# Upstream Pollution, Downstream Waste Disposal, and the Design of Comprehensive Environmental Policies

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## ABSTRACT

Many environmentalists and policymakers are shifting their focus from media-specific pollution problems to product-specific, life-cycle environmental problems. In this paper, we develop a model of production and consumption that incorporates life-cycle environmental externalities—specifically, an upstream manufacturing byproduct, air or water pollution from manufacturing, and downstream solid waste disposal. We then use the model to derive optimal government policies to address all three externalities. We assume throughout that a Pigovian tax on waste disposal is precluded because of the potential for illegal dumping. We then examine four cases: one in which Pigovian taxes on the upstream externalities are feasible, one in which such taxes are infeasible, and two final cases in which the upstream pollutant is subject to one of two different types of regulatory standards. In general, we find that no single instrument can solve multiple problems, contrary to what some observers have suggested. However, we find that there are alternative ways of reaching the social optimum. We also discover that a so-called "integrated" approach to policy appears to be important, no matter what policy options are adopted. And finally, we find that there is only a limited role for product "life-cycle assessments"—enumerations of all of the resources used and pollutants emitted throughout an entire product life-cycle.

*Key words*: life-cycle externalities, solid waste, deposit-refund

*JEL classification code*: Q28

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## INTRODUCTION

In recent years, environmentalists and policy-makers have focused increasing attention on the so-called “life-cycle” environmental problems associated with consumer products. Concern over the disposal of solid waste generated from such products has grown, in many quarters, to encompass other “upstream” environmental problems. This has led to a plethora of product Life-Cycle Assessments (LCAs)—enumerations of all of the resources used and pollutants emitted throughout the life-cycle of a product, from resource extraction through manufacturing and ultimately product disposal.[2]

Although the methodology has its critics (Arnold, 1995; Menell, 1995; Morris and Scarlett, 1996; and Portney, 1993/94), advocates of LCAs claim a myriad of uses for them. Ackerman (1993) suggests that the results of LCAs be used to set "advance disposal fees (ADFs)"—product taxes that may be partially refunded if a product is recycled. In Europe, LCAs are being used as the basis for producer responsibility laws and in formulation of so-called "integrated product policy (IPP)."[3]

In this paper, we look at how the existence of life-cycle environmental externalities affects the choice of optimal policies. We establish whether the basic Pigovian tax result holds in a world with life-cycle pollution. And we derive alternative policies that achieve the social optimum when Pigovian taxes are infeasible. We also address two specific questions along the way. First, in deriving alternative policies, we examine whether an ADF, as some suggest, can achieve the socially optimal level of both upstream and downstream externalities. And second, we ask whether LCAs have a role to play in setting policy.

[1]We appreciate the helpful comments of Paul Calcott, Don Fullerton, Debbie Nestor, Paul Portney, Hilary Sigman, and two anonymous referees.
[2] The most notable of the early LCA studies are the comparisons of cloth to disposable diapers and polystyrene to paper cups (Franklin Associates, Ltd., 1990; Hocking, 1991).
[3] The best-known producer responsibility law is the German Packaging Ordinance which requires producers to take back, or arrange for a third party to take back, and recycle product packaging. In the Netherlands, a similar law requires producers to take account of all the life-cycle pollution problems associated with their products. See OECD (1998a) and (1998b) for a discussion of these programs; see Lifset (1993) for a general discussion and defense of the producer responsibility idea. Ernst and Young and Science Policy Research Unit (1998) define integrated product policy as "public policy which explicitly aims to modify and improve the environmental performance of product systems" (p. 9), with a key requirement being a focus on the entire product life-cycle.

Our work addresses one aspect of the growing concern that environmental policy—especially in the United States—is too "piece-meal" and media-specific (Davies and Mazurek, 1998; National Academy of Public Administration, 1995). Many critics of the current system argue for a move to a more holistic, integrated approach. The European IPP effort is one manifestation of this movement. Our results here elucidate whether an integrated approach to the life-cycle environmental problems associated with consumer products has merit over a "piece-meal," individual pollutant approach.

We develop a theoretical model of production and waste disposal to derive alternative sets of taxes, subsidies, and regulatory standards that achieve the social optimum. In the model, producers choose virgin and recycled raw material inputs, along with non-material inputs, to produce a final consumer product. That product generates waste that must be disposed of after consumers use the product. It also generates a waste by-product upstream as it is being manufactured, as well as some air or water pollution. Materials balance conditions play a central role in the model: raw material inputs must eventually end up as post-consumer solid waste or upstream manufacturing by-product, and other inputs such as energy or chemical solutions must end up as either benign or polluting residuals.

