Decisions Under Uncertainty in Municipal Solid Waste Cogeneration Investments

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Abstract The issue of Municipal Solid Waste (MSW) management is an ever increasing problem for all countries. Developed countries face the problem of dealing with very large amounts of MSW per capita, forcing them to develop new technologies and systems. On the other hand, countries with developing or transitional economies may generate lower amounts of MSW per capita, but the rate of increase is high and the current practices of MSW management are not as advanced as those of developed countries. Therefore, countries with developing or transitional economies may benefit from adopting MSW management technologies used by developed economies. One aspect of MSW management in developed economies is the energy recovery from MSW. The advantages of this type of technologies are mainly the significantly reduced waste volume for landfilling, the reduction of total greenhouse gas emissions, the potential for generating electricity or co-generation of electricity and heat. In this work, a comparative study of the most prominent co-generation technologies using MSW as a fuel source is presented, focusing on the evolution of their economical performance over time. An algorithm based on real-options has been applied for four technologies of MSW energy recovery: (1) incineration, (2) gasification, (3) landfill biogas exploitation using a pipeline system and (4) anaerobic digestion facilities. The financial contributors are identified and the impact of greenhouse gas trading is analyzed in terms of financial yields, considering landfilling as the baseline scenario. The greenhouse gas trading system presents an opportunity for investing in environmentally friendly technologies for MSW energy recovery, through the Clean Development Mechanism (CDM), in most developing countries. The results of this

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A. Karagiannidis (ed.), *Waste to Energy*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2306-4_8, © Springer-Verlag London Limited 2012

work indicate an advantage of combined heat and power over solely electricity generation. The most attractive technology among the ones examined proves to be incineration, mainly due to its higher power production efficiency, lower investment costs and lower emission rates. Despite the fact that 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.

1 Introduction

The management of Municipal Solid Waste is a major issue worldwide, though its characteristics vary among developed countries and developing or transitional ones. Developed countries face mainly the problem of dealing with very large amounts of MSW per capita, forcing them to develop new technologies and systems. On the other hand, countries with developing or transitional economies may currently generate lower amounts of MSW per capita, but the rate of increase is high and the current practices of MSW management are not as advanced as those used in developed countries. Therefore, countries with developing or transitional economies may benefit from adopting MSW management technologies used by developed economies. The application of appropriate MSW management techniques constitutes an important component of sustainability and environmental protection for every country. The most important issues confronted in planned or operational waste management projects span among social acceptance, economic efficiency, organizational matters and water, soil and air pollution.

Various policies for Municipal Solid Waste management are implemented world-wide like recycling, composting and low enthalpy treatments, which are characterized by eco-friendly properties. Despite their proven environmental benefits though, not much evidence has been available regarding their efficiency and social adoption in big cities with high population density and rate of increase. On the other side, environmental experts agree that the goals set for the waste utilization rate would never be achieved without energy recovery [22]. The advantages of energy recovery from waste are mainly the significantly reduced waste volume for landfilling, the reduction of total greenhouse gas emissions, the potential for generating electricity or co-generation of electricity and heat. Furthermore, waste exists in all countries, societies and communities. This fact implies that if waste could be used to generate electricity—and potential heat—it is mostly the communities in developing countries that do not have currently access to electricity grid that would benefit from this application and would ameliorate their living conditions.

Innovative Waste-to-Energy (WtE) technologies have recently emerged, showing interesting characteristics compared to older but proven ones. However, the risk of investing in such innovative technologies might lead to the postponement of similar projects funded by private funds unless safer fiscal conditions are ensured. Moreover, interventions on environmental policies may change the relevant legal status thus further increasing uncertainty and complicating future strategies and decision making.

