OPTIMAL INTERVENTION IN UNCERTAIN WASTE RECYCLING MARKETS

Doron Lavee, Uri Regev and Amos Zemel

Discussion Paper No. 04-05

May 2004

Monaster Center for Economic Research
Ben-Gurion University of the Negev
P.O. Box 653
Beer Sheva, Israel

Fax: 972-8-6472941
Tel: 972-8-6472286

29/04/04

Optimal intervention in uncertain waste recycling markets

Doron Lavee[a], Uri Regev[b] and Amos Zemel[c]

Ben-Gurion University of The Negev,
Beer- Sheva, 84015 Israel

Abstract

This paper deals with the effect of uncertainty and irreversible investment on the decision of a municipality to switch from landfill waste disposal to recycling. We show that uncertainty regarding the price of recycled materials may induce a risk neutral municipality to prefer landfill disposal, even when recycling is less expensive. Consequently, a policy designed to reduce uncertainty is preferable to Pigouvian taxes or to subsidies as a means to enhance recycling. We estimate the parameters of a theoretical model with empirical data from 80 municipalities in Israel. The empirical results support the observation that price stabilization can be effective to establish viable recycling markets.

Keywords: Uncertainty, irreversible investment, recycling, waste, government policy.

---

[a] Department of Economics Ben-Gurion University, Beer-Sheva, 84105 Israel
E-mail: dlavee@inter.net.il
[b] Department of Economics Ben-Gurion University, Beer-Sheva, 84105 Israel.
E-mail: uri@bgumail.bgu.ac.il
[c] The Blaustein Institute for Desert Research, Ben-Gurion University, Sde-Boker campus, 84990 Israel.
E-mail: amos@bgumail.bgu.ac.il

We wish to thank Yossi Hadar for helpful comments and suggestions.

1. Introduction

Waste disposal has recently become a high priority topic on the public agenda. Recent economic literature has investigated a variety of public policies for reducing solid waste disposal and increasing the recycling thereof. The main reason for this interest is the growing public concern about environmental damage of landfill and even the fear of "landfill crisis" (Ackerman, 1997).

The recycling market is described schematically in terms of a single product (X) produced by competitive firms, using either virgin (B) or recycled (M) raw material. Consumers purchase final goods and produce waste, which is disposed of by the municipality either to landfill (H) or to recycling plants (R). The recycling plants buy the waste (R) to produce recycled raw material (M), which is sold back to the producing firms. The following flowchart describes the process:

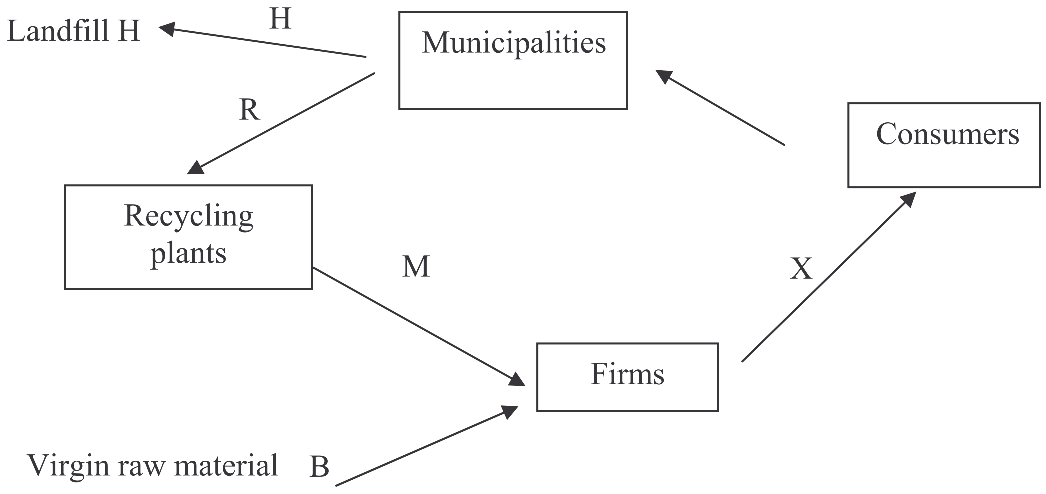

Figure 1: The recycling market

We focus attention on the role of the municipalities in the recycling market and consider the effect of uncertainty on the municipalities' considerations in selecting their method of waste removal - landfill or recycling - and on its derivative - the extent of waste sent for recycling. Initially, the municipality removes all the waste to landfill. At each time period, the municipality can decide to send part of the waste for recycling. Should it decide to switch to recycling, an investment in changing the layout of waste removal is then required. The municipality can revert to full landfill in the future, but the return will require additional investments to restore the landfill layout.

We examine the municipality's deliberations in an uncertain world, in which the cost of recycled waste at each time period is not a-priori known. In contrast, the cost of removing a unit of waste for landfill is known and fixed. We show that uncertainty and high investment cost deter the municipality from switching to recycling, even if its expected expenses on recycling are lower than on landfill. The larger the uncertainty and investment costs - the larger is the cost difference between recycling and landfill required to induce the municipality to switch to recycling.

Since recycling bears positive external effects, we examine two types of government intervention policy to motivate municipalities to switch to recycling - recycling subsidy and recycling price stabilization. We find that since the variability in the prices of recycled materials is high, price stabilization is preferable to subsidized recycling.

Many countries have adopted legislation and regulations to impose high levels of recycling, such as the German Green Dot program and similar programs in France and Austria (Ackerman 1997). Many states in the U.S. have deposit/refund on beverage containers, advanced disposal fees, and minimum standards of recycled content (Palmer et al. 1997). In Israel, the government has adopted minimum recycled content standards in 1996, recycling subsidy in 2001 and deposit/refund on beverage containers in 2002.

Recent research has analyzed the various regulation policies from the perspective of economic efficiency. Jenkins (1993) argued that charging households for waste disposal is efficient in the absence of illegal dumping of waste. Fullerton and Kinnaman (1996), however, presented some evidence that this policy may lead to increased illegal disposal and even to more severe damage than no regulation at all.