We assume throughout that a Pigovian tax on post-consumer solid waste is infeasible because of the potential for illegal disposal.[4] Some authors have argued that solutions other than Pigovian taxes might be necessary in many other instances as well—particularly when monitoring and enforcement problems are large.[5] Thus, we also analyze a situation in which Pigovian taxes on the upstream pollutant are infeasible. Finally, we address a scenario in which the upstream pollutant is subject to a regulatory standard, as many industrial pollutants in the U.S. and other OECD countries currently are.

We draw several important conclusions from our work, some that reinforce results in previous studies and some that shed new light. First, we find that multiple policy instruments are necessary to address both upstream externalities and downstream disposal. One instrument, such as an ADF, cannot fully internalize multiple externalities. Thus, we confirm a long-standing result in economics that at least as many policy instruments are needed as there are policy objectives.[6]

Second, we find that there are several different ways of achieving the first-best outcome. If taxing the upstream pollutants is feasible, then Pigovian emissions taxes along with a combined output tax and recycling subsidy will generate the social optimum. If Pigovian taxes are not feasible, then we find that there are alternative taxes that can achieve the optimum. This conclusion has been reached in other studies, but not in a model with life-cycle pollution (Fullerton and Kinnaman, 1995; Fullerton and Wolverton, 1997; Fullerton and Wu, 1998). Alternatively, we find that regulatory standards in combination with taxes can also achieve the first-best. If the standard is set per unit of a polluting input, then a tax on that input is necessary. If the standard is set per unit of output, an output tax is necessary. This brings us to our third notable result: there can be a role for an ADF to correct for life-cycle externalities, as some suggest, but *only* in conjunction with pollution standards per unit of output.

Fourth, we find that life-cycle assessments can be of use for policy in situations where alternatives to Pigovian taxes are required. Setting alternative taxes and subsidies calls for the type of detailed information usually included in an LCA. For the other policy options (either Pigovian taxes or the standards in combination with taxes ), however, information on environmental damages is necessary, but LCA-type information on resource use and emissions throughout a product life-cycle is mainly superfluous.

[4] Several studies have derived optimal sets of solid waste policies when taxing disposal is infeasible (see Dinan, 1993; Fullerton and Kinnaman, 1995; Palmer and Walls, 1997; Sigman, 1995).
[5] See, for example, Eskeland and Devarajan (1996) and Fullerton and Wolverton (1997).
[6] Tinbergen (1967) demonstrated this finding for macroeconomic policy.

Finally, we find that while an integrated approach to policy is not necessary for identifying what are the most efficient policy instruments, it is essential for setting those instruments—whether they be taxes, subsidies, or standards—at optimal levels. This is true even in a world with Pigovian taxes. The optimal upstream pollution taxes and downstream deposit-refund are equal to the marginal environmental damages at the social optimum, and the social optimum in a world with life-cycle externalities is defined over all the externalities. So, although the policy prescription is the same in a life-cycle framework as in a single-media, piece-meal approach, the size of the optimal taxes and subsidies will differ.

The integrated approach is even more crucial in a world without Pigovian taxes. The alternative taxes and subsidies that achieve the social optimum have terms that address multiple externalities. Thus, a comprehensive approach is critical. Moreover, these taxes and subsidies depend on the marginal products of the different inputs to production evaluated at the social optimum. So once again, to set the instruments at the right levels, it is critical to know the overall social optimum, not just the optimum defined over one externality.

In the following section, we present the model and the social optimum. In section III, we solve for the private market outcome, first assuming that a Pigovian tax is feasible for the upstream manufacturing waste and effluent. We then assume that the Pigovian tax is infeasible. Finally, we incorporate command-and-control style regulations. We solve for the set of taxes that generate the social optimum in each case. The final section of the paper offers some concluding remarks.

## THE MODEL AND THE SOCIAL OPTIMUM

The model is partial equilibrium in nature. For the social optimum, we assume a social planner maximizes net social surplus subject to mass balance constraints; net social surplus is defined as surplus from consumption less private production costs and the external environmental damages.

We assume that there are $n$ identical perfectly-competitive firms in the industry, each of which combines pounds of virgin materials, $v$, and recycled materials, $r$, with two nonmaterial inputs, $l$ and $s$, to produce units of a final consumer good, $q$. This production function is denoted by $q=f(v,r,l,s)$. The input $l$ can be thought of as labor (or capital); there is no pollution directly associated with its use and it does not figure in the mass balance conditions. The input $s$ is a polluting input. It could be a chemical solution that leads to emissions of a toxic substance into the atmosphere or a discharge into a waterway during production.[7] Alternatively, $s$ could be fuel use which leads to emissions into the air of, say, particulates or sulfur oxides.