The management of waste is responsible for a significant amount of carbon emissions worldwide, due mainly to logistics and waste fermentation. The Kyoto protocol and the associated directives of European Union 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 CO_2 emissions, having the option to act in another country to reduce CO_2 emissions. The Clean Development Mechanism has been established, allowing some flexibility for Annex I parties (developed economies) to reduce their carbon emissions, by performing environmentally friendly investments in developing countries. Within this framework, investments that allow environmentally friendlier waste management in developing countries may be eligible for CDM funding, thus ensuring en extra revenue stream for these projects.

Markets have 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 sold to the grid as well as the electricity demand may also present a volatile behavior. Moreover, the prices of fuels may induce additional uncertainties in energy markets: On the one hand they constitute volatile cost factors, but 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 with the volatile CO_2 allowance prices. From the above described rationale, it may 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 inquired for investments under multiple uncertainties. Project planning should thus focus not only on logistical or production-related considerations but also on strategic decisions like 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, many parameters such as 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 WtE market may not be limited to the selection of an appropriate technology but they may 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 large city with high population density and increasing rate of MSW disposal. The inputs of the case study presented come from the city of Athens, Greece. Despite the fact that Greece belongs to the developed countries group, its waste management system is mainly based on landfilling with low rates of recycling and no energy recovery from waste, thus having different structure from most West-European countries. Therefore, the results obtained from this study may be similar to applications in developing or emerging economies, where waste management is mainly or entirely based on landfilling.

The scope of the study is to compare from an economic point of view four competing methods of combined heat and power (CHP) production based on MSW: (1) incineration, (2) gasification, (3) landfill biogas combustion considering gas supply through a pipeline system and (4) anaerobic digestion. The major milestones of the study are to analyze the cost structure and identify the impact of greenhouse gas trading on MSW-CHP projects. 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 is the determination of the optimal investment entry times for each one of the competing technologies, and the identification of the most promising technology among the ones examined.

The rest of the work is organized as follows: In Sect. 2, a literature survey is given. In Sect. 3, a description of the case study is provided, followed by the mathematical formulation of time dependent CHP investments. The description of the model inputs and parameters is provided in paragraph 4. Section 5 includes the results of the model as well as analytical, explanatory comments. In Sect. 6 the sensitivity of the model proposed is investigated in respect of the assumed MSW price profile over time. Finally, in Sect. 7 the conclusions of the study are summarized.

2 Relevant Studies in Recent Literature

2.1 Waste Management in Developing Countries and Transitional Economies

Many researchers report on the status of waste management in developing countries. Despite the fact that every country has its own particular conditions, it is a common finding that in the majority of developing countries, waste management systems suffer from lack of appropriate infrastructure, which results in low rate of MSW collection and environmental hazards. According to Onu [28], solid waste management in developing countries is characterized by highly inefficient waste collection practices, variable and inadequate levels of service due to limited resources, lack of environmental control systems, indiscriminate dumping, littering and scavenging and poor environmental and waste awareness of the general public. In the work of Parrot et al. [30], the MSW management in Yaoundé, Cameroon is analyzed. The main characteristics of the system are the lack of even basic infrastructure (bins), the high population growth—and consequently growth of the MSW quantities–, the very low recycling rate, reported as about 5%, and the use of dump sites as a disposal facility, without any type of treatment for the MSW. It is also interesting that the authors acknowledge a low rate of about 40% of MSW collection, which is even lower in a large number of neighboring countries. In a similar vein, Troschinetz and Mihelcic [39] report a recovery rate from 5 to 40% for a study in 23 developing countries. The relationship between MSW generation and income varies with respect to the developmental stage of a nation. As a country develops, its waste generation rate increases. In contrast, a weak correlation exists between income and waste generation for middle- and upper-income countries, and waste generation actually decreases in the wealthiest countries [24].

