J. ENVIRONMENTAL SYSTEMS, Vol. 21(3) 257-277, 1991-92

MODELING INVESTMENT IN ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE

G. ANANDALINGAM
University of Pennsylvania, Philadelphia

ABSTRACT

A dynamic partial equilibrium model of the market for municipal solid waste (MSW) energy recovery equipment was developed to analyze the economics of energy recovery from MSW. Short-run and long-run solutions are derived, and the impact of extending investment tax credits are analyzed. Empirical results are obtained through simulations for a case in the United States. Results show that in order to offset welfare losses caused by the market distortions introduced by the tax credits, the oil use premium has to be more than $13 per barrel.

Until recently, efforts at incineration of solid waste in waterwell boilers to recovery energy in the form of steam have proven unsuccessful. This is in part due to the cost of the resulting stream, compared to the historically cheap cost of alternative energy supplies in the United States for both domestic heating and industrial process heat. It is also due in part to the difficulty of efficient combustion of refuse which has also led to failures of several municipal refuse incinerator projects in the United States. In addition, solid waste incineration has been affected by environmental concerns such as the possibility of dioxin and the imposition of air quality standards which could double costs.

There has been little formal analysis of the economics of energy recovery from MSW or the impact of energy and resource recovery on the national economy. The specific purposes of this article are to analyze the economics of investment in MSW energy recovery and to estimate the social costs and benefits of providing investment tax credits for MSW energy.

A dynamic partial equilibrium model of the market for municipal solid waste (MSW) energy recovery equipment was developed to analyze the economics of energy recovery from MSW. To analyze the impact of transient investment tax

doi: 10.2190/LJ3P-TTLP-DCV8-RVQ7
http://baywood.com

credits (the "policy case"), short-run supply is assumed; in the absence of tax credits ("reference case"), vendors are assumed to follow long-run supply behavior. The supply side is characterized by constant costs in the long-run. Due to lack of detailed information, a reasonable short-run supply elasticity is assumed. Sensitivity analysis reveals the robustness of this assumption. The demand side is obtained by summing a family of demand curves that have been derived under the assumption of profit maximization on the part of investors in MSW energy recovery equipment. A family of production functions was estimated using data on operational MSW energy recovery systems. An annual increase in investment opportunities for MSW energy recovery is assumed to be proportional to the projected annual increase in GNP. Derived demand is systematic in that future energy prices are considered in determining the value of additional investment. The time path of equipment prices and tax credits are not considered in determining the desired investment for any one year—instead, only the purchase year price and tax credit for equipment, and the amount of previous investment are considered.

The rest of the article is organized as follows: In section 2, I describe the model, and derive the short-run and long-run equilibrium solutions. Analytical features of the policy consequences of extending investment tax credits are derived in section 3. Empirical results, including sensitivity analysis, are in section 4. The article is summarized in a concluding section.

2. THE MODEL

The model determines an equilibrium market price and quantity of MSW energy recovery equipment for both a reference case and a policy case on annual basis. The policy case assumes that there would be investment tax credits for investment in MSW energy recovery equipment.

As illustrated in Figure 1, it is assumed that long-run supply is characterized by constant costs. It is assumed for the reference case, that vendors of MSW energy recovery equipment perfectly anticipate reference demand (illustrated as D_r) such that they exactly supply the reference demand quantity at the long-run price. Thus, P_{1r} and Q_0 represent the reference price and quantity respectively, and the short-run supply curve intersects reference demand at the long-run price.

Long-run equilibrium implies short-run equilibrium. Thus, short-run supply for the reference case also passes through (Q_0, P_{1r}) (see [1]).

The effect of the investment tax credit for the MSW energy recovery equipment is to increase the demand for such equipment, shown in Figure 1 as a shift from D_r to D_p. In the short-run, price and quantity become P_1 and Q_1, respectively. As adjustment to the new long run occurs, the price and quantity gradually adjust to P_{1r} and Q_2. (Intermediate values are found along D_p between (P_1,Q_1) and (P_{1r},Q_2).)

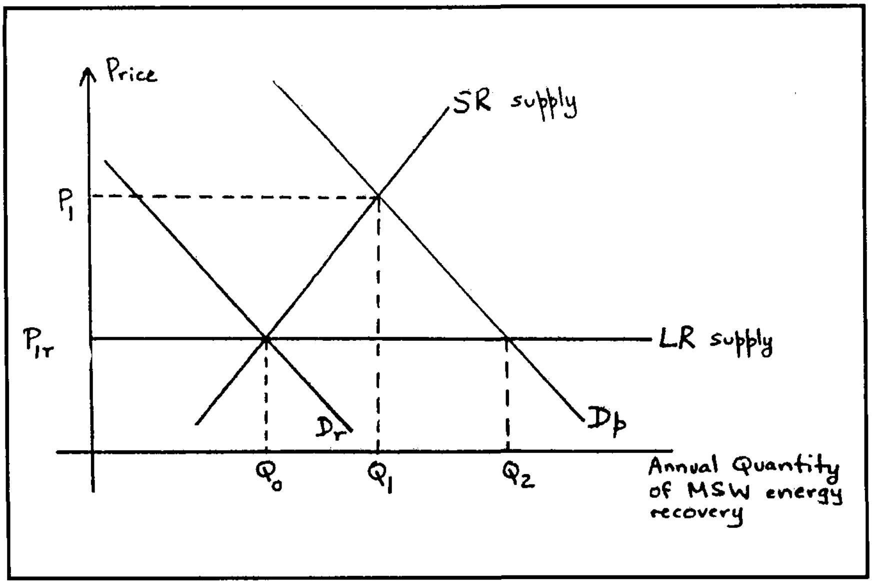

Figure 1. Overview of the model.

