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CORRECTIVE TAXATION FOR CURBING POLLUTION AND PROMOTING GREEN PRODUCT DESIGN AND RECYCLING

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Abstract

In this paper we consider a competitive economy with flows of materials from extraction via recycling to landfilling which exhibits distortions due to pollution, external landfilling costs and inefficient product design. The allocative impact of tax-subsidy policies aiming at internalizing the distortions are analyzed when the pertinent tax-subsidy rates were successively raised from zero toward their efficiency restoring levels. Promoting recyclability by greening the product design stimulates recycling as expected. But it also increases primary material extraction and – possibly – the total waste flow, and it reduces the recycling ratio.

Keywords: Green design, pollution, recycling, material

JEL Classification: H22, Q28

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1 Introduction

Since the 1970s recycling caught the attention of environmental and resource economists because it promised to promote two important ends simultaneously: reducing the rate of extraction of natural resources as well as diminishing the flow of waste from spent output and thus curbing waste-related pollution. Early contributions of Førsund (1972), Mäler (1974) and Pethig (1977) applied static general equilibrium analysis[1] and concluded, essentially, that inefficient recycling was a consequence of non-internalized waste-related pollution so that efficient pollution control, e.g. via Pigouvian taxes, appeared to be all that was needed to attain efficient recycling.

In the vast applied literature on recycling it was well acknowledged since many years, see e.g. Wolbeck (1977), that the productivity of recycling solid waste depends on the *'recyclability'* of waste and hence on design characteristics of the manufactured products that were turned into waste at the end of their useful life. If the designer and the producer of a consumer good ignores the impact of her design on the cost of recycling she tends to impose an externality on recyclers. Following Fiskel (1996), *green designing* is said to be applied by producers when they explicitly incorporate environmental and recycling issues into their product design and manufacturing decisions. The U.S. Office of Technology Assessment (1992) recommends green designing as a means of making products easier and less costly to recycle with the consequence of avoiding the generation of waste.

Since the late 1990s the issue of recyclability has received increasing attention in the theoretical environmental-economic literature. Clearly, there are various 'green' aspects of product design such as the weight, disassembly properties, the material mix embodied in the product or the packaging materials (mix). Accordingly, different approaches to recyclability can be taken. Fullerton and Wu (1998), Choe and Fraser (1999) and Calcott and Walls (2000) introduce recyclability through a technological parameter which raises the cost of producing the consumer good, on the one hand, but enhances the productivity of recycling on the other hand. To internalize this type of product-design externality Fullerton and Wu (1998) and Calcott and Walls (2000) suggest a so called deposit-refund system consisting of an output tax combined with a subsidy on recycled material.[2]

Eichner and Pethig (2000) consider the material mix of a consumer good to be an environmentally relevant aspect of product design. The mix of two materials embodied in

[1] Another line of research was initiated by Smith (1972), Schulze (1974) and Weinstein and Zeckhauser (1974) applying intertemporal analysis with stock-flow interactions. The present paper is restricted to static and comparative-static analysis.

[2] Two generalizations of the deposit-refund idea can be found in Fullerton and Wolverton (2000).

the output is assumed to be the producer's choice. One of these materials is recyclable and the hypothesis is that the greater is this material's share in the output (and hence in waste) the easier it is to reclaim the material. Eichner and Pethig (2000) investigate various potential corrective tax-subsidy schemes, and they find one of them particularly recommendable: an output tax combined with a subsidy on the producer's material input.

The present paper follows the product design approach of Eichner and Pethig (2000). A simple general equilibrium model is constructed where total spent output, called residuals, is collected for reclaiming one of the materials embodied in those residuals. The outputs of this (costly) recycling process are (i) secondary material that is reused along with primary material as an input in producing the consumer good and (ii) waste to be landfilled. Waste deposition is costly and consumers suffer from waste-induced pollution. Applying the standard Lagrangean technique, an efficient allocation of that economy can be characterized and can then be decentralized by prices supplemented by a set of suitable taxes and subsidies. While this approach provides us with some valuable information on what taxes and subsidies are required to restore efficiency, little is revealed about how the allocation of a 'no-policy' or 'laissez-faire' competitive economy deviates from the efficient one.

We clearly know that in such a model the laissez-faire allocation is characterized by two distortions caused by the non-internalized pollution externality and the product design externality. In fact, if the landfilling fee is also absent or too low, we deal, in addition, with an allocative distortion due to external landfilling costs. But it is by no means obvious what the impact of correcting for those distortions is. After all, it is conceivable in a general equilibrium context, that an efficiency-enhancing policy might raise the production of the consumer good and, along with that, the flows of primary resources, waste and pollution. Is the U.S. Office of Technology Assessment really right in its conjecture that promoting green design does reduce waste? How does such a policy affect the scale of production, the mix of primary and recycled material, the waste materials flows when the rates of all relevant taxes and subsidies are successively shifted from zero towards their efficient levels? How does a policy intended to reduce the product design externality impact on the pollution distortion and vice versa?

To our knowledge, all available studies on recyclability were restricted to deriving and interpreting first-order conditions for an efficient allocation and did not answer the questions raised above.[3] The principal objective of the present paper is to determine, by means of

[3]Some comparative static analysis is offered by Pethig (1977) and by Choe and Fraser (1999). The former did not consider a product design externality while the latter analyze households' waste reduction efforts and illegal disposal which makes the first-best optimum no longer achievable und requires second-best policies. Choe and Fraser (1999) derive comparative static results of tax rate changes but their policy instruments

rigorous comparative-static analysis, the allocative impact on all endogenous variables of tax-subsidy policies aiming at internalizing both the pollution externality and the product design externality.

The paper is organized as follows: Section 2 outlines the basic building blocks of the model. Section 3 serves to present the tax-subsidy scheme restoring efficiency of the competitive economy. Section 4 develops a comparative static analysis of various tax policies which is discussed in section 5. We consider the effects of coping with the pollution externality in section 5.1, the effects of reducing external landfilling costs in section 5.2 and the effects of correcting the product design externality in section 5.3. Section 5.4 presents the incidence of hybrid tax policies which aim at killing two birds with one stone: the product design and the pollution externality. Section 6 summarizes and concludes.

2 The model

Consider an economy producing the amount y of the *consumer good* Y. Factors of production are *labour*[4] (ℓ_y) and two types of *material*: material M (quantity m) and material N (quantity n). Weight is chosen as the common dimension of y, m and n, and, by assumption, both material inputs are completely embodied in the output:

$$y = m + n. \tag{1}$$

The materials mix can be conveniently measured by the share of material M per unit of output Y,

$$q = \frac{m}{y} \in [0, 1]. \tag{2}$$

q is an intrinsic attribute of good Y and will be called the *material content* of good Y, for short. We wish to focus on a technology of producing good Y that allows to vary the material input mix so that the material content becomes a matter of product design. For that purpose we introduce the concave and linear homogeneous production function[5]

$$y = Y\left(\underset{+}{\ell_y}, \underset{+}{m}\right). \tag{3}$$

do not stimulate producers for greening the consumption goods.

[4]Instead of labour the letter ℓ could be interpreted as a composite input, e.g. capital, that is not embodied in the product.

[5]Upper-case letters denote functions and subscripts attached to them indicate first derivatives. A plus or minus sign underneath an argument of a function denotes the sign of the respective partial derivative.

After consumption, good Y is turned into *consumption residuals* (z) of same weight:

$$y = z. \tag{4}$$

With the help of labour (ℓ_r) material M is reclaimed from these residuals according to the concave recycling function

$$r = \tilde{R}\left(\underset{+}{\ell_r}, \underset{+}{z}, \underset{+}{q}\right) \tag{5'}$$

where r is denoted the amount of *secondary material* M. The hypothesis $\tilde{R}_q > 0$ appears to be plausible, since with fixed labour input one can expect to reclaim the more material M from any given amount of residuals, the greater the share of material M embodied in those residuals. Recall that q is determined by the producer of good Y. Hence the producer's product design affects recycling and causes an externality if the producer designs her product without accounting for the impact of material content on recycling. To simplify the analysis, the production function $\tilde{R}$ from (5') is assumed to take on the special form

$$r = R\left(\ell_r, \underset{+}{s}\right), \tag{5}$$

where $s := A(q)z$ and where R is linear homogeneous in ℓ_r and s. The function A satisfies $A(0) = 0$, $A_q > 0$ and $A_{qq} \leq 0$. In addition to the secondary material (r) the recycling process generates *recycling waste*

$$w := z - r. \tag{6}$$

Consider first r, the desired output of the recycling process. The 'cycle' of material M would be closed, if $r = m$. But due to the second law of thermodynamics the cycle is necessarily incomplete ($r < qz$). Hence a positive amount, v, of *primary material* M is required to produce good Y along with the amount r of secondary material M. We set

$$v + r = m \tag{7}$$

implying that both primary and secondary material M are perfect substitutes. The extraction of primary material M is described by

$$v = \frac{1}{c_v}\ell_v, \tag{8}$$

where $c_v > 0$ and constant. For convenience of exposition, we assume that material N is not recovered at all and that its extraction is costless.