Numerous studies consider the deposit/refund system as the best tool for enhancing recycling (e.g. Fullerton and Kinnaman 1995, Sigman 1995, Palmer et al. 1997). Under this policy, the consumer bears the costs only if the waste is discarded. Palmer et al. (1997) compare three policies for reducing solid waste disposal: Deposit/refund system, advance disposal fees and recycling subsidy. They argue that imposing a deposit/refund policy that embodies the environmental costs of waste treatment would "suggest that a 7.5% reduction in these wastes would have been desirable in 1990 if it could be implemented in a least-costs manner" (p. 130). Other policies would result in a reduction of less than 4% of the total amount of waste. In Palmer's model, the relevant waste for recycling accounts for only 56% of all municipal solid waste, which means that a deposit/refund policy reduces only 4.2% (56%*7.5%) of the total waste! This modest reduction in municipal solid waste leaves open the main issue– can recycling be an attractive alternative to landfill?

This literature does not take into account two major concerns that deter municipalities from switching to recycling: price instability in the recycling markets and sunk adjustment costs borne by the municipalities when switching from conventional disposal to recycling. Ackerman (1997) observed that the prices of recycled raw material are extremely unstable, as demonstrated in Figure 2, even when the prices of the corresponding final goods are fairly stable, and suggested that this instability hinders the creation of a recycling market.

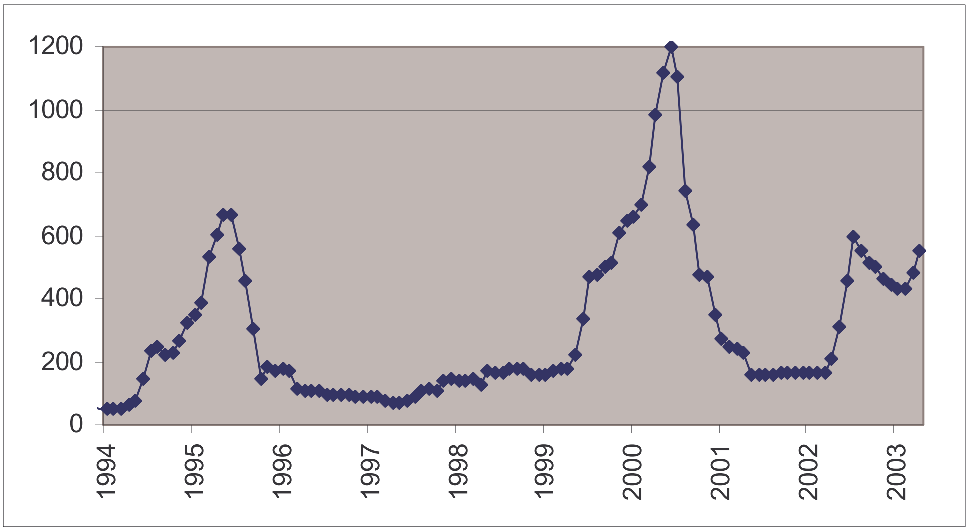

Figure 2: Price index for scrap mixed paper.

(Source: US Bureau of labor statistics – price producer index, series id: pcuso93#53)

Eichner and Rudiger (2001) argue that unstable prices are the major reason for inefficiency in waste disposal, leading to incomplete or absence of recycling markets. However, they do not discuss the reasons for this situation. Price instability is a major source of uncertainty and the latter may significantly affect the investment decisions of economic agents. Dixit and Pindyck (1994) show how the combination of irreversible investment and uncertainty can deter a risk-neutral investor from undertaking the risk. The higher the irreversible costs and the degree of uncertainty, the higher is the compensation required to induce the investor to enter the market. This compensation is related to the value of the option to delay the investment until the economic environment proves to be more favorable. This outcome is valid both for an individual investor and for the market equilibrium at the industry level. Tsur and Zemel (1998) show that the threat of exogenous irreversible events can induce less conservation and more pollution. Petrakis and Xepapadeas (2003) consider the relocation decisions of polluting firms and find that by reducing uncertainty via a long-term commitment to an environmental policy, a government can strongly affect the firms' behavior. Schatzki (2003) shows that uncertainty and sunk costs decrease the likelihood of land use conversion from agriculture to forestry even if the landowner is risk neutral. Furthermore, the conversion thresholds are significantly higher than the expected net present value. Schatzki's estimates indicate option values of up to 81% of the expected values of the land asset, and the conversion threshold tends to increase with the conversion cost.

Louberge et al. (2002) consider two main options for the disposal of nuclear waste, surface storage and deep geological disposal, and investigate the optimal timing for switching from surface storage to deep disposal. While surface storage entails high stable costs, deep disposal involves initial investment and random future expenses due to unanticipated future accidents. This analysis implies a strong effect of the degree of uncertainty on the optimal waste management policy. Our model of municipal waste disposal gives rise to a similar effect, but our attention is focused on intervention mechanisms to overcome it.

Pennings (2000) proposes to subsidize investments and tax future profits in order to stimulate irreversible investments. In the case of a municipality that has to choose between two disposal alternatives, Pennings' policy is not optimal due to the presence of high switching costs between these alternatives. Empirical cost data from three European countries support our conjecture that reducing price uncertainty could increase the efficiency of waste disposal and lower the costs of recycling (see Figure 3). In Germany and Austria, targets were set for the level of recycling, resulting in quadrupling the costs of waste disposal. In France, such goals were coupled with long-term contracts at stable prices for the recycled materials, resulting in recycling costs that were lower than those of landfill disposal.

