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A waste-to-energy firm that recycles organic waste with energy recovery performs two environmentally beneficial functions: it diverts waste from landfills and it produces renewable energy. At the same time, the waste-to-energy firm serves and collects revenue from two types of customers: waste generators who pay for waste disposal service and electricity consumers who buy energy. Given the process characteristics of the waste-to-energy operation, the market characteristics for waste disposal and energy, and the mechanisms regulators use to encourage production of renewable energy, we determine the profit-maximizing operating strategy of the firm. We also show how regulatory mechanisms affect the operating decisions of the waste-to-energy firm. Our analyses suggest that if the social planner's objective is to maximize landfill diversion, offering a subsidy as a per kilowatt-hour for electricity is more cost effective, whereas if the objective is to maximize renewable energy generation, giving a subsidy as a lump sum to offset capital costs is more effective. This has different regulatory implications for urban and rural settings where the environmental objectives may differ.

Key words: organic waste to energy; sustainability; environment; operating strategy; regulation
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1. Introduction

Two compelling environmental challenges of the industrial world today are pollution from waste disposal and emissions from energy consumption. An elegant, viable business solution to these environmental concerns is the conversion of waste into energy, as evidenced by the increasing number of waste-to-energy (WTE) operations (*Waste Business Journal* 2009). In particular, a WTE firm that recycles organic waste with energy recovery performs two environmentally beneficial functions. First, it diverts organic waste from landfills by converting it into two useful products, inert digestate and biogas, thereby reducing landfills and avoiding the release of methane, a greenhouse gas, that might otherwise be emitted. Second, it captures the methane-rich biogas produced during the digestion process and uses it to produce renewable energy, which can substitute for fossil fuel-based energy (Ata et al. 2010). These two environmentally beneficial functions performed by the WTE firm map into separate revenue streams, i.e., a per-ton tip fee for accepting waste input from the waste generator (WG), and revenue from the sale of electrical energy output. The two sides of the business are symbiotic and coupled together in the digestion

process that neutralizes the waste, which is then used to create compost, and creates biogas, which is then used to generate electricity. At a strategic level, the firm decides how much geographic coverage to offer to the WG. At a tactical level, the firm makes operational decisions to maximize profit. We study the WTE operation from the perspective of the WTE firm and the social planner.

To encourage the creation and support the operation of these businesses, regulators have created Renewable Energy Credits (RECs), i.e., certificates that are issued to providers of renewable energy. These credits can be sold in voluntary or compliance markets to energy consumers who either voluntarily wish to buy renewable energy or are mandated to do so (U.S. Environmental Protection Agency 2008). The value of these credits can range from less than one cent to over five cents per kilowatt-hour (kWh) (U.S. Department of Energy, Energy Efficiency and Renewal Energy 2010). A WTE firm can collect RECs when it sells its electricity to an energy customer, effectively garnering a per kWh premium for its electricity. Alternatively, a WTE firm can partner with a retail energy marketer who provides the firm with a capital subsidy in exchange for the expected future flow of RECs

(see Native Energy 2011, Element Markets 2011). The capital for renewable energy projects could also be funded by the government through grants. For example, renewable energy projects have been funded by the American Recovery and Reinvestment Act of 2009 (U.S. Congress 2009).

Typically, each municipality, i.e., the WG, contracts with waste management firms to dispose of its municipal solid waste, usually in landfills. The municipality can divert material from landfills by offering recycling services. Residents then divert the portion of their trash that is recyclable (e.g., plastic, glass, paper, or food scraps) into other containers and separate hauling services collect the recyclables. Because it is difficult to separate comingled organic (e.g., food scraps) and inorganic (e.g., glass, metal) recyclables, these two types of material are source separated and collected by different hauling services. Therefore, to implement organic recycling (with energy recovery) additional hauling costs must be incurred to collect the organic waste (see City and County of San Francisco, Office of the Mayor 2009). The WTE firm can contract with the WG to either take *all* the organic waste (offering full coverage), or it can contract for a *portion* of the geographic area, and hence a portion of the organic waste (offering partial coverage). The contract between the WTE firm and WG (i.e., a coverage level and a per-ton tip fee) is determined by entering into an agreement that splits the gains from their transaction. By retaining the services of the WTE firm, the WG avoids the landfill disposal cost, but incurs administrative expenses for managing another waste management service relationship and the additional hauling costs for collecting organic waste from its residents. The WTE firm gains access to the WG's organic waste and can use it to generate electricity, which it sells.

In addition to the value of the recovered material, whether recycling organic waste is economically viable depends largely on the capital cost requirements of the WTE operations, the cost of collecting the organic waste (i.e., the per-ton hauling cost), and the cost of the alternative form of disposal (i.e., the per-ton landfill tip fee). The hauling cost depends on the spatial dispersion of the waste sources. In a densely populated, spatially compact urban setting, the fixed cost of operating a collection truck can be amortized over a large load, moreover, the required travel distance to collect this load is relatively short, keeping routing costs low. Hence, in the urban setting, the WG can benefit from economies of scale to reduce the per-ton hauling cost of organic waste. In a rural setting, the per-ton hauling cost could increase in geographic coverage because the distance traveled to remote waste sources could increase the routing cost enough to overwhelm the economies of scale

advantage of increasing coverage. The cost of landfill is highly dependent on the location. Typically, the landfill tip fee in an urban setting is high because existing landfill capacity is minimal and land is scarce, making it difficult to open new landfills close to the urban center.

We study the WTE operation in urban and rural settings. Our emphasis is mainly on the urban setting as these are currently the target sites for WTE firms, however, we also extend our analysis to provide intuition on how the optimal operational decisions and associated regulatory strategy would change in the rural setting. In a spatially compact urban setting, we find that the economies of scale in hauling and the pooling of waste generation sources that lowers the volatility of waste arrivals, make it optimal for the WTE firm to offer full coverage. However, in a rural setting, where the per-ton hauling cost may increase as coverage increases beyond a certain point, partial coverage may be optimal.

Taking a broader perspective than the firm that makes operational decisions to maximize profit, the social planner also considers the environmental value created by the firm. For example, the social planner values the recycling of organic waste into a useful material, which also avoids landfills and the associated negative environmental impact. To recycle organic waste, the waste material must be diverted from the landfill to the WTE plant. Once at the plant, it needs to be processed into compost, i.e., the WTE firm should not then still end up landfilling the waste because of capacity constraints. Therefore, there are two different landfill considerations: (1) *landfill diversion* that redirects waste from the landfill to the WTE plant, and (2) *fraction landfill due to buffer overflow* at the WTE plant. The social planner also values maximization of waste utilization, i.e., the amount of electrical energy produced as a percentage of the potential energy available per ton of organic waste. To increase waste utilization, the firm must increase the *retention* or processing time. However, increasing retention time means less waste can be processed, thereby lowering landfill diversion. Therefore, there is a trade-off between landfill diversion and waste utilization.

We study two mechanisms that can be used by the social planner to influence the operational decisions of the WTE firm to increase landfill diversion and waste utilization: price premium for electricity (e.g., RECs) and lump sum capital subsidies (e.g., grants). Our analyses suggest that the price premium mechanism is more cost effective for inducing landfill diversion and that the lump sum capital subsidy is more effective for inducing waste utilization. Thus, in the urban setting, where we find that it is profit maximizing and socially optimal to offer full coverage, the regulator only needs to induce socially optimal waste

utilization. In a numerical study using parameters representative of urban settings we have observed in practice, we show that the lump sum mechanism is more effective. However, in the rural setting, the regulator may want to influence behavior along two dimensions, and must trade off the relative advantages of the price premium mechanism for increasing landfill diversion, and the lump sum mechanism for increasing waste utilization.

Our results show that the effectiveness of a regulatory mechanism is highly dependent on the market characteristics (urban versus rural) and the underlying process characteristics of the firm. Depending on whether the regulator prioritizes landfill diversion or renewable energy generation, the lump sum or price premium mechanism may be more effective. Because environmental priorities may differ regionally, this would suggest that these mechanisms would be more effectively governed at a local (versus national) level. The implications of our results underscore the complexity of environmental policy decisions and the importance of understanding the operational implications of policy.

