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Haul Trash or Haul Ash: Energy Recovery as a Component of Local Solid Waste Management[1]

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A model of municipal choice of solid waste disposal technologies is developed to examine three competing local options: incineration in energy recovery facilities (ERFs), landfilling, and recycling. We show that the desirability of incineration and the optimal size of an ERF depend on the underlying costs of the various disposal options and the characteristics of the waste stream, and that under most conditions allocating resources to incineration reduces the incentives to recycle. We examine the implications of several extra-local policies on optimal disposal strategies. Most notably, we find that successful source reduction policies and minimum-recycling targets render incineration less attractive.

INTRODUCTION

In the past decade taking out the trash has become a major headache for local governments. The volume of solid waste has risen substantially with continued increases in packaging and consumption. Increasingly stringent environmental regulation and rising land prices have made traditional solid waste disposal strategies substantially more expensive. Local opposition to new landfill construction has further increased the costs and difficulties in ensuring adequate waste disposal capacity. Meanwhile, local governments have been advised by state and federal governments to adopt a hierarchical approach to solid waste management —reduce, recycle, incinerate, and landfill [16, 3].

A rich set of economic and public policy issues are associated with solid waste management. Economic analysis of the solid waste problem has extensively addressed the problem of siting noxious facilities [6, 7, 9, 12, 13]. This line of research has focused on the difficulties engendered by (and possible solutions to) widespread citizen opposition to siting facilities such as landfills, incinerators, composting facilities, and hazardous waste dumps. Menell [8] has examined efficient public policies affecting recycling from the standpoint of the incentives facing households in their purchase and disposal decisions. His results emphasize the desirability of building in the full social cost of disposal to the amount consumers pay to purchase products or dispose of wastes.

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Our focus in this article is on a more immediate policy locus: local government decision making. It is local governments who have the direct operational and financial responsibility for solid waste disposal, and who make the decisions about what combination of land disposal, incineration, and recycling will be used to handle the waste generated in their jurisdiction. They also have some limited power in mandating or providing incentives for source reduction. The purpose of this article is to examine the economic determinants of local choice over disposal strategies. We clarify how economic variables affect a community's optimal combination of land disposal, incineration, and recycling. We then examine how state and federal policies and prospective changes in technologies and preferences may affect this decision.

The paper is organized as follows. We begin by discussing the nature of local options in solid waste disposal. We then present a model of cost-minimizing local choice to derive the conditions under which incineration might be an economically optimal choice for local governments given the relative costs of incineration, recycling, and landfilling. The model illustrates how the amounts recycled and landfilled, as well as the decision to invest in an incinerator, might change as governments change their valuation of the marginal cost of landfilling waste. Next, we examine the way that policies and trends outside the direct control of local governments might be expected to affect local choices. The final section highlights important results and suggests areas for further research.

SOLID WASTE DISPOSAL OPTIONS

Professionally engineered "sanitary" landfills replaced open dumps and urban incinerators as the waste disposal method of choice in the United States during the 1950s, largely due to health concerns and the availability of relatively cheap land near cities and suburbs [1, pp. 16–17]. Since that time available landfill space has diminished while the cost of siting and building new landfills has increased tremendously, fueled by rising land values and by the political and transactions costs of reckoning with increased local opposition to new facilities.[2] Additionally, the new federal regulations contained in Subtitle D of the Resource Conservation and Recovery Act will in all likelihood require the closing of many existing landfills in this decade for groundwater quality protection, whether or not their capacity has been exhausted, and will further add to the operating and capital costs of complying landfills. Recent surveys indicate that sanitary landfills account for 76% of waste disposal in the United States [5].

Recycling has come to play a more important role as available landfill space has diminished and environmental consciousness has expanded. Recycling reduces the amount of waste that needs to be landfilled, but does so at a cost to the local government, since the revenues from the sale of recycled materials are generally not enough to offset setup, collection, storage, and delivery charges. As of 1991, 14% of the waste stream was recycled [5].

[2]Nationally, the average tipping fee rose from $13.50 per ton in 1985 to $26.50 per ton in 1991 [5]. There is substantial geographical variation in these costs, with some communities in the Northeast charging as much as $125 per ton [3].