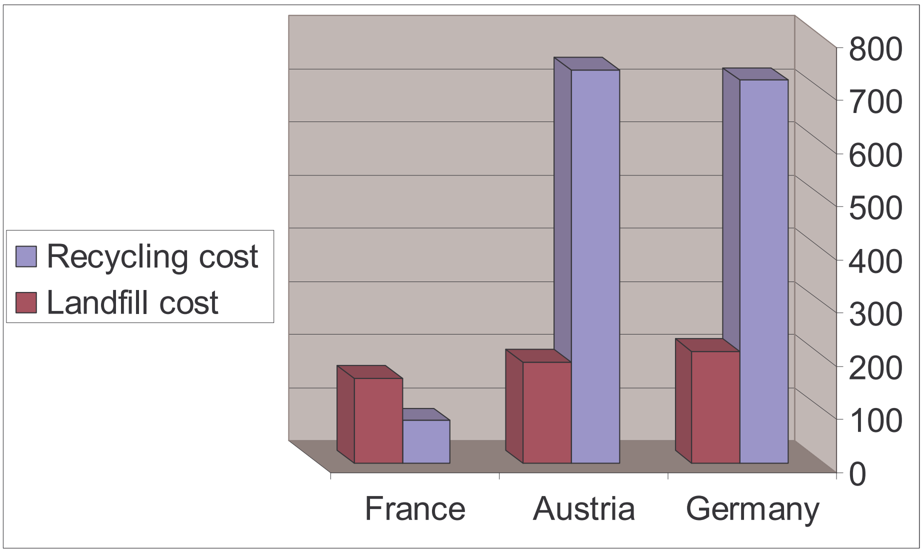

Figure 3: Comparison of recycling and landfill unit costs in three European countries.
(Source: Ackerman (1997), costs in € per ton)

In Section 2 we present a model to describe the recycling adoption decision process and show how price instability in the recycling markets and fixed adjustment costs borne by the municipalities deter them from adopting recycling technologies. We suggest a mechanism of government intervention by price stabilization, implemented via a long-term contract between the municipalities and the recycling plants, ensuring a fixed price for the waste materials to the municipalities. We show that an intervention policy implemented along these lines yields a net social gain.

In Section 3 we estimate the parameters of the model with empirical data from 80 municipalities in Israel and simulate the behavior of municipalities under a number of scenarios with various levels of price uncertainty. The results demonstrate the critical effect of government intervention via price stabilization to secure a viable recycling market.

2. A model of waste disposal under price uncertainty

We begin with the considerations of a single municipality, and determine the threshold price of waste material (received from the recycling plant), which will render it worthwhile for the municipality to switch to a recycling layout. We examine the effect of uncertainty on this threshold price relative to a certain world. The difference in prices under the two scenarios is "the cost of uncertainty". Accounting for the positive external effects of recycling, the government can encourage the municipality to switch to recycling under uncertainty by covering this difference in some form of subsidy, or by eliminating uncertainty via a stabilization program. Both methods can be used to enhance recycling, raising the question of which policy is more efficient in achieving this goal.

2.1 The municipality problem

Consider N municipalities having the choice of waste disposal by either landfill or recycling. Each municipality has a fixed, given quantity of waste per period and a given part of it (q_i) can be recycled. By recycling a quantity q_i, the i^{th} municipality saves in landfill costs a total sum of H_i, or a unit cost $C_{Hi}=H_i/q_i$. Therefore, C_{Hi} is the unit cost of the landfill alternative policy. The unit cost of recycling is C_{Ri}, including collection and transportation to the recycling plant. The municipality receives from the plant a payment (P_R) per unit of waste sent for recycling. The planning horizon is infinite and time is divided into discrete periods. The discount rate r is assumed to be fixed over the time horizon. The municipality has to decide if and when to switch back and forth between the two methods of waste disposal. Switching involves investment or set-up costs: W_R denotes the switching costs from landfill to recycling and the corresponding unit costs are $w_{Ri} = W_{Ri}/q_i$, and W_H denotes the switching costs from recycling to landfill with $w_{Hi} = W_{Hi}/q_i$. The switching process is instantaneous and once the switching investment has taken place, the quantity q_i of waste is sent for recycling. Although these costs vary across municipalities, we omit for simplicity of exposition the i-th index of the municipality from all variables when the behavior of one specific municipality is considered.

We assume that the price paid to the municipality for recycling (P_R) at each time period is an independent stochastic variable distributed according to the density function f and the cumulative distribution F that are common for all municipalities and do not vary over time. Thus, $F(x) = \text{Prob}\{P_R<x\}$; $f(x) = F'(x)$ and the expected price is $\mu_R = E\{P_R\} = \int_{-\infty}^{\infty} xf(x)dx$. The corresponding variance is denoted by σ^2. The realization of the random price P_R is revealed at the beginning of each time period, following which the decision to switch from landfill disposal to recycling or back takes place.

Denote:

V_H - expected discounted unit waste disposal costs when currently using landfill.

V_R - expected discounted unit waste disposal costs when currently using recycling.

A municipality currently using landfill must determine a threshold price (γ_R), so that it will go on using landfill during the coming period if $P_R \leq \gamma_R$, entailing expected costs of $C_H + V_H/(1+r)$. The municipality will switch to recycling when $P_R > \gamma_R$, with expected costs of $C_R - P_R + w_R + V_R/(1+r)$.

Let

$$I(P_R \leq \gamma_R) = \begin{cases} 1 & if \quad P_R \leq \gamma_R \\ 0 & if \quad P_R > \gamma_R \end{cases}$$

The municipality will choose γ_R so as to minimize the expected value

$$(1)\ V_H = Min_{\{\gamma_R\}} E\{[C_H + \frac{V_H}{1+r}]I(P_R \leq \gamma_R) + [C_R - P_R + w_R + \frac{V_R}{1+r}][1 - I(P_R \leq \gamma_R)]\}$$

Define: $EC(\gamma) = E\{P_R I(P_R \leq \gamma)\} = \int_{-\infty}^{\gamma} xf(x)dx$,

then

$$(2)\ V_H = Min_{\{\gamma_R\}}\{[C_H + \frac{V_H}{1+r}]F(\gamma_R) + [C_R + w_R + \frac{V_R}{1+r}][1 - F(\gamma_R)] - \mu_R + EC(\gamma_R)\}$$

Carrying out the minimization of (2) we find

(3) $[C_H + \frac{V_H}{1+r}]f(\gamma_R) - [C_R + w_R + \frac{V_R}{1+r}]f(\gamma_R) + \gamma_R f(\gamma_R) = 0$

Denote $\Delta C = C_R - C_H$; $\Delta V = V_R - V_H$.