1.1. Literature Review

This paper builds on the literature in sustainable operations that examines the operating strategies of profit-maximizing firms engaged in activities that also benefit the environment. There is a growing body of work in operations management that explicitly focuses on management of waste streams and the impact of regulation on their disposition. Subramanian et al. (2008) and Plambeck and Wang (2009) study the impact of extended producer responsibility regulation in two product development settings, respectively: new product introduction in the electronics industry and product design for durable goods. Atasu et al. (2009), Esenduran and Kemahlioglu-Ziya (2010), and Esenduran et al. (2010) study the operational impact of product take-back legislation. Lee (2012) examines the operating strategy of a firm that converts its waste stream into a saleable by-product, leveraging a regulated disposal cost. Similar in spirit to our analysis of the environmental implications of operational decisions, Benjaafar et al. (2009) and Cachon (2010) investigate how carbon emissions can be reduced in supply chains by operational adjustments such as delivery frequency and facility locations. We build on the literature in sustainable operations by using operational techniques to study a setting where a firm's business strategy enables it to reduce landfill waste and produce renewable energy.

Our paper is also related to the field within environmental economics that studies economic incentives. Fullerton (2001) uses a single model to determine the effectiveness of environmental policy instruments targeted at polluters to induce pollution reduction, e.g., taxes, subsidies, regulations, permits, and legal liabilities. These instruments can be categorized as either *command and control* types that specify either technology requirements or performance standards, or *incentives* such as taxes, subsidies, or permits. The incentive instruments can be further categorized as revenue generating or nonrevenue generating. In contrast to Fullerton (2001) and papers cited therein that focus on policies that deter polluting actions by firms, the WTE firm provides environmental solutions that the regulator wants to encourage. Fischer and Newell (2008) compare a number of different environmental policies including pollution deterrence policies and renewable energy subsidies that encourage renewable energy generation. They find that the optimal policy is a combination of different instruments, however, the most effective instruments directly target emissions. Our paper contributes to this literature by revealing how a policy instrument can affect the operating decisions of a firm. In particular, we examine how different methods of distributing environmental subsidies can influence the strategic and tactical operating decisions of the firm.

The rest of this paper is organized as follows. We describe the model and present preliminary results in §2. We derive results for the urban setting in §3. In §4 we present results for the rural setting. We conclude in §5. All proofs are in the online appendix (available at http://msom.journal.informs.org/).

2. Model and Preliminary Results

The WTE firm receives waste aggregated over many (small) input streams. That is, the organic waste is generated by many small entities, e.g., residents of San Francisco. In particular, let W_{ks} be the amount of organic waste generated by resident k in period s; K be the total number of residents; and $\beta \in (0, 1]$ be the geographic coverage level, i.e., the percentage of residents served by the WTE firm. For simplicity, we assume that $\{W_{ks}: s \geq 1, k = 1, \dots, K\}$ are independent and identically distributed according to the normal distribution with mean μ and variance σ^2. Thus, the cumulative amount of waste sent to the WTE firm up to time t is given by

$$A(\beta, t) = \sum_{s=1}^{t} \sum_{k=1}^{\beta K} W_{ks},$$

and is normally distributed with mean $t\beta K\mu$ and variance $t\beta K\sigma^2$. Let $\Lambda = K\mu$ so that $\beta\Lambda$ denotes the average aggregate arrival rate of waste per period.

Historically, the default method of waste disposal has been to landfill it. The WG pays a tip fee of c_L dollars per ton to landfill its waste. An alternative to landfill is incineration, however, the tip fee

for incineration is typically higher than for landfill. To compete with landfill the WTE firm must provide a coverage level ($\beta \in (0, 1]$) and tip fee that is more attractive to the WG than landfill. If the WG uses the services of the WTE firm, it incurs a fixed administrative cost to manage another waste management relationship and additional per-ton hauling cost for collecting organic waste, $c_H(\beta)$. In the vehicle routing literature, the basic cost trade-off for efficient hauling is truck utilization (volume hauled given the fixed cost of the truck) and routing costs (determined by the time and distance traveled per load) (Golden and Assad 1988). For compact geographic areas (as in an urban setting), efficiency can be increased by leveraging economies of scale and increasing the volume hauled per truck. Moreover, as coverage increases, the diverted organic waste reduces the amount of municipal solid waste (trash) collected, thereby potentially reducing the hauling cost of municipal solid waste. Combining these two effects, within certain spatial constraints, the per-ton hauling cost of organic waste decreases as coverage increases. Not only is the fixed cost of the truck amortized over more tons of waste, but there are also more degrees of freedom to optimize the collection routes (Eisenstein and Iyer 1997). Thus, for the *urban* setting, we assume that $c_H(\beta)$ decreases in β.

Unlike the urban setting, the rural setting is spatially dispersed. Waste sources are spread out so that as coverage increases routing cost increases and may overwhelm the economies of scale advantage from increasing volume. To capture this nonmonotonic effect of coverage on the per-ton hauling cost, we incorporate both the economies of scale and routing cost effects into the per-ton hauling cost. Namely, we assume that

$$c_H(\beta) = c_R(\beta) + c_S(\beta). \tag{1}$$

The first term in (1) captures the routing cost, which increases the per-ton hauling cost as coverage increases. The second term captures the economies of scale effect and the avoided municipal solid waste hauling cost, which decreases the per-ton hauling cost as coverage increases. Thus, in the *rural* setting, we assume the per-ton hauling cost first decreases in coverage and then may increase if the routing cost starts to dominate as more remote waste sources are included in the coverage.

We base the following operational characterization of our WTE plant on existing WTE plants in Europe (BEKON 2009). The WTE firm uses an anaerobic digestion process to process organic waste into biogas and an inert digestate solid. A batch of waste is processed in a digester, an airtight tank, where the digestion process occurs in the absence of oxygen (i.e.,

anaerobic digestion). Bacteria that naturally exist in the organic waste perform a multistep degradation process: hydrolysis, fermentation, and methanogenesis. During the methanogenesis step of the process, biogas typically consisting of more than 50% methane is produced. This biogas is captured and used to run a cogeneration unit (an engine) that produces electrical energy. The solid waste is converted into an inert digestate solid that is aerated to produce compost for use in agricultural or residential yard applications (Ata et al. 2010).

We assume that there are n digesters each holding τ tons of waste in the WTE plant. The digester must be big enough to allow easy loading and unloading of waste by a front-end loader, and small enough that it does not require internal support beams. Typically, this results in a digester that holds 100–150 tons of waste. The biology of the waste decomposition/biogas generation process is such that the amount of biogas generated per ton of waste increases at a decreasing rate as a function of the retention time (BEKON 2009). We represent this biological process as a concave increasing function $g(m)$ kWh per ton. The minimum retention (processing) time required to neutralize and convert the waste into inert digestate is $\underline{m}$ days. If the retention time is fewer than $\underline{m}$ days, the solid material removed from the digester must be landfilled, incurring additional cost. After $\bar{m} > \underline{m}$ days, the amount of additional biogas produced is negligible. Formally, we assume that $g(\cdot)$ is continuously differentiable with $g'(m) = 0$ for $m \geq \bar{m}$. The retention time, m, determines the level of waste utilization, i.e., the amount of energy produced from a ton of organic waste as a percentage of the potential energy inherent in that ton of waste (if the retention time were set to $\bar{m}$).

When waste arrives at the plant, it is unloaded onto the tipping floor (buffer) of size b until it can be loaded into an available digester. The size of the buffer is determined by permit and is typically set to hold 2–3 days worth of incoming waste. If waste arrives and the buffer is full, the excess waste must be landfilled at a cost of c_L dollars per ton paid by the WTE firm. In addition, we assume that a WTE plant operates for a finite number of years and the capital cost can be expressed as a (negative) cash flow per digester per time period denoted by c_K. The plant generates revenues from tip fees collected and from the sale of electricity. The WTE firm is a price taker in the electricity market, receiving p_e dollars per kWh. The tip fee is determined through bilateral negotiation between the WTE firm and the WG, which we model as a Nash bargaining solution. The WTE firm and the WG split the gains from their transaction (i.e., the avoided landfill cost, plus the revenue from electricity, minus the hauling and capital costs) and thus the

tip fee is a function of β, m, and n, which we denote by $f(\beta, m, n)$ dollars per ton. Then, the expected long-run average profit rate for the WTE firm, denoted by Π, is given by

$$\Pi(\beta, m, n) = f(\beta, m, n)\beta\Lambda + p_e g(m)[1 - u]\beta\Lambda$$
$$- c_L u\beta\Lambda - c_K n, \qquad (2)$$

where u is the long-run average fraction landfill due to buffer overflow at the WTE plant.

