Waste Management & Research
http://wmr.sagepub.com/

Electricity and combined heat and power from municipal solid waste; theoretically optimal investment decision time and emissions trading implications

Athanasios Tolis, Athanasios Rentizelas, Konstantin Aravossis and Ilias Tatsiopoulos
Waste Manag Res 2010 28: 985 originally published online 1 June 2010
DOI: 10.1177/0734242X10371355

Research Paper

wm&r

Waste Management & Research
28(11) 985–995

DOI: 10.1177/0734242X10371355
wmr.sagepub.com
SAGE

Electricity and combined heat and power from municipal solid waste; theoretically optimal investment decision time and emissions trading implications

Athanasios Tolis, Athanasios Rentizelas, Konstantin Aravossis and Ilias Tatsiopoulos

Abstract

Waste management has become a great social concern for modern societies. Landfill emissions have been identified among the major contributors of global warming and climate changes with significant impact in national economies. The energy industry constitutes an additional greenhouse gas emitter, while at the same time it is characterized by significant costs and uncertain fuel prices. The above implications have triggered different policies and measures worldwide to address the management of municipal solid wastes on the one hand and the impacts from energy production on the other. Emerging methods of energy recovery from waste may address both concerns simultaneously. In this work a comparative study of co-generation investments based on municipal solid waste is presented, focusing on the evolution of their economical performance over time. A real-options algorithm has been adopted investigating different options of energy recovery from waste: incineration, gasification and landfill biogas exploitation. The financial contributors are identified and the impact of greenhouse gas trading is analysed in terms of financial yields, considering landfilling as the baseline scenario. The results indicate an advantage of combined heat and power over solely electricity production. Gasification, has failed in some European installations. Incineration on the other hand, proves to be more attractive than the competing alternatives, mainly due to its higher power production efficiency, lower investment costs and lower emission rates. Although these characteristics may not drastically change over time, either immediate or irreversible investment decisions might be reconsidered under the current selling prices of heat, power and CO_2 allowances.

Keywords

Waste management, energy recovery, emissions trading, investment analysis, combined heat and power

Date received: 13 November 2009; accepted: 7 April 2010

Introduction

Waste management constitutes an important component of sustainability and environmental protection in particular. Social acceptance, economic efficiency, organizational matters, water, soil and air pollution are among the most important issues confronted in waste management projects, either already realized or planned in the near future. Different policies for municipal solid waste (MSW) management such as recycling, composting and low enthalpy treatments, which are characterized by eco-friendly properties, have been implemented world-wide. Despite their proven environmental benefits, little evidence is available regarding their efficiency and social adoption in big cities with high population densities and rates of increase. On the other hand, environmental experts agree that the goals set for the waste utilization rate will never be achieved without energy recovery (Luoranen and Horttanainen, 2007 and 2008). Innovative waste-to-energy (WTE) technologies have recently emerged with attractive characteristics compared to older but proven ones. However, the risk of investing on such innovative technologies might lead to the postponement of similar projects

School of Mechanical Engineering, Industrial Engineering Laboratory, National Technical University of Athens, Athens, Greece.

Corresponding author:
Athanasios Tolis, School of Mechanical Engineering, Industrial Engineering Laboratory, National Technical University of Athens, Iroon Polytechniou 9 Str., 15780, Athens, Greece
Email: atol@central.ntua.gr

funded by the private sector unless safer fiscal conditions are assured. Moreover, state or European Union (EU) interventions on environmental policies may change the relevant legal status, thus further increasing uncertainty and complicating future strategies and decision-making.

The Kyoto protocol and the associated directives of the EU have recently led to various tools for the reduction of carbon emissions. The emissions trading market is one of these tools through which carbon-intensive industries should pay a penalty for their production activities unless they take some measures for the mitigation of their CO_2 emissions. Therefore a stock market has been established for trading the CO_2 allowances and consequently, their corresponding prices acquire a non-stationary, volatile path over time. The prices of electricity selling to the grid as well as the electricity demand may also present volatile behaviour. Moreover, the prices of fuels may induce additional uncertainties in energy markets. On the one hand they constitute volatile cost contributors whereas on the other hand they may induce volatility on the revenues of co-generation projects, as long as the revenues from heat production depend on the volatile prices of fossil fuels. Co-generation plants may have additional revenues from trading the CO_2 allowances generated by the displacement of conventional, domestic boilers (fired by oil or natural gas), thus introducing more uncertainties to their economy related to the volatile CO_2 allowance prices. From the above-described rationale, it can be seen that the context of the classical investment analysis investigating immediate and irreversible decisions becomes no longer optimal in energy markets. Optimal investment entry times should rather be defined for investments under multiple uncertainties. Project planning should thus focus not only on logistical or production-related considerations but also on strategic decisions such as the selection of the most profitable energy conversion method over time, the measures for the mitigation of CO_2 emissions and the optimal investment decision timing.

Within the frame of the traditional discounted cash flow (DCF) methodology, the energy product prices, the fuel prices and the discounting factor (i.e. the interest rates) were usually assumed to be constant throughout the projects' duration. With the introduction of the real-options concept during the last two decades, the decision-making process has been drastically affected. Modern business plans have acquired time-dependent characteristics, which may allow optimization processes in respect of time. Optimal decisions in the WTE market may not be limited to the selection of an appropriate technology but may also be extended to the optimization of investing time according to the varying fiscal conditions and the volatile prices of fuels, electricity and CO_2 allowances.

The starting point of the present study is a big European city (Athens) with high population density and increasing rate of municipal solid waste (MSW) disposal. The scope of the study was to compare, from an economic point of view, three competing methods of combined heat and power (CHP) production based on MSW: incineration, gasification and landfill biogas exploitation. Analysing the cost structure and identifying the impact of greenhouse gas trading on MSW–CHP projects are major milestones of the study. The baseline scenario used for comparing the investigated WTE options is assumed to be the landfilling of the entire MSW quantity. The objective of the study was the determination of the optimal investment entry times for each one of the competing technologies.

The paper first presents a literature survey. A description of the case study is given, leading to a description of the mathematical formulation of the time-dependent CHP investments and of the model inputs and parameters. The results of the model including analytical, explanatory comments are presented followed by the conclusions of the study.