TABLE I

Construction and Operating Costs of Landfills and Energy Recovery Facilities

	Sanitary landfill[a]	Energy recovery facility[b]
Capital costs ($/ton)		
Predevelopment	0.07–1.07	
Construction	2.32–7.29	8.21–17.12
Sub-total	2.58–7.97	8.21–17.12
Operating costs ($/ton)		
Operation and maintenance	8.03–19.48	24.42
Closure	0.63–1.69	
Post closure care	0.33–5.61	
Electricity sales		(23.53)
Ash disposal		6.94
Sub-total	9.89–26.68	7.83
Total variable cost ($/ton)	12.47–34.65	16.04–24.95
Fixed costs ($/day)[c]	353–1092	1125–2346

[a]Ranges for capital and operating costs based on data for four sanitary landfills reported in Tellus Institute [14].

[b]Data on capital costs based on a range of $60,000–125,000 per ton of daily capacity reported in [3] and [16] and assuming a 20-year facility life. Data on operating and maintenance costs and revenues from electricity sales are those reported in EDF [3]. Ash disposal costs include transport costs of $1.50 per ton (assuming $0.30 per ton-mile and a 5-mile trip) and costs of landfilling residual ash (assuming a 75% weight reduction and using the mean landfilling cost from column 1).

[c]Fixed costs computed for facilities handling 1,000,000 tons over a 20-year period.

Another alternative that has been adopted by many local governments is incineration of solid waste in energy recovery facilities (ERFs).[3] Using technologies pioneered in Europe, wastes are burned to reduce the volume of landfilled waste. Sale of electricity or steam heat created as a by-product of the incineration process partially offsets the capital and operating costs. As indicated in Table I, ERFs are costly to build (on the order of $60,000–125,000 per ton of daily capacity, depending on the scale of the facility and the incineration technology employed) but have low operating costs relative to landfills [3, 16]. Incineration has come under criticism for its associated pollution problems (air pollution and toxins in residual ash which may need special disposal treatment). Opponents have also charged that it is incompatible with increased recycling as part of an integrated solid waste management strategy [1, pp. 79–81].

MODELING SOLID WASTE DISPOSAL

In this section we develop a simple static model of a local government's solid waste management problem. The model is framed within the context of a specific,

[3]As of 1991, some 167 incinerators were operational or under construction and another 55 were in various stages of planning [10]. In that same year, an estimated 10% of the waste stream was incinerated [5].

yet common, situation—that of a municipality determining whether an energy recovery facility will improve its waste disposal efficiency when combined with the recycling and land disposal options that it faces.[4] We denote the total amount of waste entering the waste stream as W, and the quantities disposed of via recycling, landfilling, and incineration as W_R, W_L, and W_I, respectively.

We denote the cost of disposing waste in a sanitary landfill as $L(W_L)$. $L(W_L)$ includes the cost of operating a landfill, as well as collection and hauling costs. The marginal cost of landfilling (L') is assumed to be positive and constant.[5] By assuming that $L'' = 0$, we ignore possible economies of scale in collection and hauling; however, as there is no reason to believe that these costs differ markedly between waste disposal methods (landfilling vs incineration), the model's qualitative results are unaffected.

For a waste stream of a given size W, the recycling cost function $R(W_R; W)$, reflects the costs of promoting, collecting, processing, and marketing collected materials net of proceeds from their sale. We assume that $R' > 0$ and $R'' > 0$—i.e., that recycling becomes costlier as the more valuable and easily recycled parts of the waste stream are exhausted and it becomes more difficult to induce citizen participation in recycling. Marginal recycling costs will also depend on the size of the waste stream—larger communities will have larger volumes of high-value recyclables like aluminum and more citizens willing to undergo a given level of expense or inconvenience to recycle. This means that the marginal cost of recycling any given quantity falls as the size of the waste stream rises. To reflect this, we assume that the marginal cost of recycling is a function of W_R/W (the percentage of the waste stream recycled).[6]

Incineration costs are divided into three parts: (a) a variable cost, $I(W_I)$; (b) an annualized capital cost, $K \cdot C$, where K is the annualized per-ton cost of constructing an energy recovery facility, and C is the capacity of the facility per unit of time; and (c) a fixed cost, F_I, unrelated to the size of the ERF. $I(W_I)$ includes collection, hauling, operating, and maintenance costs less the sale of recovered energy. As with landfilling, we assume that I' is positive and constant. F_I includes the costs of planning, siting, contracting, and permitting the plant. It also includes the political costs perceived by local government decision makers in fighting the battles required to win approval for an ERF.[7] Finally, we denote the fraction of

[4]We assume throughout our analysis that local waste disposal decisions are made purely on a cost-minimization basis. We thus abstract from important political factors that may have an impact on technology choices (see, for example, Dubin and Navarro [2]).