The following lemma provides the formulation of the tip fee.

LEMMA 1. *The WTE firm and WG split the gains from their transaction according to their relative bargaining power, $(1 - \gamma)$ and γ, respectively. Thus, the tip fee is*

$$f(\beta, m, n)$$
$$= c_L - c_H(\beta)$$
$$- \gamma\left[(p_e g(m) + c_L)[1 - u] - c_H(\beta) - \frac{c_K n}{\beta\Lambda}\right]. \quad (3)$$

It is straightforward to show that if $c_H(\beta)$ decreases in β (as in the urban setting), then $f(\beta, m, n)$ increases in β, which means that the per-ton tip fee increases in coverage. This is in contrast to the volume discount pricing we often see service providers offer. However, in the rural setting, $c_H(\beta)$ could be increasing or decreasing in β. Therefore, this monotone relationship may not hold.

The firm chooses the amount of coverage $\beta \in (0, 1]$, the retention time $m \in [\underline{m}, \bar{m}]$, and the number of digesters $n > 0$, so as to maximize the profit given in Equation (2). To calculate the profit, we need to characterize the long-run average fraction landfill by the WTE firm. We use results from the large deviations literature to approximate buffer overflow probabilities in stochastic systems. In particular, we draw on Courcoubetis and Weber (1996), who established that the steady-state buffer overflow probability decays exponentially in the number of sources for queues operating in discrete time fed by a large number of sources. Courcoubetis and Weber (1996) assume a constant service rate per server and a constant arrival rate per input source. In their discrete time model, service times are deterministic whereas the sequence of work arriving in each period is an ergodic discrete-time stochastic process. Courcoubetis and Weber (1996) also assume that the arrival process is a superposition of many input sources. The authors consider a limiting regime in which the number of servers, the number of input sources, and the buffer size grow proportionally. The WTE plant nicely fits the Courcoubetis and Weber (1996) framework because it periodically receives waste generated by many sources.

Proposition 1 provides an approximation for the landfill fraction u building on the results of Courcoubetis and Weber (1996).

Having described the firm's problem, we now turn to the social planner's problem. The social planner wants to encourage higher renewable energy generation and more diversion from landfill. We assume that the social planner puts a value of $\nu_L \geq c_L$ to diverting a ton of waste from landfill and $\nu_e \geq p_e$ to generating one kWh of renewable electrical energy. To understand why $\nu_L \geq c_L$, it is important to recognize that the WTE provides two environmental benefits beyond the disposal of waste (which is essentially the value that landfill adds). First, the WTE firm decomposes organic waste in a controlled environment where almost all the biogas is captured and used productively to generate usable energy. Even if the organic waste were buried in a landfill with a gas collection system, at most 50% of the gases emitted during decomposition in the landfill are captured, with the rest escaping into and polluting the atmosphere. Second, the compost output from the digestion process is nutrient-rich, and if used in agricultural applications, helps to increase crop yields. Moreover, the compost is rich in carbon, which means that it is fixing carbon in the ground where it is productive, rather than in the atmosphere where it is harmful (Brown 2010). The reason $\nu_e \geq p_e$ is that it can be considered a substitute for petroleum fuel, which is more polluting when burned. In this paper, we follow the approach by Atasu et al. (2009) and assume that it is possible to express the environmental benefits in monetary terms. However, to exactly quantify the benefits is beyond the scope of this paper.

The increase in the long-run average social welfare as a result of the WTE firm's operations is the net benefit added to the WTE and WG, plus the environmental value added by WTE conversion minus the total cost (i.e., the cost of operating the WTE plant, the fixed cost to the WG for maintaining the WTE contract, and additional hauling costs for collecting organic waste). Focusing only on the components that depend on the firm's operating decisions, we have the following expression for the increase in the long-run average social welfare as a result of operating the WTE plant:

$$W(\beta, m, n) = [\nu_e g(m) + \nu_L][1 - u]\beta\Lambda$$
$$- c_H(\beta)\beta\Lambda - c_K n. \qquad (4)$$

The first term is the total social value generated in each period by renewable energy production and avoiding landfill. The second term is the per-period cost of hauling organic waste to the WTE plant. The last term is the per-period capital cost of the WTE plant. The social planner wants to induce the firm to

choose the fraction coverage $\beta \in (0, 1]$, the retention time $m \in [\underline{m}, \bar{m}]$, and the number of digesters n so as to maximize $W(\beta, m, n)$.

We now derive the long-run average fraction landfill due to buffer overflow by the WTE firm. To facilitate the analysis to follow, for $\beta \in (0, 1]$, m, and n, let

$$\xi = \frac{n\tau}{m\beta\Lambda} - 1 \qquad (5)$$

denote the percentage excess capacity carried by the WTE firm because of the stochastic nature of waste arrival. In the following proposition, we characterize the long-run average fraction landfill due to buffer overflow by the WTE firm.

PROPOSITION 1. *Assume that the WTE plant sees an average waste arrival rate $\beta\Lambda$, and operates with n digesters at a retention time of m days and a buffer that holds q days of waste arrivals. Consider the asymptotic regime as Λ gets large while m, β and ξ are fixed so that $n = (1+\xi)m\beta\Lambda/\tau$ gets large as well. Then*

$$\lim_{\Lambda \to \infty} \frac{1}{\Lambda} \ln u = -\frac{2q\mu\beta\xi}{\sigma^2}, \qquad (6)$$

where u is the long-run average fraction landfill due to buffer overflow by the WTE firm.

We will use the following approximation for Λ large based on (6):

$$u(\beta, \xi) \simeq \exp\left\{\frac{-2q\mu\beta\Lambda\xi}{\sigma^2}\right\}. \qquad (7)$$

In the following sections, we use the characterizations of the waste generation process and the WTE operations presented in this section to study the socially optimal and profit-maximizing operating decisions in urban and rural settings.

3. The Urban Setting

In this section, we derive the optimal operating strategy in the urban setting under two objective functions: maximizing social welfare, which includes the environmental benefits generated by WTE operations, and maximizing profit of the WTE firm. We find that the characteristics of the urban setting naturally align the incentives of the social planner and the WTE firm to offer full coverage. We show the implication of these results in a numerical study and derive a necessary and sufficient condition for when using a lump sum mechanism to induce socially optimal behavior is more effective than using a price premium mechanism. Using a set of operating parameters that are consistent with what we have observed in practice for an urban setting, we show numerically that this condition is easily satisfied.

3.1. Optimal Operating Strategy

We first derive the operating parameters that maximize social welfare. These values are what the social planner would like the firm to choose as its operating strategy. The following proposition shows that social welfare is maximized when the WTE firm offers full coverage.

PROPOSITION 2. *In the urban setting, if providing full coverage, i.e., $\beta = 1$, improves social welfare (relative to not having a WTE plant), then full coverage is the socially optimal strategy.*

The proof of Proposition 2 proceeds by showing that (optimal) social welfare increases in coverage. Therefore, the condition that full coverage improves social welfare can be replaced by the equivalent condition that there exists a coverage level that improves social welfare. (A similar observation can be made for Propositions 4, 7, and 8 below.)

Let $\tilde{u}(\xi)$ denote $u(1, \xi)$ and rewrite the social welfare problem specified in §2 for $\beta = 1$ as a function of m and ξ as

$$\tilde{W}(m, \xi)$$
$$= \left\{[\nu_e g(m) + \nu_L][1 - \tilde{u}(\xi)] - c_H(1) - \frac{c_K m(1+\xi)}{\tau}\right\}\Lambda.$$

We assume that the WTE firm restricts attention to $\xi > 0$. Then, the social planner's problem is to choose $m \in [\underline{m}, \bar{m}]$ and $\xi > 0$ that maximizes social welfare, given ν_e and ν_L. Recall that $g(\cdot)$ is concave. Thus, $g'(\cdot)$ is decreasing and its inverse, denoted by $h(\cdot)$, is well defined and decreasing, too. The following proposition provides a characterization of the socially optimal retention time $m_s(\xi)$ for any fixed percentage excess capacity ξ.