The Clean Development Mechanism has already been used for funding projects for improving Municipal Solid Waste management in developing countries. According to the work of [41], it is interesting to note there were already 119 energy recovery from MSW projects examined in the frames of the CDM mechanism, out of which 88 projects involved generation of electricity that is supplied to the grid, which is also the case examined in this work. Furthermore, the authors acknowledge the very low standard of landfills in India and the need to improve it. Similarly, Barton et al. [3] examine the options for funding MSW management projects in developing countries, through the CDM mechanism. In their work, they evaluate the greenhouse gas emissions reduction achieved by applying several MSW management methods, such as landfilling (passive venting, gas capture with flaring) and composting of the digestate, together with two waste-to-energy options: landfill gas capture with electricity generation and composting and anaerobic digestion with electricity production. The authors conclude that there is a significant opportunity for developing CDM projects to attract investments in developing countries for improving waste management infrastructure. Energy exploitation of waste has been also examined in the past, i.e. in [7, 9, 23], but mainly in areas with lack of space for landfills, such as in the work of Kathirvale et al. [19] for Malaysia.

2.2 The Competing Waste-to-Energy 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 four different technologies will be investigated: (1) MSW Incineration, (2) MSW gasification, (3) landfill biogas (LFG) exploitation through pipelines and (4) anaerobic digestion. Moreover, two energy product scenarios will be compared:

(a) Only electricity is produced. (b) Combined Head and Power production. It is emphasized that a district heating infrastructure is not available in the case study city (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 newly built projects for electricity production seem to be more efficient, compared to older installations: WtE plant MKW Bremen with efficiency of 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% whilst 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 [42]. In the so-called Mass Burn Incinerators (MBI), the thermal energy generates electricity through steam turbines. When Combined Heat and Power is the case, the residual heat is recovered for district heating, hot water supply etc. [29].

Gasification may theoretically produce electricity at an efficiency of about 27% and heat at about 24% [26]. This would suggest that gasification of MSW is competing with incineration. However, in practice, 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 faced technical problems, whilst the average electrical efficiency noticed in Japanese installations is not more than 10% [12]. In the report of the Thermoselect project in Karlsruhe [15] it is stated that no more than 0.56 MWel/tMSW 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 [14]. In the present case-study, the methane-enriched stream is utilized for either electricity conversion or CHP production by natural gas engines. The case of anaerobic digestion is also investigated assuming multiple decentralized installations being able to handle the entire annual MSW quantities.

2.3 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 stochastic variables like demand and prices. Among the various contributions on real-options theory, one may distinguish the studies of Brennan and Schwartz [4], Dixit and Pindyck [6] and Trigeorgis [37].

The effects of combined uncertainties in climate policy interventions have been investigated in Fuss et al. [8] and Laurika and Koljonen [21] and optimal investment timing decisions were sought. In the above mentioned works, 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 work 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 to the GBM models as they are characterized by normally distributed samples of Brownian differentials [27, 35]. However, their behavior is mean-reverting according to the Ingersoll-Ross models through which positive projections are ensured [17]. The solution of the above mentioned stochastic evolution models is based on Euler simulators [20] but subsequently a Monte-Carlo algorithm [11] is used to produce multiple solution sets and average them to a final projection output.

3 Methodological Approach

3.1 The Case Study

The present study investigates 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 for the case study region are comprised of the MSW disposal rate in Athens, which is currently estimated to be close to 6,500 t/day, with a current -annually increasing- rate of approximately 3% as recorded by ACMAR [1] and a relatively low percentage (13%) of MSW, which is recycled on source. The recycled percentage of disposed MSW is currently increasing by 1.5% each year [10].

In order to ensure long-term availability of the fuel source, a small portion of the totally available quantity of MSW will be used for energy exploitation, to account for potentially successful recycling campaigns in the future. It is therefore assumed that for the entire examined time horizon (50 years) an amount of 1.300.000 t/a will be available for WtE projects, as if the current increasing rate of the recycled MSW portion would hold for 50 years. Therefore, in the present case-study, this MSW supply rate determines the annual energy production of the hypothetical WtE plant. As stated before, four different WtE technologies will be investigated: incineration, gasification, biogas exploitation from landfills using pipelines and anaerobic digestion units. Two scenarios of energy production will be examined, i.e. electricity production and alternatively CHP production. A pre-sorting facility is assumed to separate recyclable materials from the non-recyclable portion of MSW, which is utilized for energy conversion. The baseline scenario considers 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 has been 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 historical time-series. The determination of the statistical parameters (drift, volatility and correlation) needed for the GBM representation of the stochastic variables' evolution [5] was based on recent historical data. An Euler solver and a Monte-Carlo simulation sub-routine 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 [18, 34]. 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 one-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 are therefore created as a function of time. The optimality was determined numerically by selecting the maximum NPV from the oncoming decision period.

