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Economic analysis of waste-to-energy investment in the Philippines: A real options approach

Casper Boongaling Agaton[a,b,*], Charmaine Samala Guno[c], Resy Ordona Villanueva[d], Riza Ordona Villanueva[d]

[a] Utrecht University School of Economics, Utrecht University, Kriekenpitplein 21-22, 3584 EC Utrecht, the Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands
[c] Mindoro State College of Agriculture and Technology, Masipit, Calapan City, 5200 Oriental Mindoro, Philippines
[d] Holy Infant Academy, Ibaba East, Calapan City, 5200 Oriental Mindoro, Philippines

HIGHLIGHTS

- Real options approach under uncertainty for WtE investment project is evaluated.
- WtE technologies are economically better options than the landfill.
- More optimal decision to invest immediately in incineration and gasification.
- Increasing the tipping fee makes pyrolysis profitable option than the landfill.

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ABSTRACT

Waste-to-energy technologies start to gain the attention of developing countries as a sustainable energy source in response to the worsening municipal solid waste management problem. This paper proposes an investment model to analyze the economic feasibility of waste-to-energy projects in developing countries using the Philippines as a case study. Applying the real options approach under uncertainty, we compare the option values, the value of waiting, and the optimal timing of switching technologies from landfill to waste-to-energy. Considering the energy production and investment costs, the optimization results find that incineration, with an optimal electricity price of USD 3cents/KWH, is the best technology option followed by gasification and pyrolysis at USD 7cents/KWH and USD 12cents/KWH, respectively. At the current price of electricity of USD 11cents/KWH, it is more optimal to postpone investment in pyrolysis, otherwise, the tipping should be increased from USD 15/ton to USD 18.5/ton to make pyrolysis a more viable option than continue using the landfill. On the other hand, it is a more optimal decision to invest immediately in either incineration or gasification as delaying investment incurs opportunity losses from generating electricity from these technologies. Furthermore, the paper suggests that the government must support waste-to-energy program as it will significantly contribute in solving the problems on the environment particularly air quality and waste management as well as on energy security and sustainability.

1. Introduction

Solid waste management (SWM) is a universal issue that challenges policy makers and governments from both developed and developing countries. Currently, the world population produces 2.01 billion tons of garbage per year and is projected to increase by 16% in high-income countries and 40% in low to middle-income countries by 2050 [1,2]. Given this trend and the fact that about 33% of this waste is not managed in an environmentally safe manner, implications on economy, environment, and health are imminent and therefore require immediate action [1,2]. While developed countries strive to achieve an economically-viable and environmentally-acceptable disposal of municipal solid waste (MSW) [3–5], the waste management in most developing countries are inefficient with poor segregation, collection, storage, treatment and disposal practices [6–8]. These problems can be attributed to the lack of adequate infrastructure, legislated recycling,

* Corresponding author at: Utrecht University School of Economics, Utrecht University, Kriekenpitplein 21-22, 3584 EC Utrecht, the Netherlands.
E-mail addresses: c.b.agaton@uu.nl (C.B. Agaton), csguno@minscat.edu.ph (C.S. Guno).

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Nomenclature

Symbols

ρ	discount factor
δ	discount rate
μ	growth rate of electricity price
σ	volatility of electricity price
π	annual cash flow
τ	period when decision to invest is made
B	revenue
C	operations and management costs
CAP	investment cost for technology
$\mathbb{I}$	indicator for decision to invest
J	number of iterations for Monte Carlo
NPV	net present value
$\mathbb{E}[NPV]$	expected net present value
P_e	electricity price
Q	Quantity of electricity generated
T_k	lifetime of the WtE technology
T_D	decision-making period
TF	tipping fee
V_k	option value
V_{wait}	value of waiting

Abbreviation

AD	Anaerobic Digestion
DENR	Department of Natural Resources
DOE	Department of Energy
GBM	Geometric Brownian Motion
IRR	Internal Rate of Return
LCA	Life Cycle Analysis
LFG	Landfill Gas
LGU	Local Government Units
MMDA	Metro Manila Development Authority
MRF	Material Recovery Facility
MRP	Mean Reverting Process
MSW	Municipal Solid Waste
NPV	Net Present Value
NSWMC	National Solid Waste Management Commission
PBP	Payback Period
RO	Real Options
ROA	Real Options Approach
ROI	Returns on Investment
SWM	Solid Waste Management
WtE	Waste to Energy

Subscripts and Superscripts

cur	current price
D	number of years for investment decision
e	electricity
G	Gasification
I	incineration
k	WtE technology options
L	landfill
max	maximum price
min	minimum price
P	pyrolysis
$step$	difference for initial price
t	time, period
$wait$	waiting or delaying investing

financial support, and citizen awareness [9].