PROPOSITION 3. *For a given percentage excess capacity $\xi > 0$, the socially optimal retention time $m_s(\xi)$ is given by*

$$m_s(\xi) = \max\left\{h\left(\frac{c_K(1+\xi)}{\nu_e \tau(1 - \tilde{u}(\xi))}\right), \underline{m}\right\}. \qquad (8)$$

Thus, social welfare can be expressed as a function of ξ only:

$$\tilde{W}(\xi) = \left\{[\nu_e g(m_s(\xi)) + \nu_L][1 - \tilde{u}(\xi)] - c_H(1) \right.$$
$$\left. - \frac{c_K m_s(\xi)(1+\xi)}{\tau}\right\}\Lambda. \qquad (9)$$

Note that the social welfare function, $\tilde{W}(\xi)$, is not concave in general; nor does it have other suitable structures that would be amenable to analytical characterization of the optimal ξ. Nonetheless, because the welfare maximization is now a one-dimensional problem, it is easy to find its global maximum

and the maximizer numerically. We denote the socially optimal percentage excess capacity by $\xi_s = \arg\max_{\xi>0} \tilde{W}(\xi)$, which by rearranging (9) can be expressed as

$$\xi_s = \arg\max_{\xi>0}\left\{ \nu_e g(m_s(\xi)) - [\nu_e g(m_s(\xi)) + \nu_L]\tilde{u}(\xi) - \frac{c_K m_s(\xi)(1+\xi)}{\tau} \right\}. \quad (10)$$

Thus, $m_s(\xi_s)$ is the socially optimal retention time m_s. Note that although we derive the optimal $\beta(m, \xi)$, $m(\xi)$, and ξ in sequence, the optimization sequence does not matter, thus, social welfare is globally maximized at $\beta = 1$, m_s, and ξ_s (a proof of this is available from the authors).

We now derive the profit-maximizing operating strategy of the WTE firm that cannot internalize the environmental benefits generated by its activities. Even still, it is profit maximizing for the firm to provide full coverage, as shown in the following proposition.

Proposition 4. *In the urban setting, if the WTE firm achieves positive profit when $\beta = 1$, then it is profit maximizing for the firm to offer full coverage.*

In essence, the WTE firm's profit monotonically increases in coverage, therefore, if the firm is profitable offering full coverage, then it is optimal to do so. Our analysis reveals that there are statistical economies of scale associated with aggregating many waste generation sources and that the WG can take advantage of economies of scale in hauling by increasing the coverage. It is also easier to optimize collection routing over a larger coverage area (Eisenstein and Iyer 1997). This is captured in our assumption that $c_H(\beta)$ decreases in β in the urban setting. Therefore, offering more coverage creates more value for the WG-WTE firm system, which the two split according to their respective bargaining power (resulting in $f(\beta, m, n)$ increasing in β). Thus, the characteristics of the waste industry naturally align the firm's incentive to offer full coverage with the social planner's desire to maximize landfill diversion. In fact, this result reveals the mechanism that drives the socially optimal solution. Because the firm finds it optimal to provide full coverage and the social planner values landfill diversion at least as much as the landfill cost, it follows that the socially optimal coverage is full coverage. Recognizing this alignment could be a powerful way to highlight the potential environmental and business opportunities of organic WTE operations to regulators and industry members.

Using the fact that $\beta = 1$ is optimal and substituting $f(\cdot)$, the firm's profit as a function of the retention time and percentage excess capacity can be expressed as follows:

$$\tilde{\Pi}(m, \xi) = (1-\gamma)\Lambda\bigg[[p_e g(m) + c_L][1 - \tilde{u}(\xi)] - c_H(1) - \frac{c_K(1+\xi)m}{\tau} \bigg].$$

Then, the firm's problem is to choose m and ξ that maximizes $\tilde{\Pi}(m, \xi)$. The following proposition provides a characterization of the firm's retention time, $m_f(\xi)$, as a function of the percentage excess capacity.

Proposition 5. *For a given percentage excess capacity $\xi > 0$, the profit-maximizing retention time of the WTE firm is given by*

$$m_f(\xi) = \max\left\{ h\left(\frac{c_K(1+\xi)}{p_e\tau(1-\tilde{u}(\xi))} \right), \underline{m} \right\}. \quad (11)$$

Thus, the WTE firm's profit can be expressed as a function of ξ only:

$$\tilde{\Pi}(\xi) = (1-\gamma)\Lambda\bigg[[p_e g(m_f(\xi)) + c_L][1 - \tilde{u}(\xi)] - c_H(1) - \frac{c_K(1+\xi)m_f(\xi)}{\tau} \bigg]. \quad (12)$$

As in the case of social welfare maximization, $\tilde{\Pi}(\xi)$ does not have a suitable structure for characterizing the optimal ξ analytically. However, the optimal ξ is easy to find numerically because maximizing $\tilde{\Pi}(\xi)$ is a one-dimensional problem. We denote the WTE firm's optimal excess capacity by $\xi_f = \arg\max_{\xi>0} \tilde{\Pi}(\xi)$, which by rearranging (12) can be expressed as

$$\xi_f = \arg\max_{\xi>0}\left\{ p_e g(m_f(\xi)) - [p_e g(m_f(\xi)) + c_L]\tilde{u}(\xi) - \frac{c_K m_f(\xi)(1+\xi)}{\tau} \right\}. \quad (13)$$

Thus, $m_f(\xi_f)$ gives the firm's optimal retention time m_f. Note that ξ_f and ξ_s are equal if $\nu_e = p_e$ and $\nu_L = c_L$. Moreover, a comparison of Equations (8) and (11) shows that $m_f(\xi) < m_s(\xi)$.

3.2. Numerical Study

This numerical study illustrates the implications of our results for the urban setting using parameter values consistent with a large metropolitan area and WTE process specifications consistent with what we have observed in practice (Ata et al. 2010). Suppose the WTE firm operates in an area with 100,000 households and each household generates approximately two pounds of organic waste per day, with coefficient of variation of 0.25. Therefore, the average total

waste generated in this area is $\Lambda = 100$ tons per day. The WTE plant contains multiple digesters each with $\tau = 125$ tons of storage capacity. Additionally, there is a tipping floor (buffer) that holds two days worth of incoming waste. The electrical energy output per ton of waste, in kWh, is characterized by a strictly concave function of retention time, $g(m) = -0.081m^2 + 8.232m + 0.675$. This function is generated by fitting a curve to anaerobic digestion data, and is only defined for $m \in [\underline{m}, \bar{m}]$, where $\underline{m} = 15$ and $\bar{m} = 51$ (Lutz 2010). The landfill per-ton tip fee is $c_L = \$80$; the capital cost expressed as (negative) cash flow per day is $c_K = \$80$ (corresponding to a cost of $365{,}000$ per digester, which can be derived by assuming an annual interest rate of 5% paid over 20 years); and the price of electricity per kWh is $p_e = \$0.10$.

Consistent with the assumptions in our model, we lower bound the social value of renewable energy and landfill diversion by $\nu_e \geq p_e$ and $\nu_L \geq c_K$. We run the numerical example using a ν_e value that reflects the RECs seen in current voluntary and compliance markets, and a ν_L value that is higher than, but in the same order of magnitude as, the landfill tip fee. We use the following stylized hauling cost function to represent the decreasing per-ton hauling cost in the urban setting: $c_H(\beta) = 200/\beta\Lambda + 20$. For a range of $\beta \in [0.2, 1]$, the per-ton hauling cost ranges from a high of $30 per ton to a low of $22 per ton, which is the approximate range we have seen in practice. For concreteness, we assume that the WTE firm and the WG have equal bargaining power, i.e., $\gamma = 0.5$.