The second output, w, of the recycling process contains the amount $n = (1 - q)y$ of material N and the amount $yq - r = v$ of material M. Hence the flow $w = n + v$ of total materials throughput depends on the scale of good Y produced (y), the material content of good Y (q) and on the scale of recycling (r). Waste is assumed to be landfilled at (labour) costs

$$\ell_w = c_w w, \tag{9}$$

where $c_w \geq 0$ and constant. The representative consumer's utility is given by

$$u = U\left(\underset{+}{y}, \underset{-}{w}\right). \tag{10}$$

The interpretation of $U_w < 0$ is that (landfilled) waste causes environmental degradation which, in turn, adversely affects the consumers' utility. Since the waste w consists of a mix of both materials, the simplifying hypothesis implicit in (8) is that both types of landfilled materials do not differ with respect to their detrimental environmental impact. The utility function U is also required to satisfy

$$\frac{dy}{dw} = -\frac{U_w}{U_y} \in [0,1] \tag{10'}$$

on the relevant part of its domain. Although (10') appears to be restrictive, it is quite realistic for the following reason. Suppose y is increased by dy and no recycling takes place. Then in view of (4) and (6) the increment of waste $dw = dy$ is generated after consumption of dy. Obviously, $(-U_w/U_y) > 1$ would mean that the marginal net benefit $du = (U_y + U_w)\,dy$ from consumption of dy is negative implying that the damage from waste is worse than the benefit of consuming dy. This is implausible if good Y is taken to be a normal consumption good. The model is completed by listing the labour constraint

$$\ell = \ell_y + \ell_r + \ell_w + \ell_v \tag{11}$$

where the *labour supply*, $\ell > 0$, is exogenously given.

3 Corrective taxation in the competitive economy

In this section we introduce competitive markets into the model (1)-(11): There is a competitive market for labour with price p_ℓ (that is later normalized to $p_\ell \equiv 1$), a market for material with price p_m, for good Y with price p_y and for residuals with price p_z. In addition to these competitive prices we consider the following taxes:[6] a tax on good Y (τ_y) and a subsidy on material (τ_m) both levied on producers of the consumption good Y; a landfilling charge (τ_f) and a pollution charge (τ_p) both levied on the waste generated by the recyclers. The reason for introducing this particular set of taxes is that -as shown below (equation

[6]When referring to "taxes" we include subsidies as well.

(18))- specific rates of these taxes are capable to restore the efficiency of the competitive economy.[7] Using (3)-(6) and (8) the pertinent profits are

$$(p_y - \tau_y + p_z)Y(\ell_y, m) - p_\ell \ell_y - (p_m - \tau_m)m, \tag{12}$$

$$p_m v - c_v v, \tag{13}$$

$$(p_m + \tau_f + \tau_p)R(\ell_r, A(q)z) - p_\ell \ell_r - (p_z + \tau_f + \tau_p)z. \tag{14}$$

There is no market for landfilling waste. Instead, the waste is collected and deposited by a public enterprise, called the landfiller, who is required to set $\tau_f = c_w$ in compliance with the cost covering rule. It is important to note that τ_p is unrestricted in sign. In particular, if $\tau_p \in [-c_w, 0[$, the recycler pays a net tax $(\tau_f + \tau_p) \in [0, c_w[$ which is less than the unit cost of landfilling. In case of $\tau_p > 0$ the recycler's overall tax on waste covers the landfilling costs *and* a charge for reducing the environmental externality induced by the waste.

It follows from the above definitions of profits that the government's budget is

$$\phi := \tau_y y - \tau_m m + \tau_p w. \tag{15}$$

The representative consumer's Lagrangean is[8]

$$\mathcal{L}^h(y, w, \mu, \mu_w; \bar{w}) := U(y, w) + \mu(p_\ell \ell + \phi - p_y y) + \mu_w(w - \bar{w}). \tag{16}$$

The specification of (12), (14) and (16) reveals a particular sequence of trading residuals: The producers take back the residuals from the consumers and then sell them at price p_z to the recyclers.

Consider first a competitive equilibrium of the economy at hand characterized by $\tau_y = \tau_m = 0$ and $\tau_p = -\tau_f = -c_w$. Even though this state is not a no-policy situation in the strict sense, because the public landfilling enterprise is still active and the government subsidizes the recyclers we will refer to it as *laissez-faire.* There are three different reasons why such a laissez-faire economy is inefficient:

(a) *external landfilling costs.* The landfilling costs $(c_w w)$ are not paid by the recyclers who generate the waste; their production is distorted because they receive the wrong signal that waste is a free good;

[7] For a more comprehensive discussion of corrective taxes in a similar context see Eichner and Pethig (2000).

[8] Profit shares as part of the consumer's income are suppressed since maximum equilibrium profits are zero owing to the linear homogenity of all technologies. The consumer's optmization problem in (16) may appear unusual since the consumer takes the 'prevailing' waste $\bar{w}$ as given but maximizes over w, at the same time. The purpose of this procedure is to derive a shadow price for the constraint $w \geq \bar{w}$.

(b) *pollution externality.* The environmental damage caused by waste and suffered by the consumers is ignored in the recyclers' profit maximization calculus;

(c) *product design externality.* The material content of residuals affects the productivity of recycling but is chosen by the producers irrespective of the recyclers' needs or wants.

Suppose now the tax rates τ_m, τ_p and τ_y are assigned arbitrary (feasible) values. Then there is a general competitive equilibrium associated to each set of such tax rates characterized by specific values of the externality-related variables q and w, say $q = \bar{q}$ and $w = \bar{w}$. To characterize those equilibrium allocations, it is convenient to turn the problem on its head: We first maximize the representative consumer's utility subject to the usual constraints on technology and resources *and* subject to some lower bound $\bar{w}$ and some upper bound $\bar{q}$. After that the solution is decentralized by prices and taxes. The corresponding Lagrangean reads

$$\mathcal{L} = U(y,w) + \lambda_y \left[Y(\ell_y, m) - y\right] + \lambda_r \left[R(\ell_r, A(q)z) - r\right] + \lambda_z(y-z) + \lambda_q\left(\frac{m}{y} - q\right) + \lambda_{\bar{q}}(\bar{q} - q)$$

$$+\lambda_\ell\left(\ell - \ell_y - \ell_r - c_w w - c_v v\right) + \lambda_m\left(v + r - m\right) + \lambda_w(w - z + r) + \lambda_{\bar{w}}(w - \bar{w}). \qquad (17)$$

We apply the standard procedure of deriving first order conditions from (17) and match them with the first order conditions of maximizing (12)-(14), (16). As a result we obtain a vector of prices (p_ℓ, p_m, p_y, p_z) and of tax rates $(\tau_f, \tau_m, \tau_p, \tau_y)$ satisfying, for each given pair $(\bar{q}, \bar{w})$,

$$p_\ell \equiv 1, \quad p_m = c_v > 0, \quad p_y = (\tau_p + \lambda_{\bar{w}})\left(-\frac{U_y}{U_w}\right), \quad p_z = \frac{A(q)R_s}{R_\ell} - \tau_f - \tau_p,$$

$$\tau_y = \tau_m q = \left(c_v - \frac{Y_m}{Y_\ell}\right)q = \frac{qR_sA_q}{R_\ell} - \frac{q\lambda_{\bar{q}}}{y},$$

$$\tau_p + \tau_f = \frac{1}{R_\ell} - c_v = \lambda_w \geq 0, \quad \tau_f = c_w > 0. \qquad (18)$$

These prices and taxes are market clearing for any given pair $(\bar{q}, \bar{w})$. Hence the resource allocation that is efficient subject to the constraints $q \leq \bar{q}$ and $w \geq \bar{w}$ can be decentralized by prices and suitable tax rates. The tax rates (τ_y, τ_m) guide the choice of product design, and τ_p causes external landfilling costs when negative (exacerbating the environmental externality) or reduces the environmental externality when positive. While p_m and p_ℓ are obviously positive, (18) leaves p_y and p_z indeterminate in sign. But if y is positive (which is natural to assume) the solution to (16) requires $U_y = \lambda p_y$. Therefore $p_y > 0$ follows from $U_y > 0$ and $\lambda > 0$ (and (18) implies, in turn, $\tau_p + \lambda_{\bar{w}} > 0$). The price for residuals, p_z, can be either positive or negative, indeed. For example, $p_z > 0$, if $c_w = U_w = 0$, but $p_z < 0$, if $c_w > 0$ and/or $U_w < 0$ and if recycling is very unproductive or infeasible ($R_s = 0$).