Similarly, this waste management problem is evident in the Philippines as it generates more solid waste along with a growing population, increasing consumption, and expanding urbanization [10]. According to Metro Manila Development Authority (MMDA) [11], the country produces an average of 41 ktons of garbage daily with almost 10 ktons/day coming from Metro Manila alone. In 2001, the government enacted the RA 9003 or the "Ecological Solid Waste Management Act of the Philippines" to encourage the reduction of waste at source, recovery, recycling and reuse of wastes, and to create mandatory targets through the local government units [12]. To achieve this goal, every local government units needs to establish a Material Recovery Facility (MRF), implement segregation at the source and collect and process all recyclable and biodegradable materials. However, with the very limited number of MRF equipped with technologies to reduce wastes like recycling and composting, most of the MSW are either disposed in the dump sites or openly burned which further worsen the quality of heavy polluted air in the cities [13]. Another promising solution to address the problem is waste-to-energy (WtE) technology which is becoming interesting to potential investors after the Department of Energy (DOE) approved the country's first WtE facility in the country. This technology processes MSW to generate energy in the form of electricity and/or heat, hence, taking a solution addressing both the need for more sustainable source of energy and environmental concerns [14]. The development of this technology, along with other renewable energy technologies including wind, solar, hydropower, and thermal, supports the achievement of sustainable development goals (SDG), particularly on SDG 7: Affordable and Clean Energy and SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable [15,16]. Despite its huge potential, there has never been any operational WtE project to date due to the lack of financing and management support in the city and municipality levels as well as the conflict with the prevailing "Philippine Clean Air Act (RA 8749)" which prohibits incineration of MSW. Also, alternative energy sources should be developed sustainably to mitigate their adverse impacts on the ecosystem including land use, homes, natural habitat, and water [17,18]. These serve as the motivation of this study to offer an alternative solution that addresses the country's problems on SWM and energy sustainability that are highly relevant particularly in developing countries.

Investments in WtE technologies are widely discussed in the literature using various project valuation models. These include the traditional valuation methods such as life cycle analysis (LCA); net present value (NPV); internal rate of return (IRR); payback period (PBP); and returns on investment (ROI) [19–23]. Various studies extend these methods by combining economic analyses with socio-technical and environmental aspects such as LCA, multicriteria analysis, and multistep approach [24–27]. While these offer a useful tool for WtE project valuation, these methods do not cover some important characteristics that are crucial in making decisions for high-risk investments. These characteristics include irreversibility of investment project, investment risks, uncertainty in the future cash flows, and managerial flexibility in making investment decisions. Employing various risk assessment frameworks, studies show how different risks such as the waste supply, legal and government risks, technology and infrastructure risks, sociopolitical risk, and environmental risk affect WtE investment decisions [28–30]. A more comprehensive method is the real options approach (ROA) which combines risks and uncertainties with the flexibility in the timing of making investment decisions [31]. The application of this approach has expanded from the financial derivatives to power sector, utilities, industry, and transportation projects.

To date, there are limited studies applying ROA for WtE investments. For instance, Tolis et al. [14] adopted a real options (RO) algorithm investigating different options of energy recovery from waste including incineration, gasification and landfill biogas exploitation. The model identified the optimal investment strategies over time considering the uncertainties in heat production revenues, electricity and CO2 allowance prices as well as interest and inflation rates, which were used to represent the evolution of running costs and gate fees. Tolis et al. [32] extended this model by including anaerobic digestion (AD) among the WtE technology options. Applying the RO algorithm, the study identified the financial contributors and analyzed the impact of greenhouse gas trading in terms of financial yields with landfilling as the baseline scenario. The results from both studies showed the advantage of combined heat and power over solely electricity generation and identified incineration as the most attractive technology among the options due to its higher power production efficiency, lower investment costs, and lower emission rates. Xie et al. [33] applied real options-based multi-stage stochastic programming model to design an optimal decision rule considering the flexibility of capacity expansion for WtE systems. The experimental results showed that the lifecycle performance of WtE systems can be improved significantly by incorporating the flexibility of capacity expansion. Results further verified the higher value of flexibility of the proposed multistage model over a two-stage model. Li et al. [34] presented a RO model for valuing the investment of fast pyrolysis facility for producing cellulosic biofuels subject to construction lead times and uncertain fuel price. The findings indicated a more optimal decision to invest in the facility later than immediately while the profitability of the project is sensitive to the outlook of the fuel price. Ranieri et al. [35] focused on two anaerobic digestion (AD) treatment plant configurations characterized by a technological process with different degree of flexibility and applied a real options-based model using the case of the urban waste management system of the Metropolitan Area of Bari, Italy. Results from this study show the importance of pricing the flexibility of treatment plants under uncertainty in organic fraction as a critical factor in the designing WtE plants. The model analyzed how volatile variables: heat production revenues, electricity and CO2 allowance prices as well as interest and inflation rates affect the optimal investment strategy among the given WtE technology options. We aim to contribute to the existing literature by (a) proposing a ROA model for WtE investment decisions in the context of developing countries; (b) comparing the optimal timing and the value of waiting to invest in WtE technologies; (c) analyzing how uncertainties in prices and gate fees affect the flexibility of investment decisions; (d) identifying the threshold prices making WtE a better option than the landfill.

The main objective of this study is to compare the economic attractiveness of investing in WtE facility over continuing to use the sanitary landfill. Using the case of the Philippines, we apply ROA to calculate the option values of switching from landfill to WtE technologies including incineration, gasification, and pyrolysis. We then evaluate the optimal timing of WtE investment under uncertainty in electricity prices and analyze the benefit of postponing or delaying investment decisions by calculating the value of waiting. We identify the electricity price and tipping fee thresholds for each WtE technologies making investments in these projects more viable option than continuing the use landfill. Finally, we analyze how changes in the explanatory variables affect the investment decisions through sensitivity analysis.

2. Methodology

2.1. WtE technology options

Waste-to-energy refers to the recovery of the energy from waste materials into usable heat, electricity, or fuel [36]. Various WtE approaches are categorized into landfill, thermal treatment, and biological treatment as shown in Fig. 1 [37]. Landfilling can be considered WtE technology when it captures methane from waste landfill gas (LFG) and generates electricity and heat through turbines [38,36]. This is suited to municipalities and cities that yield MSW high in biodegradable content and moisture [36]. Biological treatment on the other hand involves aerobic composting and AD which produces fertilizer or biogas. AD is the most suitable WtE option for food and yard wastes [37]. It involves a complex process requiring specific environmental conditions and different bacterial populations to decompose the organic waste to produce a valuable high energy mixture of biogas [36]. In contrast, thermal treatment, the most used large-scale WtE technology, employs the traditional incineration and more advanced pyrolysis and gasification [37]. While pyrolysis and gasification involve manual sorting and indirect combustion of MSW to mainly produce syngas, incineration involves a direct combustion of unprepared MSW that yields enough energy to power a steam turbine.