Literature review

The competing technologies

Higher efficiencies and lower emission levels are the main targets of the technological innovations in power generation. These benefits characterize emerging technologies, which compete with older but proven ones. In the present study three different technologies will be investigated: (a) MSW Incineration, (b) MSW gasification and (c) landfill biogas exploitation. Moreover, two energy product scenarios will be compared: (I) only electricity is produced and (II) combined head and power (CHP) production. It is emphasized that a district heating infrastructure is not available in Athens but CHP will be investigated in order to reveal its potential benefits over electricity production. For this reason it is assumed that a suitable district-heating (or district cooling) infrastructure has been already installed. It is also assumed that a pre-sorting facility has been installed in order to separate the recyclable from the non-recyclable MSW.

Incineration is perhaps the oldest method for recovering the energy stored in MSW. The new built projects for electricity production seem to be more efficient in comparison with older installations: WtE plant MKW Bremen 30.5%, EVI Laar 30.5%, AEC Amsterdam 34.5%, AZM Moerdijk 32.5%. In the case of CHP production the net electrical efficiency is close to 23% and its thermal efficiency is approximately 45%, which is technically possible by using the back pressure turbine technology. The prevailing technology of MSW incineration is the moving grate, which is designed to handle large volumes of MSW with no pre-treatment. This type engages large-scale combustion in a single-stage chamber unit where complete combustion or oxidation occurs (Williams 2005). In the so-called mass burn incinerators (MBI), the thermal energy generates electricity through steam turbines. When CHP is the case, the residual heat is recovered for district heating, hot water supply, etc. (Papageorgiou et al., 2009).

Gasification may theoretically produce electricity at an efficiency of about 27% and heat at about 24% (Murphy and McKeogh, 2004). This would suggest that gasification of MSW is competing with incineration. In practice, however, gasification has not been proven and only recently has been realized in some WTE applications. In large-scale systems, combined cycle gas turbines may increase electrical efficiency but they may also reduce the temperature of the residual heat in the steam. Therefore, thermal energy production is significantly lower than that produced by incineration. Moreover, some installations in Europe have been ruined and the average electrical efficiency noticed in Japanese installations is not more than 10% (Gohlke 2009). In the report of the Thermoselect project in Karlsruhe (Hesseling 2002) it is stated that no more than 0.56 MW_{el} Mg MSW^{-1} may be achieved even in optimized future realizations (by assuming highly efficient gas engines). This performance indicates an electrical efficiency of about 20%, which has to be proved in practice.

Biogas may be generated by digesting the organic fraction of MSW. The produced biogas may be utilized for either electricity or CHP production. Biogas exploitation requires significantly less investment costs than the thermal conversion technologies (incineration and gasification). Anaerobic digestion with biogas recovery is one treatment option for urban organic waste. Several systems for source separation, collection and pre-treatment of the municipal organic waste prior to treatment in biogas plants are available (Hansen et al., 2007). In the present case study, the methane-enriched stream is utilized for either electricity conversion or CHP production by natural gas engines.

Time-optimal energy investments

Real options theory aims to replace traditional models of irreversible investments, since it may handle the uncertain, volatile pattern of multiple stochastic variables. Thus the potential investor may be able to select the most interesting investment using advanced time-dependent criteria and moreover to optimize the investment entry time based on the forecasts of unsteady variables such as demand and prices. Among the various contributions on real-options theory, one may distinguish the studies of Brennan and Schwartz (1985), Dixit and Pindyck (1994), and Trigeorgis (1996).

The effects of combined uncertainties in climate policy interventions have been investigated in Fuss et al. (2008) and Laurika and Koljonen (2006) and optimal investment timing decisions were sought. In the above-mentioned studies, the variables under uncertainty were: fuel and electricity prices, CO_2 allowance prices as well as demand of electricity. The time evolution of these variables was represented by geometric Brownian motion (GBM) models. In the present study the heating-energy market is also considered as stochastically evolving. This means that apart from the above-mentioned variables, the savings due to the potential displacement of conventional boilers are represented by GBM models too, as long as they rely on the stochastic projection of oil prices. Additionally, interest and inflation rates are assumed as stochastically evolving according to mean-reverting processes. The stochastic differential equations (SDE) of these models resemble the GBM models as they are characterized by normally distributed samples of Brownian differentials (Shreve, 1999; Oksendal, 2000). However, their behaviour is mean-reverting according to the Ingersoll–Ross models through which positive projections are ensured (Ingersoll and Ross, 1992). The solution of the above-mentioned stochastic evolution models is based on Euler simulators (Kloeden and Platen, 2004) but subsequently a Monte-Carlo algorithm (Glasserman, 2004) is used to produce multiple solution sets and average them to a final projection output.

Methodology

Case study modelling

The present study investigated the economy of WTE alternatives as a function of time. A long-term estimation of MSW adequacy should therefore be conducted prior to any other techno-economical consideration in order to ensure MSW availability for the entire operational life-time of a potential WTE project. The basic MSW quantitative data are listed here.

- The MSW disposal rate in Athens, which is currently estimated to be close to 6500 Mg day^{-1}, with an annually increasing rate of approximately 3%, recorded by ACMAR (2009).
- A relatively low percentage (13%) of MSW is recycled at source. Nonetheless, the recycled portion of disposed MSW is increasing at about 1.5% each year (General Secretariat of National Statistical Service of Greece, 2009).

Supposing that the above rates were to be maintained, it is concluded that at the end of the examined time horizon (50 years) an amount of roughly 1 300 000 Mg $year^{-1}$ would be available for WTE projects. Therefore, in the present case study, this supply rate determined the annual energy production of the hypothetical WTE plant. As stated before, three different WTE technologies were investigated: incineration, gasification and biogas exploitation from landfills. Two scenarios of energy production were examined, namely electricity production and alternatively CHP production. A pre-sorting facility was assumed to separate recyclable materials from the non-recyclable portion of MSW, which was utilized for energy conversion. The baseline scenario considered landfilling of the entire MSW quantity. In that case, significant CH_4 quantities would be released in the atmosphere, which correspond to significant CO_2-equivalent emissions.

Uncertainty was introduced for the following stochastic variables: electricity prices, oil prices, CO_2 allowance prices, interest rates and inflation rates. MSW price and running costs were considered to follow the evolution of inflation rate, since only current estimations were available instead of the historical time-series. The determination of the statistical parameters (drift, volatility and correlation) needed for the GBM representation of the stochastic variables' evolution (Clewlow and Strickland, 2000) was based on recent historical data. An Euler solver and a Monte-Carlo simulation subroutine were used to produce multiple SDE solutions and average them thus providing the requested time paths. The investment costs were calculated as a function of time too, through appropriate learning curves thus considering the experience acquired by previous installations of the same technologies (Rubin, 2007; Junginger et al., 2005). The above forecasts were introduced as inputs to a real-options algorithm which in turn determined the net present values (NPV) of the project. This process was performed using an iterative procedure. The NPV numerical calculation was repeatedly shifted by 1-year steps, meaning that the decision for investment may be postponed for as many years as needed for the investment to be more profitable. Arrays of project NPVs were therefore created as a function of time. The optimality was determined numerically by selecting the maximum NPV from the oncoming decision period.