To examine the consequences of a transient tax credit, we operate the model through the years of tax credit availability and beyond, until a new long-run equilibrium is established. Welfare analysis is applied to measure the private distortion costs of the tax credit, and energy savings, as a function of equipment accumulation. An earlier version of the model given below also appears in the chapter by Brown and Kosanski [2].

Profit Maximization

It is assumed that the decision maker would invest in energy recovery from MSW to maximize profits. The conditions for maximizing the profitability of economy wide accumulation of MSW energy recovery equipment in any year j are obtained from:

$\max \pi_j =$

$$\left(\sum_{k=0}^{j} \Delta E_{kj}\right) \cdot \left(\sum_{i=j+1}^{j+15} (1+r)^{j-i} \cdot P_i\right) - \left(\sum_{k=0}^{j} \Delta K_{kj}\right) \cdot (1+t_j) \cdot C_j \tag{1}$$

for $k = 0, \ldots, j$

where

π_j is the present value profitability of adding capital in period j;

$\Delta E_{k,j}$ is the annual MSW energy recovery associated with investment opportunities that arise in period k and that mature during period j;

r is the discount rate;

P_i is the average price of industrial energy from all fuels during period i;

$\Delta K_{k,j}$ is the amount of productive capital available in period j which was installed in period k;

t_j is the tax rate on capital during period j (a negative value denotes a tax credit);

C_j is the price of capital in period j as obtained by its vendor.

Note that there is double vintaging of capital. We assume that investment grows with GNP. However they mature only with a time lag because it could be more economical to wait before the equipment is made operational [3].

Hence the amount of capital that is considered to be "added" in period j is the sum of all the capital invested during the previous periods which are installed with the notion of becoming productive in period j. Similarly the energy recovered in period j would be the energy recovered from all the equipment of vintage k that are productive in period j.

Let us now examine the profitability function: The value of energy savings during any period i is given by the multiple of annual energy savings associated with productive equipment ($\Sigma_k \Delta E_{k,j}$) and the average price of fuel in industry, P_i. This energy savings is obtained every year over the life of the equipment. Thus the present value of energy savings is obtained by discounting the annual energy savings by the private discount rate r, and summing over the life of the equipment. The first expression of the profitability function captures the PV of energy savings. The second term gives the cost of the investment.

The Kuhn-Tucker conditions for maximum profit are:

$$\frac{\partial \pi j}{\partial \Delta K_{k,j}} \leq 0, \; \frac{\partial \pi j}{\partial \Delta K_{k,j}} \cdot \Delta K_{k,j} = 0 \quad \text{for } k = 0, \ldots, j \tag{2}$$

Note that there are j pairs of Kuhn-Tucker conditions for each year j we examine. Satisfaction of these conditions simply requires that MSW energy recovery equipment be added if and only profitability is increased by further accumulation; and that equipment additions be zero (negative accumulation is uneconomic because acquisition costs are sunk) if further accumulation would decrease profitability. If we ignore the nonzero boundary constraint we obtain:

$$\frac{\partial \Delta E_{k,j}}{\partial \Delta K_{k,j}} \cdot B_j = (1 + t_j) \cdot C_j \quad \text{for } k = 0, \ldots, j \tag{3}$$

where:

$$B_j = \sum_{i=j+1}^{j+15} (1+r)^{j-i} \cdot P_i; \tag{4}$$

as the conditions for optimal acquisition of MSW energy recovery equipment. If satisfaction of equation (2) requires a negative value of any $\Delta K_{k,j}$, zero will replace the negative value.

The Production Function

To solve equation 2 for the optimal increments to the j capital stocks requires j production functions. Using engineering data taken from publications of the National Center for Resource Recovery [4] and regression analysis a family of production functions was obtained. They are:

$$E_{k,j} = \alpha_k K_{k,j}^b \tag{5}$$

where

- $E_{k,j}$ is the total amount of MSE energy recovered in year $j+1$ with equipment of installation vintage k accumulated in years k through j (in 10^{15} Btu).
- b is the marginal product of capital (estimated from data to be 0.454).
- α_k is the scaling parameter of production function that captures the investment arising in year k. It is a function of the difference between GNP in year k and year $k - 1$.
- $K_{k,j}$ is the total stock of MSW energy recovery equipment of vintage k that is accumulated by the end of year j (in 10^9 capital units 1990 dollars).

Taking the derivative of equation (5) with respect to $K_{k,j}$ we obtain the marginal productivity of the capital stock:

$$\frac{\partial E_{j,k}}{\partial K_{k,j}} = b\alpha_k \; K_{k,j}^{b-1} \cdot \tag{6}$$

The Stock-Flow Relation

However, to solve equation (6) for the optimal increment to capital—as opposed to the optimal stock—we must determine $\partial E_{k,j} / \partial K_{k,j}$. We have implicitly defined:

$$\Delta E_{k,j} = E_{k,j} - E_{k,j-1} \tag{7}$$

and

$$\Delta K_{k,j} = K_{k,j} - K_{k,j-1} \tag{8}$$

$$\frac{\partial \Delta E_{j,k}}{\partial \Delta K_{k,j}} = \frac{\partial E_{j,k}}{\partial K_{k,j}} \tag{9}$$