Among these MSW treatment technologies, our study focuses on the thermal treatments which include incineration, pyrolysis, and gasification, in line with the country's WtE projects currently under evaluation.

2.2. Concept of real options

Investment decisions have characteristics that are not captured by traditional project valuation methods such as irreversibility, highly risky and uncertain, and flexibility [39]. The ROA, on the other hand, captures these characteristics by combining uncertainty and flexibility which characterize many irreversible investment decisions in the WtE projects. ROA is more appropriate when the investment environment and market conditions for a project are highly volatile and flexible. Otherwise, traditional methods are more useful if the conditions are stable or rigid.

Myers [40] first used ROA as the application of option pricing theory to valuate non-financial assets termed as "real" assets. A real option (RO), is the right, but not the obligation to undertake certain project initiatives such as deferring, abandoning, expanding, or contracting capital investment based on economic, technological, or market conditions [41]. These options typically fall under three categories of project management. The first group is the options related to the size of a project which include the options to expand, contract, or expand and contract the project over time given various contingencies. The second group relates to the life and timing of the project such as options to initiate a project, delaying or deferment, abandonment, and sequencing of inter-related projects. The third group relates to project operations including output mix, input mix, and operating scale options.

Valuing RO is as important as identifying the type of options. Literature presents methods to value RO including the (a) Black-Scholes model which uses differential equation to estimate the options; (b) Binomial trees (or lattices) which represents a discrete-time model of asset price evolution with two or more alternative future outcomes in each step; (c) Monte Carlo simulation which can be considered as the

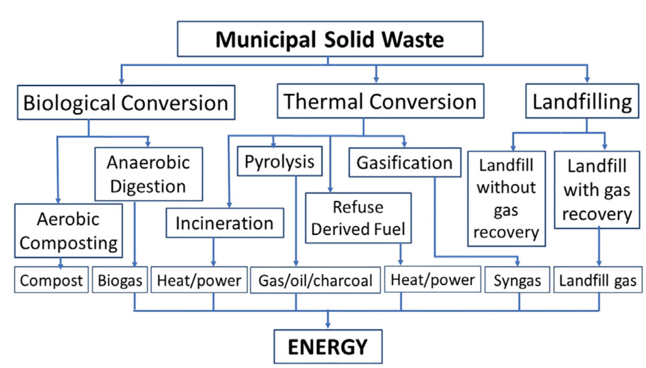

Fig. 1. Different MSW treatment techniques and their products [37].

easiest way to value RO of complex projects; (d) Fuzzy sets based approaches used for modelling value distribution as fuzzy numbers allows the advantages of simulation-based methods reducing computational requirements; and (e) Dynamic programming which allows the calculation of the optimal timing of investment and enables different types of RO to be combined with various possible scenarios [41].

Another crucial step in ROA is the modelling of risk and uncertain variables. Stochastic process, such as the Geometric Brownian Motion (GBM) and Mean Reverting Process (MRP), are commonly used to describe the evolution of stock prices, commodity prices, and energy prices [39,41]. GBM is a log-normal diffusion process with the variance growing proportionally to the time interval, while for MRP, the variance grows in the beginning and stabilizes on a certain value. Stochastic processes are not applicable for all sources of uncertainty as technological cost, efficiency, and knowledge capital, for instance, are usually modelled with learning curves and Poisson jump [42,43]. The learning curve describes the cost reductions in more mature technologies due to learning, while the Poisson jump is a process subject to jumps of fixed or random size for which the arrival times follow Poison distribution. Once an appropriate uncertainty model has been chosen, the parameters are estimated based on historical data.

In this research, we use the timing option to compare the economic attractiveness of either investing in WtE technologies or continuing the use of landfill. To value these options, we apply the dynamic programming which estimates the optimal timing of switching technologies combined with Monte Carlo simulation to estimate the expected value of options considering the uncertainty in prices. We finally model this uncertainty using the GBM.

2.3. Real options model

We consider an investor who has the option to invest in WtE project k or continue dumping all MSW in the landfill L given a certain decision-making period T_D. The WtE technology options include $k = 1$ incineration; $k = 2$ gasification; and $k = 3$ pyrolysis. The net present value $NPV_k$of each investment is calculated using Eq. (1)

$$NPV_k = \sum_{1}^{T_{k+1}} \rho^t (B_k + C_k) - CAP_k = \sum_{1}^{T_{k+1}} \rho^t [(P_{e,t} Q_k + TF) + C_k] - CAP_k \tag{1}$$

where CAP_k is the investment cost for technology k; T_k is the lifetime of WtE technology; $\rho^t = \frac{1}{(1+\delta)^t}$ is the discount factor at δdiscount rate; B_k is the revenue which is equal the tipping fee TF and the amount of electricity generated Q_k from each technology times the generation rate P_e; and C_k is the operational costs which include all operations, maintenance, insurance, taxes, and employees' salary.