We can elicit further interesting information from (18) by defining

$$\delta_w(\tau_m, \tau_p) := -\tau_p - p_y \frac{U_w}{U_y} \quad \text{and} \quad \delta_q(\tau_m, \tau_p) := \frac{R_s A_q}{R_\ell} - \tau_m. \tag{19}$$

(i) If we set $\lambda_{\bar{q}} \equiv 0$ and $\lambda_{\bar{w}} \equiv 0$ the solution to (17) obviously characterizes an unconstrained Pareto efficient allocation. Marking the associated equilibrium values and terms by an asterix (18) yields for $\lambda_{\bar{q}} \equiv 0$ and $\lambda_{\bar{w}} \equiv 0$ $\quad \delta_w(\tau_m^*, \tau_p^*) = \delta_q(\tau_m^*, \tau_p^*) = 0$ or

$$\frac{\tau_p^*}{p_y^*} = -\frac{U_w^*}{U_y^*} \quad \text{and} \quad \tau_m^* = \frac{R_s^* A_q^*}{R_\ell^*}. \tag{20}$$

The equations (20) are readily interpreted as the marginal conditions for internalizing the environmental externality and the product design externality, respectively. As an implication of (20) the efficiency restoring tax rates τ_p^* and τ_m^* are positive.

(ii) $\delta_w(\tau_m, \tau_p) > 0$ $\quad [\delta_q(\tau_m, \tau_p) > 0$, respectively], if and only if the constraint $w \geq \bar{w}$] [$q \leq \bar{q}$] is strictly binding (while the other constraints may or may not be binding). $\delta_w > 0$ tells us that the marginal environmental damage is greater than the marginal waste reduction costs in terms of good Y. δ_w is therefore an index measuring the non-internalized pollution externality. Hence δ_w measures the pollution distortion or the implementation gap. Similarly, $\delta_q > 0$ means that the marginal cost of greening the product design via a subsidy on the producers' material input and a tax on their output is less than the marginal benefit from the implied improvement in the productivity of recycling. Sufficient for $\delta_w > 0$ is $\tau_p \leq 0$ and sufficient for $\delta_q > 0$ is $\tau_m = 0$.

(iii) $\delta_w(\tau_m, \tau_p) = 0$ $\quad [\delta_q(\tau_m, \tau_p) = 0$, respectively], if and only if the constraint $w \geq \bar{w}$] [$q \leq \bar{q}$] is not binding (while the other constraint may or may not be binding). If $\delta_w = 0$, then $\tau_p > 0$ and if $\delta_q = 0$ then $\tau_m > 0$.

We conclude from (i) - (iii) that if the initial situation exhibits an internalization gap of the pollution externality [of the product design externality] this gap can be closed by sufficiently raising τ_p [τ_m].

As argued above, the procedure of solving (17) and deriving an equilibrium characterized by the prices and taxes (18) can be applied for any given $(\bar{q}, \bar{w})$ satisfying $\bar{q} \leq q^*$ and $\bar{w} \geq w^*$. There is, in particular, a laissez-faire equilibrium defined by $\tau_{mo} = 0$ and $\tau_{po} = -c_w$ exhibiting $q_o < q^*$, $w_o > w^*$ (and hence $\lambda_{\bar{q}o}$, $\lambda_{\bar{w}o} > 0$) and $U(y^*, w^*) > U(y_o, w_o)$. Thus the standard techniques of Lagrangean analysis yield some interesting information about the allocative distortions due to non-internalized externalities, but it would be desirable to know more about exactly how the laissez-faire allocation deviates from the efficient one. We certainly have some informed conjectures about the sign of the differences $b_o - b^*$ for $b = p_y, p_z, y, m, n, r, v$. But since relying on plausibility is somewhat unsatisfactory we aim at deriving the directions of change in rigorous analysis. For that purpose it is necessary to carry out an exercise of comparative statics taking as a starting point a market equilibrium with tax rates $\tau_y \in [0, \tau_y^*[$, $\tau_m \in [0, \tau_m^*[$ and $\tau_p \in [-c_w, \tau_p^*[$. Following the standard methodology we will calculate the allocative effects of marginal changes in those tax rates. But in this way the sign of the difference $b_o - b^*$ for an endogeneous variable b can be determined unambiguously only if the sign of the effects from marginal tax rate changes (i) are unambiguous and (ii) are the same for any initial value of tax rates below their efficient level.

4 Allocative impacts of marginal tax reforms

This section develops a comparative static analysis of marginal changes in the tax rates τ_m, τ_p and τ_y along the lines of Jones (1965). As a first step, it is necessary to define an initial competitive equilibrium through a set of appropriate equations that incorporate profit maximizing behavior in production, recycling and extraction.[9] Owing to the assumption of linear homogeneous technology, zero profits are a necessary equilibrium condition. For computational convenience we rewrite the recycler's zero-profit equation $p_m + \tau_f + \tau_p = \ell_r/r + (p_z + \tau_f + \tau_p)z/r$ as

$$p_m + c_w + \tau_p = p_\ell a_{\ell r} + \frac{p_z + c_w + \tau_p}{A(q)} a_{sr} \tag{21}$$

where $a_{\ell r} := \ell_r/r$ and $a_{sr} := s/r = A(q)z/r$ are the pertinent input-output coefficients. Similarly, we have

$$p_y - \tau_y + p_z = p_\ell a_{\ell y} + (p_m - \tau_m)q, \tag{22}$$

$$p_m = c_v \tag{23}$$

where $a_{\ell y} := \ell_y/y$ and $q = m/y$. The linear homogeneity of technologies combined with the producers' and recyclers' cost minimization exercise (which is a necessary condition for profit maximization) also implies that the input-output coefficients $a_{\ell r}$, a_{sr}, $a_{\ell y}$ and q are functions of factor prices:

$$a_{\ell r} = A^{\ell r}\left(p_\ell, \frac{p_z + c_w + \tau_p}{A(q)}\right), \quad a_{sr} = A^{sr}\left(p_\ell, \frac{p_z + c_w + \tau_p}{A(q)}\right),$$

[9]Utility maximization is trivial in the present model since there is one consumption good only, and consumers take the 'prevailing' pollution (through landfilled waste) as given.

$$a_{\ell y} = A^{\ell y}(p_\ell, p_m - \tau_m), \quad q = Q(p_\ell, p_m - \tau_m). \tag{24}$$

Combining the consumer's budget equation $p_\ell \ell + \phi = p_y y$ and (15) yields

$$p_\ell \ell = (p_y - \tau_y)y + \tau_m m - \tau_p w. \tag{25}$$

To eliminate the degree of freedom in prices we choose labour as the numeraire and set

$$p_\ell \equiv 1. \tag{26}$$

From (4) and $s = A(q)z$ we obtain

$$a_{sr} r = A(q)y. \tag{27}$$

We also combine (4) and (6) to get

$$w = y - r. \tag{28}$$

Finally, using (2) and input-output coefficients, we rewrite (7) and (11), respectively, as

$$qy = v + r, \tag{29}$$

$$\ell = a_{\ell y} y + a_{\ell r} r + c_v v + c_w w. \tag{30}$$

Observe that the 13 equations (21)-(30) contain the 12 variables p_ℓ, p_m, p_y, p_z, $a_{\ell r}$, a_{sr}, $a_{\ell y}$, q, r, v, w and y. Owing to Walras' law one of the equations (21)-(30) can be shown to be redundant. We eliminate (30) so that the comparative statics will be based on (21)-(29). Note also that the solution to (21)-(29) can be readily used to determine the utility (10) as well as

$$m = qy \qquad \text{and} \qquad n = (1 - q)y. \tag{31}$$

We showed that the taxes, τ_y and τ_m, jointly serve for correcting the product design externality and that the optimal tax rates satisfy $\tau_y^* = \tau_m^* q^*$ (see (18)). In the subsequent comparative statics we take advantage of this equality by restricting our attention to tax reforms (τ_m, τ_y) that satisfy $\tau_y = q\tau_m \in [0, \tau_y^*]$. The implied loss of generality is not restrictive, because our principal interest is not to study all possible paths of tax changes from laissez-faire to the efficient allocation but rather, as argued above, to determine the sign of the differences $b_o - b^*$ for $b = r, v, w, y$.

Setting $\tau_y = q\tau_m$ has two consequences for the system of equations (21)-(29): Equation (25) now becomes

$$p_\ell \ell = p_y y - \tau_p w \tag{32}$$

and we substitute τ_y by $q\tau_m$ in (22) to the effect that (22) is turned into

$$p_y + p_z = a_{\ell y} + p_m q. \tag{33}$$

To sum up: For any given set of tax rates $\tau_m \in [0, \tau_m^*]$, $\tau_y \in [0, q^*\tau_m^*]$, $\tau_f = c_w$ and $\tau_p \in [-c_w, \tau_p^*]$ there exists a competitive equilibrium completely determined by (21), (23), (24), (26)-(29), (32) and (33).