Optimal Equipment Stock and Acquisition

Substituting equation (6) into eq. (2) via eq. (9), rearranging terms and recalling the implications of the Kuhn-Tucker boundary conditions we obtain an expression for the optimal stock of MSW energy recovery equipment:

$$K_{k,j} = \max \left[K_{k,j-1}, (b\alpha_k)^{\frac{1}{(1-b)}} \cdot \left(\frac{B_j}{1+t_j} \right)^{\frac{1}{1-b}} \cdot C_j^{-\frac{1}{(1-b)}} \right] \tag{10}$$

Subtracting $K_{k,j-1}$ from both sides we obtain:

$$\Delta K_{k,j} = \max \left[0, (b\alpha_k)^{\frac{1}{(1-b)}} \cdot \left(\frac{B_j}{1+t_j} \right)^{\frac{1}{1-b}} \cdot C_j^{-\frac{1}{(1-b)}} - K_{k,j-1}, \right] \tag{11}$$

which is an expression for the optimal increment to capital stock. Note that both eq. (10) and eq. (11) prevent the uneconomic retirement where capital costs are sunk.

Substituting eq. (10) into the production function, eq. (5), reducing and rearranging terms enables us to calculate the optimal quantity of MSW energy recovery in period $j + 1$.

$$E_{k,j} = \max \left[E_{k,j-1}, ,\alpha_k^{\frac{1}{(1-b)}} \left(\frac{B_j}{1+t_j} \right)^{b/_{1-b}} \cdot C_j^{-b/_{(1-b)}} \right] \tag{12}$$

Demand

Examining eq. (11), we observe that desired accumulation is a function of the equipment price C_j. Thus, eq. (11) is the derived demand for MSW energy recovery equipment by vintage of installation k in year j. Summing eq. (11) from, $k = 0$ to j we obtain the total derived demand for new application MSW energy recovery equipment.

The Reference Case

In deriving the production function, we lacked sufficient information to determine the price and quantities of MSW energy recovery equipment independently of each other. Consequently, we defined the long run price of MSW energy recovery equipment as one (1990) dollar, and physical units of MSW energy recovery equipment as the amount of equipment that may be purchased for one (1990) dollar when the long run price prevails.

Setting $C_j = 1$, and with appropriate manipulation of equations (10), (11) and (12) we obtain six equations that describe the reference case for each year j.

$$KR_{k,j} = \max\left[KR_{k,j-1,}\ (b\alpha_k)^{\frac{1}{(1-b)}} \cdot \left(\frac{B_j}{1+t_j}\right)^{\frac{1}{1-b}}\right] \tag{13}$$

$$TKR_j = \sum_{k=0}^{j} KR_{k,}j \tag{14}$$

$$\Delta KR_{k,j} = KR_{k,j} - KR_{k,j-1} \tag{15}$$

$$\Delta TKR_j = \sum_{k=0}^{j} \Delta KR_{k,j} \tag{16}$$

$$ER_{k,j} = \max\left[ER_{k,j-1,}\alpha_k^{\frac{1}{(1-b)}} \cdot \left(\frac{B_j}{1+t_j}\right)^{b/_{1-b}}\right] \tag{17}$$

$$TER_j = \sum_{k=0}^{j} ER_{k,j} \tag{18}$$

where

- $KR_{k,j}$ is the reference case stock of equipment of vintage k which is productive before year $j + 1$
- TKR_j is the reference case stock of all equipment installed before year $j + 1$.
- $\Delta KR_{k,j}$ is the reference case addition to productive equipment of vintage k made during year j
- ΔTKR_j is the reference case total addition of productive equipment during year j
- $ER_{k,j}$ is the MSW energy recovered in year j+1 attributable to equipment of vintage k
- TER_j is the total MSW energy recovery in year $j + 1$ (attributable to equipment installed through the end of year j).

All other variables were previously defined.

The Policy Case

Calculating the policy case is more complex than calculating the reference case because the short run equilibrium price of MSW energy recovery equipment must be determined simultaneously with quantity, unlike in the reference case where it is assumed that the long-run price will prevail. Determination of short run equilibrium requires modeling short-run supply in addition to demand.

Supply

Lacking much direct data for the vendor industry of MSW energy recovery equipment, we assume short-run supply is of the form:

$$KS_j = A_j \cdot C_j^{\eta_j} \tag{19}$$

KS_j is the quantity of equipment supplied in year j
A_j is the scalar parameter of the supply function in year j
η_j is constant elasticity of supply for new application equipment.

The exponential supply function (19) exhibits a constant elasticity of supply η_j and setting $A_j = \Delta TKR_j$ forces the short-supply function through the point $(\Delta TKR_j,1)$ which is the reference case equilibrium for period j (see Figure 2).

Given that a portion of the MSW energy recovery equipment market is for replacement application, the elasticity of supply for new application equipment is greater than for the total supply of MSW energy recovery equipment. Mathematical manipulation of the above function reveals that the elasticity of supply for new application equipment can be written as:

$$\eta_j = \frac{QR_j}{QN_j}\bar{\eta} + \bar{\eta} \tag{20}$$

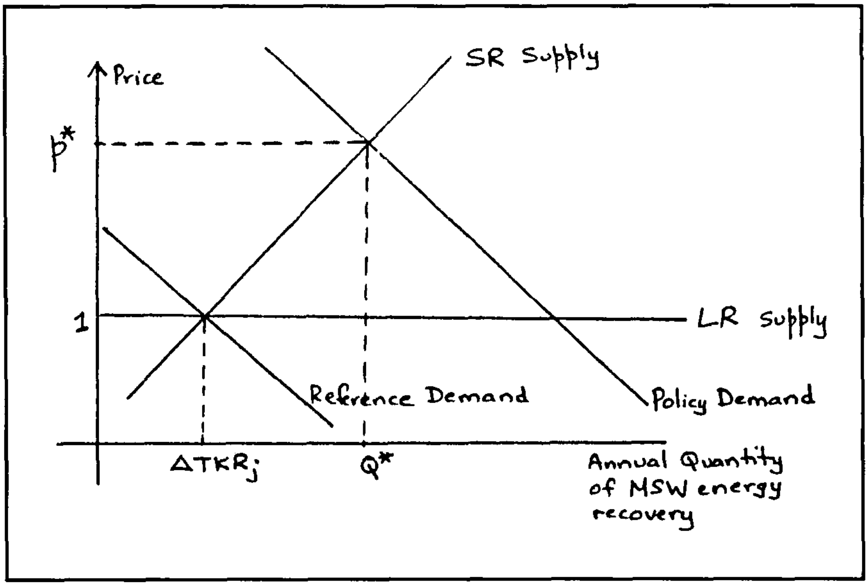

Figure 2. Long-run and short-run supply.

η_j is the effective elasticity of supply for new application equipment in year j

QR_j is the quantity of replacement equipment.

QN_j is the quantity of new application equipment.

$\overline{\eta}$ is the industry elasticity of supply.

In our model we represent (20) as:

$$\eta_j = \frac{X_j \cdot TR_0}{\Delta TKR_j}\overline{\eta} + \overline{\eta} \qquad \text{for } j = 0, \ldots, r. \tag{21}$$

$$\eta_j = \frac{(X_{j-15} \cdot TK_0) + \Delta TKP_{j-15}}{\Delta TKR_j}\overline{\eta} \quad \text{for } j = r + 1, \ldots, N \tag{22}$$

where:

X_j is the parameter indicating how much of the "initial year" (and earlier vintage) stock must be replaced in year j for use in year $j + 1$).

TK_0 is the total (and earlier vintage) capital stock.

ΔTKP_{j-15} is the capital stock installed under the policy in year $j - 15$, which must be replaced in year j for use in year $j + 1$.

τ is the time period for which there are tax credits.

N is the planning horizon of the problem.

Note that we implicitly assume all replacement will occur at the long-run price, and that capacity in the replacement market increases the elasticity of supply in the new application market. The effect is to give the model some sensitivity to the quantity of replacements, but to reduce sensitivity in comparison to a jointly modeled replacement/new application market.

An Overview of Short-Run Equilibrium

Evaluating equation (11) j times with the tax credit policy in place and summing we obtain $KD_j = KD_j(C_j)$ which is the policy case flow demand for MSW energy recovery equipment. For any year in which no adjustment towards long-run equilibrium has taken place, equation (19) with $A_j = TKR_j$; describes short-run supply for the tax credit policy case. In Figure 3 we illustrate short run supply, policy demand and the consequent equilibrium as S_1, D_p and B respectively.

Adjustment to Long-Run Equilibrium

If the vendor industry has fully adjusted capacity to establish long-run equilibrium in the policy case, point C (in Figure 3) represents the equilibrium and S_2 must represent short-run supply. Hence adjustment of supply towards long run equilibrium is represented in Figure 3 as a moving of short-run supply from S_1 to S_2. Possible short-run supply curves arising between no-adjustment and full adjustment are illustrated by the dashed-line supply curves between S_1 and S_2. To

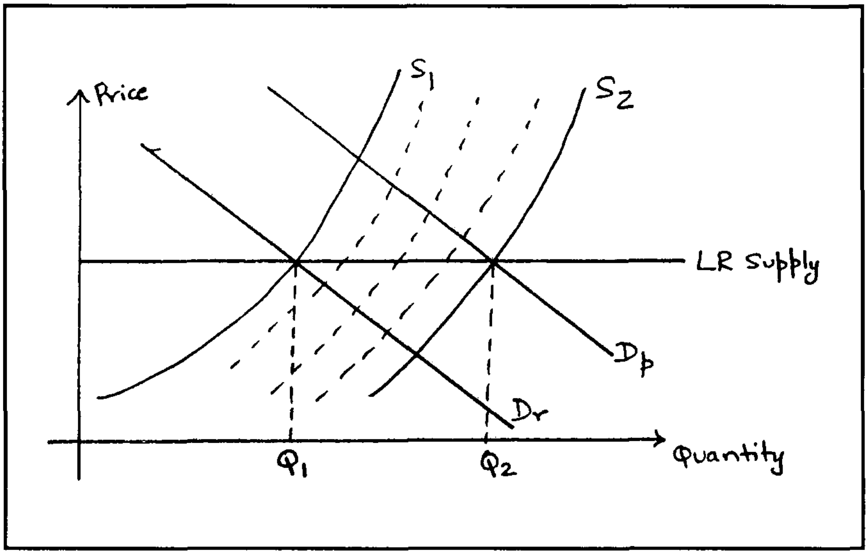

Figure 3. Supply adjustment to long-run equilibrium.