In line with previous literature [44–46], we assume that the price of electricity P_e is stochastic and follow GBM with a drift as shown in Eq. (2)

$$dP_e = \mu P_e dt + \sigma P_e dz \tag{2}$$

where dP_e and dt are changes in price and time; μ is the growth rate of electricity price, σ is the volatility, and dz is a Wiener process equal to $\varepsilon\sqrt{dt}$ such that $\varepsilon\ N(0, 1)$ is a normal distribution with zero mean and one standard deviation.

We use the Monte Carlo simulations to estimate the path of electricity prices as shown in Eq. (3). With $0 \le t_1 < t_2 < \ldots < t_n$ be the points in time and $\Delta t = t_1 - t_{i-1}$, we generate a standard normally distributed random numbers $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_n$ and estimate $P_{e,t}$ with the current electricity price as $P_{e,0}$. We repeat the same procedure for various initial prices of electricity $P_{e,min}$: $P_{e,step}$: $P_{e,max}$ from the minimum $P_{e,min}$ to maximum $P_{e,max}$ at a price difference of $P_{e,step}$. This provides a vector of various price paths at different initial prices of electricity.

$$P_{e,t} = P_{e,t-1} exp\left[\left(\mu - \frac{1}{2}\sigma^2\right)\Delta t + \sigma\sqrt{\Delta t}\,\varepsilon_t\right] \tag{3}$$

We incorporate this price vector in Eq. (1) to estimate the expected net present value $\mathbb{E}[NPV_k]$ of each WtE options. This is done by calculating the $NPV_{k,j}$ with many J times and taking its average from various initial prices of electricity as shown in Eq. (4). This provides a vector of $\mathbb{E}[NPV_k]$ at different initial prices of electricity for all WtE technologies.

$$\mathbb{E}[NPV_{k,j}\ |P_{e,0}] = \approx \frac{1}{J}\sum_{1}^{J} NPV_{k,j} \approx \mathbb{E}[NPV_k|P_{e,0}] \tag{4}$$

Using dynamic optimization, the investors problem is to find the optimal timing of investment τ_k by maximizing the value of k investment for each decision-making period as shown in Eq. (5).

$$max\left\{\begin{matrix} \sum_0^{\tau_k} \rho^t \pi_{L,t} + \\ \left(\sum_{\tau_k}^{T_D} \rho^t \pi_{L,t}(\mathbb{I}_k - 1), \mathbb{E}[NPV_k](\mathbb{I}_k)\right)\end{matrix}\right\} \tag{5}$$

where $\mathbb{I}_k$ is an indicator equal to 1 if investment is made, otherwise equal to zero; and $\pi_{L,t}$ is the annual cash flow for the landfill equal to the revenue from tipping fee minus the operations and managements costs.

The problem is solved backwards from the terminal period $t = T_D$ to $t = 0$ by calculating the option value $V_{k,t}$ at each decision-making period by either investing in k or continuing the landfill as shown in Eq. (6). This provides a vector of option values at different initial prices of electricity for all WtE technologies.

$$V_{k,t} = max\{\pi_{L,t}, \mathbb{E}[NPV_k]|P_{e,t}\} \tag{6}$$

The optimal timing of investment for each type of WtE project is characterized by the minimum price of electricity where the option value of each project at initial period is equal to the option value at the terminal decision-making period as shown in Eq. (7).

$$P_e^{k^*} = min\{P_{e,0}|V_{k,0}(P_{e,0}) = V_{k,T_k}(P_{e,0})\} \tag{7}$$

From this optimal price of electricity, investment in WtE over landfill is maximized, otherwise, investment incurs loses. Comparing these prices offers the best investment opportunity among the different WtE technologies.

We further estimate the value of waiting or delaying to invest in each WtE technology $V_{wait,k}$ as the difference between the option value at various investment periods $V_{k,T}$minus the option value at the initial decision-making period $V_{k,0}$at the current price of electricity P_e^{cur} as described in Eq. (8).

$$V_{wait,k} = V_{k,T}(P_e^{cur}) - V_{k,0}(P_e^{cur}) \tag{8}$$

2.4. Parameter estimation and assumptions

We apply the proposed real option model for WtE investment using the case of the Philippines. The choice is based on the following reasons: (1) there are no existing WtE facility in the country and therefore this feasibility study is timely and relevant; (2) high supply of MSW for WtE facility with a total of 41 kton of (sorted) garbage produced daily which are either burned or dumped in the landfill; (3) the country is highly dependent on imported fossil fuels for energy generation and is currently finding alternative sources of energy; and (4) a developing country which lacks effective MSW management and capacity to finance huge investment costs for WtE facility. We gather the data from the DOE, National Solid Waste Management Commission (NSWMC) of the Department of Environment and Natural Resources (DENR), and Clean Technology Solutions. For standard comparison of the WtE technologies, we set the plant capacity to 100 tons/day for all technologies based on the approved WtE project proposal in the country. We assume that the plant will be operational and generates electricity a year after the investment period τ_k. For the NPV calculation, we set $T_k = 20$ years of electricity generation for all technologies. The annual cash flows are discounted according to the social discount rate set by the government at 10% for public infrastructure projects.

For the estimation of stochastic prices, we use a 10-year time series data to approximate the future prices of electricity. Using ADF unit root test, we confirm that electricity prices follow GBM with $\mu = 0.028651$ and $\sigma = 0.12192$. We substituted these parameters in Eq. (3) and generate a matrix of stochastic prices of electricity. We set the initial prices of electricity from USD 2c/kWh USD 40c/kWh at USD 0.5c/kWh step. For each initial price, we calculate the expected NPV for each type of WtE technology. On the dynamic optimization, we maximize the value of either investing in WtE or continuing the landfill from terminal to initial decision-making period using backward induction on a yearly basis. We set the terminal period $T_D = 25$ years. For sensitivity analysis, we compare the option values for each WtE at various levels of tipping fee from the current USD15/ton to USD20/ton, USD10/ton, USD5/ton, and zero tipping fee. Finally, we carry out sensitivity analyses to identify how changes in volatility and growth rate of electricity price, discount rate, investment and operational costs, and plant capacity affect the optimal electricity price for shifting landfilling to WtE technologies. The summary of estimated parameters is shown in Table 1.

