ, t_ρ, t_q) that each contain a number of terms, so it entails substantial information requirements, but it may still be the most feasible policy if illegal dumping or collection costs prevent the use of the simpler "downstream" policy with a single fee per unit trash (t_g).

Case C: No Payment for Recycling

To deal with possible market failures separately, we return to the case with no failure in the market for garbage collection (so $p_g = 1/\gamma$ and $t_g = -nu_G/u_h$) and instead consider a failure in the market for recycling collection. The price p_r paid by the firm for its input of recycling may be close to zero, and the cost of counting out the pennies per pound of glass or plastic recycling may outweigh the value of the material. We do not model these transactions costs explicitly, but suppose they preclude the formation of a private market for recycling. Households would then place this recyclable material into the garbage for the landfill, unless the municipality collects curbside recycling for free. Effectively, the municipal subsidy matches the price, so households face $(p_r - t_r) = 0$. A remaining problem is that households do not get paid for recycling, so they do not demand enough recyclability.

This problem can be corrected by a subsidy $t_\rho = -f_r r_\rho / f_k q = -p_r r_\rho / q$, which reflects the marginal social value of the extra recycling generated by the change in ρ. The optimal tax rate on packaging in this case is $t_\theta = 0$, since packaging is effectively discouraged by the optimal charge for garbage. We still need to impose consumption tax $t_q = (f_r/f_k)(\rho r_\rho/q - r_q)$, which equals $-\rho t_\rho - p_r r_q$. The first term collects a tax per unit of output to correct for the fact that t_ρ is supposed to subsidize recyclability and not output generally. The second term is the opposite sign, to reflect the marginal social value of the recycling generated by the extra q.

Case D: No Payment for Recycling and Free Garbage Collection

The purpose of separate Cases B and C is to prepare for this case where households face no price either for garbage collection or for recycling ($p_g + t_g = 0$ and $p_r - t_r = 0$). Municipal subsidies enable free curbside collection of garbage and recycling, so the household is totally freed from worrying about solid waste disposal. Even though the model now includes multiple constraints and market failures, it also includes multiple policy instruments. Government can still correct these market failures. The optimal tax rate on recyclability is

$$t_\rho = \left(\frac{1}{\gamma} - \frac{nu_G}{u_h} \right) \frac{g_\rho}{q} + \left(- \frac{f_r r_\rho}{f_k q} \right),$$

which is exactly the sum of the subsidies from the two cases above. The rationale for policies to encourage "green design" is doubly strong in this case. The tax on packaging is still $t_\theta = (1/\gamma - nu_G/u_h) g_\theta / q$, from Case B, because it was zero in Case C. The tax per unit of output is also the sum of the tax rates from Cases B and C, and can be written as $t_q = MSC_g \cdot g_q - p_r r_q - \rho t_\rho - \theta t_\theta$. The first two terms reflect the costs and benefits of the extra disposal and recycling generated by an extra unit of output. The other two terms correct the output price for the subsidy on recyclability and the tax on packaging.

Case E: *Manufacturer Take-Back Requirement*

Table I also includes a proposal to ''mandate manufacturer take-back and recycling of products.'' The idea is that firms would have the right incentives to reduce packaging and to design for recyclability if they had to dispose of all their own packaging and products. Firms might *choose* to use fewer different types of plastic, and to use fewer one-way fasteners, if they had to take apart and recycle their own product. This idea has been at least partially implemented in Germany's Green Dot program.[19]

This proposal can be illustrated with modifications to our model. First, the household does not pay for garbage disposal and recycling, so its budget constraint changes to

$$k - k_h = (p_q + t_q)q. \tag{16}$$

The take-back requirement shifts responsibility for garbage disposal and recycling to the firm, so the profit function becomes

$$\pi = p_q q - k_q - (p_g + t_g)g - t_r r - q\rho t_\rho - q\theta t_\theta. \tag{17}$$

We could set all of these tax rates to zero for the case with *just* the take-back requirement, to see if private markets match the social optimum. If not, we can then find what additional tax instrument might be necessary.