Mathematical formulation

1. An existing electricity market in which electricity, fuel and CO_2 allowance prices evolve according to a GBM process. The stochastic differential Equation (1) that describes the process is:

$$\mathrm{d}\mathbf{X}_t = \boldsymbol{\mu}(t) \cdot \mathbf{X}_t \mathrm{d}t + \mathbf{D}(t, \mathbf{X}_t) \cdot \mathbf{V}(t) \mathrm{d}\mathbf{W}_t \qquad (1)$$

In the above equations, $\mathbf{X}_t$ denotes the vector of the stochastic processes (variables), $\boldsymbol{\mu}(t)$ denotes the drift vector as a function of time (t), $\mathbf{V}(t)$ denotes the volatility vector function of time (t), $\mathbf{D}(t, \mathbf{X}_t)$ denote the diffusion vector function of time (t) and $\mathrm{d}\mathbf{W}_t$ denotes the Brownian motion vector differential. The variables are given in vector form thus corresponding to any stochastic variable they may represent.

2. State or private investors willing to undertake a new WTE project, thus contributing to the waste management of the non-recyclable proportion of the available MSW.

The investment costs are assumed to depend on technical advances arising from long periods of cumulative experience on construction of power production units. This can be mathematically formulated, through global learning curves according to the following Equation (2):

$$I_{i,t} = I_{i,0} \left(\frac{Q_{i,t}}{Q_{i,0}} \right)^{\log_2(LR_i)} \quad \forall i \text{ where } LR_i = 1 - b_i \; \forall i \qquad (2)$$

where b_i is an appropriate learning rate used for each technology i, $I_{i,t}$ is the capital cost needed for realizing an investment (i) at time-point (t). $Q_{i,t}$ denotes the globally installed capacity of technology (i) at the time point (t).

The financial balance of the plant is calculated on a day-by-day basis. By integrating for each year (z) of the operational life-time, the annual financial balances are obtained. The time differential (dt) is assumed to be equal to 1-day interval. The carbon allowances, generated by replacing conventional energy sources with MSW, contribute to the annual revenues. The above-mentioned economic terms are described using the following Equation (3), which represents the annual financial balance $E(z)$:

$$E(z) = P_{\mathrm{el}} \cdot C \int_0^{365} F(t)\mathrm{d}t + P_{\mathrm{th}} \cdot H \cdot \int_0^{365} F_{\mathrm{th}}(t)\mathrm{d}t + \int_0^{365} F_{\mathrm{CO_2}}(t)\mathrm{d}t \quad \forall z \in \left[v + C_{t,i}, v + C_{t,i} + O_{t,i} \right] \qquad (3)$$

where P_{el} and P_{th} denote the electricity and heat capacity of the planned energy conversion system, and C and H denote the power and thermal capacity coefficients, respectively. The cost-terms inside the two first integrals of Equation (3) are expressed in € per energy unit thus justifying the external multiplication with the plant capacity (either power or thermal). The operational life and the construction lead time for each technology (i) are denoted by $O_{t,i}$ and $C_{t,i}$, respectively, while v denotes the investment decision time. $F(t)$ denotes the unitary algebraic balance of the daily cash flows due to electricity production. In the case of CHP production, it is assumed that the conventional domestic burners may be displaced while the produced heat may be distributed using a pre-installed district heating grid thus allowing significant fossil fuel savings. Therefore, a second integral is included in Equation (3) corresponding to the revenues from the heat selling ($F_{\mathrm{th}}(t)$). Obviously the second integral is accounted only in the CHP case whereas it is omitted when solely electricity production is considered. The unitary algebraic balance of the daily cash flows is calculated by subtracting the unitary operational expenses of the power plant (MSW costs f_{MSW} and other running costs f_{r}) from the electricity selling incomes (f_{el}):

$$F(t) = (f_{\mathrm{el}} - f_{\mathrm{MSW}} - f_{\mathrm{r}})(t) \quad \forall t \in [0,365], \forall z \qquad (4)$$

The $F_{\mathrm{co_2}}$ term in Equation (3) represents the daily revenues from the greenhouse gas emission trading:

$$F_{\mathrm{CO_2}}(t) = f_{\mathrm{CO_2}}(t) \cdot Ef \cdot Q_{\mathrm{MSW}}(t) \quad \forall t \in [0,365], \forall z \qquad (5)$$

where $f_{co_2}(t)$ denotes the daily CO_2 allowance prices, simulated by Equation (1) and presented graphically in Figure 2 below. $Q_{MSW}(t)$ denotes the daily MSW supply rate, which in the present case study correspond to 1 300 000 Mg year^{-1} or equivalently 3560 Mg day^{-1}. The differential time ($\mathrm{d}t$) is equal to a 1-day interval. The utilized emissions factor, denoted by Ef is explained in detail in below (Equation (8)).

By taking into account Equations (4) and (5), Equation (3) becomes:

$$\int_0^{365} (f_{\mathrm{el}} - f_{\mathrm{MSW}} - f_{\mathrm{r}})(t)\mathrm{d}t + P_{\mathrm{th}} \cdot H \cdot \int_0^{364} F_{\mathrm{th}}(t)\mathrm{d}t + \int_0^{365} f_{\mathrm{CO_2}}(t) \cdot |Ef| \cdot Q_{\mathrm{MSW}}(t)\mathrm{d}t \quad \forall z \in [v + C_{t,i}, v + C_{t,i} + O_{t,i}] \tag{6}$$

The cost terms inside the integrals represent the evolution of stochastic variables (prices of MSW and electricity as well as the heat production revenues) which are endogenously modelled by the stochastic differential Equation (1). Especially for the heat production revenues $F_{\mathrm{th}}(t)$, it was assumed that an attractive pricing strategy has been adopted (75% of simulated heating oil prices per energy unit). The urgency for smooth penetration of MSW-based district heating in the domestic heating energy market and the need for the social acceptance of this method might justify the above-mentioned pricing assumption.