Table 1 shows the socially optimal coverage, β_s, and retention time, m_s, and the associated fraction landfill due to buffer overflow for high and low values of ν_e and ν_L. Note that the results presented in the first row for $\nu_e = p_e$ and $\nu_L = c_L$ are equivalent to the profit-maximizing solution for the WTE firm. A striking observation from this table is that the socially optimal fraction landfill, u_s, is extremely small. This is driven by the statistical economies of scale because of the many input sources, which also drives the socially optimal excess capacity to be very low. In practical terms, this means that any plant will be designed with more excess capacity than is socially optimal because plants are typically designed with some slack

capacity (to accommodate unanticipated events such as equipment failure). Additionally, consistent with Propositions 2 and 4, we see that $\beta = 1$ is socially optimal and profit maximizing. The per-ton hauling cost decreases, more renewable energy is generated, and more waste is diverted from landfill as β increases. All these effects increase social welfare. Finally, note that ν_e increases optimal retention time, but the effect of ν_L is imperceptible. This is because the fraction landfill due to buffer overflow is already so small that increasing ν_L has little effect on the retention time, which is affected indirectly through the capacity decision. A simulation study that validates the results derived from our analytical model is available from the authors.

3.3. Effectiveness of Lump Sum vs. Price Premium

In Proposition 4 and §3.2, we showed that full coverage is profit maximizing and the fraction landfill due to buffer overflow at the WTE plant is negligible for a range of parameters comparable to what we have observed in practice. Thus, the primary concern for the social planner in the urban setting is to ensure that the organic waste resource is optimally used, i.e., to induce the socially optimal retention time. We compare the effectiveness of two mechanisms for increasing retention time (or equivalently, waste utilization): (1) a per kWh price premium for electricity, e.g., REC, and (2) a lump sum subsidy to offset capital costs, e.g., a government grant. As can be seen from Proposition 5, changing the price of electricity or the capital cost will affect the firm's retention time, and hence its waste utilization.

We use subscripts p and l to denote the optimal operating decisions of the WTE firm under the price premium and lump sum mechanisms, respectively. The following proposition provides a necessary and sufficient condition under which the price premium mechanism is more costly than the lump sum mechanism for inducing the firm to operate at the socially optimal retention time. We restrict attention to the interesting case where $m_s > m_f$ and consequently $m_s > \underline{m}$.

PROPOSITION 6. *Inducing the socially optimal retention time, m_s, using the price premium mechanism is more costly than using the lump sum mechanism if and only if*

$$\frac{g(m_s)}{g'(m_s)m_s}\left[1 + \frac{c_K(\xi_p - \xi_l) - p_e\tau g'(m_s)(u(\xi_l) - u(\xi_p))}{c_K(1 + \xi_l) - p_e\tau g'(m_s)(1 - u(\xi_l))}\right] > 1. \tag{14}$$

To illustrate the result in Proposition 6, we continue with the setup of the numerical example from §3.2. As shown, the socially optimal excess capacity is so low that it would be unrealistic for actual plant to

Table 1 Impact of ν_e and ν_L on the Socially Optimal Operating Strategy and Resulting Percentage Waste Landfilled by the WTE Firm

ν_e	ν_L	β_s	m_s	$u_s[\%]$
p_e	c_L	1	15.00	1.66×10^{-6}
p_e	$c_L + 10$	1	15.00	1.49×10^{-6}
$p_e + 0.02$	c_L	1	17.95	1.90×10^{-6}
$p_e + 0.02$	$c_L + 10$	1	17.95	1.71×10^{-6}

Note. The first row is equivalent to the profit-maximizing solution for the WTE firm.

carry such little excess capacity. For example, semi-conductor manufacturers typically run their facility in a utilization range of $[0.75, 0.85]$, even though their operations are very capital intensive and the cost of this excess capacity is very high (Hopp 2007). More-over, based on conversations with industry execu-tives, building in some excess capacity in the WTE plant, e.g., an additional digester, is standard practice to accommodate operational uncertainty (e.g., break-downs). Therefore, to reflect what we see in practice, we assume for the numerical example that the excess capacity carried by the WTE is greater than an arbi-trarily small lower bound, in this case, $\xi \geq \underline{\xi} = 0.01$. This then implies that the excess capacity carried by the firm exceeds the optimal excess capacity, i.e., $\xi > \xi_p, \xi_l$. Note that for $\underline{\xi} > \xi_p, \xi_l$, the condition in (14) reduces to

$$\frac{g(m_s)}{g'(m_s)m_s} > 1,$$

which is always true by the concavity of $g(\cdot)$.

Figure 1 shows the retention time of the WTE firm as a function of how much subsidy it receives under the two distribution mechanisms. Note that the flat part of the graph represents conditions under which the biological constraint that dictates $m \geq \underline{m}$ is bind-ing. One way to interpret Figure 1 is that per dol-lar spent by the regulator, distributing it as a lump sum induces higher retention time than distributing it as a price premium. Another way to interpret Fig-ure 1 is to consider how much subsidy is required to induce a particular retention time. For example, suppose $\nu_e = 0.12$ and $\nu_L = 90$, and the socially opti-mal retention time is 18 days. It would cost \$191.81 per day using the lump sum mechanism (i.e., \$13.35 per day, per digester), and \$244.88 per day using the

price premium mechanism (i.e., \$0.02 per kWh of elec-tricity generated), to induce the WTE firm to operate at this retention time.

The result in Proposition 6 is driven by the physi-cal characteristics of the anaerobic digestion process, namely, the fact that $g(m)$ is a concave increasing function. Recall that it is profit maximizing for the firm to offer full coverage regardless of the incentives provided by the regulator. Therefore, any subsidy, in either lump sum or price premium form, can only induce the firm to add capacity to increase the reten-tion time, thereby increasing waste utilization, i.e., to generate more electricity per ton of waste. Whereas the lump sum mechanism directly reduces the cost of capital, the price premium mechanism works indi-rectly to increase capacity. By increasing the per kWh price of electricity, the firm is incentivized to increase the retention time to extract more biogas per ton of waste input fuel. However, each additional day of retention time generates a *decreasing* incremental amount of biogas, whereas the incremental cost of capacity required for each additional day of reten-tion time remains constant. Therefore, the price pre-mium mechanism becomes less effective as the reten-tion time increases, and is thus less effective overall than the lump sum mechanism for inducing the WTE firm to increase retention time.

In light of the results presented in Figure 1 from the numerical example, the result given in Proposi-tion 6 is particularly opportune because one of the obstacles for start-up WTE firms is securing capital. In an urban setting, a grant or the REC as a lump sum at the beginning can therefore increase the likelihood that the firm will exist, and by extension, that it will be able to offer full coverage.
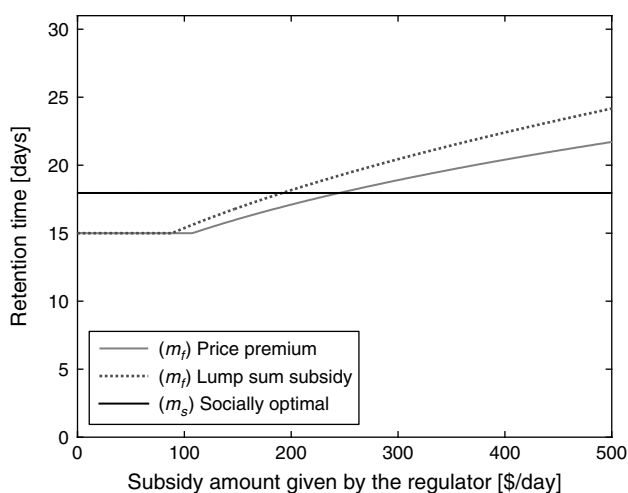
4. The Rural Setting

In this section, we derive insights on how the socially optimal and profit-maximizing solutions in the rural setting differ from the urban setting. The key physi-cal difference in the rural setting is that waste sources are spatially dispersed. Thus, beyond a certain cov-erage level, the per-ton hauling cost could increase as coverage increases. For analytical tractability, we assume the following stylized form for the per-ton hauling cost:

$$c_H(\beta) = \frac{H}{\beta\Lambda} + L\beta^2, \tag{15}$$

where H and L are positive. The per-ton hauling cost first decreases in β to reflect the economies-of-scale effect and the avoided municipal solid waste hauling cost. However, as β increases beyond a certain cov-erage level, the routing cost may dominate and thus the per-ton hauling cost would then increase in β.