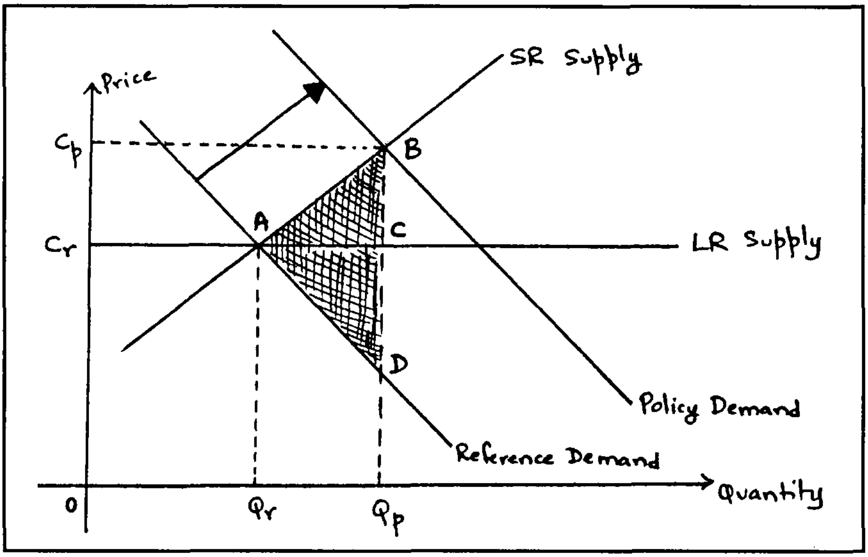

Figure 4. Determining the welfare consequences using a static model.

establish short-run supply functions intermediate to S_1 and S_2 we can establish a weighted average of the two short-run supply functions. For our analysis we assumed that no adjustment toward long-run supply equilibrium has occurred.

Demand and Equilibrium

Demand in the policy case is obtained by evaluating (11) j times under the policy tax, T_j, and summing:

$$K D_j = \sum_{k=0}^{j} \max \left[0, (b\alpha_k)^{1/(1-b)} \cdot \left(\frac{B_j}{1+T_j} \right)^{1/1-b} \cdot C_j^{-1(1-b)} - K P_{k,j-1,} \right] \tag{23}$$

where:

$KD_{k,j-1}$ is the policy case stock of MSW energy recovery equipment of vintage k which is productive before year j.

The policy case equilibrium price and quantity are established by finding a single value of C_j for equations (19) and (23), it is proved impossible to find the equilibrium using analytic methods. An *iterative procedure* is utilized in the computer program of the model to find the equilibrium.

Concluding the Policy Case

Given C_j for the policy case in year j, we evaluate (19) through (23) to finish the policy case.

$$K P_{k,j} = \max \left[K P_{k,j-1,} \, (b\alpha_k)^{1/1b} \cdot \left(\frac{B_j}{1+t_j} \right)^{-b/1-b} \cdot C_j^{1/-(1-b)} \right] \tag{24}$$

$$T K P_j = \sum_{k=0}^{j} K P_{k,j} \tag{25}$$

$$\Delta KP_{k,j} = KP_{k,j} - KP_{k,j-1} \tag{26}$$

$$E P = \max \left[E P_{k,j-1,} \alpha_k^{1/(1-b)} \cdot \left(\frac{B_j}{1+t_j} \right)^{b/1-b} \cdot C_j^{-b/(1-b)} \right] \tag{27}$$

$$T E P_j = \sum_{k=0}^{j} E P_k j \tag{28}$$

where

p refers to the policy case. All other notation is previously defined.

POLICY ANALYSIS

We divided our examination of policy consequences into three groups: 1) those which may be obtained directly from the differences between the policy and reference cases, 2) welfare effects that must be calculated by more circular means, and 3) calculations for cost benefit analysis and revenue estimates.

Impact on Capital Investment and Energy Production

Capital investment due to the tax credit policy under investigation is given for year j by

$$TKIMP_j = TKP_j - TKR_j \tag{29}$$

The impact of the tax credit policy under examination on the increment to capital stock in year j is obtained from:

$$\Delta TKIMP_j = \Delta TKP_j - \Delta TKR_j \tag{30}$$

Energy production from municipal solid waste in year $j + 1$ due to the investment tax credit is given by:

$$TEIMP_j = TEP_j - TER_j \tag{31}$$

Calculating Welfare Consequences

In a static model, the welfare consequences of a tax policy would be determined as follows: The existence of an investment tax credit increases demand from reference demand to policy demand (as shown in Figure 4). Reference demand is the marginal revenue product of capital. Policy demand is the marginal revenue product of capital plus the tax credit. $\overline{OQ_p} \cdot \overline{OC_p}$ is the total cost of equipment under the tax policy; $\overline{OQr} \cdot \overline{OC_r}$ is total cost without. Of the difference between the policy case total cost and the base case total cost, $\overline{C_rC_p\mathrm{BA}}$ accrues to the vendor industry as economic rent, $\overline{Q_rQ_p\mathrm{DA}}$ is the value of increased MSW energy recovery. The shaded area $\overline{ABD}$ is a dead weight loss resulting from the tax credit. Of this triangle, $\overline{ABC}$ is the increased production cost in the short run, and $\overline{ACD}$ is the decreased value of additional MSW energy recovery.

However, only the supply side of our model is static. The flow demand in any period is dependent not only upon the equipment price and energy prices, but also upon the stock of capital in the previous period. Thus, while we may utilize the static approach to measure the dead weight loss that are attributed to increased production costs, we must evaluate the remainder of dead weight loss by evaluating the time paths of capital formation and MSW energy recovery with and without the tax credit. We do each in turn.