The annual integrals of Equation (6) are given in nominal prices, but they are further converted to present values (PV), using the stochastically evolving interest rates modelled by a mean reverting derivative of Equation (1). The cash-flow PVs are summed up, thus resulting to an aggregate NPV, which accounts for the entire operational life-time of each technology (plant). The above procedure is described in the following Equation (7):

$$NPV_{i,v} = \sum_{z=v+C_t}^{v+C_t+O_t} \left[\frac{E(z)}{(1+r_z)^z} \right] - I_{i,v} \tag{7}$$

where $(I_{i,v})$ denotes the capital cost needed for realizing an investment (i) at time-point (v), calculated using Equation (2), while (r_z) denotes the stochastic interest rates. It is noted that the stochastic rates are averaged on a yearly basis in order to produce annual NPV results. The entire process is iterated for every year (v) of a 15-year period within which an optimal investment entry time-point should be decided. Optimality is achieved for the year (v) and technology (i) with the maximum value of the project's $NPV_{i,v}$ [max($NPV_{i,v}$)].

Numerical analysis

The model's input data

The historical data of actual loads and electricity system marginal prices (SMP) were acquired by the Hellenic Transmission System Operator (HTSO SA, 2009). The historical data were available on an hourly basis for the time-period 2001–2009, but a mean daily average was finally used. The historical data of inflation and central bank interest rates were acquired by the Hellenic Transmission Statistical Service (HTSO SA, 2009). The CO_2 allowance prices were retrieved by Point Carbon (PointCarbon 2009) whereas heating oil prices were acquired by the Greek Ministry of Development (YPAN, 2009).

The net calorific value of the non-recyclable portion of the MSW used for energy conversion is assumed to be 10 GJ Mg MSW^{-1} or 2.8 MW$_{\mathrm{th}}$ Mg MSW^{-1} (Reimann 2009), which is assumed to remain constant over time. The complete set of techno-economical inputs is presented in Table 1. The data correspond to 1 300 000 Mg of MSW on a yearly basis. This quantity determines the specification of power production for each technology, based on recorded electrical and thermal efficiencies per MSW unit, which have been retrieved by Murphy and McKeogh (2004), Hesseling (2002) and Gohlke (2009). The investment and operational costs (either running or fixed costs) were retrieved by the study of Tsilemou and Panagiotakopoulos (2006).

Table 1. Model inputs for electricity and CHP production

WTE process of MSW	Power generation capacity (MW$_{\mathrm{el}}$)	Investment costs (for 2009)[a] (€ Mg MSW^{-1} year^{-1})	Efficiency El. only or (El.)–(Th.) (%)	CO_2 emissions (tn CO_2 Mg MSW^{-1})	Fixed costs (€ kW^{-1} year^{-1})	Running costs (€ Mg MSW^{-1})	Learning rate
Incineration (electricity only)	135	500	30	–2.02	4.5	42	0.01
Incineration (CHP)	102		(23)–(45)	–2.17	5		
Gasification (electricity only)	90	730	20	–1.78	3.2	60	0.02
Gasification (CHP)	56		(12)–(26)	–1.79	4		
Landfill biogas (electricity only)	26	180	6	–1.39	1.4	15	0.05
Landfill biogas (CHP)	25		(5)–(9)	–1.46	2		

[a]Concerning a WtE plant with the throughput and efficiency of the present case study (City of Athens).

The emission factors correspond to the CO_2 emission savings obtained by exploiting the entire MSW quantity for a WTE project instead of landfilling them (baseline scenario). The CO_2 savings were calculated by considering the replacement of the current conventional mix of electricity generation plants and a corresponding emission savings factor. Additional CO_2 emission savings are considered through the displacement of conventional (fossil-fuelled) heat generation plants. The endogenous CO_2 emissions from the energy conversion process are the only positive pollutant contributors. The above rationale is analytically formulated in Equation (8), which provides the emission saving factors of Table 1:

$$Ef = -e \cdot Ef_{\mathrm{e}} - h \cdot Ef_{\mathrm{h}} + Ef_{\mathrm{p}} - Ef_{\mathrm{lf}} \tag{8}$$

where e and h denote the electricity and thermal production per fuel unit, respectively, whereas Ef_{e} and Ef_{h} denote the emissions savings due to fossil power and thermal plants' displacement, respectively. The CO_2 emissions of the process and the landfill emissions are denoted by Ef_{p} and Ef_{lf}, respectively.

The above computed emissions factor (Ef) is utilized in the calculation of the annual integrals of the greenhouse gas trading revenues (Equations (5) and (6)). The notation, the units and the numerical values of each variable shown in Equation (8) are presented in Table 2.

The source for the Ef_{e}, Ef_{h} values was the study of Rentizelas et al. (2009). e, h and Ef_{p} values were acquired by processing the numerical data reported in Gohlke (2009), Hesseling (2002), Murphy and McKeogh (2004) and Papageorgiou et al. (2009). Finally, the Ef_{lf} data have been retrieved by Tuhkanen et al. (2000).

Prediction of stochastic variables

The simulation of the stochastic variables resulted to the MSW and oil prices evolution shown in Figure 1 as well as to the CO_2 allowance and electricity price forecasts shown in Figure 2.

The stochastic differential equations representing the evolution of the relevant stochastic variables are solved with an Euler solver. A Monte-Carlo algorithm is used in order to produce multiple results based on past data and normally distributed samples of Brownian differentials (noise). These are further averaged thus contributing to the reduction of noisy variations. From the SDE solution it is shown that increasing gate fees may be anticipated while on the other hand the evolutions of oil and electricity prices are mean-reverting, despite their GBM modelling. This behaviour is in line with past relevant studies (Barlow, 2002). The results of the CO_2 allowance price representation are based on recent data and therefore, not enough experience has been gathered concerning its behaviour within this newly born market. Also, it has to be noted that the future projections shown in Figures 1 and 2 may not be considered as safe forecasts. They are rather based on historical data and represented through GBM stochastic processes, thus constituting modelled evolution paths.

Concerning the MSW gate-fees evolution path, a starting point is required and this may be based on its current (2009) value. This has been derived using a holistic reverse-logistics algorithm (Tatsiopoulos and Tolis, 2003) and the resulting range was approximated between 21 and 24 € Mg MSW^{-1}, which is close to optimal gate-fee calculations retrieved from the literature (Murphy and McKeogh, 2004; Papageorgiou et al., 2008). The evolution of MSW price (gate fee) over time has been assumed to follow the inflation rate, which in turn has been represented by an appropriate mean-reverting derivative of the stochastic differential Equation (1). The same assumption holds for the running costs of each technology for which, only current values were available and retrieved by the studies of Murphy and Mc Keogh, (2004) and Tsilemou and Panagiotakopoulos, (2006).