Given that $f(\gamma_R) \neq 0$, (3) implies

(4) $\gamma_R = \Delta C + w_R + \Delta V/(1+r)$.

Denote $U(\gamma) = \gamma F(\gamma) - EC(\gamma) = \int_{-\infty}^{\gamma}(\gamma - x)f(x)dx = \int_{-\infty}^{\gamma}F(x)dx$.

Using (4) in (2) yields

(5) $V_H = C_H + \frac{V_H}{1+r} + \gamma_R[1-F(\gamma_R)] - \mu_R + EC(\gamma_R) = C_H + \frac{V_H}{1+r} + \gamma_R - \mu_R - U(\gamma_R)$,

hence

(6) $V_H/(1+r) = [C_H + \gamma_R - \mu_R - U(\gamma_R)]/r$.

Let γ_H be the threshold price for a recycling municipality. It will switch back from recycling to landfill technology if $P_R \leq \gamma_H$, with the expected cost $C_H + V_H/(1+r) + w_H$, or it will go on recycling (when $P_R > \gamma_H$), with the expected cost $C_R - P_R + V_R/(1+r)$. The threshold γ_H is selected so as to set

(7) $V_R = Min_{\{\gamma_H\}} E\{[C_H + \frac{V_H}{1+r} + w_H]I(P_R \leq \gamma_H) + [C_R - P_R + \frac{V_R}{1+r}][1 - I(P_R \leq \gamma_H)]\}$

or

(8) $V_R = Min_{\{\gamma_H\}}\{[C_H + \frac{V_H}{1+r} + w_H]F(\gamma_H) + [C_R + \frac{V_R}{1+r}][1-F(\gamma_H)] - \mu_R + EC(\gamma_H)\}$.

Carrying out the minimization of (8) we find

(9) $[C_H + \frac{V_H}{1+r} + w_H]f(\gamma_H) - [C_R + \frac{V_R}{1+r}]f(\gamma_H) + \gamma_H f(\gamma_H) = 0$.

Hence, given that $f(\gamma_H) \neq 0$:

(10) $\gamma_H = \Delta C - w_H + \Delta V/(1+r)$.

Defining $\Delta\gamma = \gamma_R - \gamma_H$ and subtracting (4) from (10) we find

(11) $\Delta\gamma = \gamma_R - \gamma_H = w_H + w_R$,

which shows how the switching costs determine the level of irreversibility regarding the choice of the waste disposal technology. Indeed, the price range $[\gamma_H, \gamma_R]$ corresponds to economic hysteresis (Dixit and Pindyck 1994, p.17) because in this range a municipality prefers to stick to its current disposal technology although the price does not justify adopting this technology if the current technology were different. According to (11), the extent of the hysteresis phenomenon is related to the sum of the irreversible switching costs.

Using (10) in (8) yields

$$(12)\ V_R = C_R + \frac{V_R}{1+r} - \gamma_H F(\gamma_H) - \mu_R + EC(\gamma_H) = C_R + \frac{V_R}{1+r} - \mu_R - U(\gamma_H).$$

Hence

$$(13)\ V_R/(1+r) = [C_R - \mu_R - U(\gamma_H)]/r.$$

Subtracting (6) from (13), we find

$$(14)\ \ \Delta V/(1+r) = [\Delta C + U(\gamma_R) - U(\gamma_H) - \gamma_R]/r = [\Delta C + \Delta U - \gamma_R]/r$$

where, noting (11),

$$(15)\ \ \Delta U = U(\gamma_R) - U(\gamma_H) = \int_{\gamma_H}^{\gamma_R} F(x)dx = \int_{\gamma_R-(w_H+w_R)}^{\gamma_R} F(x)dx$$

With (14) at hand, we can use (4) to implicitly determine γ_R

$$(16)\ \ \gamma_R = \Delta C + rw_R/(1+r) + \Delta U/(1+r).$$

The first two terms of (16) measure the difference in the direct disposal costs and the imputed switching cost. These are known and fixed, so their sum is the decision criterion in a world of certain prices. The last term of (16) - $\Delta U/(1+r)$ - can be interpreted as a risk premium, since it represents the additional payment, above the certainty world criterion, that is required by the municipality for switching under uncertainty. In a certain-price world the distribution function *F* collapses to a jump at the expected value μ_R and (15) reduces to $\Delta U = 0$. Thus, $\gamma_R^{UC} = \gamma_R^{C} + \Delta U/(1+r)$, where γ_R^{UC} and γ_R^{C} are the threshold prices under uncertain and certain conditions, respectively.

Inspecting (15), we see that two parameters determine ΔU:

1. The level of price uncertainty, measured by the variance (σ^2). Indeed, ceteris paribus, ΔU is a monotonically increasing function of σ.
2. The sum of switching costs. Since $\Delta\gamma = \gamma_R - \gamma_H = w_H + w_R$, it follows that ΔU is a monotonically increasing function of both switching costs.

In fact, ΔU is constructed from contributions of all realizations of the random price P_R falling in the hysteresis interval below γ_R (rendering the transition to recycling unattractive), but above γ_H (hence the transition back to landfill is not justified). Thus, $\Delta U/(1+r)$ represents the discounted value of expected future losses due to the irreversibility of present switch decisions[1]. This term can, therefore, be interpreted as the cost of irreversible investments under uncertainty, or the cost of uncertainty. The effect of this term may induce a municipality to keep on landfilling even when recycling is cheaper. Only if the difference between the price of landfill and that of recycling is high enough to cover this cost of uncertainty, a landfilling municipality will agree to undertake the risk and switch to recycling. The result of uncertainty is therefore less recycling and higher costs of waste disposal[2].