[5]For many communities, particularly in the Northeast, trucking or shipping waste to landfills in other areas has been a preferred alternative. In our model, this cost serves the same role as the (constant) marginal landfilling cost.

[6]It is possible that at very low levels of W_R recycling cost could be negative, if only the highest value parts of the waste stream (e.g., aluminum cans) were collected at a central drop-off point. However, in order to collect enough materials to have any significant impact on the amount to be landfilled or incinerated, the marginal cost of recycling will be in the positive range. It is also possible that marginal costs will decline over some range as curbside pickup programs achieve greater participation rates. Eventually, however, the declining value of the remaining parts of the waste stream will cause marginal costs to rise. There is some empirical evidence of rising marginal recycling costs as the percentage of the waste stream recycled increases [11].

[7]It is clear from experience that the combination of paying for the technical expertise necessary for planning and permitting and the financial and political costs required to overcome local opposition are extremely significant in determining whether an ERF will be built by a given municipality. While these

W_I remaining after incineration (in the form of residual ash) by the parameter β and assume that this residual ash is disposed of in a landfill.[8]

We consider the case of a municipality debating construction of an energy recovery facility. The municipality must decide whether to build an incinerator and, if so, how large it should be. The municipality's decision problem is to minimize the sum of recycling, landfilling, and incineration costs subject to the constraints that (a) total waste is exhausted through a combination of recycling, landfilling, and incineration; (b) a fraction β of the amount incinerated must be subsequently landfilled; (c) incinerator capacity must be at least as large as incinerator throughput ($C \geq W_I$); and (d) the amount of waste landfilled is at least as large as the amount of residual ash from incineration ($W_L \geq \beta W_I$). The fixed costs of incineration F_I are incurred only if an incinerator is constructed; we specify a variable κ defined as $\kappa = \begin{cases} 0, & C = 0 \\ 1, & C > 0 \end{cases}$ to introduce these costs into the optimization problem. The resulting Lagrangean expression is

$$\begin{aligned} \operatorname*{Min}_{W_R, W_I, W_L, C} \mathscr{L} = {} & R(W_R) + L(W_L) + I(W_I) + KC + \kappa F_I \\ & + \lambda[W - W_R - W_L - (1-\beta)W_I] \\ & + \mu(C - W_I) + \delta(W_L - \beta W_I). \end{aligned} \tag{1}$$

The Kuhn–Tucker conditions for this problem yield the solution

$$R' = \begin{cases} I' + \beta L' + K, & \kappa = 1 \\ L', & \kappa = 0 \end{cases} \tag{2}$$

$$C = \begin{cases} W - W_R, & \kappa = 1 \\ 0, & \kappa = 0. \end{cases} \tag{3}$$

The decision whether to build an energy recovery facility comes out of a comparison of the minimum costs of waste disposal with ($\kappa = 1$) and without ($\kappa = 0$) incineration. We denote solutions for the ERF case with a ^ and for the no-ERF case with a ~. In the former case, Eq. (2) indicates that it is optimal to recycle until the marginal cost of recycling equals the full marginal cost of incineration—i.e., $R'(\hat{W}_R) = I' + \beta L' + K$. The optimal incinerator size is given by Eq. (3): capacity should be large enough to handle all of the waste that is not recycled. Without an incinerator, recycling takes place until $R'(\tilde{W}_R) = L'$. Obviously, if $L' \leq I' + \beta L' + K$ then an ERF will not be the least cost disposal technology. When $L' > I' + \beta L' + K$, the magnitude of F_I and the size of the waste stream become important in determining the optimal choice. Higher fixed costs of planning, siting, and construction make an incinerator less attractive. Higher levels of waste make an ERF

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costs will probably vary somewhat with the size of the waste stream, it is reasonable to believe that there would be such extreme economies of scale in adding additional capacity that treating these costs as independent of capacity is a reasonable approximation which should not qualitatively affect our results.