There are two mass balance constraints. The first states that raw materials $v$ and $r$ must end up as produced output—which eventually ends up as post-consumer solid waste or recycling—or a manufacturing waste by-product, which we denote by $z$. This by-product could be hazardous or nonhazardous and could be disposed of in a landfill or incinerated.[8] If we let $a$ equal *pounds* of final product per *unit* of final product, we can express this mass

[7] In pulp and paper mills, for example, the use of chlorinated bleaching agents leads to toxic effluents discharged into waterways and volatile organic compounds released into air. The metal fabricating process usually employs the use of cutting oils (e.g., ethylene glycol), degreasing and cleaning solvents, acids, alkalis, and heavy metals. These substances can lead to toxic air emissions and emissions which contribute to ground-level ozone, as well as discharges into waterways, sludge, and hazardous wastes.

[8] Alternatively, it could be a marketable product for which the firm can receive a positive price (see Deutsch, 1999, for examples). We treat $z$ as waste in this paper but our results carry through to the case where some portion of $z$ is sold in a competitive market.

balance condition as $v+r=aq+z$.[9]

The total mass of solid waste disposed of is $W$. Total disposal equals total production minus total recycling or $W=naq-nr$.[10] Notice that combining this expression for waste disposal with the above mass balance condition yields a slightly different interpretation for mass balance: $nv=W+nz$ says that the sum of all new material inputs used in the production process across all firms must equal the sum of solid waste residuals from both consumption and production.

Our second mass balance constraint states that the mass of the non-material input, $s$, must end up as either an effluent, $e$, which causes environmental damage or a benign residual, $y$. This constraint is thus written as $s=e+y$, with all variables measured in mass units. The effluent or emissions, $e$, from use of $s$ can be transformed into $y$ by use of abatement inputs, $a$. For example, the firm can treat its wastewater to remove damaging pollutants. To reduce particulate emissions associated with fuel use, the firm might install an electrostatic precipitator. We represent the abatement function as $q(a)$, where $e = q(a)(e+y)$ and $q$ lies between zero and one. More abatement leads to less of the pollutant, $e$, as a fraction of total residual, $e+y$, thus $q'<0$. We assume that there are decreasing returns to abatement, however, thus $q''<0$. Combining the mass balance condition for $s$ with the expression for $e$ gives $e=q(a)s$. Figure 1 illustrates how the production process and mass balance conditions work.[11]

The environmental damage functions associated with $z$, $W$, and $e$ are, respectively: $D_z = D_z(nz)$, $D_W = D_W(W)$, and $D_e = D_e(ne)$, thus the damages are assumed to depend only on the total amount of each of the wastes or pollutants. Each of the marginal damage functions is assumed to be positive and increasing—i.e., the first and second partial derivatives are positive.

[9] We treat $a$ as fixed. Allowing the firm some control over $a$, product weight, does not alter our basic results about life-cycle externalities. Since the exposition is quite a bit more complicated when $a$ is not fixed, we omit this feature here.

[10] To avoid issues of discounting and price changes over time, we assume that products last only one period or that the market is in a long-run steady state.

[11] This representation of production and mass balance is similar to that of Anderson (1987) although we include abatement, post-consumer waste disposal, and recycling.

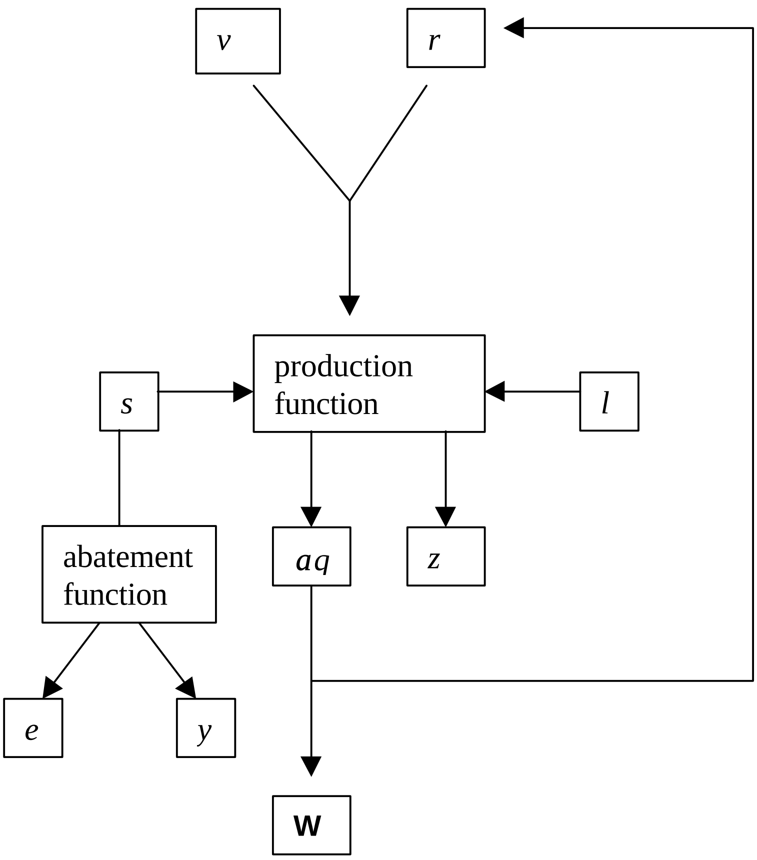


**Figure 1. The production process and mass balance constraints.**

Firms take all prices—the price of output, $P_q$, the price of the virgin material, $p_v$, the price of recyclables, $p_r$, the price of labor, $p_l$, the price of the chemical solution (or energy) input, $p_s$, and the price of the abatement input, $p_a$—as given.