Into this profit function, we substitute the firm's production function for q and the solid waste generation technologies $g = g(q, \rho, \theta)$ and $r = r(q, \rho)$. We also need to add the constraint that this r generated by households is the same as the r that enters the production function. The firm maximizes profits subject to this constraint, and it determines the amount of garbage and recycling it will receive by its choice of q, ρ, and θ. Since the firm gets to use the resulting r back in production, we find that it faces a shadow price (the Lagrangian on the constraint) equal to what the market price would have been ($p_r = f_r/f_k$, in Eq. (12)). Since the firm is also setting all variables that determine g, it will face all the correct market signals if it has to pay the social marginal cost of garbage disposal. In other words, we find that optimality requires the firm to pay $p_g = 1/\gamma$ and $t_g = -nu_G/u_h$. All other tax rates are zero.

With the take-back requirement, plus $t_g = -nu_G/u_h$, the firm has all the right incentives. This solution does not require any extra tax on packaging, disposal-content charges, recycled-content standards, or subsidies for ''green design'' that would encourage recyclability. These results are intuitive, given the nature of the model, but an important corollary result is that the ''take-back requirement'' by itself is not enough. Even a firm that pays the market price for garbage disposal does not account for all social costs if u_G is not zero.

[19] Transaction costs could become important. In Germany, manufacturers do not take back the packaging themselves but subscribe to the ''Duales System Deutschland'' (DSD). The firm puts a green dot on their packages and contracts with a recycling company that collects all packages with green dots. See Rousso and Shah [26].

Case F: *A Deposit-Refund System*

Only relative prices affect behavior in this general equilibrium model, so a tax on one activity may be equivalent to a combination of taxes and subsidies on other activities. The choice between these policies can depend on which combination is more easily administered and enforced. The fee per unit of household disposal in Case A would require the difficult enforcement of antidumping laws. That problem is avoided in Case B, with the same optimal outcome, by setting the disposal fee to zero and instead using a tax on the firm's packaging, subsidy to recyclability, and tax on output.

Our final case is similar to Case B, where the disposal fee is zero ($p_g + t_g = 0$), and instruments are directed at firms instead of households. But suppose the subsidy is not feasible for "recyclability." That concept may be difficult to quantify. With $t_\rho = 0$, the same outcome can again be obtained, with the use of a subsidy to recycling. The optimal tax on packaging from Case B is unchanged at $t_\theta = (1/\gamma - nu_G/u_h)g_\theta/q$, which equals $MSC_g \cdot g_\theta/q$, the marginal disposal cost per unit of output from a change in θ. Then the subsidy to recycling is $t_r = (1/\gamma - nu_G/u_h)g_\rho/r_\rho$, which equals $MSC_g \cdot g_\rho/r_\rho$. Finally,

$$t_q = \left(\frac{1}{\gamma} - \frac{nu_G}{u_h}\right)\left(g_q - \frac{g_\rho r_q}{r_\rho} - \frac{\theta g_\theta}{q}\right),$$

which equals $MSC_g \cdot g_q - r_q t_r - \theta t_\theta$. The first term is positive to account for the disposal cost of output, and the second term is positive to correct output price for the subsidy to recycling. This term is the "deposit" of a deposit-refund system: this tax on output is given back if the item is recycled. Only the third term of this output tax is negative, to correct for the tax on packaging.

As usual, the "refund" is intended to encourage recycling and thereby avoid the socially costly disposal of waste. In this model, however, the rate of subsidy depends on g_ρ and r_ρ, so it encourages design for recyclability. Profit-seeking firms change their design because of the demand for recyclability by consumers who want to get the subsidy for recycled items.