As shown in the appendix, total differentiation of the equations (21), (23), (24), (26)-(29), (32) and (33) results in the following set of equations:

$$p_z\hat{p}_z = -\frac{w}{y}a\pi_s\hat{\tau}_p + \alpha_y a\pi_s\varepsilon_{aq}\hat{\tau}_m \tag{34}$$

$$p_y\hat{p}_y = \frac{w}{y}a\pi_s\hat{\tau}_p - \alpha_y q\delta_q\hat{\tau}_m, \tag{35}$$

$$\ell\hat{y} = -\frac{\alpha_r r^2\tau_p}{y}\hat{\tau}_p + \alpha_y\left[m\delta_q - \varepsilon_{aq}r\tau_p\right]\hat{\tau}_m, \tag{36}$$

$$\ell\hat{w} = -\frac{\alpha_r r^2 p_y}{w}\hat{\tau}_p + \alpha_y\left[m\delta_q - \frac{\varepsilon_{aq}rp_y y}{w}\right]\hat{\tau}_m, \tag{37}$$

$$\ell\hat{r} = \alpha_r r\pi\hat{\tau}_p + \alpha_y\left[m\delta_q + \varepsilon_{aq}\pi y\right]\hat{\tau}_m, \tag{38}$$

$$\ell\hat{v} = -\frac{\alpha_r r^2}{v}(\pi + q\tau_p)\hat{\tau}_p + \alpha_y\left[m\delta_q + \pi y\left(1 + \frac{r}{v}(1-\varepsilon_{aq})\right) + \frac{mr}{v}\tau_p(1-\varepsilon_{aq})\right]\hat{\tau}_m, \tag{39}$$

$$\ell\hat{m} = -\frac{\alpha_r r^2\tau_p}{y}\hat{\tau}_p + \alpha_y\left[m\delta_q + \pi y + \tau_p r(1-\varepsilon_{aq})\right]\hat{\tau}_m, \tag{40}$$

$$\ell\hat{n} = -\frac{\alpha_r r^2\tau_p}{y}\hat{\tau}_p + \alpha_y\left[m\delta_q - \varepsilon_{aq}r\tau_p - \frac{m}{n}\ell\right]\hat{\tau}_m. \tag{41}$$

In (34)-(41) the 'hat variables' are defined as $\hat{x} = dx/x$ except for $\hat{\tau}_m$ and $\hat{\tau}_p$ (see footnote 12). The positive terms α_r, α_s, α_y, ε_{aq}, π and π_s are defined in the appendix and are introduced only to improve readability of (34)-(41).

It is also interesting to know that the recycling ratio, $\rho := r/m$, responds to tax rate changes according to

$$\ell\hat{\rho} = \ell\hat{r} - \ell\hat{m} = \frac{\alpha_r r\ell}{y}\hat{\tau}_p - \alpha_y\left[(1-\varepsilon_{aq})\ell\right]\hat{\tau}_m. \tag{42}$$

Finally, we demonstrate in the appendix that the utility impact of marginal tax reforms can be assessed by the inequality

$$\frac{\ell du}{U_y} \geq y\ell\hat{y} - w\ell\hat{w} = \alpha_r r^2 \pi \hat{\tau}_p + \alpha_y \left[mr\delta_q + \varepsilon_{aq} ry\pi \right] \hat{\tau}_m. \tag{43}$$

The equations (34)-(43) represent the complete comparative statics of our model. They will now be used for analyzing the allocative impact of marginal tax rate changes. We find it convenient to organize our interpretation of the comparative statics by focussing on five different tax change scenarios as specified in table 1 and discuss them one at time.

tax policy			$\hat{p}_y$	$p_z\hat{p}_z$	$\hat{q}$	$\hat{y}$	$\hat{r}$	$\hat{w}$	$\hat{m}$	$\hat{n}$	$\hat{v}$	$\hat{\rho}$	$\hat{u}$
I	$\hat{\tau}_p > 0,\ \hat{\tau}_m = 0$	$\tau_p \in [0, \tau_p^*[$	$+$	$-$	0	$-$	$+$	$-$	$-$	$-$	$-$	$+$	$+$
II	$\tau_m \in [0, \tau_m^*]$	$\tau_p \in [-c_w, 0[$	$+$	$-$	0	$+$	$+$	$-$	$+$	$+$	$-$	$+$	$+$
III	$\hat{\tau_m} > 0,\ \hat{\tau}_p = 0$ $\tau_m \in [0, \tau_m^*],\ \tau_p \in [-c_w, \tau_p^*]$		$-$	$+$	$+$	$+?$	$+$	?	$+$	?	$+$	$-$	$+$
IV	$\hat{\tau}_p = \dfrac{\alpha_y m\delta y}{\alpha_r r^2 \tau_p}\hat{\tau_m} > 0$ $\tau_m \in [0, \tau_m^*],\ \tau_p \in]0, \tau_p^*]$		?	?	$+$	$-$	$+$	$-$	$+$	$-$	?	?	$+$
V	$\hat{\tau}_p = \dfrac{\alpha_y y\left[m\delta + \ell - \tau_p r\varepsilon_{aq}\right]}{\alpha_r r^2 \tau_p}\hat{\tau_m} > 0$ $\tau_m \in [0, \tau_m^*],\ \tau_p \in]0, \tau_p^*]$		?	?	$+$	$-$	$+$	$-$	0	$-$	$+$	$+$	$+$

Table 1: Incidence of five different tax policies

5 Efficiency enhancing tax policies

Table 1 lists five different tax policies denoted policies I - V. Each of these policies is characterized by its starting point, an initial inefficient competitive equilibrium, and by a specific mix of marginal tax changes. As discussed above, an initial equilibrium is inefficient, in general, because the product design externality, the pollution externality and/or the deposition costs are not fully internalized. The policies I - III are designed to address one and only one of these distortions. But since multiple distortions are present, all of them will, in general, influence the performance of the policy under consideration through interdependence effects which, in turn, depend on how the initial situation is specified.

The policies I and II ignore the product design externality ($\tau_y = q\tau_m$ constant) and focus on taxing or subsidizing non-recycled consumption waste. Policy I is defined by

$\hat{\tau}_p > 0$ and by an initial situation $\tau_p \geq 0$. We know from our discussion in section 3 that the internalization gap $\delta_w(\bar{\tau}_m, \tau_p)$ is positive for any given $\bar{\tau}_m \geq 0$, if $\tau_p = 0$, and that there is $\tau_p(\bar{\tau}_m) > 0$ such that $\delta_w(\bar{\tau}_m, \tau_p(\bar{\tau}_m)) = 0$. Hence policy I is readily characterized as a pollution control policy by means of raising τ_p, the pollution charge. If τ_p is a subsidy in the initial situation, $\tau_p \in [-c_w, 0[$, the internalization gap $\delta_w(\bar{\tau}_m, \tau_p)$ is still positive (and probably larger than in case of $\tau_p \geq 0$). But it will be shown below that $\tau_p < 0$ characterizes a situation with landfilling costs that are external to the recyclers' profit maximization calculus. $\hat{\tau}_p > 0$ then amounts to reducing those external landfilling costs (policy II).

Policy III aims at fighting the inefficient product design leaving the external landfilling costs and the pollution externality aside ($\hat{\tau}_p = 0$). If there is an initial equilibrium in which the internalization gap $\delta_q(\tau_m, \bar{\tau}_p)$ is positive for any given $\bar{\tau}_p$ then there is $\tau_m(\bar{\tau}_p)$ such that $\delta_q(\tau_m(\bar{\tau}_p), \bar{\tau}_p) = 0$. Hence policy III is capable of internalizing the product design externality. The tax policies IV and V consist of specific combinations of simultaneous marginal increases in τ_p, τ_m and τ_y designed to reduce all distortions simultaneously. The interest in such hybrid policies is to find one whose implied sequence of equilibrium allocations uniquely determines the direction of change in the relevant quantities and prices.

Before we discuss each of the policies I - V in more detail it is worth noting that all of them are efficiency-enhancing ($\hat{u} > 0$, last column of table 1). This is not a trivial result, since it is well-known from the theory of second best that, in general, the transition from an initial situation with multiple distortions to the efficient allocation is not strictly monotone in the utility of the representative consumer.