3. Results and discussion

3.1. Optimization result

The result of dynamic optimization is shown in Fig. 2. Each point on the curve represents the option values at every initial prices of electricity and at every period of investment. These values describe the optimal value of shifting technologies from landfilling to WtE technologies. For each WtE technology option, the bold curve represents the option values at initial period of investment $t = 0$ while the dashed curve for the terminal period $t = T_L$. At the current price of electricity P_e^{cur*}, the value of waiting V_{wait} is the distance between the option value curves. Finally, the optimal timing of investment is represented by the maximum point on the curves in which the option values are equal for the initial and terminal periods.

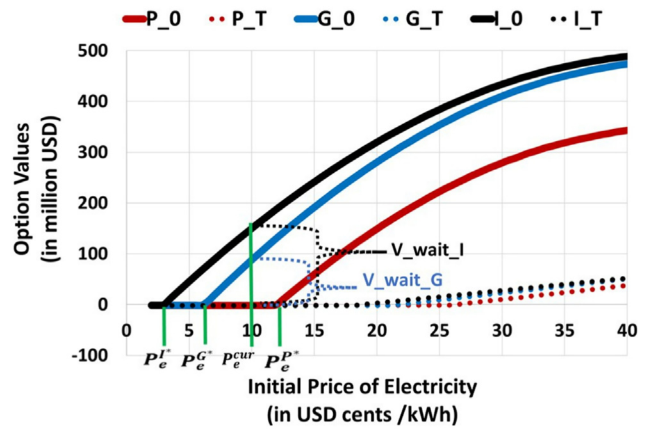

Fig. 2. Option values of various WtE technologies at different initial prices of electricity.

The first point of interest in Fig. 2 is the upwards direction of the curves. This trend implies that the option values increase with electricity prices, hence, higher initial price of electricity creates better investment opportunity for WtE technologies. It can be observed that there are negative option values in some points in the curves. This describes conditions where the continuing landfill option is a more economical option than WtE. Comparing the option values of various WtE technologies, the figure shows higher curves for incineration followed by gasification and pyrolysis. This indicates that investment in incineration project generates the highest returns among other technologies.

Comparing the curves at various investment periods, Fig. 2 shows that option values decrease with time. This implies a decrease in returns in any investment projects due to opportunity loses from generating electricity from the WtE technology. For instance, at the current price of

Table 1
Summary of estimated parameters for different WtE technologies.

Parameter	Unit	Description	Incineration	Gasification	Pyrolysis	Landfill[1]
CAP_k	USD million	Investment cost[2]	13.846	18.889	33.333	–
C_k	USD million/year	Annual Marginal operations and management cost[3]	4.380	5.475	5.475	0.730
Q_k	MWh/year	Electricity generated per year[4]	21,353	24,090	24,090	–
TF1[5]	USD million /year	Tipping Fee of USD 15/ton/day	0.548	0.548	0.548	0.548
TF2	USD million /year	Tipping Fee of USD 20/ton/day	0.730	0.730	0.730	0.730
TF3	USD million /year	Tipping Fee of USD 10/ton/day	0.356	0.356	0.356	0.356
TF4	USD million /year	Tipping Fee of USD 5/ton/day	0.183	0.183	0.183	0.183
TF4	USD million /year	Tipping Fee of USD 0 /ton/day	0	0	0	0
T_k	years	Lifetime of operations[6]	20	20	20	20
Other Parameters						
P_e^{cur}	USD /kWh	Current electricity price	11 cents			
$P_{e,min}$	USD /kWh	Minimum Initial electricity price	2 cents			
$P_{e,max}$	USD/kWh	Maximum Initial electricity price	40 cents			
$P_{e,step}$	USD/kWh	Steps for Initial electricity price	0.5 cents			
J		Number of iterations for Monte Carlo	10,000			
μ		Drift of electricity prices	0.028651			
σ		Volatility of electricity prices	0.12192			
δ		Discount rate	10%			
T_D	years	Decision period[7]	25			

[1] Our ROA model assumes an existing landfill; hence, investment cost is zero.
[2] Investment costs are based on WtE plant capacity of 100tons/day.
[3] Operations and maintenance cost based on WtE plant capacity of 100tons/day.
[4] Electricity generated from WtE plant capacity of 100tons/day.
[5] Current tipping fee.
[6] We assume a uniform lifetime of operation for all WtE technologies for better comparison.
[7] We set a medium-term of 20 years for an investor to decide whether to invest in WtE or continue using landfill, [8]While studies use plant capacity of 1–22 kton/day, this study uses 100 tons/day based on the existing project proposals in the country.

electricity, $P_e^{cur^*} = USD11cents/kWh$, the option value for incineration is USD 169.12 million at initial decision making period while USD 91.10 million if the decision is postponed in 10 years. This postponement results to the value of waiting equal to USD 45.37 million opportunity loss as shown in Table 2. In the case of gasification, option values decrease from USD 109.45 million to USD 34.36 million in 10 years resulting to a value of waiting equal to USD 43.56 opportunity loss. With the case of pyrolysis, option values are negative for all decision-making period which implies that landfilling is a more optimal solution than pyrolysis at the current price of electricity. The other estimations for option values and the value of waiting at different investment periods are shown in Table 2.