Table 2. Emission factors

WTE process of MSW	Electricity production per fuel unit	Thermal production per fuel unit	Emission savings due to fossil power-plant displacement[b]	Emission savings due to fossil thermal plant displacement	CO_2 emissions of the process	Landfill emissions
[Symbol] Unit	[e] MWh_{el} Mg MSW^{-1}	[h] MWh_{th} Mg MSW^{-1}	[Ef_{e}] tn CO_2 $MWh_{el}{}^{-1}$	[Ef_{h}] tn CO_2 $MWh_{th}{}^{-1}$	[Ef_{p}] tn CO_2 Mg MSW^{-1}	[Ef_{lf}] tn CO_2 Mg MSW^{-1}
Incineration (Electricity only)	0.8	0	0.876	0	0.28	1.6
Incineration (CHP)	0.6	1.2	0.876	0.27	0.28	1.6
Gasification (Electricity only)	0.53	0	0.876	0	0.28	1.6
Gasification (CHP)	0.33	0.7	0.876	0.27	0.28	1.6
Landfill biogas (Electricity only)	0.2	0	0.876	0	0.35	1.6
Landfill biogas (CHP)	0.2	0.3	0.876	0.27	0.35	1.6

[b]Only related to the Greek conventional mix of energy production.

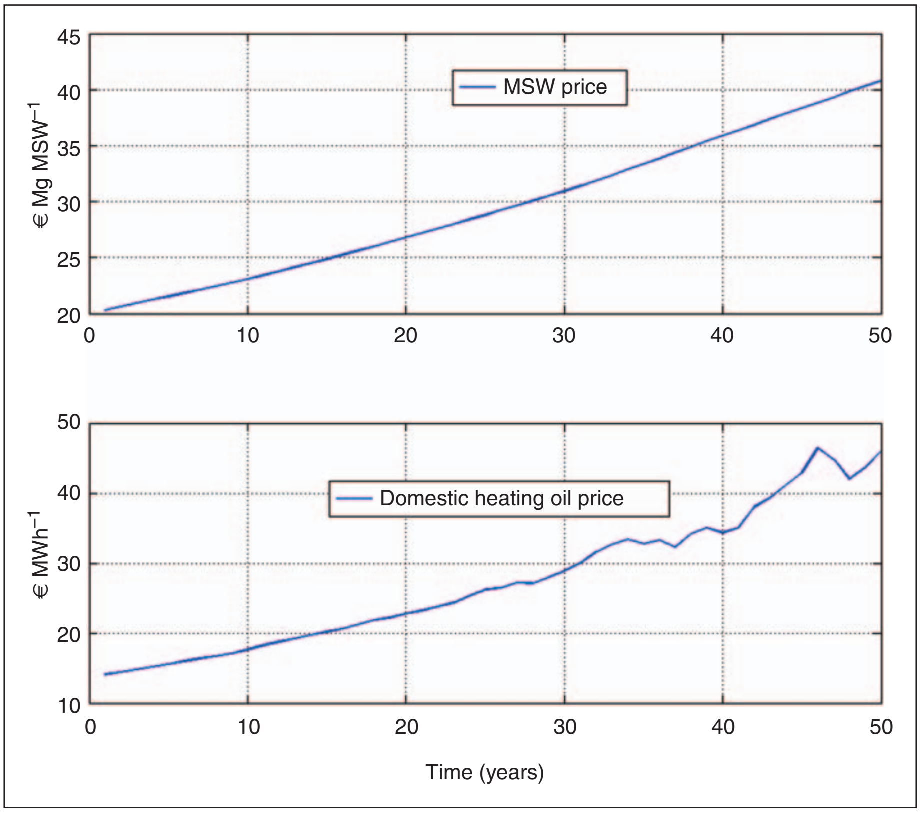

Figure 1. Simulated projection of MSW price (up) and heating oil price (down).

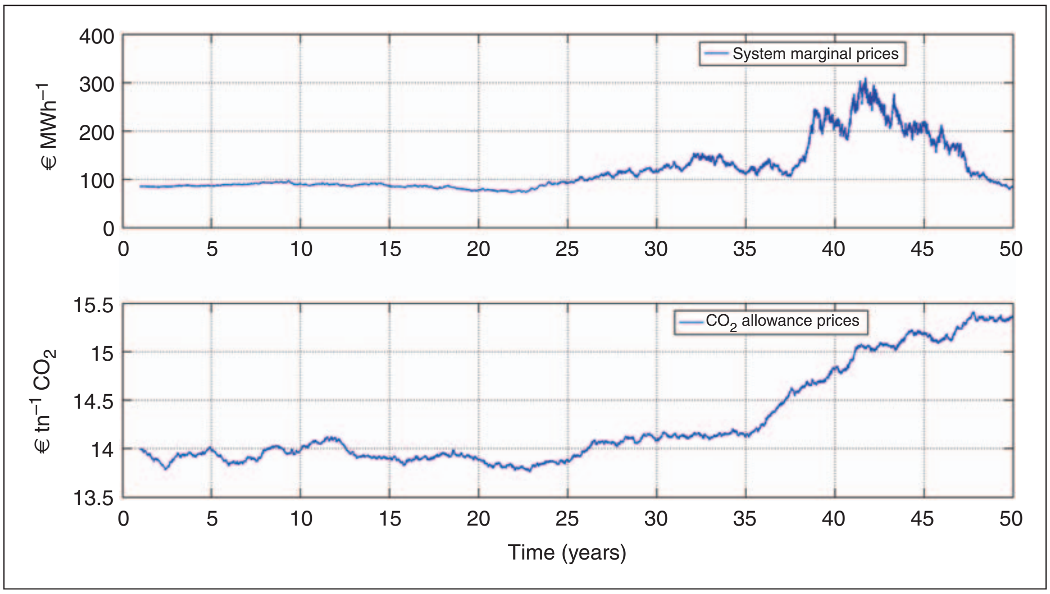

Figure 2. Simulated projection of electricity price–SMP (up) and CO2 allowance price (down).