[8]This residue has a greater concentration of heavy metals and other toxins than is found in normal solid waste, and there is considerable controversy over whether it should be landfilled or treated as hazardous waste (with its much higher disposal costs). In this paper we assume that it can be landfilled; this is the most optimistic assumption from the standpoint of incineration proponents.

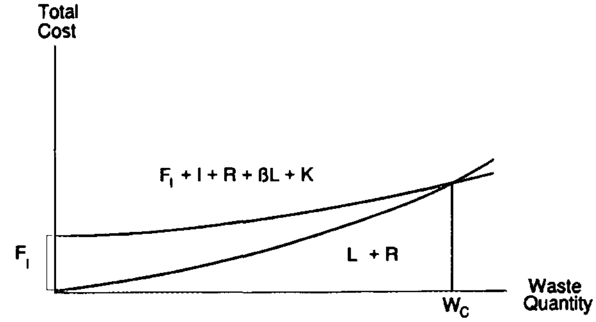

FIG. 1. Solid waste disposal cost.

more attractive by reducing the per-ton impact of F_I.[9] Figure 1 shows how, for an arbitrary set of costs, landfilling is the least-cost alternative over some range even when its marginal costs are above the full marginal costs of incineration. Only when the size of the waste stream is sufficiently large does the ERF alternative have lower total costs.

Not surprisingly, these results show that it is more attractive to incinerate when landfill costs are high and when incinerators burn efficiently (low β). This accords well with recent interest in energy recovery facilities. Energy recovery technologies have been used extensively in Europe and Japan for at least 20 years. In this country, however, it was only in the 1980s that many communities began to perceive shifts in the cost of landfilling due to regulatory activity and citizen opposition to new landfills. Coupled with an ever-growing local waste stream, these realized and anticipated cost increases made the high capital costs of constructing energy recovery facilities begin to appear to be a worthwhile investment.

Equations (2) and (3) indicate that if incineration is a part of the municipality's least-cost option, the optimal capacity of an energy recovery facility will be equal to the total quantity of waste that is not recycled. Thus, marginal recycling costs directly influence the choice between alternative disposal technologies (landfilling vs incineration): the more of the waste stream that is recycled at a particular

[9]Given the marginal cost structure represented in Fig. 2, the total costs of waste disposal in the no-ERF case will rise more rapidly with increases in the size of the waste stream; this ensures that the total cost of waste disposal without energy recovery will eventually exceed costs with energy recovery beyond some critical level of waste (W_C in Fig. 1). Intuitively, this results from the lower marginal cost of incineration. It can be formally shown as follows: in conjunction with Eq. (2), our assumption that the marginal cost of recycling is a function of W_R/W ensures that the proportion of the waste stream recycled remains constant over different waste stream sizes. Letting $\Delta TCI = TCI_2 - TCI_1$ and $\Delta TCL = TCL_2 - TCL_1$ denote changes in total disposal costs with and without energy recovery when the waste stream increases from W_1 to W_2, some algebraic manipulation reveals that

$$\Delta \mathrm{TCL} = \delta \tilde{R}^1 + \delta(W^1 - \tilde{R}^1)L' = \delta TCL^1$$

$$\Delta TCI = \delta \hat{R}^1 + \delta(W^1 - \hat{R}^1)(I' + \beta L' + K) + (F_1 - F_1) = \delta\left(TCI^1 - F_I\right),$$

where $\delta = (W_2/W_1) - 1$. Therefore, whenever incinerators are a relevant alternative—i.e., incineration without considering fixed costs is cheaper than landfilling—larger (smaller) volumes of total waste make incineration more (less) attractive.