We further identify the optimal timing of investment for each WtE technology characterized by the initial price of electricity that maximizes the profit of shifting technologies from landfill to WtE. The optimization results in Fig. 2 show that the optimal timing of investment for pyrolysis is $P_e^{P^*} = USD12cents/kWh$, $P_e^{G^*} = USD7cents/kWh$ for gasification, and $P_e^{I^*} = USD3cents/kWh$ for incineration. These indicate that at the current price of electricity, investment in either gasification or incineration is more profitable than continue using the landfill. On the other hand, shifting from landfill to pyrolysis is only profitable at initial electricity prices above $USD12cents/kWh$.

3.2. Tipping fee

In this scenario, we describe how sensitivity in tipping fee affects investment decisions in WtE technologies. The current tipping fee in the Philippines is at USD 15/ton of waste collected from the households. In most cities, this value is subsidized by the local government as garbage collection and sanitation are parts of the city operations. However, in this research, we identify the threshold value of tipping fee that makes WtE technologies more viable option than landfill. Fig. 3 describes the dynamics of optimal prices of electricity at different values of tipping fee. The result shows the inverse relationship between the optimal prices and the value of tipping fee. This consequently indicates that WtE becomes more attractive than landfill as the increase in tipping fee incurs additional revenue for investors.

The result in Fig. 3 also shows that the profitability of incineration and gasification is robust at various levels of tipping fee. Hence, we do not estimate the tipping fee threshold for incineration and gasification as these alternatives are already viable options than landfill as explained in the previous subsection. On the other hand, the critical value of tipping fee for pyrolysis is at USD 18.5/ton. This implies that in order to make pyrolysis more attractive option than landfill, the tipping fee must be increased by USD 3.5/ton from its current value. Further, comparing the curves for the three WtE projects confirms the previous claim that incineration is the most profitable option among the analyzed technologies.

3.3. Sensitivity analysis

We carried out sensitivity analyses to identify how changes in tipping fee, volatility and growth rate of electricity price, discount rate, investment and operational costs, and plant capacity affect the optimal prices of electricity for shifting landfilling to WtE technologies. The results in Table 3 show that increasing the tipping fee by 1% decreases the optimal electricity prices between 0.32% and 0.67% for WtE technologies. This inverse relationship supports the analysis in the tipping fee scenario that WtE becomes more attractive than landfill as the increase in tipping fee incurs additional revenue for investors. Further, this confirms the previous claim that the tipping fee is an effective factor in the construction and installation of new WtE plants [47]. Moreover, increasing the plant capacity also decreases the optimal electricity price. This is due to economies of scale as higher capacity which incurs higher electricity production and therefore higher returns while reducing the average cost of production [48].

Given the current trend, the electricity price increases with a growth rate of 2.87% per year and with a volatility of 12.19%. Increasing the growth rate lowers the optimal electricity price. This is because the expected increase in prices incurs higher returns from selling the electricity generated from WtE and therefore higher NPV and option values. On the other hand, higher volatility increases the optimal electricity price. This implies a better option to delay investment in WtE with volatile prices while investing earlier at more deterministic prices of electricity. Such result conforms with previous studies that higher uncertainty in prices further delay the investment as most investors are risk-averse accepting a riskier project only with the expectation of receiving higher returns to compensate risk [39,49].

The government sets the social discount rate at 10% for public infrastructure projects including WtE projects. The sensitivity analysis shows that a higher discount rate increases the optimal electricity price implying a better decision to delay investment WtE. This result also agrees with previous studies that energy projects with a higher proportion of capital investments are more expensive with a high discount rate [50,39]. In terms of costs, an increase in investment, as well as operational costs, increases the optimal electricity prices for WtE technologies. This is because higher costs decrease the NPV and the option values for WtE and therefore increasing the benefit of waiting to invest.

4. Discussion

4.1. WtE technologies over landfill

In this study, we compare the profitability of investing in WtE technologies over landfilling. Using ROA, we calculate the option values, value of waiting, and optimal timing of investment for each technology option. Our results show the economic benefits of investing in WtE over continue dumping waste into the landfill. The landfilling of waste without any generation of energy results in a negative cost impact from the transportation, tipping fee, and operation & maintenance [36]. In addition to financial benefits, WtE is a reasonable and more sustainable alternative technology than a landfill [51]. This is in support to the positive environmental impacts of replacing landfill with WtE as they provide GHG reduction potential compared to landfilling [52].

Among the WtE technologies analyzed, investment in an incineration is the best option, followed by gasification and pyrolysis. This result verifies previous studies showing incineration to be the most attractive WtE option among the competing alternatives due to its higher power production efficiency, lower investment costs, and lower emission rates [53,36]. Incineration, among other WtE technologies, yields the highest amount of electricity with the highest capacity to lessen pile of wastes in landfills through direct combustion [14]. While incineration is most widely used among WtE technologies, many cities are now recognizing the benefits of gasification over incineration as the syngas

Table 2
Option values and the values of waiting (in million USD) at various investment periods at the current price of electricity.

	Investment period			
	0	5	10	15
Incineration	169.12	138.85 (−28.75)	91.10 (−45.37)	23.00 (−64.69)
Gasification	109.45	80.21 (−27.78)	34.36 (−43.56)	−1.70*
				(−34.25)
Pyrolysis	−1.70*	−1.70*	−1.70*	−1.70*

Note: Numbers in red indicate the values of waiting (in million USD).
* Optimal decision to continue landfill.