Results and discussion

The NPV comparison of the investigated technologies for the scenario of electricity production is presented in Figure 3 while the corresponding NPV comparison for the CHP scenario is shown in Figure 4.

Investing on proven CHP-incineration constitutes the optimal strategy in terms of economic efficiency. Higher power generation efficiency and lower emission rates render it the most promising method. Gasification, on the other hand, is not yet a mature technology despite the long-lasting research, and may not seem to be able to compete with the other two. In the case of electricity production, the incineration technology also proves to be the most interesting WTE option due to its higher electrical efficiency and lower investment costs and emission rates. On the other hand the gasification technology constitutes the worst option comprising of negative NPVs over time. Landfill biogas exploitation does not seem to be able to follow the energy market trends, despite its low running and capital costs. The biogas NPVs are also negative in both scenarios of energy production – independently of the investing entry time. Low efficiencies of power and heat production per input unit of MSW fuel are responsible for this poor performance. It is emphasized that biogas exploitation is an environmentally friendly activity that ensures efficient controlling of methane gas generated by landfill reactions. It is believed that oncoming improvements in power (and/or heat) production per input MSW-unit, will lead to much more efficient biogas projects in the near future. In the CHP production scenario, the economic performance of each technology may be significantly improved. District-heating grids based on MSW fuel, may

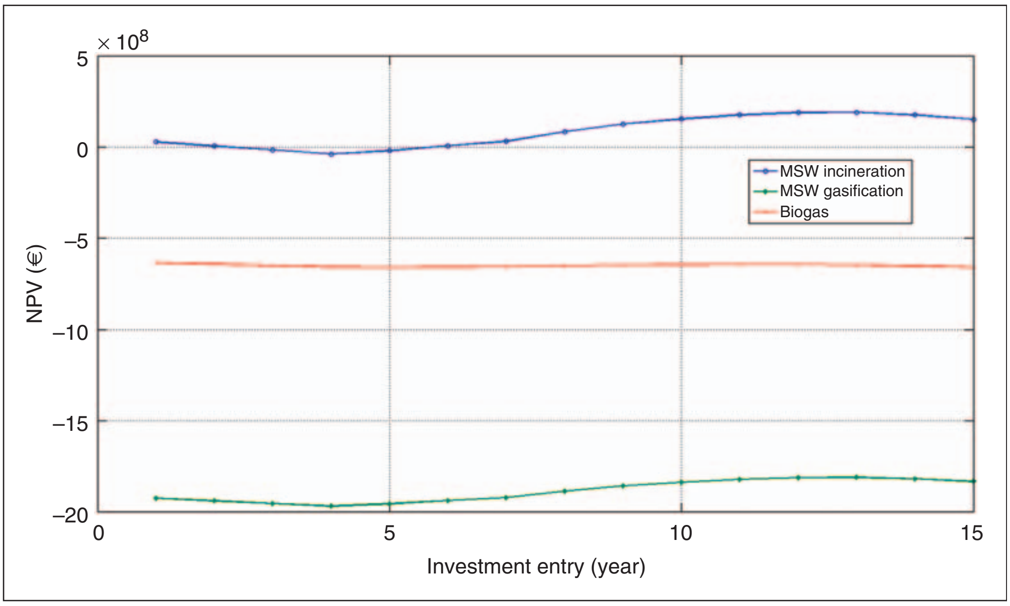

Figure 3. NPV of the competing technologies assuming electricity production.

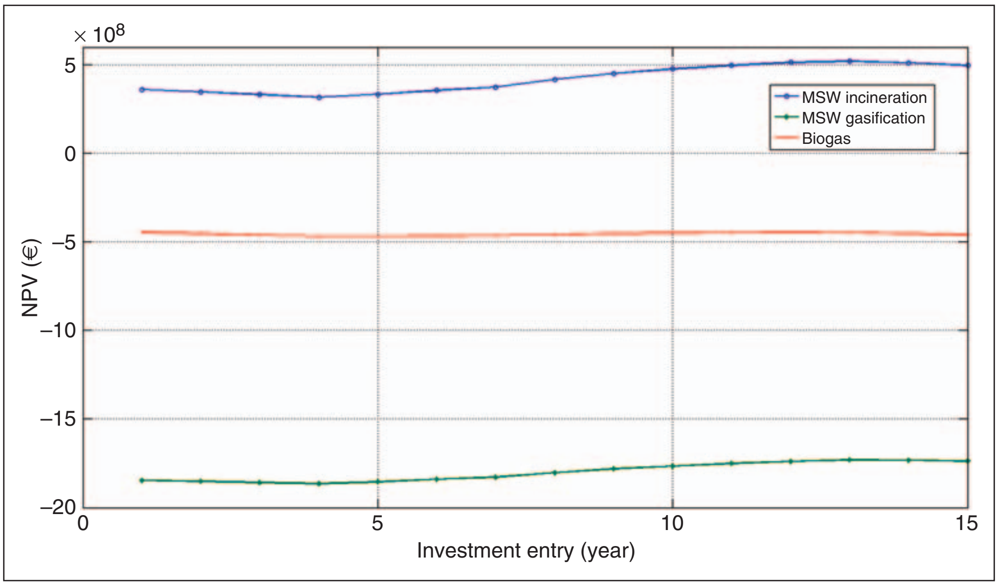

Figure 4. NPV of the competing technologies assuming CHP production.

contribute to additional revenues for WTE-CHP plants. As stated before, an attractive pricing is a pre-requisite for the acceptance of MSW-fired district heating and for the subsequent displacement of the conventional domestic burners.

From the above results an optimal time of investment entry may be identified, based on the stochastic evolution of incomes and expenses. One would expect that the anticipated increasing of electricity prices in the distant future (Figure 2) might necessitate the postponement of the investment decision for more than a decade. From the results obtained, it is concluded that this may be the case for all the examined WTE technologies except from the exploitation of landfill biogas. Its lower power-generation efficiency leads to lower sensitivity on electricity price variations thus resulting to almost constant NPV time-paths. Of particular interest for a potential investor may be the option of immediate investments, which should not be easily rejected. Although the optimal NPVs correspond to investments that may be decided in almost 13 years from today – as indicated by the model and the analysis of the results, the NPVs of immediate investment entries are expected to be slightly lower than the optimal ones. The business strategy of potential investors, the environmental policies, as well as state/EU interventions are among the factors that may necessitate the realization of WTE project plans and may finally determine the time-point of investment decision. It is emphasized that the time-dependent NPVs shown in the Figures 3 and 4 are solely based on the stochastic representation of variables under uncertainty (fuel, CO_2 and electricity prices, interest rates and inflation rates) which in turn depend on their historical data and on their respective statistical parameters.