Because the policies we derive focus on producers, we direct our attention to that side of the market. Consumers are assumed to maximize utility taking prices as given and this yields the (inverse) market demand function, $P_q(nq)$. Consumers also make decisions about recycling and disposal of used products. We assume throughout that consumers pay a zero price for disposal. We also assume that each consumer has increasing marginal costs of recycling—these could include time, effort, and storage costs—and that this leads to a market supply curve for recyclables represented by $c_r(nr)$.

The social planner maximizes net social surplus subject to the mass balance constraints. The mass balance constraints are incorporated by substituting for $z$ in the $D_z$ function and for $e$ in the $D_e$ function. Substituting also for $W$ yields the following expression for net social surplus:

$$(1)\quad NSS = \int_0^{nf(v,r,l,s)} P\ (s)ds - \int_0^{nr} c_r(x)dx - np_v v - np_l l - np_a a - np_s s - D_W\left(naf(v,r,l,s) - nr\right) - D_z\left(n\left(v + r - af(v,r,l,s)\right)\right) - D_e\left(nq(a)s\right)$$

Maximizing with respect to *v*, *r*, *l*, *s* and *a*, under the assumption that the market for the secondary material is in equilibrium, and therefore $p_r^* = c_r$, yields the following first-order conditions:

$$(2)\quad P_q^* \frac{\partial f}{\partial v} = p_v + D_W' a \frac{\partial f}{\partial v} + D_z'\left(1 - a \frac{\partial f}{\partial v}\right)$$

$$(3)\quad P_q^* \frac{\partial f}{\partial r} = p_r^* - D_W' + D_W' a \frac{\partial f}{\partial r} + D_z'\left(1 - a \frac{\partial f}{\partial r}\right)$$

$$(4)\quad P_q^* \frac{\partial f}{\partial l} = p_l + D_W' a \frac{\partial f}{\partial l} - D_z' a \frac{\partial f}{\partial l}$$

$$(5)\quad P_q^* \frac{\partial f}{\partial s} = p_s + D_W' a \frac{\partial f}{\partial s} - D_z' a \frac{\partial f}{\partial s} + D_e' q(a)$$

$$(6)\quad p_a = -D_e' q' s$$

where $P_q^*$ is the market-clearing price of output.

Equations (2)-(5) state that each input, *v*, *r*, *l*, and *s* should be employed up to the point where its marginal social benefit equals its marginal social cost. The marginal social benefit is the value to consumers of the additional output produced with an additional unit of the input. The marginal social cost is the price of the input in competitive markets plus the marginal environmental damages from the additional solid waste, *W*, and upstream residual, *z*, and in the case of *s*, the marginal damages from the additional upstream emissions, *e*. For *r*, the marginal social cost is reduced by $D_W'$, the sold waste environmental damages avoided by recycling an additional unit. Since more output and thus more solid waste is generated from using more of each of the inputs, the term involving $D_W'$ multiplied by a marginal product is positive in each of the equations. The term involving $D_z'$ is positive in equations (2) and (3)—i.e., adds to social costs—but negative in equations (4) and (5)—i.e., reduces social costs. It is negative in equations (4) and (5) because *l* and *s* are not material inputs; increasing these inputs increases output by increasing the material efficiency of the production process—i.e., more units of output are obtained for a *given amount of raw material input*. This necessarily means less residual by-product, *z*, and less upstream environmental damage from that residual. Equation (6) states that the marginal social cost of abatement, $p_a$, should equal the marginal social benefit, the reduction in environmental damages.

In the next section, we derive the set of policies that will lead private markets to generate the social optimum. In all cases, we assume that *W* cannot be taxed directly because of the potential for illegal dumping. In section A, we solve for alternative sets of taxes and subsidies that generate the social optimum. In section B, we look at regulatory standards.