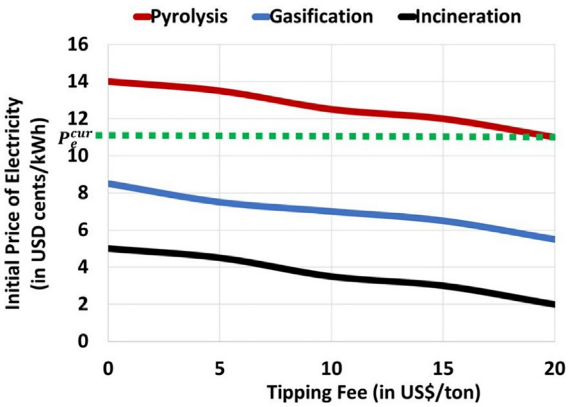

Fig. 3. Optimal timing of WtE investments at various tipping fees.

Table 3
Influence of changes in various variables on optimal prices of electricity.

Variables	Pyrolysis	Gasification	Incineration
Tipping Fee	−0.32	−0.46	−1.33
Volatility of Electricity Prices	0.16	0.31	0.67
Growth Rate of Electricity Prices	−0.72	−1.08	−0.33
Discount rate	1.44	1.15	0.33
Investment Cost	1.20	0.77	3.33
Operational Cost	1.60	3.08	6.67
Plant Capacity	−0.04	−0.08	−0.08

produced by this technology can be used for energy storage and electricity generation [54]. This technology captures the energy content from waste at a higher efficiency, especially in the absence of a heat load, thereby producing electricity with decreased air pollutants from gasification [54]. On the other hand, Samolada and Zabaniotou [55] found that pyrolysis is the most optimal thermochemical treatment option among other WtE technologies. This is because pyrolysis has zero waste and is characterized by lower and acceptable gas emission [55].

4.2. Uncertainty and timing of investment

Traditional methods to evaluate the financial and economic performance of WtE investment project do not allow investors to assess the value of flexibility [35]. For instance, the initial results show positive NPV's for all WtE technologies analyzed. Using the NPV criterion, the optimal decision is to invest in WtE technologies as investment in these projects incur net profits. This conforms with the good profitability results of WtE valuation in other countries including Saudi Arabia [22]; China [56]; Malaysia [57], and Thailand [58]. However, there are unavoidable uncertainties in cost and benefit estimates that should be acknowledged to enhance the reliability in the decision-making process [59]. The real options approach captures these limitations as it combines uncertainties and flexibility in making investment decisions [60].

In this study, we analyzed how uncertainty in electricity prices and tipping fees affect the value of options and the optimal timing of investment in WtE technologies. Our findings show that at the current electricity price, incineration and gasification are more economical solutions to address the problem of MSW management than landfills in the Philippines. We also find that investing immediately in these technologies is a better option as waiting or delaying investment incurs additional cost from paying the tipping fee and operations for landfills, while losing the opportunity to sell the energy produced from WtE facility. On the other hand, it is a more optimal decision to delay investment in pyrolysis until the electricity price increase from its current value. These investment decision implications are not considered using the traditional NPV making real options a powerful tool in project valuation particularly in energy investments. Moreover, previous studies apply real options under uncertainties in heat production revenues, electricity and CO2 allowance prices as well as interest and inflation rates; and compare the option values for various WtE technologies [35,32]. Therefore, analyzing the timing of making investment decisions as well as the threshold prices that make WtE technology a better option than continue dumping waste into the landfill confirms the current research' contribution.

4.3. Implication of WtE on energy sustainability and the environment

In addition to economic benefits, investment in WtE provides supplemental energy supply and environmental benefits [36]. The conducted study estimations show energy generation potentials of 21 GWh/year from incineration, 24 GWh/year from gasification, and 24 GWh/year from pyrolysis. Since the Philippines is highly dependent on imported fossil fuels for electricity generation [39], localized WtE facilities can augment and provide a more sustainable source of energy. These energy generation potentials may still be increased if the plant capacity is higher than the assumed 100 ton of MSW per day. Contrary to other studies, the plant capacity for a typical WtE facility in most developing countries is set between 1 and 22 kton/day [22,61]. The basis for this study's assumption is from the existing WtE project proposals in the country including 105 ton/day in Palawan; 50–1000 ton/day in Bacolod; 5.6 ton/day in Cebu. Further, we did not assume a higher plant capacity, relative to WtE product standards of mainstream suppliers in the world, to ensure a more stable supply of MSW as the case country is archipelagic and the transportation of MSW from one island to another incurs additional cost. However, we are optimistic that upon the implementation of a successful WtE pilot project, there will be more WtE projects with higher capacity in major cities in the country.

On the other hand, WtE is expected to decrease the volume of waste that is either dumped or illegally burned in the landfill. At present, the country generates 41 kton of garbage daily. According to the MMDA, 38% of MSW are manually sorted and recycled through community-based MRF before diverted to final disposal sites [62]. At the dumpsites, the "scavengers" or garbage pickers manually sort MSW and collect paper, cans, glass and other materials bought by some companies. The rest of MSW are either openly burned or continuously piling up resulting to more water, land, and air pollution. It shows here that among other MSW management options, the landfills are the least environmentally viable technology since they contribute to global warming and depletion of the ozone layer through emissions of polluting gases; require large land areas; and allow greater contamination of the local environment, such as groundwater and soil [19]. One of the alternatives to improve MSW management is through WtE which largely reduces the amount of waste in sanitary landfills while enabling energy generation [63]. Further, WtE can significantly reduce the contribution of MSW on GHG emissions by avoiding the release of methane from landfills since CH4 has much higher GHG potential and global warming potential than CO2 emitted from WtE facility [64].