In the chart of Figure 5 the financial break-down of a WTE project is presented. These results have been obtained for: (a) the optimal investment entry time, (b) the optimal technology selection (MSW incineration and CHP production) and (c) by assuming a 33-year period of operational lifetime. The most important income and expense contributors may be identified. It is noted that the revenues from electricity selling to the grid exceed the respective heat-selling revenues (fossil fuel savings) despite that the electrical efficiency has been assumed to be lower than that of heat production. This may be attributed to the higher electricity (MWh_{el}) prices, compared to the anticipated unitary oil prices (€ $MWhth^{-1}$) shown in Figures 1 and 2.

The anticipated pay-back period for the optimal scenario (CHP production) is presented in the graph of Figure 6. Interestingly, the payback period for incineration seems to vary disproportionally with the NPV over time. This behaviour is justified by the differentiation of the cash flow profile over the operational life, depending on the investment decision time. It is also noted that high pay-back periods should be expected due to very low positive NPV levels, derived for the incineration case. The payback period for biogas and gasification projects is non-computable, due to the negative NPVs expected throughout their operational life (Figures 3 and 4).

It is reminded that stochastic modelling might not be considered to represent the real future evolution of the corresponding stochastic variables. It rather reflects their past behaviour by sampling the induced uncertainties through appropriate probability distributions, determined by recent history. This inherent limitation of stochastic modelling should definitely be accounted during any decision making process.

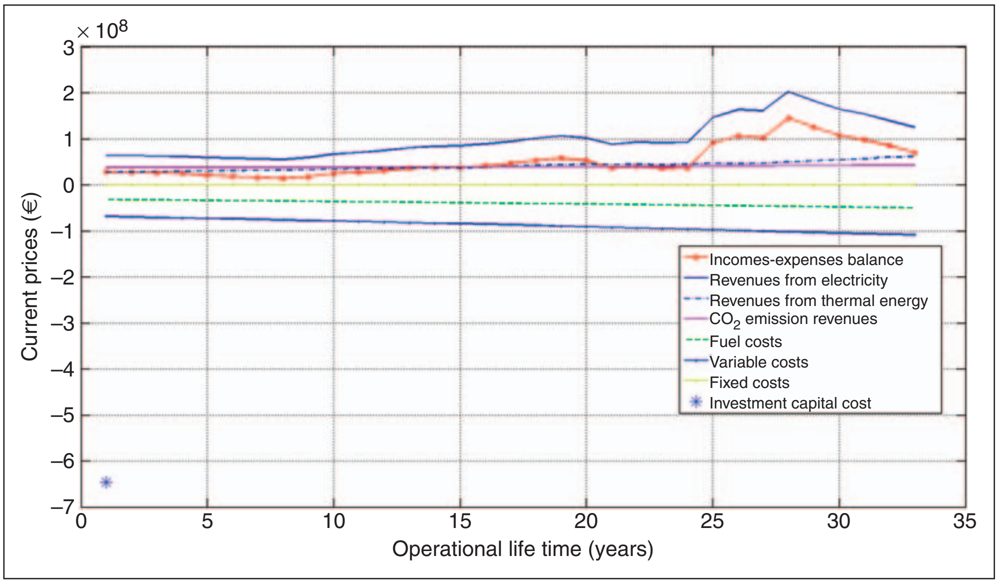

Figure 5. Financial break-down for the project's operational life time assuming optimal investment.

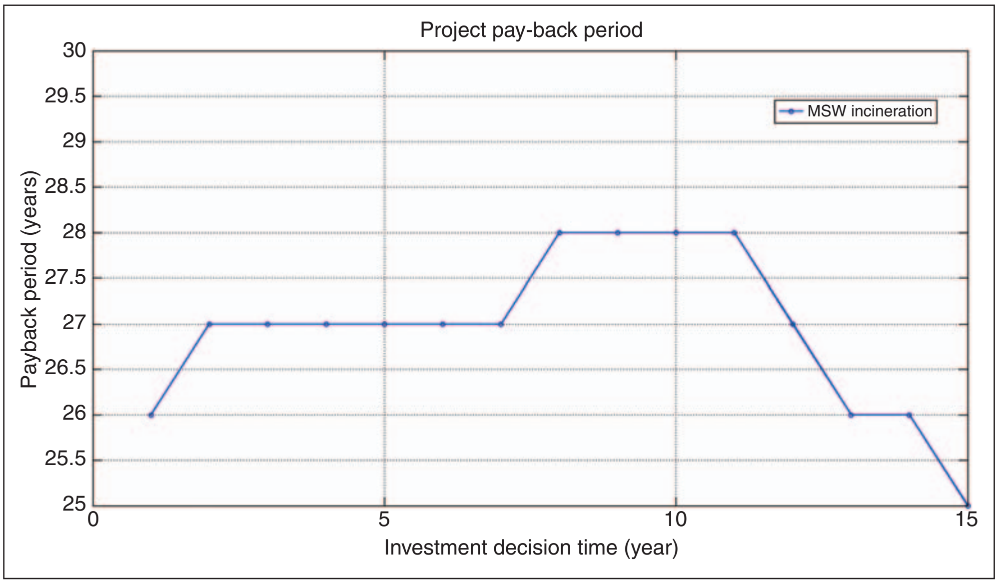

Figure 6. Pay-back period for the optimal investment.

Conclusions

An investigation of three different WTE options has been conducted respecting their long-term economical efficiency. MSW incineration, gasification and landfill biogas exploitation have been compared, either by solely considering electricity production or by assuming combined heat and power production. The comparison was based on a modern investment analysis tool, namely the real options theory, thus forcing the determination of optimal investment strategies over time. Prior to the investment analysis, the stochastic modelling of the introduced uncertainties allowed the simulation of the participating volatile variables: heat production revenues, electricity and CO_2 allowance prices as well as interest and inflation rates, which were used for representing the evolution of running costs and gate fees. The current gate fee has been externally derived in the range of 21–24 € Mg MSW^{-1}. The conclusions from the analysis may be summarized in the following manner.