Supply Side Welfare Losses

Vendor rent is obtained by integrating the quantity supplied with respect to the price of capital and evaluating over the internal C_r to C_p. This yields:

$$VRENT_j = \frac{1}{1+\eta_j} QLRP_j(c_j^{1+\eta_j} - 1) \tag{32}$$

Thus, supply side dead weight loss would be:

$$DWLS_j = \Delta TKP_j \cdot (C_j - 1) - VRENT_j \tag{33}$$

Interestingly, (33) implies a positive supply side dead weight loss for any $C_j \neq 1$; it is consistent with economic theory which indicates that any deviation from an interference-free competitive market solution results in a welfare loss.

The present value supply side dead weight loss is given by:

$$PVDWLS = \sum_{j=0}^{r} DWLS_j \cdot (1+r)^{-j} \tag{34}$$

Demand Side Welfare Losses

Evaluation equations (32) and (34) $j = 0....,\tau$ yields the impact of the tax credits on the time paths of capital formation and MSE energy recovery respectively. The per unit purchases cost of equipment is C_j in the policy case. However, part of the purchase cost, $C_j - 1$ per unit, is transferred to the vendor industry and is treated on the supply side. Thus the cost that the buyer alone faces is unity. Thus, the present value of the demand site cost due to the policy is:

$$PC = \sum_{j=0}^{r} TKIMP_j(1+r)^{-j} \tag{35}$$

This present cost, PC, must be expended every fifteen years, when equipment is replaced at the end of its life. The present value equipment cost is:

$$PVCOSTPC + (1+r)^{-15} \cdot PA + (1+r)^{-30} PC + \ldots \tag{36}$$

Summing the infinite series we obtain:

$$PVCOST = (1 - (1+r)^{-15})^{-1} \cdot \sum_{j=0}^{r} \Delta TKIMP_j(1+r)^{-j} \tag{37}$$

The estimation of present value benefit in terms of energy bills foregone of the impact of policy on MSW energy recovery is straightforward:

$$PVBEN = \sum_{j=0}^{r} P_{j+1} \cdot TEIMP_j(1+r)^{-j} \tag{38}$$

The present value demand side dead weight loss is:

$$PVDWLT = PVCOST - PVBEN. \tag{39}$$

Total Welfare Losses

The total present value dead weight loss is obtained by summing the present value dead weight losses on demand and supply sides:

$$PVDWLT = PVDWLD + PVDWLS \tag{40}$$

Required Energy/Oil Usage Premium

External benefits to energy savings may offset the private costs (dead weight losses) attributable to tax credit induced market distortions. The net social benefit of such a tax credit program would be:

$$NSB = PVDWLT = \sum_{j=0}^{r} EB \cdot TEIMP_j(1 + r)^{-j} \tag{41}$$

where

EB is the per unit external benefit.

If we wish to determine the external benefits per unit required to offset $PVDWLT$ we set $NSB = 0$ and solve for EB to obtain:

$$EBREQ = PVDWLT = \cdot \left(\sum_{j=0}^{r} TEIMP_j(1 + r)^{-j} \right)^{-1} \tag{42}$$

This latter method for approaching external benefits has the advantage of letting us examine our required external benefits against various per unit measures of possible benefits.

Revenue Estimates

The direct revenue effect of policy is simply:

$$REV_j = (T_j - t_j) \cdot C_j \cdot TKP_j \tag{43}$$

ECONOMIC ANALYSIS

Estimated MSW Energy Recovery

The energy recovered from municipal solid waste was estimated by assuming that the solid waste generated is proportional to the population and that MSW has an energy content of 4500 Btu per pound [5, 6]. The northeast states (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, and New Jersey) has a population of 38.93 million in 1990 and generated 26.5×10^4 tons of MSW. Assuming that 10 percent of MSW produced in 1990 is converted to energy, and using the estimated U.S. population of 249 million, we get that 1.57×10^{12} Btu of energy was produced from MSW in 1990.

Model Calibration

Under the assumptions that demand is determined by profit maximization, and that long-run equipment prices prevailed during 1990, we may calibrate the model so that optimization of the stock of equipment during the 1990 investment year results in the actual estimate of 1990 MSW energy recovery. Because we only have one data point, adjustment is accomplished through a proportional scale-up or scale-down.

Recognizing that $E_{j,j-1} \equiv 0$, $\alpha_j = (GNP_j/GNP_{1990})$, and that $C_{1990} = 1$, we make a preliminary estimate of TE_{1990}.

$$\overline{TE}_{1990} = \frac{B_{1990}^{b/(1-b)}}{0.9} \tag{44}$$

where:

$\overline{TE}_{1990}$ is the initial value estimate of TE_{1990}; $1 + t_j = 0.9$

An adjustment scalar is developed by dividing the actual estimate for 1990 NSW energy recovery by the unadjusted model estimate, to obtain the multiple 'a'. All results then need to be multiplied by a to obtain consistency. We define $\alpha = a(GNP_k - GNP_{k-1}/GNP_{1990})$ for $k = 1990, \ldots,$. Use of the new α_k's complete calibration.