5.1 Correcting for the pollution externality (policy I)

Consider an initial competitive equilibrium with $\tau_p \geq 0$ where the pollution distortion $\delta_w(\tau_m, \tau_p)$ is positive. Policy I is a conventional pollution control policy that aims at reducing $\delta_w(\tau_m, \tau_p)$ by setting $\hat{\tau}_p > 0$ while τ_m is kept constant. The incidence of policy I is completely characterized in the first row of table 1.

For interpretative purposes, let us identify y as national product or (material) standard-of-living and w as pollution or its inverse, an index for environmental quality. The utility function then tells us that consumers strive for increases in both national product and environmental quality. As the first row of table 1 shows, policy I succeeds in promoting environmental quality ($\hat{w} < 0$) but only at the expense of the second goal, national product ($\hat{y} < 0$). The choice between conflicting goals is made in favor of environmental quality and this is a good choice because the benefit from improving environmental quality is greater than the cost of forgoing consumption ($\hat{u} > 0$). In that respect the performance of policy I is as expected and well known: pollution control does not provide a free lunch, but it is worth the cost.

Our model also allows to assess the changes in material flows and recycling brought about by policy I. The recyclers' sales price $\pi_r = p_m + c_w + \tau_p$ of recycled material rises, while selling their second output 'waste' at a negative price becomes more expensive. As a response they shift their output mix towards recycled material ($\hat{r} > 0$ and $\hat{w} < 0$). Moreover, the recyclers pay a higher price for their input 'residuals' ($\hat{\pi}_s > 0$) which induces them to increase the labour intensity, ℓ_r/s, of recycling. This allows them to expand the output of recycled material ($\hat{r} > 0$) and to diminish, at the same time, their demand for residuals ($\hat{z} = \hat{y} < 0$). The producers of good Y are not affected by any change in prices or taxes. Therefore, they do not change their product design ($\hat{q} = 0$) and the ratio of inputs ($\hat{m} = \hat{\ell}_y$). However, to accomodate for the shrinking demand for their output ($\hat{y} < 0$), they reduce their inputs material and labour in fixed proportion ($\hat{m} = \hat{\ell}_y < 0$). $\hat{m} < 0$ and $\hat{r} > 0$ clearly implies an increasing recycling ratio $\rho := r/m$. Since $m = r + v$, we also infer from $\hat{r} > 0$ and $\hat{m} < 0$ that less material M is extracted ($\hat{v} < 0$). In fact, since $\hat{v} = (\hat{m} - \rho\hat{r})/(1 - \rho)$, the reduction $\hat{v}$ is significantly greater than $\hat{m}$ in absolute terms.

Taking all these shifts in material flows together, policy I's performance is outstanding with regard to resource conservation. The materials (net) throughput, i.e. the extraction and ultimate deposition, of both types of materials is reduced. The reduction in the use of both materials was to be expected since by assumption both (waste) materials do not differ with respect to their harmful environmental effects. Observe, however, that the use of material N can be only curbed through cutting back on extraction, while the reduction in the extraction of material M is partly brought about by fostering its reuse through recycling.

5.2 Reducing external landfilling costs (policy II)

As in policy I we keep constant the tax rates (τ_y, τ_m) and set $\hat{\tau}_p > 0$, but this time the initial tax rate τ_p is assumed to be negative. Broadly conceived, policy II is about pollution control as is policy I, since (19) implies that the allocative distortion $\delta_w(\tau_m, \tau_p)$ caused by the pollution externality is positive if $\tau_p < 0$ and since raising τ_p sufficiently will eventually close the internalization gap. Hence policy II can be viewed as a policy that reduces pollution through increasing a 'negative pollution charge' ($\hat{\tau}_p > 0$) by which the pollution-induced distortion had probably been artificially aggravated in the first place. In this perspective, policy II appears as a strange theoretical curiosity since pollution control, properly and conventionally conceived, should be associated only with tax rates $\tau_p \in]0, \tilde{\tau}_p[$.

We find it interesting to study this case, nevertheless, because it allows for analyzing an empirically relevant scenario following a reinterpretation of the model without any change in its formal structure. To see this we restrict the initial tax rates τ_p to the interval $[-c_w, 0[$ and drop the assignment of the landfilling charge $\tau_f = c_w$. Instead, we define an alternative landfilling fee, $\tilde{\tau}_f$, by $\tilde{\tau}_f := \tau_p + c_w$. Hence rather than saying that the recyclers pay the landfilling charge τ_f and receive a subsidy τ_p we consider their net payment for waste[10] as the new landfilling fee $\tilde{\tau}_f$. It follows that the recyclers do not bear the full (social) cost of landfilling per unit of waste. The amount $-\tau_p$ is external to their profit-maximizing calculus. The external landfilling costs, $-\tau_p$, and the private landfilling costs clearly add up to total landfilling costs: $-\tau_p + \tilde{\tau}_f = -\tau_p + \tau_p + c_w = c_w$. In this perspective, policy II that starts at $\tau_p \in [-c_w, 0[$ and sets $\hat{\tau}_p > 0$ is naturally interpreted as a policy for reducing external landfilling costs.

We are now in the position to discuss the incidence of this policy as summarized in the second row of table I. Observe first that policy II results in raising the supply of good Y and lowering the waste flow. In this way it promotes both principal goals: it augments the national product and improves the environmental quality. Since each of these changes is utility enhancing, policy II is obviously a utility-enhancing strategy. While in policy I both goals were in conflict the internalization of external landfilling costs through policy II is a win-win strategy which can be therefore expected to be endorsed unanimously by all consumer-voters in the political decision-making process.

We now look more closely at policy II's impact on material flows. The changes in those prices that are relevant to the recyclers are the same in sign as under policy I. Hence the recyclers produce more recycled material ($\hat{r} > 0$), less waste ($\hat{w} < 0$) and raise the labour intensity, ℓ_r/s. But this time, they produce so much more recycled material that their demand for residuals increases ($\hat{z} = \hat{y} > 0$) overcompensating the reduction in demand induced by the increase in the labour intensity. As in case of policy I the producers have no reason to change their product design ($\hat{q} = 0$) or the ratio of their inputs ($\hat{m} = \hat{\ell}_y$). They react to the increasing demand for good Y ($\hat{y} > 0$) by raising their inputs material and labour in fixed proportion ($\hat{m} = \hat{\ell}_y > 0$). $\hat{m}$ turns out to be smaller than $\hat{r}$ implying (i) that the recycling ratio, ρ, is enhanced and (ii) that the extraction rate of material M is diminished ($\hat{v} < 0$). Regarding (i) and (ii), the policies I and II exhibit the same performance. But while policy I also economizes on the throughput of material N ($\hat{n} < 0$), under policy II the extraction of material N is expanded ($\hat{n} > 0$). In other words, the reduction of the external

[10] As a consequence, the landfiller runs a budget deficit which must be covered by lumpsum taxation. It is easy to show that the reinterpretation at hand does not change the consumer's budget constraint or equation (32).

landfilling costs (policy II) brings about a substitution of material M by material N in the waste stream ($\hat{v} < 0$ and $\hat{n} > 0$). We did not succeed in offering a convincing explanation for this substitution effect since we find it plausible that internalizing the external costs of waste should result in economizing on both components of waste, on material M and on material N.

From the conservationist's point of view growing throughput of material N might be considered undesirable but we should keep in mind that the total materials throughput measured by $w = n + v$ is diminished through policy II (as through policy I), and that counts for enhancing the quality of the environment.

Summing up, the allocative impacts of the policies I and II differ markedly regarding the growth of national product and the change in the mix of materials throughputs. This is quite surprising in view of the observation made above that policy II is, in a broad and somewhat unconventional sense, also a pollution control strategy like policy I. The difference being that policy II starts from a situation where the internalization gap $\delta_w(\tau_m, \tau_p)$ is 'deliberately' widened by setting $\tau_p < 0$. It is also worth noting - and easy to see - that policy I recommends itself even if waste does not cause any pollution at all ($U_w \equiv 0$) because it boosts the national product.

5.3 Correcting for the product design externality (policy III)

The policies I and II discussed above have in common that τ_m was kept constant. Hence they did not affect the product design q. If the initial situation is characterized by some given $\tau_p \in [-c_w, \tau_p^*]$, by $q < q^*$ and hence by $\delta_q(\tau_m, \tau_p) > 0$ the product design externality cannot be internalized unless τ_m is raised. This strategy is denoted policy III and its allocative impact is listed in the third row of table 1.

Unfortunately, we do not obtain clear-cut results concerning the direction of change of national product and environmental quality, even though policy III is unambiguously utility-enhancing. (36) reveals that $\hat{y} > 0$, if $\tau_p \leq 0$. Otherwise $\hat{y}$ is indeterminate in sign, but $\hat{y} < 0$ is the more likely, the smaller is the product design distortion and the greater is the (positive) pollution charge, i.e. the smaller is the non-internalized pollution externality. More specifically, let an initial situation satisfy $\hat{y} > 0$, $\tau_p > 0$, $q < q^*$ and $\tau_{mo} < \tau_m^*$ and consider a sequence of increasing tax rates $\tau_{mo}, \tau_{m1}, \ldots$ converging to τ_m^* from below. In view of (36) the ratio $\hat{y}/\hat{\tau}_m$ which is associated to that sequence will then turn negative when τ_m comes sufficiently close to τ_m^*.