Figure 1   **Profit-Maximizing Retention Time of WTE Firm as a Function of the Subsidy Amount Using the Lump Sum and Price Premium Mechanisms**

Unlike the urban setting, we show in §4.1 that, in the rural setting, it may be profit maximizing or socially optimal to offer partial coverage. Moreover, the profit-maximizing coverage may be strictly less than what is socially optimal. Thus, the social planner needs to prioritize which dimension is more important in her geographical area. Note that by using only one mechanism (either price premium or lump sum), the social planner may be unable to achieve the socially optimal solution for both coverage and waste utilization. Our focus in this section is to understand which mechanism is more effective for influencing each decision. Our results in §4.2 (derived using a fluid model) suggest that, consistent with the results from the urban setting, the lump sum mechanism is more cost effective for increasing retention time, however, the price premium mechanism is more effective for increasing coverage. In §4.3, we perform a series of numerical studies using stochastic arrivals that corroborate our fluid model results.

4.1. Optimal Operating Strategy

We now show how the change in the per-ton hauling cost as a result of spatial dispersion in the rural setting affects the socially optimal and profit-maximizing coverage. Using (15) as the hauling cost, let $\underline{\beta}$ be the minimizer of $c_H(\beta)$. The following proposition gives sufficient conditions under which full and partial coverage are socially optimal in the rural setting.

PROPOSITION 7. *If providing full coverage, i.e., $\beta = 1$, improves social welfare (relative to not having a WTE plant) and*

$$\nu_e g(\underline{m}) + \nu_L - \frac{c_K \bar{m}}{\tau}\left(1 + \frac{\sigma^2}{2q\mu\underline{\beta}\Lambda}\right) > 3L, \qquad (16)$$

then full coverage is the socially optimal strategy. On the other hand, if

$$\nu_e g(\bar{m}) + \nu_L - \frac{c_K m}{\tau}\left(1 + \frac{\sigma^2}{2q\mu\Lambda}\right) < 3L, \qquad (17)$$

then partial coverage is socially optimal.

It is intuitive that as the routing cost, L, increases, full coverage becomes less likely (condition (16) is violated) and partial coverage becomes more likely (condition (17) is satisfied). The following proposition shows an analogous result for the profit-maximizing coverage.

PROPOSITION 8. *If the WTE firm achieves positive profit when $\beta = 1$ and*

$$p_e g(\underline{m}) + c_L - \frac{c_K \bar{m}}{\tau}\left(1 + \frac{\sigma^2}{2q\mu\underline{\beta}\Lambda}\right) > 3L, \qquad (18)$$

then it is profit maximizing for the firm to offer full coverage. On the other hand, if

$$p_e g(\bar{m}) + c_L - \frac{c_K m}{\tau}\left(1 + \frac{\sigma^2}{2q\mu\Lambda}\right) < 3L, \qquad (19)$$

then partial coverage is profit maximizing.

In the rural setting, although $c_H(\beta)$ is convex increasing for $\beta > \underline{\beta}$, full coverage could still be socially optimal and/or profit maximizing. The main trade-off for the coverage decision is the per-ton hauling cost (which is inversely correlated to the per-ton tip fee) versus revenue from electricity sales. Depending on how quickly the hauling cost increases in coverage, it may still be optimal to offer full coverage. Therefore, $c_H(\beta)$ decreasing in β (or equivalently, $f(\beta, m, n)$ increasing in β) is only a sufficient condition for full coverage, i.e., it is not a necessary condition.

It is straightforward to derive the socially optimal (or profit-maximizing) retention time and excess capacity for a given coverage level. In the urban setting, the expressions for the socially optimal (or profit-maximizing) retention time and excess capacity are derived for the case where full coverage is socially optimal (or profit maximizing). Similar expressions can be derived more generally for any coverage level. For instance, suppose the socially optimal coverage level β_s is known and let $\tilde{u}(\xi)$ denote $u(\beta_s, \xi)$. Then expressions in (8) and (10) provide the socially optimal retention time and percentage excess capacity, respectively. Similarly, expressions in (11) and (13) give the profit-maximizing retention time and percentage excess capacity, respectively, when $\tilde{u}(\xi)$ denotes $u(\beta_f, \xi)$ for any given β_f.

4.2. Effectiveness of Lump Sum vs. Price Premium

In the following propositions, we compare the effectiveness of the lump sum and price premium mechanisms for increasing coverage and retention time in the rural setting using a fluid model of waste arrivals. To be specific, arrivals and processing are modeled as deterministic flows at constant rates. We first derive the profit-maximizing retention time and coverage level.

PROPOSITION 9. *The profit-maximizing retention time, m_f, and coverage level, β_f, of the WTE firm are given by*

$$m_f = \min\left\{\bar{m}, \max\left\{h\left(\frac{c_K}{p_e \tau}\right), \underline{m}\right\}\right\} \quad \text{and}$$

$$\beta_f = \min\left\{1, \sqrt{\frac{p_e g(m_f) + c_L - (c_K/\tau)m_f}{3L}}\right\}. \qquad (20)$$

In the remainder of this section, we assume the following form for the biogas production function for simplicity: $g(m) = 2\sqrt{m}$ for $m \le \bar{m}$ and $g(m) = 2\sqrt{\bar{m}}$ for $m > \bar{m}$. Using this functional form, Proposition 9 can be expressed as follows.

COROLLARY 1. *Assuming interior solution and setting* $g(m) = 2\sqrt{m}$, *the profit-maximizing retention time,* m_f, *and coverage level,* β_f, *of the WTE firm are given by*

$$m_f = \left(\frac{p_e \tau}{c_K}\right)^2 \quad and \quad \beta_f = \sqrt{\frac{c_L + p_e^2 \tau / c_K}{3L}}. \quad (21)$$

Replacing p_e and c_L with ν_e and ν_L gives the socially optimal retention time and coverage level. It is clear from (21) that $m_f < m_s$ and $\beta_f < \beta_s$. As one would expect, the optimal retention time, m_f, increases with the price of electricity, p_e, and decreases with the cost of capacity, c_K. Similarly, the optimal coverage level increases with the cost of landfilling, c_L, and the price of electricity, p_e, whereas it decreases with the cost of capacity, c_K, and the routing cost. Furthermore, either the lump sum or price premium mechanisms can be used to increase retention time, m_f, by effectively decreasing c_K or increasing p_e, respectively. Similarly, either mechanism can be used to increase the coverage level, β_f. Because the regulator may want to influence behavior along two dimensions, she must trade off the relative advantages of each mechanism. Propositions 10 and 11 compare the effectiveness of each mechanism for increasing the retention time and the coverage, respectively. We restrict attention to the interesting case of the interior solution where $\underline{m} < m_f < m_s$ and $\beta_f < \beta_s < 1$.

PROPOSITION 10. *Per dollar of subsidy, the lump sum mechanism induces the WTE firm to increase retention time more than the price premium mechanism.*

Proposition 10 implies that if the regulator prioritizes renewable energy generation, it is more cost effective to use the lump sum mechanism. This is consistent with the findings in the urban setting (see Proposition 6). The result of Proposition 10 could be useful in a situation where the coverage is already quite high, and further increasing it would require a significant cost increase for hauling organic waste. Imagine a municipality where 80% of the residents lived within a certain radius of the town center, and the remaining 20% lived in the far outskirts. In such a setting, the regulator may be more interested in prioritizing renewable energy generation, and thus would be better off using a lump sum mechanism.

However, in many areas in the United States (both urban and rural), landfill capacity is running out and diverting waste from landfill is a priority for the municipalities' waste management department (NSWMA 2011). Thus, we now compare the lump sum and price premium mechanisms for increasing coverage. Recall that in the urban setting $\beta_s = \beta_f = 1$, so the regulator did not have to worry about this problem. The following proposition shows that, for $\beta_f < \beta_s < 1$, the price premium mechanism is more cost effective for increasing coverage in the rural setting.