2.2 Policy Implications

As shown above, the combination of sunk switching costs and price uncertainty hampers the adoption of recycling technologies by reducing the number of municipalities that are willing to undertake the required investment and switch to recycling. Therefore, the level of recycling activities is smaller than what would be expected in a certain world. In view of the positive external effects of recycling, this situation calls for some intervention mechanism to enhance these activities. Typically, the mechanisms proposed to achieve such goals involve Pigouvian taxes (on municipalities, consumers or producers) to reduce landfill or subsidies to reduce the recycling costs. While these mechanisms can increase recycling, they do not address the issue of uncertainty hence they cannot remove the inefficiency it entails. We consider, therefore, a mechanism for stabilizing the price of recycled materials and investigate how it can be implemented to enhance recycling.

We suggest a mechanism of government intervention by price stabilization, implemented via a long-term contract between the municipalities and the recycling plants that ensures a fixed price for the waste materials to the municipalities. The goal for this policy is defined by the level of recycling obtained in a certain world, i.e., we set the cost required to stabilize the recycling market at the expected value μ_R so that all municipalities will act in the same way as they do in a certain world. To induce recycling plants to undertake long-term commitments under the risk of future drops in the price of raw materials, the government insures them against such losses: whenever the raw material price falls below a given threshold level, the government will compensate the plants for the difference between market price and the promised threshold price. This contract offers obvious advantages to the recycling plants

---

[1] This result is consistent with the `principle of bad news` (Bernanke, 1983), which states that the effect of uncertainty solely depends on future losses, but is independent of the states of nature corresponding to gains.

[2] This results from the assumption that the municipalities are currently landfilling. If the municipalities were initially recycling, we would get an opposite effect of uncertainty. This is another manifestation of the hysteresis phenomenon.

because they can enjoy the profits of high-price periods without bearing the losses during low-price periods.

Aware of this situation, the government can recover its low-price periods expenses by taking advantage of the competition among the plants and collect their extra profits via an auction that requires plants to bid an entrance fee in order to be admitted to the stabilization program. This mechanism gives rise to a government guaranteed stabilization program with administration expenses being the only cost, because in the long run the compensation expenses are covered by the entrance fees. An intervention policy implemented along these lines yields a net social gain: the municipalities benefit from the lower costs of recycling, the recycling plants are secured from losses during low-price periods, while society gains from the positive externalities of enhanced recycling. This suggests higher efficiency relative to conventional (Pigouvian or administrative) intervention policies in recycling that do not tackle the losses to society entailed by price uncertainty.

More specifically, consider numerous identical competitive recycling plants with:

Y_t – random price that the recycling plants receive at the time period t for a unit of recycled raw material (after waste is converted to raw material).

K – fixed investment costs.

L – cost of treatment of a unit of waste.

P_{Rt} – price paid to the municipality per unit of waste at time t.

r – discount rate.

q_t – total treatment during a time period.

The profit of a representative recycling plant is: $\Pi_t = (Y_t - L - P_{Rt})q_t - rK$. Without the intervention program, the expected profit in a competitive market equilibrium is reduced to zero. The price P_{Rt} paid to the municipalities for the waste is determined each year by the fluctuating price Y_t received by the plants, hence the relation between these stochastic prices is given by $P_{Rt} = Y_t - L - rK/q_t$.

In order to convince the plants to sign long-term contracts with the municipalities to treat the quantity q at the fixed price $\mu_R = E\{Y_t\} - L - rK/q$, the government must compensate them for temporary losses incurred when P_R drops below its expected value. The government can come up with the following proposition: any plant that signs a such a long term contract with a municipality will be admitted to the following insurance program: Let $\Omega_t = \mu_R + L - Y_t$ be the difference between the plant's variable costs (excluding the long-term fixed investment K) and its revenues at time t. When $\Omega_t > 0$ (representing a net short-run loss for the plant), the government will compensate it by that amount for each unit of waste recycled, hence it will have no incentive to get away from its contractual obligations and reduce recycling during that period. In contrast, during high price periods when $Y_t - L - rK/q > \mu_R$, the plant is allowed to keep its profits, hence the program entails positive long-run profits for the recycling plant.

Obviously, the plant's gains are due to net transfers from the government. The latter, however, can exploit the competition among the recycling plants and run a balanced-budget program (except for the administrative cost of managing it) by requiring the plants to buy a permit to participate in the program via an auction in which they bid an entrance fee (a fixed amount for the entire contract duration). The revenues from this auction fully cover the government expenses on compensation during the low price periods without deterring the plants from taking part in the stabilization program.

The advantage of price stabilization as an intervention policy is that it directly addresses the root of the problem, namely price uncertainty. In contrast, a subsidy program can enhance recycling but it does not eliminate uncertainty. As a result, the municipalities may switch back and forth between recycling and landfill according to the price fluctuations, creating extra sunk costs compared to the stabilization program. Louberge's (2002) proposal of subsidizing the switching cost and taxing the profits may even exacerbate the problem, because it does not eliminate uncertainty and creates an incentive for excessive switching between the disposal technologies. Price stabilization thwarts the motivation of the municipalities to switch between disposal technologies, thus eliminating a major inefficiency of the price uncertainty.

3. Empirical estimation

The model shows the potential effect of uncertainty on a single municipality – preferring landfilling even when recycling is cheaper. We investigate this problem empirically in order to examine the significance of this effect. We consider if and by how much landfilling is more costly than recycling and estimate the relative weight of uncertainty as the cause of underperformance of the recycling markets. These data are then used to evaluate the efficacy of governmental policy of price stabilization to encourage waste recycling.