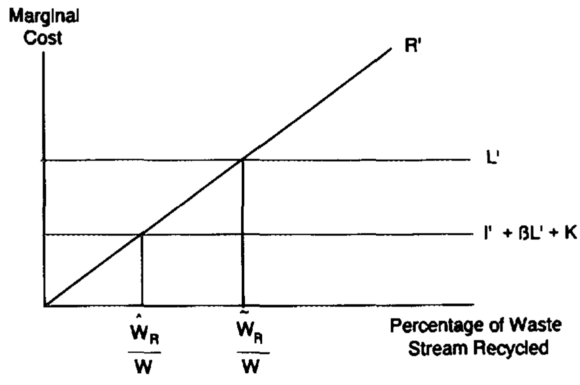

FIG. 2. Marginal disposal costs and equilibrium recycling quantities.

marginal cost, the less attractive an ERF will be *ceteris paribus*. Moreover, where incineration is optimal, recycling costs will affect capacity choice. The lower the marginal cost of recycling at any point, the more will be recycled and hence the smaller the optimal size of the energy recovery facility.

The optimality conditions found in Eqs. (2) and (3) yield two simple but powerful results regarding the optimal level of recycling. First, the conditions leading to the construction of an energy recovery facility ensure that the optimal quantity recycled when no such facility exists will exceed the optimal quantity recycled when waste is being incinerated (Fig. 2). Second, the optimal quantity recycled will increase with both the marginal cost of incineration and the marginal cost of landfilling. However, at the point at which incineration becomes the least-cost disposal option, the optimal quantity recycled will shift back discontinuously because the marginal cost of recycling will now be equated with the (lower) marginal cost of incineration. The important implication of these results is that the decision to invest in an energy recovery facility reduces the attractiveness of putting resources into a local recycling program.

An additional complication to the simple optimization problem posed above is that the marginal cost of incineration is affected by recycling programs. Incineration costs depend on the energy content and completeness of combustion of the incoming waste stream. In general, recycling programs that remove paper and plastics from the waste stream render incineration more expensive, while recycling that removes metals (other than aluminum), glass, yard waste, and large unburnable items make incineration less expensive. We can include this effect by writing the variable cost of incineration as $I(W_I, W_R)$ and denoting the partial derivatives with respect to W_I and W_R as I_{WI} and I_{WR}, respectively. In this case, the optimality condition in Eq. (2) is altered slightly:

$$R' = I_{WI} + \beta L' + K - I_{WR}. \tag{2'}$$

The sign of I_{WR} depends on the composition of the waste stream as well as choices made by the local government on how to expend recycling resources. Given current recycling practices and the amount of paper and plastic found in solid waste, it is likely that I_{WR} will be positive until recycling percentages reach a level much higher than those currently achieved. Equation (2′) indicates that when $I_{WR} > 0$, it becomes optimal to recycle less and/or to build larger capacity incinerators than when the effect of recycling on the composition of W_1 was assumed to be neutral. Of course, the sign of I_{WR} is in part a function of choices made by the recycling effort. Given that an energy recovery facility is a least-cost component of the solid waste management system, its construction creates incentives for reassigning priorities in the recycling effort—i.e., to allocate resources toward activities where $I_{WR} < 0$. In particular, this would involve placing greater emphasis on recycling metals and glass and on composting yard waste, while assigning newspaper, mixed paper, cardboard, and plastics recycling a relatively lower priority. This would shift the recycling cost function upward on a total tonnage basis, but would decrease the combined costs of incineration and recycling.

EFFECTS OF EXTRA-LOCAL POLICIES

Thus far we have demonstrated how the costs of incineration trade off against the costs of recycling and the costs of landfilling to determine a local government's least-cost strategy. As we stressed in the introduction, local governments are making solid waste management decisions in an environment of changing state and federal policy initiatives. These policies have critical importance for the relative costs of various disposal strategies. In this section we examine the effects of four distinct types of extra-local policies on local solid waste management decisions: (a) minimum recycling laws; (b) regulations increasing the marginal cost of incineration; (c) policies reducing the size of the waste stream; and (d) policies affecting the cost of recycling.

Minimum Recycling Laws

As of 1990, 15 states had enacted legislation requiring that local governments enforce a mandatory reduction in the quantity of solid waste being disposed of through means other than recycling, and an additional 9 states had set targets that were not yet binding. These waste reduction targets range from 15 to 50% over the next 2 to 10 years [5]. In most, but not all,[10] cases volume reduction through incineration is not allowed as a method of meeting waste reduction requirements, and these laws therefore amount to the imposition of minimum recycling targets.