4.4. Challenges of WtE investment in developing countries

Despite the positive impacts of WTE technologies on energy, economy, and the environment, the replacement of MSW management from landfill to WTE technologies in most developing countries is impossible over a short period due to the associated cost needed for the initial investment [36]. Given the high costs for WtE technologies, private investors should play an important role for this project. However, in many developing countries, private investors are still reluctant to invest due to the associated financial risks and other non-market uncertainties. These can be addressed by providing guaranteed legal security, transparency, and clear government vision for a more sustainable MSW management services [53]. In the case of the Philippines, policy conflict has always been a problem on adopting WtE technology as it overlaps the Philippine Clean Air Act which prohibits burning of MSW. Another relevant challenge is the continued empowerment of the local government units (LGU) to act locally or regionally in addressing waste management. As such, the LGU can initiate local financing of WtE technologies and not fully relying on the national government capacities. Public-Private Partnership could be an option in financing this type of project as the LGU has limited capacities in doing so.

Further, WtE facilities in most of the developing countries lack proper infrastructure, pollution control system, and regular maintenance [37]. Also, the lack of financial and logistical planning as well as a strong policy framework for WtE results in several failures that have turned the public and investors against the technology [65]. These can be addressed by providing truthful information about the technical and environmental performances of WtE facilities particularly the emissions of CO2 and other toxic gases that are harmful to both the public and the environment [66]. Finally, WtE should be supported by sound policy and functional markets for secondary products and should be promoted by transparent sharing of accurate information to improve the public perception and social acceptance of WtE technology [67].

5. Conclusion

Developing countries like the Philippines have limited experiences on waste-to-energy technologies. However, the rise on the volume of municipal solid waste in the local landfills, the growing health and environmental problems brought by burning and dumping wastes, and the increasing demand for cleaner sources of energy urge governments to respond and adapt to alternatives that these waste-to-energy technologies offer. Investment in WtE have been explored in several studies using various project valuation methods. We contribute to these literatures by proposing a real options approach framework that evaluates the advantage of investing in waste-to-energy over using the landfill and compare various waste-to-energy technologies in terms of the option values, the value of waiting to invest, and the optimal timing of making investment decisions.

The results highlight real options to describe the flexibility in making waste-to-energy investment decisions under uncertainties. Such findings conclude that waste-to-energy technologies are better options than continue dumping wastes in the landfill. Among the alternatives analyzed, incineration appears to be the most profitable option with an optimal electricity price of USD 3cents/KWH, followed by gasification and pyrolysis at USD 7cents/KWH and USD 12cents/KWH, respectively. Considering the current price of electricity of USD 11 cents/kWh, it is more optimal to wait to invest in pyrolysis. Otherwise, the tipping fee should be increased from USD 15/ton to USD 18.5/ton to make pyrolysis a more viable option than continuing the landfill option. On the other hand, it is a more optimal decision to invest immediately in either incineration or gasification as delaying investments incurs opportunity losses from generating electricity from these technologies. Sensitivity analyses show that the increase in tipping fee, a growth rate of electricity prices, and plant capacity favors earlier investment in WtE while the increase in volatility of electricity prices, investment and operational costs, and discount rate further delay the investment in WtE.

Given these findings, we recommend governments to support waste-to-energy projects as these will significantly contribute in addressing the problems of the environment, particularly air quality and municipal solid waste management as well as energy security and sustainability. These further need investment forerunners to initiate WtE investments as well as effective managers to make the projects rolling. Successful project propagates another, hence, encouraging investors to pursue further investments, creating a good waste-to-energy market, and advancing the technology through innovations. Finally, we believe that this technology is not the ultimate solution to waste problems in developing countries but only serves as a transition technology until the governments establish a more sustainable solid waste management strategies such as putting back the waste into the supply chain creating a circular economy; producing biodegradable packaging materials like bioplastics; and intensifying various recycling facilities that process different types of wastes including toxic, hazardous, and e-wastes.

In this research, we made several assumptions for valuing real options leading to various limitations of the study. First are the sources of data. At present, there are no operating waste-to-energy facility in the Philippines, hence, all the data related to costs and electricity generation are derived from the existing waste to energy project proposals in the country. To apply the proposed model in other developing countries, we recommend using the data from existing facilities to produce a more realistic estimation result. Second, in the real options model, we assume that the investment decisions are affected by the uncertainty in electricity prices. As the case country is highly dependent on imported fossil fuels for power generation, sudden changes in the world market prices of these fuels lead to uncertainty in electricity prices in the country. Future research may also consider other technical and non-technical uncertainties relevant to their country such as government policy, social acceptance, and waste management policies. In this study, we focused our analysis on the financial feasibility of waste-to-energy technologies. However, there are several factors considered in the decision-making process to approve a waste-to-energy project that involves environmental and health risks. We recommend extending our real options model by including environmental assessment; health risk analysis; and/or economic impacts on income, employment, and local electricity market. Further studies may also consider other technology options including thermal depolymerization, plasma gasification, and non-thermal technologies such as anaerobic digestion, fermentation, and mechanical biological treatment. Despite these limitations, we believe that our research is a good benchmark for further analysis addressing the country's problems on municipal solid waste management and energy sustainability, and for applying the proposed real options model for waste-to-energy investment decisions in other developing countries.

CRediT authorship contribution statement

Casper Boongaling Agaton: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Writing - original draft. **Charmaine Samala Guno:** Conceptualization, Investigation, Formal analysis, Validation. **Resy Ordona Villanueva:** Investigation, Validation, Visualization. **Riza Ordona Villanueva:** Investigation, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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