Initialization

Calculation of the optimal flow of investment in each period requires us to know what the stock was at the end of the previous period. Defining $K_{j,j-1} \equiv 0$ solves part of the problem. In addition, for every year, except 1990, calculation of the previous year stock is accomplished by the model. Initialization for 1990 is accomplished by assuming that optimization of the stock for 1990 is independent of any constraints of maintaining previous year capital. Given rising energy prices such an assumption is quite reasonable. Thus we calculate:

$$TK_{1990} = K_{1990,1990} = b\alpha_{1990}^{1/(1-b)} \cdot \frac{B_{1990}^{1/(1-b)}}{0.9}; \tag{45}$$

$$TK_{1990} = K_{1990,1990} = (\alpha_{1990}^{1/(1-b)} \cdot \frac{B_{1990}^{1/(1-b)}}{0.9} ; \qquad (46)$$

Principal Scenario

For our principal scenario we had to make the following assumptions. Lacking information on the vendor industry, we took the normal supply elasticity assumptions of $\overline{\eta} = 1$. We note, however, that the η_j's will be slightly greater than one; see equations (20), (21) and (22). We assumed that 10 percent of the investment costs were returned to the industry as tax credits for five years. Note that this mimics the tax credits mandated by the U.S. Congress in the 1980 windfall Profits Tax [7].

As is evident in Tables 1 and 2, the impact of the tax credit is relatively short lived and small given rising energy prices. The impact of the tax credit on energy savings rises from zero in 1990 (utilization year) to a high of 40.52×10^9 Btu in

Table 1. Reference and Policy Scenarios

Installation Year	Utilization Year		MSW Energy Recovery 10^{12} Btu	Capital 10^6 Units[a]	Capital Increment 10^6 Units[a]	Installation Year Capital Cost $(1990)
1989	1990		1.400	24.724	—	1.000
1990	1991	Reference	1.491	27.621	2.896	1.000
		Policy	1.504	28.152	3.428	1.113
1991	1992	Reference	1.546	29.915	2.294	1.000
		Policy	1.569	30.879	2.726	1.106
1992	1993	Reference	1.620	32.574	2.659	1.000
1993	1994	Reference	1.725	35.874	3.300	1.000
		Policy	1.765	37.756	3.776	1.094
TAX CREDIT EXPIRES AT THE END OF THE 1993 INSTALLATION YEAR						
1994	1995	Reference	1.830	39.196	3.321	1.000
		Policy	1.860	40.617	2.860	0.981
1995	1996	Reference	1.933	42.446	3.249	1.000
		Policy	1.950	43.257	2.640	0.990
1996	1997	Reference	2.034	45.601	3.155	1.000
		Policy	2.041	45.910	2.653	0.996
1997	1998	Reference	2.138	48.795	3.194	1.000
1998	1999	Reference	2.241	51.950	3.154	1.000
1999	2000	Reference	Reference and Policy			
		Policy	Cases Have Identical Values			

Note: Values in the table have been rounded independently.
[a]The unit of account for physical capital is the amount of equipment that can be purchased with a 1990 dollar at the long-run price.

Table 2. Policy Consequences

Installation Year	Utilization Year	Energy Saved 10^9 Btu	Capital 10^6 Units[a]	Capital Increment 10^6 Units
1990	1991	12.965	0.964	0.532
1991	1992	22.439	0.964	0.432
1992	1993	31.379	1.405	0.441
1993	1994	40.515	1.881	0.426
TAX CREDIT EXPIRES AT THE END OF THE 1993 INSTALLATION YEAR				
1994	1995	29.835	1.421	–0.461
1995	1996	16.689	0.811	–0.610
1996	1997	6.260	0.309	–0.502
1997	1998	1.174	0.590	–0.250
1998	1999	0.000	0.000	–0.590
1999	2000	0.000	0.000	0.000

Note: Values in the table have been rounded independently.
[a]The unit of account for physical capital is the amount of equipment that can be purchased with a 1990 dollar at the long-run price.

1994 and falls back to zero by 2000 (Table 2). This occurs against a backdrop in which estimated MSW energy recovery will at the greatest. Figure 5 presents an exaggerated picture of impact of policy on energy savings.

Table 3 gives the details of the welfare consequences of the tax credit. A sizable direct revenue loss is expected, because all units installed between 1990 and 1994 qualify for the tax credit. The revenue loss to the government is estimated at a present (1990) value of 1.25×10^6 (1990 dollars) (Table 4). Revenue losses for the five-year tax credit period are exactly one tenth of installed cost during the same period.

Total private cost of the program is estimated at 0.279×10^6 (Table 5). Given the oil savings, the external benefits required from reduced energy use (per barrel of oil equivalent energy) to offset the private cost are $13.29.

Because only a portion of energy savings may be oil, the oil use premium would have to exceed the $13.29 figure. A greater per barrel external benefit will result in a net social benefit from the tax credit program.

Sensitivity Analysis

Results of sensitivity analysis are shown in Table 6. With the elasticity of MSW energy recovery equipment increased, the response to the tax credit is greater than in the principal scenario. At the lower supply elasticity, equipment price has to increase to establish equilibrium, thus choking off demand. As the supply elasticity increases, supply price does not choke off demand as much. The greater