In order to examine these questions we estimate the cost parameters of waste management in 79 Israeli municipalities, which account for over 60% of the municipal solid waste in Israel. First, we analyze the costs of landfill disposal, then we estimate the recycling costs and finally we simulate the volume of recycling activities for varying levels of uncertainty regarding the price of recycled materials.

Data for this study were available only for inert materials, comprising 40% of the total municipal waste, whereas the recycling potential is higher than 85% of the total waste. We discuss first the estimation methodology and then present and analyze the results.

Switching to waste recycling requires a minimal quantity of treated waste, which cannot be obtained from a single recyclable component. Therefore the analysis is carried out for a combination of waste components and we estimate the parameters for an "average waste bundle", where the average is weighted by the relative contribution of each individual component. The components of municipal waste treated in Israel, suggested as suitable for recycling, include paper of various kinds (white paper, newspaper and other, cardboard), glass, PET plastic (polyethylene exterior terephyalat) and other plastics (especially HDPT- High Density Polyethylene terephyalat).

3.1 The price of recycled waste – P_R

A reference unit price for every component in the "bundle" has been obtained from a survey we conducted in Israel during January 2003. To trace the price fluctuations, we used the time series of monthly relative price indices (108 observations) for the period of 1995-2003, from the US Bureau of Labor Statistics database. For each component, the corresponding time series has been used to derive the time-average P_{Ri} and the associated standard deviation. In addition we have constructed the time series of the bundle and calculated its average $\mu_R = \sum \frac{\alpha_i}{\beta} P_{Ri}$, where α_i is the percentage of the *i*'th component out of total waste, and β is the percentage of all recycled components out of total waste. The bundle variance, σ^2, was derived from the bundle time series.

3.2 Recycling costs – C_R

Lavee (2000) obtained the costs for the collection, separation and transportation of the recyclable waste. The recycling cost for each component is $C_{Ri} = \frac{M_i / Ti}{\Phi_i V_i / R_i}$, where C_{Ri} is cost of disposal of the *i*'th component (per ton); M_i is yearly cost of removal of the recycling containers; T_i – number of removals per year; V_i – container volume; Φ_i - waste fraction of the container's capacity at the time of removal and R_i – volume to weight ratio. The components' costs are then averaged, yielding the bundle cost $C_R = \sum \frac{\alpha_i}{\beta} C_{Ri}$. The results are presented in Table 1.

While these data represent national averages, large differences in the costs of waste treatment are observed across municipalities. A study, conducted in 50 municipalities in Israel (Lavee 2000), determined the basic costs and the additional costs associated with the municipality characteristics (small vs. large, urban vs. rural, distance from the center of the country and from recycling plants, etc.) The detailed results are used in the simulation studies discussed below.

3.3 Landfill costs – C_H

In figure 4 we show the flow of waste from the households to the landfill site. We distinguish between the internal and external municipal sectors (the importance of this distinction is explained below).

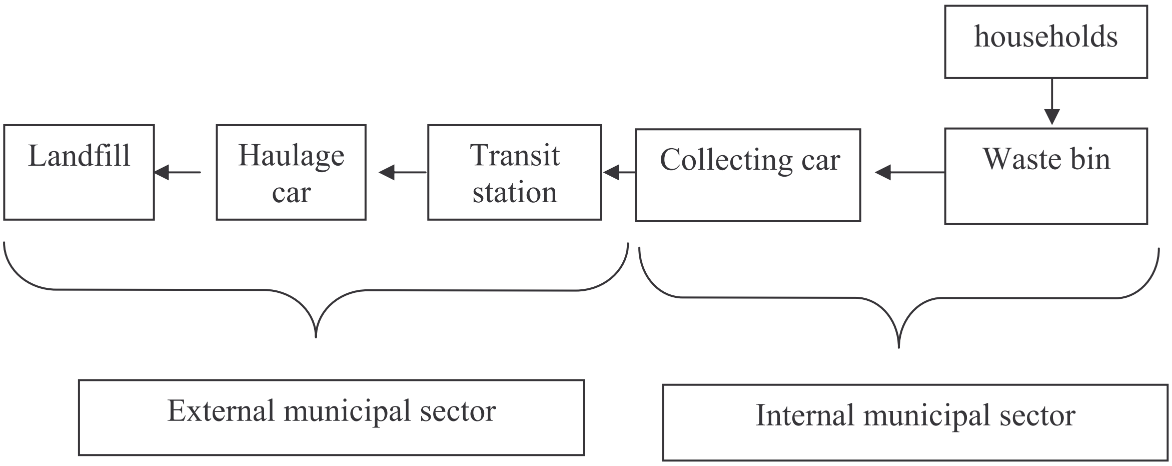

Figure 4: The flow of waste to landfill

The relevant cost for our comparison is not the actual cost of landfill disposal but the alternative cost to recycling. The municipality can send only part of the waste to recycling, so the alternative cost to recycling is the incremental cost of landfill disposal when all the waste is sent to landfill relative to the cost of landfill when part of the waste is sent to recycling. In other words, C_H is calculated as the saving (per ton) in landfill costs due to recycling. The flowchart in Figure 5 delineates these calculations.

On the left side of Figure 5 the reduction of waste to landfill due to recycling is presented. We distinguish between the internal municipal sector where the relevant reduction is in terms of volume[3], and the external municipal sector where the relevant reduction is in weight.

On the right side of Figure 5 we present the total costs of disposal by landfill in the internal and the external municipal sectors. The alternative cost to recycling is given by the product of the amount of volume/weight reduction and the internal/external costs. The unit cost saving is obtained by dividing this alternative cost by the quantity of waste sent to recycling.