PROPOSITION 11. *Per dollar of subsidy, the price premium mechanism induces the WTE firm to increase coverage more than the lump sum mechanism.*

Interestingly, irrespective of the subsidy amount, the lump sum subsidy mechanism may not induce the socially optimal coverage. In particular, it is easy to see from (20) that $\beta_f < \sqrt{(p_e g(\bar{m}) + c_L)/3L}$. Therefore, for high routing costs, the upper bound on β_f may be lower than the socially optimal coverage, β_s.

Note that the results of Proposition 11 apply when partial coverage is profit maximizing in the rural setting because the marginal revenue associated with a unit increase in coverage is less than the marginal cost. Thus, the social planner may want to induce the WTE firm to increase coverage using subsidies. To understand the intuition behind Proposition 11, it is instructive to consider a particular example. Suppose the subsidy dollar amount given to the WTE firm per day exactly equalled the capital cost. In this case, given as a lump sum, capacity would be free and the firm would keep building digesters as long as each digester was producing positive revenue. This implies that the profit-maximizing retention time would be at the maximum (maximizing waste utilization) and coverage would be set so that the marginal increase in hauling cost was equal to the marginal increase in revenue from electricity sales. Essentially, the lump sum mechanism relaxes the firm's physical capacity constraint.

The same subsidy dollar amount given through the price premium would induce different behavior from the firm. Because capacity is not free, the firm would decide to build fewer digesters. Given the capacity constraint, the firm is forced into a trade-off. It needs to decide how much of the capacity to use to increase coverage and to increase retention time. The two dimensions are now in direct competition for digester space. However, because of the concavity of $g(m)$, increasing retention time has diminishing benefits, whereas increasing coverage allows the firm to generate more electricity from fresher waste. Although the per-ton hauling cost increases in coverage, because the firm is paid a premium for electricity, it is willing to incur a higher hauling cost to capture the subsidy value. Essentially, the price premium mechanism induces the firm to increase the output rate of electricity. It does this by adding more capacity, but not as much capacity as under the lump

Figure 2 Effect of the Lump Sum and Price Premium Mechanisms on the Firm's Coverage Level and Retention Time for Low Routing Cost, $L = 20$
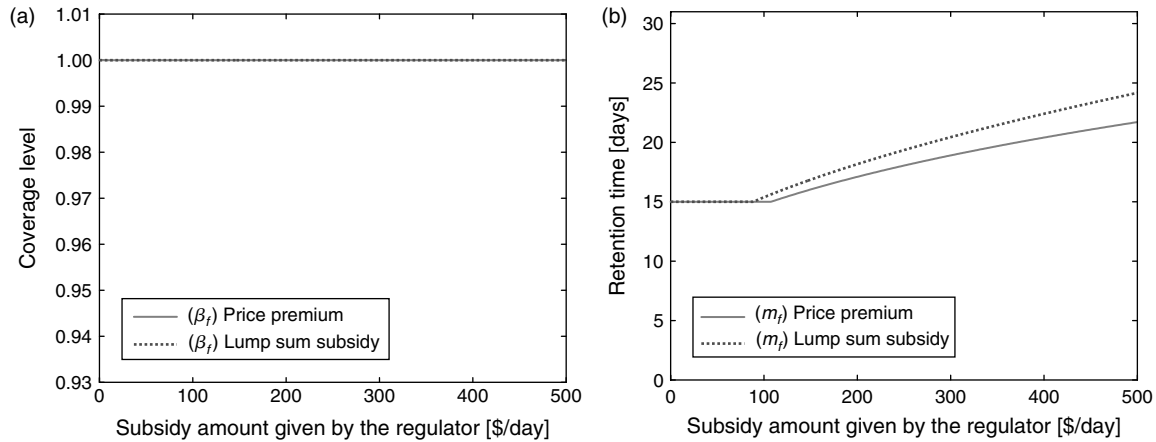
sum mechanism because capacity is expensive. Moreover, the firm uses the additional capacity to increase coverage more (relative to under lump sum) because the price premium allows it to incur higher hauling cost, and it can increase the output rate of electricity by using fresher waste to capture more subsidy value.

4.3. Numerical Study

To gain intuition on whether our results from the fluid model case in §4.2 can apply when waste arrivals are stochastic, we perform a series of numerical studies. We continue with the setup of the numerical study from §3.2, with $g(m) = -0.081m^2 + 8.232m + 0.675$, $\nu_e = \$0.12$, $\nu_L = \$90$, and $c_H(\beta) = 200/\beta\Lambda + L\beta^2$. Note that the per-ton hauling cost is parameterized by L, which represents the routing cost portion of the hauling cost. We show results in Figures 2 and 3 that are representative of a broader set of numerical examples (available from the authors) with different parameter values. In these examples, the results for stochastic arrivals were consistent with our analytical results from §4.2.

In Figure 2, the routing cost is low, $L = 20$. Here, we see that $\beta_f = \beta_s = 1$, even though the hauling cost is convex and increasing for large β (Figure 2(a)). Therefore, the results of this case are exactly the same as in the urban setting. The social planner only needs to increase retention time. Consistent with the results from Proposition 10, the lump sum mechanism is more cost effective (Figure 2(b)).

Figure 3 shows results for a high routing cost, $L = 60$. In this case, $\beta_f < \beta_s < 1$, so partial coverage is both socially optimal and profit maximizing, however, the socially optimal coverage is higher. Consistent with the results from Proposition 11, the price premium mechanism is more cost effective for inducing the firm to increase coverage (Figure 3(a)). Figure 3(b) corroborates the results shown in Figure 2(b) that the lump sum mechanism is more effective for inducing the firm to increase retention time.

These numerical results show that the social planner must prioritize which dimension is more important when deciding which mechanism to use. Regardless of the mechanism used, the firm reacts in a way that is beneficial for the environment, i.e.,

Figure 3 Effect of the Lump Sum and Price Premium Mechanisms on the Firm's Coverage Level and Retention Time for High Routing Cost, $L = 60$
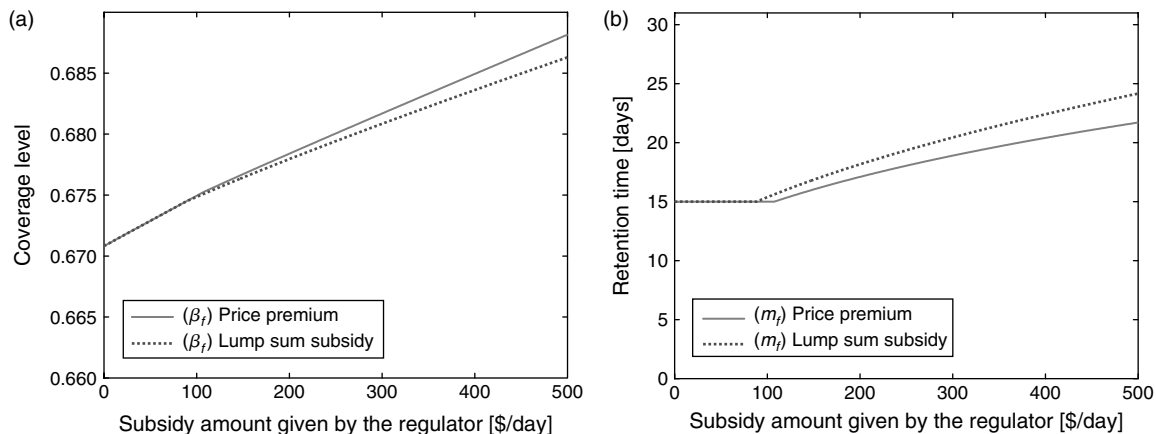
increasing coverage and retention time. However, depending on the mechanism, it does more of one or the other.

5. Discussion and Limitations

Organic WTE firms operationalize Talbot's (1920, p. 11) keen observation that "waste is merely raw material in the wrong place." These firms deserve thoughtful examination because their core operating model is designed specifically to perform two revenue generating and environmentally useful activities, i.e., divert waste from landfills to produce compost and generate renewable energy. Not only do these firms present an attractive business proposition, but they also could play a significant role in creating a sustainable industrial ecosystem.