With enforced minimum recycling targets the quantities of waste disposed via recycling and either landfilling or incineration are no longer determined by equating marginal disposal costs; rather, they are determined by the size of the waste stream and the imposed target percentage. If binding, a recycling target reduces the quantity of non-recycled waste. This has two major implications. First, it will cause the municipality's total disposal costs to unambiguously rise above the least-cost solution, regardless of whether the municipality incinerates or landfills its non-recycled waste. Second, by lowering daily throughput levels (and hence spreading fixed costs over a smaller amount of waste), it will reduce the relative attractiveness of incineration.

[10]For example, the North Carolina State Assembly recently passed legislation allowing local governments to partially meet mandatory 25% waste reduction requirements through incineration.

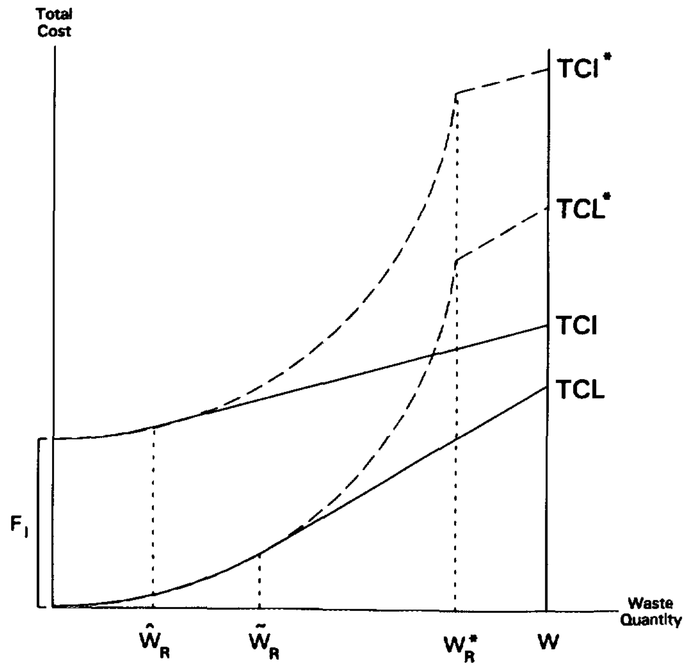

FIG. 3. Effect of mandatory recycling targets.

Figure 3 illustrates these effects of a mandatory recycling target. We denote total disposal costs for the case in which an energy recovery facility exists as TCI and total disposal costs for the case in which all non-recycled waste is landfilled as TCL. These cost curves contain a non-linear portion (up to W_R) corresponding to the recycling cost schedule, and a linear section corresponding to the disposal cost of the non-recycled portion of the waste stream. Thus, for a community with a waste stream of size W, comparison of TCI(W) and TCL(W) indicates the relative attractiveness of the two disposal systems of interest.

As before, $\hat{W}_R$ and $\tilde{W}_R$ denote the least-cost quantities recycled with and without incineration, respectively. Imposition of a mandatory recycling target W_R^* extends the region over which recycling costs are incurred (i.e., from $\hat{W}_R$ or $\tilde{W}_R$ to W_R^*), shifting the cost curves to TCL* and TCI* and causing total disposal costs to rise. The convexity of recycling costs ensures that the deviation from the least-cost solution is greater for waste disposal systems in which incineration is a component; consequently, the cost advantages of incineration will be reduced (or even reversed) by mandatory recycling. For localities contemplating construction of an energy recovery facility, this diminishes the likelihood of incineration being a part of the (second-best) solid waste management system because the fixed costs of siting such a facility would now be spread over a smaller number of tons of waste. In any event, mandatory recycling will reduce the optimal incinerator size.

Finally, in cases where incineration is an allowed method of meeting waste reduction guidelines—and again assuming that the reduction target is binding—the attractiveness of energy recovery facilities will be enhanced *vis-a-vis* landfills. In this case, the quantities recycled and incinerated would remain at their least-cost values ($\hat{W}_R$ and $W - \hat{W}_R$), while total disposal costs in the absence of incineration would be driven up (in accordance with a shift from TCL to TCL*). It is even conceivable in this case that energy recovery facilities could prove economic even when marginal incineration costs exceed marginal landfilling costs (i.e., $I' + \beta L' + K > L'$), as long as incineration is cheaper at the margin than recycling.