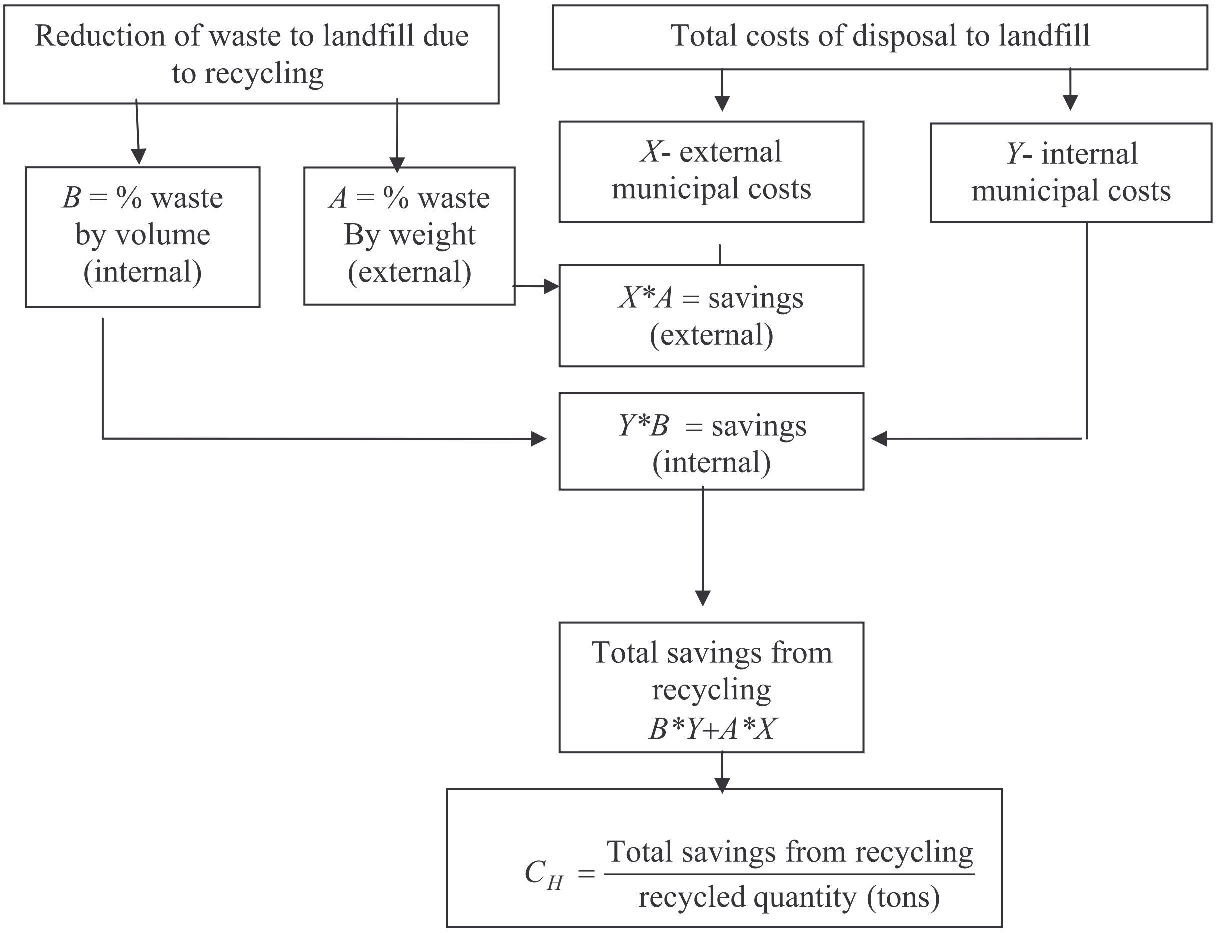

Figure 5: Evaluation of $\boldsymbol{C_H}$, the alternative landfill cost.

3.4 Switching costs – W_R and W_H.

The costs required for switching from landfill to recycling – W_R – include management reorganization, information and public awareness, reduction of the labor force, and changing

---

[3] In the internal sector the cost is determined mainly by the volume of the waste rather than by its weight. Because there is a significant difference in the volume/weight ratio of the waste components for recycling and the other waste components, this distinction is necessary for an accurate evaluation of the alternative costs.

the terms of contract with waste collecting contractors. Proceeds from the sale of surplus equipment are subtracted from these costs.

The costs required for switching from recycling to landfill – W_H – include purchase of equipment, management arrangements, information, recruiting labor and operations organization.

The switching costs depend on the nature of each municipality and they are therefore estimated according to its individual characteristics. Estimates of the costs described in sections 3.2-3.4 were obtained by Lavee (2000), for every municipality in the survey.

3.5 Risk premium – ΔU

In order to calculate the risk premium, we assumed a normal distribution for the prices (P_R can be negative as well as positive). Using the parameters' estimates described above (μ_R, σ, C_R, C_H, w_R and w_H), we used equations (15,16) to obtain ΔU for every waste component as well as the average value of ΔU for the waste "bundle". This value is different for each municipality, because the switching costs vary across municipalities. The national average value is presented in Table 1 together with the results of the cost calculations of the previous sub-sections.

Component	Relative Weight	μ_R (NIS/ton)	$C_R - \mu_R$ (NIS/ton)	σ/μ_R	$\Delta U/\mu_R$
White paper	4.50%	292.5	–2.5	16.6%	12.6%
Newspaper and others	31.33%	56	187	87%	66%
Cardboard	20.77%	100	60	55%	48%
PET Plastic	4.83%	600	200	9%	4.6%
Other plastics	30.21%	200	300	27%	27.6%
Glass	8.35%	73	147	17%	10%
"Bundle"	100%	147	184	38%	34%

Table 1: Average cost parameters.

3.6 Results

Using the model of the previous section and the empirical cost data we analyze the effect of the level of uncertainty on the municipalities' decisions to adopt recycling. We evaluated the number of municipalities that would switch to recycling and the percentage of recycling out of the total waste (in weight and volume). Table 2 presents these results for several levels of price uncertainty (corresponding to the value of σ obtained above for each component). The data display a strong effect of uncertainty on withholding recycling.