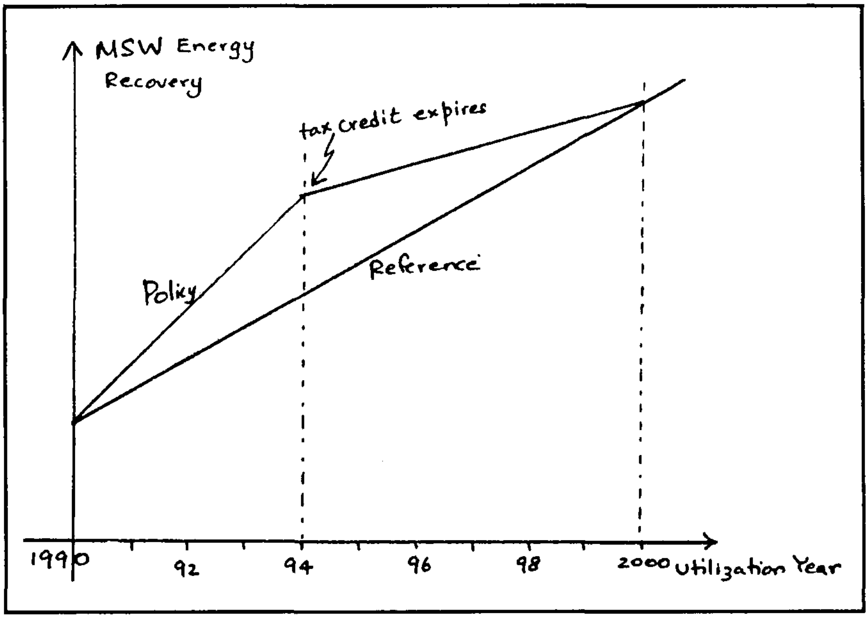

Figure 5. Energy impact of tax credit.

Table 3. Supply Side Welfare Consequences

Installation Year	Transfer to Vendors 10^6 (1990)	Change in Vendor Rent 10^6 (1990)	Supply Side Dead Weight Loss 10^6 (1990)	
1990	0.389	0.358	0.031	
1991	0.288	0.265	0.023	
1992	0.308	0.286	0.022	
1993	0.355	0.333	0.022	
1994	–0.055	–0.056	0.001	
1995	–0.027	–0.027	0.000	
1996	–0.010	–0.010	0.000	
1997	–0.002	–0.002	0.000	
1998	0.000	0.000	0.000	
Present value (1990) of the supply side dead weight loss			0.087	$\$10^6$

Note: Values in table have been rounded independently.

Table 4. Estimated Revenue Effects

Year	Direct Revenue Effects $\$10^6$ (1990)
1990	–0.382
1991	–0.301
1992	–0.341
1993	–0.413
1994	—
1995	—
1996	—
1997	—
1998	—
1999	—
Present Value (1990) of Direct Revenue Effects	–1.248 $\$10^6$

Table 5. Cost Benefit Analysis (1990 Dollars)

Present Value (Supply Side)	$\$0.087 \times 10^6$
Present Value (Demand Side)	$\$0.192 \times 10^6$
Present Value (Total Private Cost) Dead Weight Loss	$\$0.279 \times 10^6$
Extra benefits required from reduced industrial energy use	\$13.29/boe

Note: boe = barrel of oil equivalent

impact of supply elasticity increases on capital investment and energy savings also leads to greater welfare and revenue losses. The increase in welfare losses associated with increased energy savings leads to fairly stable estimates of oil price premium required to offset private costs. The energy usage premium is \$12.91 for $\eta = 5$ and \$11.68 for $\eta = \infty$; the lowest value is just 12 percent less than that for the principal scenario and above the \$10 criterion values.

Table 6. Summary of Sensitivity Analyses

	Total Savings 10^9 Btu	Present (1990) Cost $\$10^6$	Value Direct Loss $\$10^6$	Required Energy Premium $bbl
Principal scenario	161.3	0.279	1.248	13.29
Supply elasticity				
$\eta = 5$	469.2	0.839	1.355	12.91
$\eta = \infty$	756.0	1.119	1.521	11.68
World oil price				
High EIA	179.3	0.313	1.337	13.76
Low EIA	160.1	0.252	1.223	12.12

The model proved insensitive to the projection of energy prices. When the projected oil price is high, there is greater investment and energy savings. Welfare losses increase as well. Conversely when the world oil price is lower, energy savings and welfare losses are lower. These changes are within 12 percent of the principal estimation scenario.

Model estimates would be sensitive to GNP growth rates although this was not established by empirical analysis. Given the likely range of GNP growth rates, we expect that the required energy use premium would not change by much.

Model estimates would also be robust with respect to discount rates when the private and social rates are identical. However, if private investors require a hurdle rate higher than the social discount rate, the tax credit policy should not lead to the same premium requirement.

ACKNOWLEDGMENT

I wish to thank, without implicating, Steve Brown for proposing a similar model to the model used in this article (see Ch. 3 in [2]), and for numerous discussions and comments.

REFERENCES

1. H. L. Varian, *Microeconomic Analysis*, (2nd Edition), Norton, New York, 1984.

2. G. Anandalingam and S. P. A. Brown, Modeling Tax Credit Incentives for Business Investment in Selected Energy Conservation and Production Technologies, Report No. BNL 31278, Brookhaven National Laboratory, Upton, New York, March 1982.
3. S. A. Ravid, The Optimal Timing of Investment in Energy Conservation Technology, BNL 51173, Brookhaven National Laboratory, Upton, New York, July 1978.
4. NCRR, Resources Recovery Activities, *The Journal of Resource Recovery*, National Center for Resource Recovery, Washington, D.C., pp. 15-24, March 1981.
5. W. C. Metz, Refuse Equals Energy: Can the Northeast be powered by its Municipal Refuse?, *Geographical Perspectives*, No. 47, Spring 1981.
6. P. M. Meier and T. H. McCoy, Solid Waste as An Energy Source for the Northeast, Report No. BNL 50559, Brookhaven National Laboratory, Upton, New York, June 1976.
7. *Federal Register*, Investment Credit for Energy Property—Final Regulation, *46*: 15, January 1981.

Direct reprint requests to:

Professor G. Anandalingam
School of Engineering and Applied Science
Department of Systems
University of Pennsylvania
Philadelphia, PA 19104-6315