Changes in the Marginal Cost of Incineration

During the past decade increasingly stringent regulation coupled with increased public awareness and demands for more environmental safeguards led to a significant increase in the cost of constructing and operating sanitary landfills. The rising cost of landfilling has in large measure created the current widespread interest in incineration. Energy recovery facilities already face a similar set of costs in overcoming local opposition to new facilities. Moreover, the air pollution problems associated with incineration are a certain target for stricter regulation, particularly in areas where ambient air quality standards are not met.[11] These may be expected to increase both the capital and operating costs of energy recovery facilities in the future. In addition, the concentration of metals in incinerator ash may in many cases be toxic enough that disposal in a hazardous waste facility will be required [16, 104].[12] If this becomes the general case, the marginal costs of incineration will rise considerably.

As the marginal cost of incineration increases, the relative cost advantages of energy recovery *vis-a-vis* sanitary landfills will be eroded (Fig 4). Expectations of future increases in operating or capital costs of energy recovery facilities—for example, the need to install more sophisticated equipment to control and measure pollutants such as NO_x should reduce the attractiveness of incineration by the same logic. Of course, once an ERF is operational, local solid waste authorities have a powerful incentive to continue operations even if it is less cost effective than land disposal. In the case of an existing ERF, rising marginal incineration costs will increase the optimal quantity of waste that is recycled (e.g., from $\hat{W}_R^0$ to $\hat{W}_R^1$ in Fig. 4).

Policies Reducing the Size of the Waste Stream

Regulation and taxation of packaging, along with voluntary reductions by industry (e.g., recent changes in packaging practices undertaken by McDonald's [15]) will in all likelihood change the size of the waste stream. Reductions in the size of the waste stream will lower the number of tons of waste over which fixed incineration costs are spread. Again, this will tend to reduce or reverse the cost advantages of incineration and will also reduce the optimal size of the incinerator. Additionally, if paper and plastics (particularly in packaging) are more responsive to source reduction policies than other materials, incineration costs would be driven up even further. This would cause energy recovery to become a less

[11] In addition to criteria pollutants such as NO_x, stricter regulation of hazardous air pollutants such as lead and cadmium would also drive up incineration costs.

[12] There is currently considerable scientific debate, as well as two pending court cases, concerning the classification of incinerator ash [3]; there are also EPA regulatory proposals for controlling incinerator emissions.

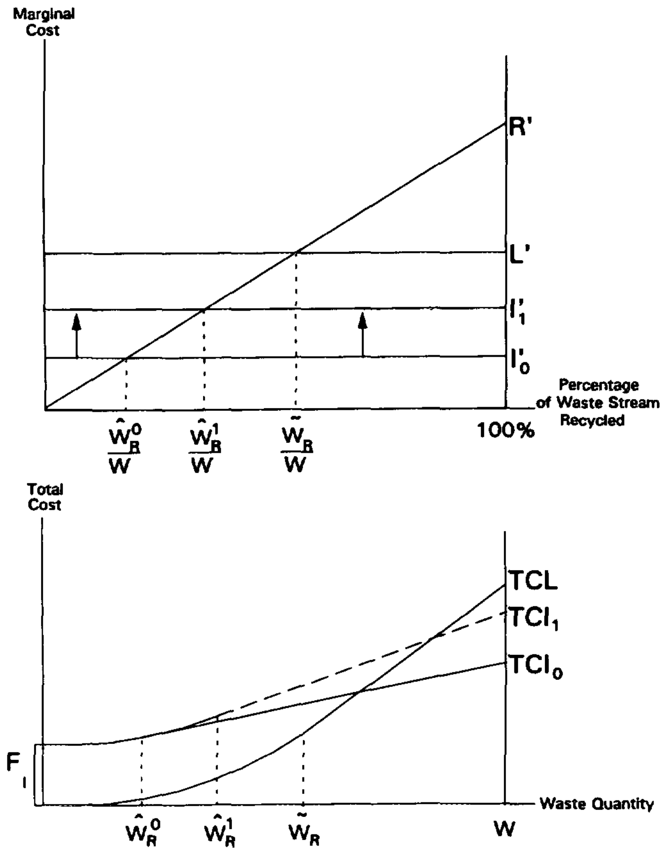

FIG. 4. Effect of an increase in marginal incineration costs.

attractive option, and in the case where an energy recovery facility was already operational would reduce the cost advantages offered by successful source reduction policies.