## OPTIMAL POLICIES TO ADDRESS UPSTREAM POLLUTION AND DOWNSTREAM WASTE DISPOSAL

### Taxes and Subsidies.

In this first section, we solve for alternative combinations of taxes that yield the social optimum. A perfectly competitive representative firm chooses its inputs to maximize profits, subject to the mass balance conditions, taking all prices as given. There are no pre-existing distortions in the economy. Each of the taxes is written with the corresponding subscript, and we let $t_m$ be an output tax assessed per pound of final product produced. Taxes can be positive or negative. Substituting for *z* and *e*, the firm's profit function is written as:

(7) $$\Pi = P_q f(v,r,l,s) - t_m af(v,r,l,s) - (p_v + t_v)v - (p_r + t_r)r - (p_l + t_l)l - (p_a + t_a)a - (p_s + t_s)s - t_z\big(v + r - af(v,r,l,s)\big) - t_e\theta(a)s$$

The first-order conditions are:

(8) $$P_q \frac{\partial f}{\partial v} = p_v + t_v + t_m a \frac{\partial f}{\partial v} + t_z\left(1 - a \frac{\partial f}{\partial v}\right)$$

(9) $$P_q \frac{\partial f}{\partial r} = p_r + t_r + t_m a \frac{\partial f}{\partial r} + t_z\left(1 - a \frac{\partial f}{\partial r}\right)$$

(10) $$P_q \frac{\partial f}{\partial l} = p_l + t_l + t_m a \frac{\partial f}{\partial l} - t_z a \frac{\partial f}{\partial l}$$

(11) $$P_q \frac{\partial f}{\partial s} = p_s + t_s + t_m a \frac{\partial f}{\partial s} - t_z a \frac{\partial f}{\partial s} - t_e\theta(a)$$

(12) $$-t_e\theta' s = p_a + t_a$$

Equations (8)-(11) state that the firm is maximizing profits by setting the marginal revenue product of each input equal to its full marginal cost, including all taxes. Equation (12) says that the firm hires abatement inputs until the savings in tax payments on *e* just equals the extra cost of another abatement input, $p_a+t_a$.

*Case 1.* Assuming $P_q = P_q^*$ and $p_r = p_r^*$ (conditions that must hold to achieve the optimum) and comparing (8)-(12) to (2)-(6), we find that the following taxes achieve the social optimum:

$$t_m = D_W' \qquad t_z = D_z'$$
$$t_r = -D_W' \qquad t_e = D_e'$$
$$t_v = t_l = t_s = t_a = 0$$

The taxes on $z$ and $e$ are equal to the marginal damages from an additional mass unit of those residuals, evaluated at the optimum. Thus, the Pigovian tax result still holds in a world with multiple environmental problems. The tax on the pounds of output produced, $\alpha q$, and the subsidy on the pounds of recycled inputs to production, $r$, are equal to each other and equal to the marginal damages from an additional pound of solid waste disposal, $W$. This is the deposit-refund mentioned in the introduction.

At first glance, then, these results call into question the value of moves from a more media-specific approach toward "integrated product policy." The taxes on $z$ and $e$ and the deposit-refund seem to be the same as would be prescribed in a single-media setting. However, the marginal damages used to set the optimal taxes are those that exist at the *overall social optimum*. And the social optimum in a world with life-cycle externalities is one that simultaneously addresses all those externalities. To set the optimal tax on $z$, for example, a policy-maker needs to know the marginal damages from $z$, at the socially optimal level of $z$, $e$, and $W$. An integrated approach is important.

Notice also that at least three instruments are necessary to address the three environmental problems. This finding goes back to Tinbergen (1967) who demonstrated, for macroeconomic policy, that at least as many instruments are needed as policy objectives.[12] Thus it is not possible, as suggested by some observers, for a single instrument such as an ADF to fully internalize life-cycle environmental externalities.

*Case 2.* Because of monitoring and enforcement problems, it may be impossible in some cases—or at least, prohibitively costly—to tax either $z$ or $e$ directly. In this case, the following set of taxes achieves the optimum:

$$t_m = D_W' \qquad t_v = D_z'\left(1 - \alpha \frac{\partial f}{\partial v}\right)$$
$$t_r = -D_W' + D_z'\left(1 - \alpha \frac{\partial f}{\partial r}\right) \qquad t_l = -D_z' \alpha \frac{\partial f}{\partial l}$$
$$t_s = D_e' q(a) - D_z' \alpha \frac{\partial f}{\partial s} \qquad t_a = D_e' q' s$$
$$t_z = t_e = 0$$

Now that $z$ cannot be taxed directly, internalizing the externality associated with $z$ can only be achieved by placing taxes on the inputs to $z$—$v$, $r$, $s$, and $l$. Likewise, now that $e$ cannot be taxed, internalizing its externality can only be achieved by taxing $a$ and $s$. The tax on $a$, the abatement input, is negative (recall that $q'<0$), as is the tax on $l$. Labor is subsidized because increasing labor input improves the material efficiency of the production process and thereby reduces the amount of manufacturing residual, $z$. The tax on $v$ is positive to account for the additional $z$ generated by using additional virgin materials. The other material input, $r$, also generates additional $z$, thus the subsidy to $r$ that accounts for avoided solid waste disposal—i.e., the refund component of the deposit-refund—is reduced in this case. Finally, the tax on $s$, the nonmaterial, polluting input, could be positive or negative. The

[12] Hahn (1986) discusses this result in the context of tradable permits for air pollution.

first term in $t_s$, which accounts for the additional *e* generated by using additional units of *s*, is positive and the second term, which accounts for the fact that less *z* is generated by using additional units of *s*, is negative. The output tax, $t_m$, is the same as above and is equal to the marginal damages from additional post-consumer solid waste. Thus, while in case 1 the deposit equaled the refund, here the deposit is greater than the refund.