- The traditional but proven MSW incineration remains the most interesting method of energy recovery from waste- in terms of financial yield, for either electricity or CHP production. The results of the analysis indicated that gasification may not constitute a profitable WTE choice. Moreover, it is not yet a reliable method of MSW energy recovery; several gasification plant failures have been recently experienced in Europe, despite the intensive research focusing on that technology during the last decades. The energetic exploitation of landfill biogas is the second option, but the anticipated yields over time are negative. Nonetheless, the environmental benefits of biogas exploitation render it a crucial requirement for any existing landfill. It should be reminded although, that according to the European environmental policy, landfilling is not considered a sustainable waste treatment option. Therefore, in the proposed model, the landfilling option has been assumed to be the baseline scenario, thus taking into account its significant environmental issues (methane emissions, CO_2 equivalent emissions, leachates etc.).
- CHP is economically a superior option but an existing infrastructure of district heating is a prerequisite. The higher surplus of anticipated yields might probably be invested for promoting such infrastructure.
- Under the current conditions and prices, immediate investments might be reconsidered in favour of future – potentially more profitable – opportunities. If immediate investments are required, the above-mentioned classification of WTE technologies still holds; actually the ranking of the WTE technologies remains the same in the short and medium terms. The incineration technology may be the most attractive technology, but is rather sensitive in the variations of fiscal conditions over time. The gasification is significantly less competitive than incineration but simultaneously it is equivalently sensitive over time.
- The gas trading revenues constitute an important profit factor. The CO_2 allowances generated by assuming landfilling as the baseline scenario, contribute significantly to the financial yields of WTE-CHP projects. The analysis of the incomes through the entire operational life of such projects renders electricity selling revenues as the most important income source followed by CO_2 trading revenues, and district heating incomes, respectively.

Further research is required for investigating additional emerging technologies possibly interesting for WTE projects, like: anaerobic digestion, thermal depolymerization, plasma arc gasification, etc. The real options algorithm described in the present work may contribute to the investment analysis of such planned projects over time, thus leading to interesting policies and strategic WTE interventions.

References

ACMAR Association of Communities and Municipalities of the Attica Region (2009) www.esdkna.gr Accessed 11 September 2009.

Barlow MT (2002) A diffusion model for electricity prices. *Mathematical Finance* 12: 287–298.

Brennan MJ, Schwartz E (1985) Evaluating natural resource investments. *Journal of Business* 58: 135–157.

Clewlow L, Strickland C (2000) *Energy Derivatives: Pricing and Risk Management*. London: Lacima Publications.

Dixit A, Pindyck R (1994) *Investment Under Uncertainty*. Princeton, NJ, USA: Princeton University Press.

Fuss S, Szolgayova J, Obersteiner M, and Gusti M (2008) Investment under market and climate policy uncertainty. *Applied Energy* 85: 708–721.

General Secretariat of National Statistical Service of Greece (2009) www.statistics.gr Accessed 10 September 2009.

Glasserman G (2004) *Monte-Carlo Methods in Financial Engineering*. NY, USA: Springer-Verlag, New York Inc.

Gohlke O (2009) Efficiency of energy recovery from municipal solid waste and the resultant effect on the greenhouse gas balance. *Waste Management and Research* 27: 894–906.

YPAN (Greek Ministry of Development) (2009) www.ypan.gr Accessed 13 September 2009.

Hansen TL, Jansen J, Davidson A, and Christensen TH (2007) Effects of pretreatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. *Waste Management* 27: 398–405.

Hesseling WFM (2002) Thermoselect Facility Report, TNO R2002/126 TNO, Apeldoorn, The Netherlands.

HTSO SA. (2009) Hellenic Transmission System Operator. www.desmie.gr Accessed 08 August 2009.

Ingersoll JE, Ross SA (1992) Waiting to invest: investment and uncertainty. *Journal of Business* 65: 1–29.

Junginger M, Faaij A, and Turkenburg WC (2005) Global experience curves for wind farms. *Energy Policy* 33: 133–150.

Kloeden PE, Platen E (1999) *Numerical Solution of Stochastic Differential Equations*. Berlin, Germany: Springer.

Laurikka H, Koljonen T (2006) Emissions trading and investment decisions in the power sector – a case study in Finland. *Energy Policy* 34: 1063–1074.

Luoranen M, Horttanainen M (2007) Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system. *Waste Management and Research* 25: 426–439.

Luoranen M, Horttanainen M (2008) Co-generation based energy recovery from municipal solid waste integrated with the existing energy supply system. *Waste Management* 28: 30–38.

Murphy JD, McKeogh E (2004) Analysis of energy production from municipal solid waste. *Renewable Energy* 29: 1043–1057.

Øksendal B (2000) *Stochastic Differential Equations*. Berlin, Germany: Springer-Verlag.

Papageorgiou A, Barton JR, and Karagiannidis A (2009) Assessment of the greenhouse effect impact of technologies used for energy recovery from municipal waste: A case for England. *Journal of Environmental Management* 90: 2999–3012.

PointCarbon (2009) Carbon Market Indicator. http://www.pointcarbon.com Accessed 12 August 2009.

Reimann D (2009) *CEWEP Energy Report II (Status 2004–2007)*. Bamberg, Germany: Confederation of European Waste to Energy Plants.

Rentizelas A, Tolis A, and Tatsiopoulos I (2009) Biomass district energy trigeneration systems: emissions reduction and financial impact. *Water, Soil and Air Pollution Journal: Focus* 9: 139–150.

Rubin ES (2007) Learning rates and future cost of power plants with CO_2 capture. IEA International Workshop on Technology Learning and Deployment June 11 2007, OECD/IEA 2007, Paris, France.

Shreve R (2004) *Stochastic Calculus for Finance II: Continuous-Time Models*. New York, USA: Springer-Verlag.

Tatsiopoulos I, Tolis A (2003) Economic aspects of the cotton-stalk biomass logistics and comparison of supply chain methods. *Biomass and Bioenergy Journal* 24: 199–214.

Trigeorgis L (1996) *Real Options*. Cambridge, MA, USA: The MIT Press.

Tsilemou K, Panagiotakopoulos D (2006) Approximate cost functions for solid waste treatment facilities. *Waste Management and Research* 24: 310–322.

Tuhkanen S, Pipatti R, Sipilä K, and Mäkinen T (2000) The effect of new solid waste treatment systems on greenhouse gas emissions. In Greenhouse Gas Control Technologies. Proceeding of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5), pp. 1236–1241. CSIRO Publishing, Collingwood, Victoria 3066, Australia.

Williams P (2005) Waste Treatment and Disposal, *2nd edn*. Chichester, UK: John Wiley & Sons Ltd.