(37) shows that $\hat{w}$ may be positive, if the product design distortion δ_q is large enough.

Hence the growth of the national product at the cost of more pollution ($\hat{y} > 0$ and $\hat{w} > 0$) is feasible. But as shown above for the case of $\hat{y}$, $\hat{w}$ will turn negative when τ_m approaches τ_m^* from below. Moreover, since $w\hat{w} = y\hat{y} - r\hat{r}$ and $\hat{r}$ is positive, $\hat{y} \leq 0$ is sufficient for $\hat{w} < 0$, and it must also be true that for some $\tau_m < \tau_m^*$ one has $\hat{y} > 0$ and $\hat{w} < 0$. ($\hat{y} < 0$ and $\hat{w} > 0$ is excluded because that constellation would reduce the utility.)

We now investigate the performance of policy III regarding the use of materials. Clearly, the material content q increases thus improving the product design. $\hat{q} > 0$ means that for any given output Y more material M and less labour is employed. Sharp cuts in output would imply $\hat{m} < 0$. But since we know that $\hat{m} > 0$ we are led to conclude that if the output shrinks under policy III at all ($\hat{y} < 0$) then this reduction must be rather small.

The implementation of policy III leaves all prices unchanged that are relevant to the recyclers. But the recyclers benefit from the increase in material content that raises the output of recycled material ($\hat{r} > 0$) even if $\hat{z} = \hat{y} < 0$. (This is another indication for reductions in y being small, if they occur at all.) Though $\hat{r}$ is positive, it is smaller than $\hat{m}$ so that the recycling ratio shrinks. As a corollary, the extraction of material M is expanded. Using and recycling more material M following the change in product design is plausible, but it is not so obvious why these shifts are nourished by an increased extraction of material M rather than by raising the recycling ratio. The producers' extra demand for material M, both primary and recycled, is apparently stronger than the productivity-induced increase in the recycled material output. Unfortunately, the direction of change in $\hat{n}$ cannot be determined but we know, at least, that if $\hat{w} < 0$, then $\hat{n} < 0$, too, and that $\hat{y} \leq 0$ is sufficient for $\hat{n} < 0$ (see (41) and (36)). These observations indicate, not unconditionally though, that policy III induces a shift in the material mix of the waste flow in favor of material M. This substitution effect does not come as a surprise since by raising q the unit share of material M embodied in the output is increased and that of material N is reduced. The expansion in the use of material M is induced to exploit the benefits of the improved productivity of recycling. As already mentioned, there is a sense in stepping up the use of that type of material which makes consumption residuals more recyclable. The productivity effect of 'greening' the product design renders the national product less expensive as compared to environmental quality and that is why it tends to be worthwhile to raise the national product even at the cost of environmental deterioration ($\hat{y} > 0$ and $\hat{w} > 0$).

The preceding discussion showed that -and to some extent, how- the allocative impact of policy III depends on the initial tax rates (τ_m, τ_p). It is therefore not possible to determine for any given τ_p the allocative changes occuring when τ_m is increased from $\tau_m = 0$ to that particular level which removes the distortion δ_q altogether.

5.4 Hybrid efficiency-enhancing tax policies (policies IV and V)

In the previous sections 5.1 - 5.3 we investigated three tax policies that aimed at tackling one distortion at a time. We now wish to focus on both the pollution externality and the product design externality simultaneously. Since the issue of external landfilling costs is well understood, we will leave it aside by setting $\tau_p \in [0, \tau_p^*]$ in what follows. With this qualification it is interesting to ask the question whether there are tax policies specifying a path of simultaneous tax increases $(\hat{\tau}_m, \hat{\tau}_p)$, starting at $(\tau_m, \tau_p) = (0, 0)$ and leading toward (τ_m^*, τ_p^*), such that the changes in the (relevant) endogenous variables of the model induced by these policies are strictly monotone. The motivation of searching for such policies is the hope that the ambiguities related to fighting the product design externality (policy III) can be overcome by combining it with fighting the pollution externality (policy I) which we were able to completely characterize. It should be emphasized that the main purpose of this exercise is not to recommend to policy makers those particular sequences in time of joint increases in the tax rates (τ_m, τ_q) that we will specify below - even though politicians might find them attractive because they are utility-increasing. Rather, we are primarily interested in determining the net allocative impact of internalizing both types of externalities.

The last two rows of table 1 summarize the allocative impact of policies IV and V, respectively.[11] Since their performance is very similar we first comment on their common features and then point to some differences. To begin with, it is quite remarkable that most effects are determinate in sign even though price changes are not. The expansion of recycled material in policies IV and V is no surprise since both policies I and III exhibit also $\hat{r} > 0$. $\hat{q} > 0$ is an immediate consequence of $\hat{\tau}_m > 0$ as in policy III. The performance regarding the prime policy goals, national product and environmental quality, is like in policy I: environmental quality improves at the expense of national product. In that regard the impact of diminishing the pollution externality dominates the impact of improving upon the product design. This is also true with respect to the declining waste flow ($\hat{w} < 0$) and the extraction of material N ($\hat{n} < 0$) while the impact of policies IV and V tends to deviate from that of policy I regarding $\hat{m}$ and $\hat{v}$.

Recall that under policy I the throughput of both types of materials was reduced ($\hat{n} < 0$ and $\hat{v} < 0$) while under policy III the extraction of material M grew ($\hat{v} > 0$) and $\hat{n}$ was indeterminate in sign. Tentatively, we interpreted this impact of policy III as a shift of

[11]The changes of prices and variables induced by policies IV and V are listed in equations (44)-(63) of the appendix.

the waste materials mix in favor of material M. This substitution effect now fully manifests itself in policy V ($\hat{v} > 0$ and $\hat{n} < 0$) and also tends to be present in policy IV ($\hat{n} < 0$ and $\hat{v}$?) with some ambiguity remaining, though. Note, finally, that the recycling ratio improves under policy V like under policy I, so that the partial effect $\hat{\rho} < 0$ from policy III is overcompensated in policy V. Under policy IV the recycling ratio is indeterminate in sign implying that the net effect on $\hat{\rho}$ as composed of the opposing effects from policies I and III is not settled.

6 Concluding remarks

In this paper we considered a competitive economy with flows of materials from extraction via recycling to landfilling which exhibits distortions due to pollution, external landfilling costs and inefficient product design. Our principal focus was to determine the allocative effects of five policies when the pertinent tax rates were successively raised from zero towards their efficiency-restoring levels.

A basic insight of our comparative static analysis is that for each distortion there is an independent tax policy capable to completely remove it irrespective of the degree of internalization of the other externality. Policy I controls for pollution and policy III for green product design.

Policy I is conventional pollution control by means of a pollution charge on waste. Its impact would be qualitatively the same if the recycling technology were assumed to be independent of material content (as in Førsund (1972), Mäler (1974) and Pethig (1977)). In that case there is no need for a policy directed toward promoting recycling since curbing excessive pollution stimulates recycling towards its efficient level: *all* material flows are reduced from extraction to landfilled waste by expanding recycling and the recycling ratio. The price to be paid is a sacrifice of national product.

Correcting for the product design externality (policy III) consists, first of all, in raising the material content which alleviates recycling and consequently increases the amount of recycled material. It expands the use of material M and stimulates the extraction of material M so much that the recycling ratio declines. Moreover, we cannot rule out that policy III aggravates pollution.

Policy II is a rather unexpected implication of our model. As argued in section 5.2, this policy is about increasing a negative pollution charge. While it would be rather foolish to study such a scenario, in general, in the present model the negative pollution charge amounts to a distortion caused by landfilling costs being partly or totally external to the recyclers' optimization problem. The incidence of internalizing those external landfilling costs provides the clear message that eliminating that distortion is a win-win stategy of raising both national product and environmental quality. Recycling and the recycling ratio are stimulated while the material mix extracted and ultimately landfilled is changed in favor of material N.

Leaving external landfilling costs aside the question arises what the allocative net impact is of moving from a laissez-faire situation ($\tau_p = 0, \tau_m = 0$) toward the efficient state ($\tau_p^* > 0, \tau_m^* > 0$) where both externalities are internalized. Policies IV and V are designed to answer this question. Even though some ambiguities remain, the net effect appears to come quite close to the incidence of the pollution control policy I (except for the shifts in material content, material M as production factor and extraction of material M). Policy V is particularly interesting because ignoring price changes it eliminates all ambiguities of policy III. It is remarkable that in all cases of determinate signs the net impact of the hybrid policies IV and V does not depend on how severe one distortion is as compared to the other.