Again we find that multiple instruments are necessary to address multiple environmental problems. An ADF cannot internalize all the externalities. We also find, however, that the social optimum can be achieved by means other than Pigovian taxes. And our results suggest that there could be a role for life-cycle assessments in a world in which Pigovian taxes are infeasible. Each of the input taxes and subsidies that address the *z* externality depends on the additional *z* generated from an additional unit of that input, which in turn—because of mass balance—depends on the additional output produced from an additional unit of the input. Similarly, the subsidy for abatement and tax on *s* depend on *q(a)*, the amount of the pollutant, *e*, as a fraction of *s*, and on *s*, the amount of the chemical solution or energy input. These are the kinds of information that are usually included in an LCA.[13]

Now an integrated approach to environmental policy seems to be especially important. The overall deposit-refund addresses not just the downstream solid waste disposal externality but the upstream manufacturing externality as well. And the tax on *s* accounts for both upstream externalities (from *e* and *z*). If we modified the model to allow *s* to lead to two types of pollution—say, both air and water—then the optimal tax on *s* would be set to account for both effects to avoid cross-media pollution. Also, the taxes depend on marginal products evaluated at the optimum and once again, that optimum is defined over all the externalities.

Another recent study that derives alternatives to Pigovian taxes, although not in a life-cycle setting, is Fullerton and Wolverton (1997). In their model, there is only a single "clean" input and a single "dirty" input to production. They find that when it is infeasible to impose a tax directly on the dirty input, a perfect substitute policy is to tax output and subsidize the use of the clean input. Although our framework is different, our results suggest a somewhat similar approach. The "clean" inputs receive a subsidy and the "dirty" inputs a tax.[14]

[13] Typically, though, an LCA would report averages, not marginals—for example, quantities of virgin materials per unit of output and/or emissions of particular pollutants per unit of output or energy input—or it might report total raw materials and emissions and total output (from which averages can be computed). Moreover, LCAs provide information for the current production process under study, whereas the optimal taxes given above are functions of the marginal products *at the social optimum*.

[14] Some of the inputs in our model are clean in one respect and dirty in another, since we are allowing for multiple environmental problems. For example, using more *r* increases the solid waste by-product from production, *z*, but reduces *W*, all else equal; also, using more *s* increases the manufacturing pollution, *e*, but reduces the solid by-product, *z*, by increasing the material efficiency of production.

## Standards and Taxes

An alternative to price-based policies is a command-and-control regulatory standard. Most industrial pollution in the U.S. and other OECD countries is already subject to such standards. Menell (1995) and Portney (1993/94), in their critiques of the LCA methodology, argue that this existing regulation should result in significant internalization of production externalities. They argue that LCAs can present a misleading picture of the magnitude of environmental problems as a result. We address these issues more formally here. In particular, we explore whether any additional taxes or subsidies are necessary if firms' emissions of *e* are subject to standards.

Industrial air and water pollution regulations take various forms. Water effluents such as BOD (bio-chemical oxygen demand) or TSS (total suspended solids) are subject to limits per unit of output produced. Pulp and paper manufacturers—the single largest emitter of BOD in the U.S. as well as a significant source of TSS—face limits per ton of paper produced per day.[15] Battery manufacturers, primary metal producers, and iron and steel producers, among others, face limits on TSS and a number of chemicals and hazardous substances, all expressed on a per unit of output produced basis.

Air emissions regulations in the U.S. are more of a mixed bag. Much of the air pollution from industrial sources comes from burning fuel and regulations governing emissions from these processes are usually stated as pounds of pollutant per unit of heat input. However, when air emissions are more directly related to the industrial process they may be stated in terms of pollutant per unit of output. For example, the new source performance standard (NSPS) for particulate emissions from glass manufacturing is stated in terms of pounds of particulates per pound of glass produced. Other NSPSs are written as a limit per unit of raw material input. Still others are written as parts per million of total gas emissions. In general, the form of U.S. air pollution standards, either for new sources or for existing sources, varies considerably by industry and by pollutant.