III. HETEROGENEOUS COMMODITIES AND OTHER EXTENSIONS

This section will consider several extensions to the basic model. First, suppose the utility function in Eq. (3) is modified to include a vector of commodities q_i, where $i = 1, \ldots, m$. Each good then requires its own attributes ρ_i and θ_i, its own garbage generation function in Eq. (1), its own recycling generation function in Eq. (2), and its own production function in Eq. (4). In the simplest case, each output is produced using a recycled amount of the same good ("closed-loop" recycling). Total garbage is the sum from all consumption goods, and each industry may face its own set of tax rates.

This extension involves keeping track of more goods, but results are remarkably similar to those above. As long as only total garbage G enters utility, the first-best outcome can still be obtained by a single fee per unit of garbage (Case A). If illegal dumping or collection costs prohibit the use of a price or tax per bag of garbage, then the first-best allocation can still be achieved (Case B), but only by meeting substantial information requirements since the solution then requires many policy instruments. The optimal tax on packaging still looks like $t_\theta = (1/\gamma - nu_G/u_h)g_\theta/q$, except subscripts are added to q and g_θ. All other tax rates in Section II are modified by adding similar subscripts. Thus, in Case B, each industry would need a unique tax on packaging, subsidy to recyclability, and tax on output. This complicated result points to an advantage of the ‘‘take-back’’ rule (Case E), since each industry then deals only with its own packaging and with recycling its own product.

A second extension would replace closed-loop recycling and allow a good to be recycled as an input to production of a different good.[20] In Dinan’s [7] model, a tax on one industry’s use of virgin materials encourages that industry to use recycled input, but it does not encourage other industries to use this output as recycled input. Similarly, in our model, the subsidy to recycling (in Case F) would have to be provided to all possible users of a recycled good. In contrast, the subsidy to recyclability (in Cases B, C, and D) would only have to be provided to the original producer. A question, however, is whether one kind of ‘‘recyclability’’ would make the good equally reusable in all other industries.

In a third extension, suppose the m goods have different toxicity. Batteries in household garbage are more damaging than vegetable matter. In this case, the utility function must be modified to include a vector of negative externalities (and not just one externality from total garbage). This complication means that the first-best cannot be achieved by a single fee per bag of garbage: a different fee must apply to each component of the household’s waste. These different disposal fees could be impossible to administer, providing some reason to use policies directed at firms. The optimum in this model can still be achieved with an appropriate differential tax (that is, deposit) on each output and subsidy (refund) to anyone who recycles it, or a subsidy to recyclable designs, as long as the extra recyclability helps all others who reuse that good.

In a fourth extension, not undertaken here, the model could be modified to consider heterogeneous jurisdictions. States might differ in terms of natural endowments, and they might trade in various outputs, recycled goods, and types of waste.[21] A jurisdiction with abundant land suitable for waste disposal would charge a lower disposal fee (Case A), and import waste, even accounting for all the social costs of disposal at that location. The optimal disposal fees would differ by location, however, so this solution could *not* be replicated by a system of taxes and subsidies on producing firms as in Case B.

Fifth, the model could allow for altruism by households who recycle even without compensation, simply because they feel good about helping the environment. This modification would presumably reduce the optimal level of policy intervention, but it could make the optimal policies more complicated.

Finally, the model could be extended to allow for a number of other possibilities. Markets could be added to consider tradable permits, and other quantity constraints could be used to represent command and control regulations such as recycled-content standards. A model with more significant modifications such as

[20] *Greenwire* (March 25, 1996) reports that Ford uses recycled drink containers in its door padding, grille reinforcements, and luggage-rack side rails. The top cover of some of Chrysler’s instrument panels are made from recycled compact disks, water bottles, and computer parts.

[21] See, for example, Copeland [5].

other distorting taxes could be used to solve for a second-best revenue-raising system of taxes and subsidies. Or, the model could be modified to account for heterogeneous households at different levels of income, in order to analyze distributional effects of environmental policies.