In concluding, we readily concede that the model underlying our comparative statics is quite simple. Without linear and linear homogeneous technologies the analysis would have been untractable. Further studies that aim providing support for practical pollution control and resource policy will have to resort to large(r) scale computable general equilibrium analysis.

Appendix: The comparative statics

Before we turn to the differentiation of the equilibrium equations (21), (23), (24), (26)-(29) and (31)-(33) it is convenient to define the following terms used below to avoid clutter.

$$a = A(q), \quad \alpha_r = \sigma_s \theta_{\ell r}, \quad \alpha_y = \sigma_y \frac{a_{\ell y}}{p_y - \tau_m q + p_z}, \quad \delta_q = \frac{R_s A_q}{R_\ell} - \tau_m, \quad \varepsilon_{aq} = \frac{A_q q}{A(q)},$$

$$\pi = p_y - \tau_p, \quad \pi_r = c_v + c_w + \tau_p, \quad \pi_s = \frac{p_z + c_w + \tau_p}{A(q)}, \quad \pi_y = p_y + p_z, \quad \pi_m = p_m - \tau_m,$$

$$\theta_{\ell r} = \frac{a_{\ell r}}{\pi_r}, \quad \theta_{\ell y} = \frac{a_{\ell y}}{\pi_y}, \quad \theta_q = \frac{p_m q}{\pi_y}, \quad \tilde{\theta}_q = \frac{\pi_m q}{p_y - \tau_m q + p_z}, \quad \theta_{sr} = \frac{a_{sr}\pi_s}{\pi_r},$$

$$\sigma_s = \frac{\hat{a}_{\ell r} - \hat{a}_{sr}}{\hat{\pi}_s - \hat{p}_\ell}, \; \sigma_y = \frac{\hat{a}_{\ell y} - \hat{q}}{\hat{\pi}_m - \hat{p}_\ell}.$$

All these terms are positive. In cases where the positive sign is not readily seen it will be proved below when the term is first introduced. Next we substitute $p_m = c_v$ from (23) and $p_\ell = 1$ from (26) in all remaining equilibrium equations. With this simplification, differentiation of (21) yields[12]

$$\hat{\pi}_r = \theta_{\ell r}\hat{a}_{\ell r} + \theta_{sr}\hat{a}_{sr} + \theta_{sr}\hat{\pi}_s. \qquad [1']$$

As observed by Jones (1965), cost minimization implies $\theta_{\ell r}\hat{a}_{\ell r} + \theta_{sr}\hat{a}_{sr} = 0$, so that [1'] is turned into

$$\hat{\pi}_r = \theta_{sr}\hat{\pi}_s. \qquad [1'']$$

We find that $\hat{\pi}_r = \frac{a\pi_s}{\pi_r}\hat{\tau}_p$ and $\hat{\pi}_s = \frac{p_z}{a\pi_s}\hat{p}_z + \hat{\tau}_p - \varepsilon_{aq}\hat{q}$ so that [1''] becomes

$$\frac{p_z}{a\pi_s}\hat{p}_z = -\frac{w}{y}\hat{\tau}_p + \varepsilon_{aq}\hat{q}. \qquad [1]$$

Differentiation of (33) yields

$$\theta_{\ell y}\hat{a}_{\ell y} + \theta_q\hat{q} = \hat{\pi}_y. \qquad [2']$$

When $\theta_{\ell y}\hat{a}_{\ell y} + \theta_q\hat{q} - \frac{\tau_m q}{\pi_y}\hat{q} = 0$ (cost $(\ell + \pi_m m)$ minimization) is considered we have from [2']

$$\hat{\pi}_y = \frac{\tau_m q}{\pi_y}\hat{q}. \qquad [2'']$$

In view of the definition of π_y it is true that $\hat{\pi}_y = \frac{p_y}{\pi_y}\hat{p}_y + \frac{p_z}{\pi_y}\hat{p}_z$. Hence [2''] is turned into

$$\tau_m q\hat{q} - p_y\hat{p}_y - p_z\hat{p}_z = 0. \qquad [2]$$

Following Jones (1965), the equations (24) imply

$$\hat{a}_{\ell r} = \frac{\sigma_s\theta_{sr}}{\pi_s a}\left[\hat{p}_z p_z + \hat{\tau}_p\pi_s a - \varepsilon_{aq}\pi_s a\hat{q}\right], \qquad [3]$$

$$\hat{a}_{sr} = -\frac{\sigma_s\theta_{\ell r}}{\pi_s a}\left[\hat{p}_z p_z + \hat{\tau}_p\pi_s a - \varepsilon_{aq}\pi_s a\hat{q}\right], \qquad [4]$$

$$\hat{a}_{\ell y} = -\tilde{\theta}_q\sigma_y\hat{\tau}_m, \qquad [5]$$

$$\hat{q} = \alpha_y\hat{\tau}_m. \qquad [6]$$

Equations (27)-(29), (31) and (32) result in

$$p_y y\hat{y} + p_y y\hat{p}_y - \tau_p w\hat{w} = \pi_s a w\hat{\tau}_p, \qquad [7]$$

$$\hat{a}_{sr} + \hat{r} = \hat{y} + \varepsilon_{aq}\hat{q}, \qquad [8]$$

$$\hat{w} = \frac{y}{w}\hat{y} - \frac{r}{w}\hat{r}, \qquad [9]$$

$$\hat{v} = \frac{m}{v}\hat{q} + \frac{m}{v}\hat{y} - \frac{r}{v}\hat{r}, \qquad [10]$$

[12] In what follows we denote by $\hat{x} := \frac{dx}{x}$ the marginal relative changes of all variables x. Exceptions are made for $\hat{\tau}_m := \frac{d\tau_m}{\pi_m}$ and $\hat{\tau}_p = \frac{d\tau_p}{A(q)\pi_s}$ to avoid that $\hat{x}$ is not defined for $x = 0$ $(x = \tau_m, \tau_p)$.

$$\hat{m} = \hat{q} + \hat{y}, \quad [11]$$

$$\hat{n} = -\frac{q}{1-q}\hat{q} + \hat{y}. \quad [12]$$

The next step is to solve [1]-[12] by means of suitable substitutions of variables. First we consider [1] and [6] to obtain

$$p_z \hat{p}_z = -\frac{w}{y} a \pi_s \hat{\tau}_p + \alpha_y a \pi_s \varepsilon_{aq} \hat{\tau}_m. \quad [A]$$

$\pi_s = (p_z + \tau_w)/a$ is strictly positive, since otherwise (14) would induce the recycler to ever increase her demand for residuals to reach for unlimited profit.

We now use [A] and [6] in [2] to write

$$p_y \hat{p}_y = \frac{w}{y} a \pi_s \hat{\tau}_p - \alpha_y \left[\varepsilon_{aq} a \pi_s - \tau_m q\right] = \frac{w}{y} a \pi_s \hat{\tau}_p - \alpha_y q \delta_q \hat{\tau}_m. \quad [B]$$

For the last equality sign in [B] observe that equilibrium allocations satisfy $\pi_s = R_s/R_\ell$. The term δ_q is positive in view of the second inequality of (19).

Next we insert [6] and [A] into [4] which yields after some rearrangement of terms

$$\hat{a}_{sr} = -\alpha_r \frac{r}{y} \hat{\tau}_p. \quad [C']$$

In order to determine $\hat{y}$ we first combine [6], [8], [9] and [C']:

$$\hat{w} = \hat{y} - \frac{\alpha_y \varepsilon_{aq} r}{w} \hat{\tau}_m - \frac{\alpha_r r^2}{yw} \hat{\tau}_p. \quad [C'']$$

Next we substitute $\hat{p}_y$ and $\hat{w}$ from [B] and [C"], respectively, in [7]:

$$\ell \hat{y} = -\frac{\alpha_r r^2 \tau_p}{y} \hat{\tau}_p + \alpha_y \left[m \delta_q - \varepsilon_{aq} r \tau_p\right] \hat{\tau}_m. \quad [C]$$

Combining [C] and [C"] solves for $\hat{w}$:

$$\ell \hat{w} = -\frac{\alpha_r r^2 p_y}{w} \hat{\tau}_p + \alpha_y \left[m \delta_q - \frac{\varepsilon_{aq} r p_y y}{w}\right] \hat{\tau}_m. \quad [D]$$

$\hat{r}$ follows from [C], [D] and [9]:

$$\ell \hat{r} = \alpha_r r \pi \hat{\tau}_p + \alpha_y \left[m \delta_q + \varepsilon_{aq} \pi y\right] \hat{\tau}_m. \quad [E]$$

Sufficient for $\pi = p_y - \tau_p$ to be positive is $\tau_p \leq 0$. But we wish to show that $\pi > 0$ for all $\tau_p \in [-c_w, \tau_p^*]$. According to (18) we have $p_y = (\tau_p + \lambda_{\bar{w}}) \left(-\frac{U_y}{U_w}\right)$ which can be rearranged to $p_y - \tau_p = -\tau_p \left(1 + \frac{U_y}{U_w}\right) - \lambda_{\bar{w}} \frac{U_y}{U_w}$. Assumption (10') implies $\left(1 + \frac{U_y}{U_w}\right) < 0$ and $\lambda_{\bar{w}} > 0$ and hence ensures $p_y - \tau_p > 0$ for all $\tau_p > 0$.