It is impossible for us to analyze all the different types of regulations here but we look at two cases: in case 1, we assume the effluent (or emission), *e*, is subject to a standard per unit of output and in case 2, we assume *e* is subject to a standard per unit of the input *s*. Case 1 will apply more to water pollution and 2 to air pollution from burning fuel. In both of these cases, we assume that the firm pays a positive tax on *z*. We discuss the implications for a standard on *z* at the end of the section.[16]

*Case 1*. In this case, the firm faces the following constraint on its emissions: $e/aq \leq \Omega^q$ or $e \leq \Omega^q af(v,r,l,s)$. Assuming the constraint is binding and substituting, as before, $q(a)s$ for *e*, we now have the following constrained optimization problem for the firm:

$$
\begin{aligned}
L = {} & P_q f(v,r,l,s) - t_m af(v,r,l,s) - (p_v + t_v)v - (p_r + t_r)r - (p_l + t_l)l - (p_a + t_a)a \\
& - (p_s + t_s)s + t_z\left(v + r - af(v,r,l,s)\right) + l\left(q(a)s - \Omega^q af(v,r,l,s)\right)
\end{aligned} \tag{13}
$$

[15] Permits for BOD and TSS are actually issued to a facility on a pounds per day basis assuming that the facility operates at full capacity. This means that the standard actually varies to some degree with the amount of output produced rather than being a fixed limit over all units. We ignore this detail in our model here.

[16] If there is neither a tax nor a standard on *z*, then a solution similar to the one we derived in case 2 of the previous section will hold.

The first-order conditions are:

(14) $P_q \frac{\P f}{\P v} = p_v + t_v + t_m a \frac{\P f}{\P v} + t_z \left(1 - a \frac{\P f}{\P v}\right) + l \Omega^q a \frac{\P f}{\P v}$

(15) $P_q \frac{\P f}{\P r} = p_r + t_r + t_m a \frac{\P f}{\P r} + t_z \left(1 - a \frac{\P f}{\P r}\right) + l \Omega^q a \frac{\P f}{\P r}$

(16) $P_q \frac{\P f}{\P l} = p_l + t_l + t_m a \frac{\P f}{\P l} - t_z a \frac{\P f}{\P l} + l \Omega^q a \frac{\P f}{\P l}$

(17) $P_q \frac{\P f}{\P s} = p_s + t_s + t_m a \frac{\P f}{\P s} - t_z a \frac{\P f}{\P s} + l \left(\Omega^q a \frac{\P f}{\P s} - q(a)\right)$

(18) $p_a + t_a = l q' s$

The shadow price of the constraint, $l$, gives the marginal effect on the firm's profits of tightening the standard on *e*—i.e., decreasing $\Omega^q af(v,r,l,s)$. If the standard is set to generate the optimal level of *e*, then $l$ is equal to $-D_e^{'}$, the marginal social cost of *reducing e* by one unit, at the optimum. Substituting $-D_e^{'}$ for $l$ in the expressions above yields the following set of taxes (again, $P_q = P_q^*$ and $p_r = p_r^*$ to achieve the optimum):

$$t_m = D_W^{'} + D_e^{'}\Omega^q \qquad t_z = D_z^{'}$$
$$t_r = -D_W^{'} \qquad t_v = t_l = t_s = t_a = 0$$

In this case, when the standard is set to generate the optimal level of effluent for a given level of output, no other taxes or subsidies on any other inputs are necessary (with the exception of the subsidy to recycling necessary to address the solid waste disposal externality). The output tax must be larger now, however. This arises from the fact that the upstream pollution standard is set per unit of output, thus necessitating an additional tax on output to generate the overall optimum. Thus, the overall output tax has a component to address the solid waste disposal problem and a component to address the fact that the effluent standard is set per unit of output.[17]

This result supports the recommendation of Eskeland and Devarajan (1996) who argue for the use of output taxes in combination with standards to mimic the results achieved by a Pigovian emissions fee. Moreover, it is straightforward to show that if an additional upstream pollutant, with its own standard per unit of output, were added to the model, the social optimum could still be generated with the output tax and that tax would have another

[17] If the standard is not set optimally, then taxes on all the inputs to production are necessary in order to generate the social optimum. These taxes, as well as the output tax, would be a function of $l$, the shadow price of the constraint on *e*.

component to address the additional externality. If $z$, for example, were subject to a limit per unit of output rather than a tax, the output tax, $t_m$, would have an additional component to address the additional environmental damages associated with $z$.

This finding lends some support to the notion of an ADF—i.e., an output tax—to address multiple environmental externalities. Here, the output tax addresses both the downstream disposal externality as well as the upstream pollution—even multiple upstream pollutants. In all cases, though, the output tax *must* be coupled with the upstream pollution standard. An integrated perspective to policy continues to be important in this case. The output tax must correct for multiple environmental problems to achieve the social optimum and the social optimum needs to be assessed with all externalities.

*Case 2.* In this case, the firm faces the following constraint on its emissions: $e/s \le \Omega^s$.