We characterized the operations of the WTE firm by incorporating the dynamics of the biological process for converting organic waste into energy. By modeling the operational dynamics of waste generation and WTE processing, we showed that there are significant economies of scale in this business. However, the added hauling cost for collecting organic waste could make increasing coverage more costly. We modeled these two trade-offs in the urban and rural settings.

We found that, in the spatially compact urban setting, more volume meant more revenue from tip fees and electricity sales, and lower per-ton hauling cost. Therefore, full coverage is both socially optimal and profit maximizing. Thus, the social planner's problem becomes incentivizing the WTE firm to operate to achieve socially-optimal waste utilization. To influence the operating decisions of the firm, the social planner can give a per kWh price premium for electricity or a lump sum subsidy to offset capital costs. For the range of parameters we observed in practice, we found that distributing these subsidies as a lump sum is more cost effective for inducing socially optimal waste utilization. The lump sum mechanism directly subsidizes capacity whereas the price premium works through the decreasingly effective biological process that converts waste into energy. It is encouraging to observe that, in urban settings, which are currently the target sites for WTE firms, our results for the firm's profit-maximization problem and the regulator's mechanism choice are complementary. Offering full coverage is more profitable for the firm, diverts more waste from landfills, and generates more renewable energy. The lump sum mechanism is more cost effective for inducing the firm to add capacity, thereby allowing higher waste utilization to generate renewable energy. Moreover, the lump sum mechanism can be used to help capital-constrained start-up WTE firms.

In the rural setting, our results suggest that full coverage may not be optimal as the routing cost for organic waste collection could become prohibitively high. In this case, partial coverage is optimal. Moreover, the profit-maximizing coverage could be less than what is socially optimal. Thus, the regulator has to worry about influencing the coverage and waste utilization decisions of the firm. Our results suggest that the price-premium mechanism is more cost effective for inducing the WTE firm to increase coverage level, however, consistent with the urban setting, the lump sum mechanism is more effective for inducing higher waste utilization. Hence, the regulator must decide which environmental goal is more important. One could imagine that the balance of this trade-off is quite situational, suggesting that the regulatory mechanism decision should be made at a local level. Further research on alternate regulatory mechanisms (perhaps a combination of the two studied here) would be a constructive way to build on the work in this paper.

We focused our model on the simplest case to derive intuition on the dynamics of the waste generation and WTE operational system. We considered only one possible optimal retention time as this is generally what we have observed in practice. However, a potential operational improvement and, hence, extension to the model, is to dynamically determine the optimal retention time depending on the waste arrival rate and the biological state of the waste in the digesters. Moreover, we limited the sphere of social welfare to include the WTE firm, the WG, and environmental impact. However, the actions of the WTE firm and the WG have ripple effects into the broader economy (e.g., suppliers of the WTE firm) and the community. These effects could be an interesting avenue for further research.

Another possible extension is to delve more deeply into the lump sum mechanism. A retail energy marketer who gives a lump sum subsidy essentially partners with the WTE firm and therefore has full visibility into operational details. However, if the lump sum mechanism were distributed by a regulatory agency, the agency would likely require and, hence, have access to less operational information. This may lead to a suboptimal lump sum amount, perhaps resulting in the WTE firm building too much capacity. Given the inefficiencies that might arise when there is information asymmetry, an alternate form of financial support for WTE firms, such as a low interest loan, may be a preferable instrument for regulators. Given the high interest in alternative energy ventures, we feel that this would be a very fruitful avenue for future research.

Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://msom.journal.informs.org/.

Acknowledgments

References

Ata, B., D. Lee, M. H. Tongarlak. 2010. Harvest: Organic waste recycling with energy recovery (A). HBS Case 611-033, Harvard Business School. Boston.

Atasu, A., L. N. Van Wassenhove, M. Sarvary. 2009. Efficient takeback legislation. *Production Oper. Management* **18**(3) 243–258.

BEKON. 2009. Waste to energy. Presentation, BEKON Energy Technologies GmbH & Co. KG, Unterföhring, Germany. Accessed February 22, 2010, http://www.rwmexhibition.com/files/bekon_rwm_17.09.2009.pdf.

Benjaafar, S., Y. Li, M. Daskin. 2009. Carbon footprint and the management of supply chains: Insights from simple models. Working paper University of Minnesota, Minneapolis.

Brown, S. 2010. Putting the landfill energy myth to rest. *BioCycle* **51**(5) 23–33.

Cachon, G. P. 2010. Carbon and supply chain structure. Presentation, NSF Symposium on the Low Carbon Footprint Supply Chain, October 15. National Science Foundation, Arlington, VA.

City and County of San Francisco, Office of the Mayor. 2009. Mayor Newsom signs mandatory recycling and composting ordinance. Accessed February 21, 2010, http://www.sfmayor.org/archives/PressRoom_NewsReleases_2009_106733/.

Courcoubetis, C., R. Weber. 1996. Buffer overflow asymptotics for a buffer handling many traffic sources. *J. Appl. Probab.* **33** 886–903.

Eisenstein, D. D., A. V. Iyer. 1997. Garbage collection in Chicago: A dynamic scheduling model. *Management Sci.* **43**(7) 922–933.

Element Markets. 2011. Renewable energy credits. Accessed July 5, 2010, http://www.elementmarkets.com/renewable-energy-credits.php.

Esenduran, G., E. Kemahlioglu-Ziya. 2010. Complying with takeback legislation: A cost comparison and benefit analysis of compliance schemes. Working paper, University of North Carolina at Chapel Hill, Chapel Hill.

Esenduran, G., E. Kemahlioglu-Ziya, J. Swaminathan. 2010. The impact of take-back legislation on remanufacturing. Working paper, University of North Carolina at Chapel Hill, Chapel Hill.

Fischer, C., R. G. Newell. 2008. Environmental and technology policies for climate mitigation. *J. Environ. Econom. Management* **55**(2) 142–162.

Fullerton, D. 2001. A framework to compare environmental policies. *Southern Econom. J.* **68**(2) 224–248.

Golden, B. L., A. Assad. 1988. *Vehicle Routing: Methods and Studies.* Elsevier Science, New York.

Hopp, W. J. 2007. *Supply Chain Science.* Chapter Capacity, Irwin, New York.

Lee, D. 2012. Turning waste into by-product. *Manufacturing Service Oper. Management* **14**(1) 115–127.

Lutz, P. 2010. *New BEKON.* Biogas technology for dry fermentation in batch process. BEKON Energy Technologies GmbH & Co. KG, Unterföhring, Germany. Accessed February 22, http://www.bekon-energy.de/english/BEKON-Process description.pdf.

National Solid Waste Management Association (NSWMA). 2011. Accessed September 2, 2010, http://www.environmentalistseveryday.org/about-nswma-solid-waste-management/overview-and-history/index.php.

Native Energy. 2011. Renewable energy credits (RECs). Accessed June 5, 2010, http://www.nativeenergy.com/renewable-energy-credits.html.

Plambeck, E. L., Q. Wang. 2009. Effects of e-waste regulation on new product introduction. *Management Sci.* **55**(3) 333–347.

Subramanian, R., S. Gupta, B. Talbot. 2008. Product design and supply chain coordination under extended producer responsibility. *Production Oper. Management* **18**(3) 259–277.

Talbot, F. A. 1920. *Millions from Waste.* J. B. Lippincott Company, Philadelphia.

U.S. Congress. 2009. American recovery and reinvestment act of 2009. U.S. Congress, Washington DC. Accessed June 5, 2010, http://www.recovery.gov/News/featured/Pages/RecoveryActSeedsGreenEnergySources.aspx.

U.S. Department of Energy, Energy Efficiency and Renewal Energy. 2010. Green power markets. U.S. Department of Energy, Energy Efficiency and Renewal Energy, Washington, DC. Accessed June 5, 2010, http://apps3.eere.energy.gov/greenpower/markets/certificates.shtml?page=1.

U.S. Environmental Protection Agency. 2008. EPA's green power partnership: Renewable energy certificates. U.S. Environmental Protection Agency, Washington, DC. Accessed June 5, 2010, http://www.epa.gov/grnpower/documents/gpp_basics-recs.pdf.

Waste Business Journal. 2009. Waste market overview & outlook 2009. Accessed June 5, 2010, http://www.wastebusinessjournal.com/.