IV. CONCLUSION

The advantage of this general equilibrium model is that it encompasses the entire life-cycle of each product from the design phase to production, consumption, and disposal. It also captures each price paid along the way, so a tax at one stage of production or sale has an equivalent counterpart at another stage of consumption or disposal. We show conditions where the efficient solution can be obtained either by a ‘‘downstream’’ tax on waste disposal or by an equivalent ‘‘upstream’’ tax on production processes that give rise to the subsequent waste.

If market signals can be corrected by the appropriate disposal charges (Case A), then consumers will induce firms to use less packaging and to design products for easier subsequent recycling. If market signals cannot be corrected in this way, however, then welfare can be improved by policies directed at the firm. The solution might involve a subsidy to recycling (Case F), or if that is not possible, a subsidy to recyclability (Cases B, C, and D). In the extended model, with disaggregate commodities of differing toxicity, separate output taxes and recycling subsidies can deal with hazardous and nonhazardous generation of waste. With other modifications, the model can be used to compare virtually all of the 34 policy options listed in Table I.

The reason for comparing all of these options is that some may be implemented more easily than others. The difficult enforcement of penalties on improper waste disposal is not necessary, if the equivalent outcome can be obtained by a tax (deposit) on all output in combination with a subsidy (rebate) on all proper waste disposal. Indeed, the objections of municipalities to unit pricing of curbside garbage collection may be motivated not by a lack of appreciation for the scarcity of space in landfills, but instead just by these problems of implementation. Any charges for household waste might have to deal with 100 million taxpaying units, while equivalent instruments could apply to substantially fewer firms. If the downstream tax on waste disposal cannot be administered effectively, this paper shows how to derive the equivalent upstream tax on packaging and subsidy to recyclability.

REFERENCES

1. A. J. Auerbach, The theory of excess burden and optimal taxation, *in* ‘‘Handbook of Public Economics,’’ (Alan J. Auerbach and M. Feldstein, Eds.), Vol. 1, Elsevier, Amsterdam (1985).
2. W. J. Baumol and Wallace E. Oates, ‘‘The Theory of Environmental Policy,’’ 2nd ed., Cambridge University Press, New York (1988).
3. P. Bohm, ‘‘Deposit-Refund Systems: Theory and Applications to Environmental, Conservation, and Consumer Policy,’’ Johns Hopkins University Press, Baltimore, MD (1981).
4. C. Choe and I. Fraser, ‘‘An Economic Analysis of Household Waste Management,’’ Department of Economics, La Trobe University, Bundoora, Victoria, Australia (1998).
5. B. R. Copeland, International trade in waste products in the presence of illegal disposal, *J. Environ. Econom. Management* **20**, 143–162 (1991).