Substituting for $e$, this constraint can be rewritten as $q(a) \le \Omega^s$. The firm's constrained optimization problem in this case is:

$$
\begin{aligned}
(18)\quad L = {} & P_q f(v,r,l,s) - t_m a f(v,r,l,s) - (p_v + t_v)v - (p_r + t_r)r - (p_l + t_l)l - (p_a + t_a)a \\
& - (p_s + t_s)s + t_z\big(v + r - a f(v,r,l,s)\big) + l\big(q(a) - \Omega^s\big)
\end{aligned}
$$

Because the production function does not enter the constraint, the first-order conditions for $v$, $r$, and $l$ are the same as in section III.A. above, equations (8), (9), and (10). The first-order conditions for $s$ and $a$ are:

$$(19)\quad P_q \frac{\partial f}{\partial s} = p_s + t_s + t_m a \frac{\partial f}{\partial s} - t_z a \frac{\partial f}{\partial s}$$

$$(20)\quad p_a + t_a = l q'$$

Now the shadow price of the constraint, $l$, gives the marginal effect on the firm's profits of tightening the standard on $e/s$—i.e., decreasing $\Omega^s$. If the standard is set to generate the optimal level of $e$, then $l$ is equal to $-D_e' s$, the marginal social cost of reducing $e/s$ by one unit, at the optimum. Substituting $-D_e' s$ for $l$ in equation (20) yields the following optimal taxes (again, $P_q = P_q^*$ and $p_r = p_r^*$):

$$
\begin{array}{ll}
t_m = D_W' & t_z = D_z' \\
t_r = -D_W' & t_s = D_e' q(a) \\
t_v = t_l = t_a = 0 &
\end{array}
$$

For the same reason that we needed to add a tax on output when the standard was set per unit of output, we now need to add a tax on $s$ because the standard is set per unit of $s$. Combined with the Pigovian tax on $z$ and the deposit-refund, this tax and standard can achieve the social optimum. No other tax or subsidy—including a subsidy for abatement—is necessary. Now an ADF would be the wrong approach. The output tax, $t_m$, reflects only the solid waste disposal externality while the externality from emissions, $e$, is handled with the input tax on *s*. If use of *s* led to two types of emissions—say, air and water pollution—then the tax on *s* would need to reflect both environmental damages, but that tax along with the two standards per unit of output (and the deposit-refund and Pigovian tax on *z*) would yield the social optimum.

It is interesting to note that an LCA would not typically provide useful information for the purposes of setting optimal standards and accompanying output taxes. Only information on environmental damages is necessary (and *q(a)* in case 2) and this is not typically provided in an LCA. The detailed information on material use, energy use, and emissions over an entire product life-cycle that is in an LCA would be mostly superfluous for setting optimal policies.

## CONCLUDING REMARKS

Many environmentalists and policymakers have shifted their focus in recent years from media-specific pollution problems to product-specific life-cycle environmental problems. This shift in focus has led to recommendations for a move away from what many view as a piece-meal approach to policy toward so-called integrated product policy and integrated environmental management. Accompanying this shift in focus is an increasing use of product life-cycle assessments, "cradle-to-grave" enumerations of all of the resources used and pollutants emitted in the manufacture, use and disposal of a product. In this paper, we explored the implications of such life-cycle issues for environmental policy-setting.

We find that an integrated approach to policy is important, as many are suggesting, even in a world in which Pigovian emissions taxes are feasible. Although the basic Pigovian prescription continues to hold when there are multiple environmental externalities throughout the product life-cycle, the optimal taxes will depend on the marginal environmental damages evaluated at the socially optimal level of *all* the relevant externalities. If Pigovian taxes are not feasible, the integrated perspective is even more important. Alternative instruments must correct for multiple externalities—e.g., upstream air or water pollution along with downstream waste disposal. This makes it critical that all externalities be considered simultaneously.

Although life-cycle externalities may be important for optimal policies, this does not imply that product life-cycle assessments are a necessary tool for setting those policies. LCAs provide detailed information on materials and energy use and emissions but not typically any information on environmental damages—i.e., on the marginal social cost of emissions. The latter information is necessary for setting Pigovian taxes and an optimal deposit-refund to address waste disposal externalities. It is also necessary if the government is using a standards approach. The only case in which LCA information might be useful is when it is necessary to use another policy alternative, taxes and subsidies on all the inputs to production. These alternative instruments depend on marginal products of the various inputs and marginal emissions and manufacturing by-product per unit of additional input. This kind of information might be available from an LCA.

Our results support some findings from earlier studies. We confirm a long-standing result in economics that as many policy instruments are necessary as policy objectives (Tinbergen, 1967). One instrument, such as an advance disposal fee, as suggested by some observers, cannot achieve the overall social optimum. We also find that there are multiple ways of reaching the social optimum. This is consistent with findings in Fullerton and Wolverton (1997) in a general setting and with other findings from studies focused on solid waste policies (Fullerton and Kinnaman, 1995; Palmer and Walls, 1997; Fullerton and Wu, 1998). We extend this result to a setting with life-cycle externalities.

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