The standard deviation of the "bundle" recycling price is 38% and corresponds to the fourth line in Table 2. Comparing the recycling fraction (relative to the recycling potential) under certainty with the "bundle" uncertainty, we see a drop of 16 percentage points (from 85% to 69%) in recycling and of 19 percentage points (from 53% to 34%) in the number of recycling municipalities. The risk premium (ΔU) required to induce enough municipalities to switch to recycling is 34% of the average recycling price, which amounts to 50 NIS per ton (34% of 147 NIS). This sum is significant, since the total cost of waste management in Israel is about 260 NIS per ton.

Uncertainty Level	$\Delta U/\mu_R$	Recycling municipalities	Recycling/ potential	Recycling/ total waste (in weight)	Recycling/ total waste (in volume)
Certainty	0	53%	85%	21%	42%
$\sigma/\mu_R = 9\%$	4.6%	51%	83%	20%	40%
$\sigma/\mu_R = 17\%$	10%	48%	82%	19%	38%
$\sigma/\mu_R = 38\%$	34%	34%	69%	17%	35%
$\sigma/\mu_R = 55\%$	48%	29%	64%	16%	32%
$\sigma/\mu_R = 87\%$	66%	23%	59%	15%	30%

Table 2: The effect of uncertainty on the level of recycling.

The data reveal that the municipalities are highly heterogeneous, and no particular level of uncertainty can change dramatically the number of municipalities that will switch to recycling. A gradual reduction of uncertainty will induce a gradual increase in the number of recycling municipalities.

To test the relation between uncertainty and adoption, empirically, we compare in Table 3 the model results with actual recycling data on two materials that are commonly recycled in Israel.

Type of waste	$\Delta U/\mu_R$	$C_R-\mu_R$ (NIS/ton)	Recycling municipalities		Recycling/ potential	
			observed	model	observed	model
Newspaper and Others	66%	187	20%*	23%	20%	59%
PET Plastic	4.6%	200	46%	51%	60%	83%

Table 3: Modeled and observed recycling activities.

Source: The Israel Ministry of the Environment (2003).

* In most of the municipalities - recycling is only partial.

The empirical data are in accordance with the model predictions. While the recycling costs are somewhat higher for plastic than for paper, the former is recycled to a larger extent than the latter, because price uncertainty is much smaller (Table 1).

Thus, our results indicate that price uncertainty can be more important for the switching decisions than the average costs of recycling. The relatively large PET recycling fraction is consistent with the observation that a PET recycling plant in Israel offers the municipalities a five to ten year contract with fixed prices, whereas the paper recycling plants offer fixed price contracts for only a one-year period. The long-range contract diminishes uncertainty and allows the municipalities to enjoy the savings derived from adopting the recycling technologies, which explains their enhanced recycling activities.

4. Concluding remarks

There may be several reasons why recycling technologies are not adopted to the extent that is fully compatible with their positive externalities. In this paper we investigate one important obstacle to the development of the recycling market, namely the effect of uncertainty on the waste management decisions of a risk neutral municipality. We present evidence on the very large fluctuations in the prices of recycled raw materials and construct a simple model to describe the considerations of municipalities when they need to decide on their waste disposal technology under these conditions. The results demonstrate the negative effects of uncertainty on the level of waste recycling. Our empirical study of the Israeli recycling market lends support to this conclusion and shows that uncertainty can be more important than the cost of recycling in affecting the municipalities' decision to switch from landfill to recycling. This is so because the risk premium associated with the sunk switching costs under price uncertainty amounts to a large fraction of the total disposal cost.

This situation calls for government intervention. The classic Pigouvian approaches to enhance recycling may fail to achieve this goal, since they do not eliminate the price uncertainty. In this work we suggest a new approach to the problem via a mechanism designed to stabilize the recycling market and ensure long-term, fixed-price contracts between municipalities and recycling plants. The mechanism takes full advantage of the competition among the recycling plants hence it does not require public funding (except for the administration cost). While other intervention policies can also enhance recycling, this approach is advantageous because it eliminates the need to switch back and forth among the disposal methods and saves on redundant investments to the economy.

Bibliography

Ackerman F. *Why do we recycle? Markets, Values and Public Policy,* Island press, (1997).

Bernanke, B.S. Irreversibility, uncertainty, and cyclical investment, *Quarterly Journal of Economics*, 98 (1983) 85-106.

Dixit A.K. and Pindyck R.S. *Investment under uncertainty*. Princeton university press. Princeton, N.J. (1994).

Eichner T. and Rudiger P. Product design and efficient management of recycling and waste treatment, *Journal of Environmental Economics and Management,* 41 (2001) 109-134.

Fullerton D. and Kinnaman T. Household demand for garbage and recycling collection with the start of a price per bag*, American Economic Review,* 86 (1996) 971-984.

Jenkins R. *The Economics of Solid Waste Reduction,* Edward Elgar (1993).

Lavee A. *Economic valuation of recycling in municipalities in Israel*, Report submitted to the Israeli Ministry of the Environment (2000), (in Hebrew).

Louberge H., Villeneuve S. and Chesney M. Long–term risk management of nuclear waste: a real options approach, *Journal of Economic Dynamics & Control,* 27 (2002) 157-180.

Palmer K., Sigman H. and Walls M. The costs of reducing solid waste, *Journal of Environmental Economics and Management.* 33 (1997) 128-50.

Pennings E. Taxes and stimuli of investment under uncertainty, *European Economic Review,* 44 (2000) 383-391.

Petrakis E. and Xepapadeas A. Location decisions of a polluting firm and the time consistency of environmental policy, *Resource & Energy Economics*, 25 (2003) 197-214.

Schatzki T. Option, uncertainty and sunk costs: an empirical analysis of land use change, *Journal of Environmental Economics and Management.* 46 (2003) 86-105.

Sigman H. A comparison of public policies for lead recycling, *Rand Journal of Economics,* 26(3) (1995) 452-78.

Tsur Y. and Zemel A. Pollution control in an uncertain environment, *Journal of Economic Dynamics & Control,* 22 (1998) 967-975.