6. R. A. Denison and J. Ruston, "Recycling and Incineration: Evaluating the Choices," Island Press, Washington, DC (1990).
7. T. M. Dinan, Economic efficiency effects of alternate policies for reducing waste disposal, *J. Environ. Econom. Management* **25**, 242–256 (1993).
8. I. M. Dobbs, Litter and waste management: Disposal taxes versus user charges, *Canad. J. Econom.* **24**, 221–227 (1991).
9. D. Fullerton, Environmental levies and distortionary taxation: Comment, *Amer. Econom. Rev.* **87**, 245–251 (1997).
10. D. Fullerton and T. C. Kinnaman, Garbage, recycling, and illicit burning or dumping, *J. Environ. Econom. Management* **29**, 78–91 (1995).
11. D. Fullerton and T. C. Kinnaman, Household responses to pricing garbage by the bag, *Amer. Econom. Rev.* **86**, 971–984 (1996).
12. M. E. Henstock, "Design for Recyclability," The Institute of Metals, London (1988).
13. S. Hong, R. M. Adams, and H. A. Love, An economic analysis of household recycling of solid wastes: The case of Portland, Oregon, *J. Environ. Econom. Management* **25**, 136–146 (1993).
14. R. R. Jenkins, "The Economics of Solid Waste Reduction," Edward Elgar, Brookfield, VT (1993).
15. P. S. Menell, Beyond the throwaway society: An incentive approach to regulating municipal solid waste, *Ecology Law Quart.* **17**, 655–739 (1990).
16. A. K. Miedema, Fundamental economic comparisons of solid waste policy options, *Resour. Energy* **5**, 21–43 (1983).
17. M. L. Miranda, J. W. Everett, D. Blume, and B. A. Roy, Jr., Market-based incentives and residential municipal solid waste, *J. Policy Anal. Management* **13**, 681–698 (1994).
18. G. E. Morris and D. M. Holthausen, The economics of household solid waste generation and disposal, *J. Environ. Econom. Management* **26**, 215–234 (1994).
19. J. R. Mrozek, "Beverage Container Recycling: Incentives versus Attitudes as Explanations of Behavior," working paper, Georgia Institute of Technology, Atlanta (1995).
20. K. Palmer and M. Walls, Optimal policies for solid waste disposal: Taxes, subsidies, and standards, *J. Public Econom.* **65**, 193–205 (1997).
21. K. Palmer, H. Sigman, and M. Walls, The cost of reducing municipal solid waste, *J. Environ. Econom. Management* **33**, 128–150 (1997).
22. A. C. Pigou, "The Economics of Welfare," 4th ed., Macmillan, London (1932).
23. Project 88—Round II," A Public Policy Study Sponsored by Senator Timothy E. Wirth and Senator John Heinz, Directed by Robert N. Stavins, Washington, DC (1991).
24. J. D. Reschovsky and S. E. Stone, Market incentives to encourage household waste recycling: Paying for what you throw away, *J. Policy Anal. Management* **13**, 120–139 (1994).
25. R. Repetto, R. C. Dower, R. Jenkins, and J. Geoghegan, "Green Fees: How a Tax Shift Can Work for the Environment and the Economy," World Resources Institute, Washington, DC (1992).
26. A. S. Rousso, and S. P. Shah, Packaging taxes and recycling incentives: The German green dot program, *National Tax J.* **47**, 689–701 (1994).
27. H. Sigman, A comparison of public policies for lead recycling, *RAND J. Econom.* **26**, 452–478 (1995).
28. V. L. Smith, Dynamics of waste accumulation: Disposal versus recycling, *Quart. J. Econom.* **86**, 600–616 (1972).
29. R. N. Stavins, Transaction costs and tradeable permits, *J. Environ. Econom. Management* **29**, 133–148 (1995).
30. E. J. Stilwell, R. C. Canty, P. W. Kopf, and A. M. Montrone, "Packaging for the Environment: A Partnership for Progress," A. D. Little, Inc., New York (1991).
31. A. M. Sullivan, Policy options for toxic disposal: Laissez-faire, subsidization, and enforcement, *J. Environ. Econom. Management* **14**, 58–71 (1987).
32. U.S. Congress, Congressional Budget Office, "Federal Options for Reducing Waste Disposal," U.S. Government Printing Office, 1991 0-304-900 QL 3, Washington, DC (1991).
33. U.S. Congress, Office of Technology Assessment, "Green Products by Design: Choices for a Cleaner Environment," U.S. Government Printing Office, OTA-E-541, Washington, DC (1992).
34. U.S. Environmental Protection Agency, "The Solid Waste Dilemma: An Agenda for Action," EPA Technical Report EPA/530-SW-89-019, Washington, DC (1989).

35. U.S. Environmental Protection Agency, ''Charging Households for Waste Collection and Disposals: The Effects of Weight or Volume-Based Pricing on Solid Waste Management, EPA 530-SW-90-047, Washington, DC (1990).
36. U.S. General Accounting Office, ''Solid Waste: Tradeoffs Involved in Beverage Container Deposit Legislation,'' GAO/RCED-91-25, Washington, DC (1990).
37. K. L. Wertz, Economic factors influencing households' production of refuse, *J. Environ. Econom. Management* **2**, 263–272 (1976).
38. M. L. Weitzman, Prices vs. quantities, *Rev. Econom. Stud.* **41**, 477–491 (1974).