Policies Affecting the Cost of Recycling

A range of policies and industrial practices that would make it easier to recycle or increase the demand for recycled materials have the capacity to substantially shift the costs of recycling. Among these are severance taxes, federal and state procurement requirements, and company-sponsored initiatives taken to improve public image and avoid future regulation. Changes in the cost of recycling alter the optimal quantity of recycled material and hence the amount of waste requiring disposal via landfilling or incineration. Policies that stimulate demand for recyclables, technological changes that increase the efficiency of collection and quality of recycled materials, and new technologies enhancing the ability of industrial and agricultural processes to make use of recycled materials will increase the amount recycled and lower the amount landfilled or incinerated. If recycling becomes less expensive in the future, then both the attractiveness and the optimal size of energy recovery facilities will fall in the present.

Charging households a fee based on the amount they send to be landfilled or incinerated may be expected to have two effects. First, it will shift the supply of recycled materials outward as households put more effort into recycling. Second, it will reduce the size of the waste stream as households alter their consumption behavior by purchasing less heavily packaged goods in order to produce less waste. Both effects would tend to decrease the attractiveness of energy recovery facilities.

Finally, a factor that could work in the the opposite direction is the effect of widespread increases in recycling on the prices of recycled materials. The outward shifts in supply caused by minimum-recycling laws, increased landfill costs, and changes in public desire to recycle will tend to drive down prices and thus increase any individual community's net recycling costs. Such a shift will tend to make investment in an energy recovery facility appear more attractive.

CONCLUSION

Using a simple model of municipal choice of waste disposal technologies, we have demonstrated how the costs associated with landfilling, incineration, and recycling determine the optimal local strategy. The results highlight the importance of siting costs and other fixed costs relative to the size of the waste stream in determining whether it is worth investing in an ERF. This model lends support to the contention that there is an inherent tension between recycling and incineration: the decision to go the ERF route implies reduced incentives to devote resources to recycling programs. In addition, a solid waste management strategy that includes incineration with energy recovery will provide incentives to pull resources away from paper and plastic recycling in favor of metals, glass, and organic wastes.

We discussed the effect of state and federal policies on local choices of disposal technologies. Minimum-recycling laws will decrease the attractiveness of ERFs when energy recovery does not count toward recycling targets; when it does count, ERFs can become much more economical. Policies that increase recycling or decrease the size of the waste stream generally make ERFs a worse investment. Perhaps the most important set of policies are the environmental regulations associated with alternative disposal technologies. We have noted that the trend toward incineration has largely been driven by increases in the marginal cost of landfills, and that much of this cost comes from the expense of complying with increasingly stringent environmental regulation. The air pollution problems associated with energy recovery facilities are a likely target for stricter regulation, in terms of both new source performance standards for conventional pollutants and emissions standards for hazardous air pollutants. In addition, the concentration of metals in incinerator ash may in many cases be toxic enough that disposal in a hazardous waste facility will be required. Any of these factors could cause the marginal costs of incineration to rise considerably.

Because there is much less experience with ERFs than with landfills, the course of future regulation is not entirely clear. Once an ERF is built there will be strong incentives to continue using it even if regulatory changes render it more costly than expected. Governments should be aware, however, that the changes such regulations make in the costs associated with energy recovery facilities could have a considerable impact on the desirability of alternative strategies. Specifically, investment in an energy recovery facility on the basis of the current economic and regulatory environment could lead some communities to commit themselves to incineration technologies when such technologies are not their best long-run waste disposal strategy.

The model developed in this paper did not incorporate uncertainty about the size and composition of the waste stream nor the underlying cost functions of alternative disposal technologies. Extending the model to explicitly incorporate these uncertainties in a multiperiod framework could provide useful insights regarding the risks and opportunities for adaptive choices associated with alternative waste disposal strategies.

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