We now complete the comparative statics by using [6], [E] and [C] to transform [10]-[12] into

$$\ell\hat{v} = -\frac{\alpha_r r^2}{v}(\pi + q\tau_p)\hat{\tau}_p + \alpha_y \left[m\delta_q + \pi y\left(1 + \frac{r}{v}(1-\varepsilon_{aq})\right) + \frac{mr}{v}\tau_p(1-\varepsilon_{aq})\right]\hat{\tau}_m, \qquad [F]$$

$$\ell\hat{m} = -\frac{\alpha_r r^2 \tau_p}{y}\hat{\tau}_p + \alpha_y\left[m\delta_q + \pi y + \tau_p r(1-\varepsilon_{aq})\right]\hat{\tau}_m, \qquad [G]$$

$$\ell\hat{n} = -\frac{\alpha_r r^2 \tau_p}{y}\hat{\tau}_p + \alpha_y\left[m\delta_q - \varepsilon_{aq} r\tau_p - \frac{m}{n}\ell\right]\hat{\tau}_m. \qquad [H]$$

In [F], $\hat{v}/\hat{\tau}_m$ is indeterminate in sign if $\tau_p < 0$ and $\hat{\tau}_p = 0$. But since $\ell = \pi y + \tau_p r$, we know that $\tau_p = \frac{\ell}{r} - \frac{\pi y}{r} > -\frac{\pi y}{r}$. In view of this inequality it follows from [F] that

$$\frac{\ell\hat{v}}{\alpha_r\hat{\tau}_m} = m\delta_q + \pi y + \frac{\pi y r}{v}(1-\varepsilon_{aq}) + \frac{mr\tau_p}{v}(1-\varepsilon_{aq}) > m\delta_q + \pi y - \frac{\pi y(m-r)}{v}(1-\varepsilon_{aq}) = m\delta + \varepsilon_{aq}\pi y > 0.$$

The sign of $\hat{m}/\hat{\tau}_m$ from [G] is also ambiguous for $\tau_p < 0$ and $\hat{\tau}_p = 0$. But it is easy to show that

$$\frac{\ell\hat{m}}{\alpha_y\hat{\tau}_m} = m\delta_q + \pi y + r\tau_p(1-\varepsilon_{aq}) = m\delta_q + \ell - \varepsilon_{aq} r\tau_p > 0.$$

Hence $\hat{m}/\hat{\tau}_m > 0$ for all feasible τ_p.

We are also interested in the change of the recycling ratio $\rho := r/m$. Invoking [E] and [G] we derive

$$\ell\hat{\rho} = \ell\hat{r} - \ell\hat{m} = \frac{\alpha_r r\ell}{y}\hat{\tau}_p - \alpha_y\left[(1-\varepsilon_{aq})\ell\right]\hat{\tau}_m. \qquad [J]$$

To determine the impact of tax changes on welfare, we differentiate (10)

$$du = U_y dy + U_w dw = \frac{U_y}{\ell}\left[y\ell\hat{y} + \frac{U_w}{U_y}w\ell\hat{w}\right].$$

In view of (10'), [C] and [D] we find that

$$\frac{\ell du}{U_y} \geq y\ell\hat{y} - w\ell\hat{w} = \alpha_r r^2\pi\hat{\tau}_p + \alpha_y\left[mr\delta_q + \varepsilon_{aq} ry\pi\right]\hat{\tau}_m. \qquad [K]$$

Policy IV is defined by $\hat{\tau}_p = \dfrac{\alpha_y m\delta y}{\alpha_r r^2\tau_p}\hat{\tau_m}$. When this equation is considered in (34)-(43) the allocative impact of policy IV is completely described by

$$p_z\hat{p}_z = \alpha_y\pi_s a\left[-\frac{w}{\alpha_r r^2\tau_p}m\delta_q + \varepsilon_{aq}\right]\hat{\tau}_m, \qquad (44)$$

$$p_y\hat{p}_y = \alpha_y\delta_q\left[\frac{wa\pi_s m}{\alpha_r r^2\tau_p} - q\right]\hat{\tau}_m, \qquad (45)$$

$$\ell\hat{y} = -\alpha_y\varepsilon_{aq} r\tau_p\hat{\tau}_m, \qquad (46)$$

$$\ell\hat{w} = -\frac{\alpha_y}{w}\left[\frac{\ell}{\tau_p}m\delta_q + \varepsilon_{aq}rp_y y\right]\hat{\tau}_m, \tag{47}$$

$$\ell\hat{r} = \alpha_y\left[\frac{\ell}{r\tau_p}m\delta_q + \varepsilon_{aq}\pi y\right]\hat{\tau}_m, \tag{48}$$

$$\ell\hat{v} = \alpha_y\left[-\frac{\ell}{v\tau_p}m\delta_q + \pi y\left(1 + \frac{r}{v}(1-\varepsilon_{aq})\right) + \frac{mr}{v}\tau_p(1-\varepsilon_{aq})\right]\hat{\tau}_m, \tag{49}$$

$$\ell\hat{m} = \alpha_y\left[\pi y + \tau_p r(1-\varepsilon_{aq})\right]\hat{\tau}_m, \tag{50}$$

$$\ell\hat{n} = -\alpha_y\left[\varepsilon_{aq}r\tau_p + \frac{m}{n}\ell\right]\hat{\tau}_m, \tag{51}$$

$$\ell\hat{\rho} = \alpha_y\left[\frac{\ell}{r\tau_p}m\delta_q - (1-\varepsilon_{aq})\ell\right]\hat{\tau}_m, \tag{52}$$

$$\frac{\ell du}{U_y} \geq \alpha_y\left[\frac{\ell}{\tau_p}m\delta_q + \varepsilon_{aq}ry\pi\right]\hat{\tau}_m. \tag{53}$$

Policy V is defined by $\hat{\tau}_p = \dfrac{\alpha_y y\left(m\delta_q + \ell - \tau_p r\varepsilon_{aq}\right)}{\alpha_r r^2\tau_p}\hat{\tau_m}$. Applying the same procedure as in case of policy IV we combine this equation with (34)-(43) to obtain

$$p_z\hat{p}_z = \alpha_y a\pi_s\left[\frac{w\left(m\delta_q + \ell - \tau_p r\varepsilon_{aq}\right)}{y\alpha_r r^2\tau_p} + \varepsilon_{aq}\right]\hat{\tau}_m, \tag{54}$$

$$p_y\hat{p}_y = \alpha_y\left[\frac{wa\pi_s}{\alpha_r r^2\tau_p}\left(m\delta_q + \ell - \tau_p r\varepsilon_{aq}\right) - q\delta\right]\hat{\tau}_m, \tag{55}$$

$$\ell\hat{y} = -\alpha_y\ell\hat{\tau}_m, \tag{56}$$

$$\ell\hat{w} = -\frac{\alpha_y\ell}{\tau_p w}\left[m\delta_q + p_y y\right]\hat{\tau}_m, \tag{57}$$

$$\ell\hat{r} = \frac{\alpha_y\ell}{\tau_p r}\left[m\delta_q + \pi y\right]\hat{\tau}_m, \tag{58}$$

$$\ell\hat{v} = -\alpha_y\left[\left(\frac{\pi y}{v\tau_p} + \frac{r}{v}\right)m\delta_q + \frac{\pi^2 y^2}{v\tau_p} + \pi y\right]\hat{\tau}_m, \tag{59}$$

$$\ell\hat{m} = 0, \tag{60}$$

$$\ell\hat{n} = -\frac{\alpha_y\ell y}{n}\hat{\tau}_m, \tag{61}$$

$$\ell\hat{\rho} = \frac{\alpha_y\ell}{r\tau_p}\left[m\delta_q + \pi y\right]\hat{\tau}_m, \tag{62}$$

$$\frac{\ell du}{U_y} \geq \alpha_y\left[\left(\frac{\pi y}{\tau_p} + r\right)m\delta_q + \frac{\pi y\ell}{\tau_p}\right]\hat{\tau}_m. \tag{63}$$

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