3.2 Problem Formulation

The experience accumulated during the last decades on the construction of power production units is reflected in the investment costs, which may be mathematically formulated through global learning curves according to Eq. 1:

$$I_{i,t} = I_{i,0}\left(\frac{GQ_{i,t}}{GQ_{i,0}}\right)^{\log_2(LR_i)} \qquad \forall i \tag{1}$$

where $LR_i = 1 - b_i \, \forall i$

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). $GQ_{i,t}$ denotes the globally installed capacity of technology (i) at the time point (t).

The problem includes the following two agents:

- a developing or transitional electricity market in which fuel, CO_2 allowance and electricity prices follow a GBM generated path. The SDE that describes this process is represented by Eq. 2:

$$d\mathbf{Y}_t = \mu(t) \cdot \mathbf{Y}_t dt + D(t, \mathbf{Y}_t) \cdot \mathbf{V}(t) d\mathbf{W}_t \tag{2}$$

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

- potential WtE investors, planning to engage in WtE projects.

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 one-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 Eq. 3, which represents the annual financial balance $E(z)$:

$$\begin{gathered} E(z) = P_{el} \cdot C \int_0^{365} F(t)dt + P_{th} \cdot H \cdot \int_0^{365} F_{th}(t)dt + \int_0^{365} F_{CO_2}(t)dt \\ \forall z \in \left[v + C_{t,i}, v + C_{t,i} + O_{t,i}\right] \end{gathered} \tag{3}$$

where (P_{el}) and (P_{th}) denote the electricity and heat capacity of the planned energy conversion system, while (C) and (H) denote the power and thermal capacity coefficients, which are the percentage of operational time within a year respectively. The cost-terms inside the two first integrals of Eq. 3 are expressed in Euros 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 network, thus allowing significant fossil fuel savings. Therefore, a second integral is included in Eq. 3 corresponding to the revenues from the heat sales ($F_{th}(t)$).

Obviously the second integral is accounted only in the CHP case whilst 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}):

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

The F_{co_2} term in Eq. 3 represents the daily revenues from the greenhouse gas emission trading:

$$F_{CO_2}(t) = f_{CO_2}(t) \cdot Ef \cdot \dot{Q}_{MSW}(t) \qquad \forall t \in [0, 365], \forall z \tag{5}$$

Where $F_{CO_2}(t)$ denotes the daily CO_2 allowance prices, simulated by Eq. 2 (shown in Fig. 2). $\dot{Q}_{MSW}(t)$ denotes the daily MSW supply rate, which in the present case-study correspond to 1.300.000 t/a or equivalently 3,560 t/day. The differential time (dt) equals to one-day interval. The utilized emissions factor, denoted by Ef is explained in detail in paragraph 4.1 (Eq. 8). By accounting Eqs. 3, 4 and 5 becomes:

$$\begin{aligned} E(z) = {} & P_{el} \cdot C \cdot \int_{0_t}^{365} (f_{el} - f_{MSW} - f_r)(t)dt + P_t h \cdot H \cdot \int_{0}^{365} F_{th}(t)dt \\ & + \int_{0}^{365} f_{CO_2}(t) \cdot |Ef| \cdot \dot{Q}_{MSW}(t)dt \forall z \in [v + C_{t,i},\ v + C_{t,i} + O_{t,i}] \end{aligned} \tag{6}$$

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 modeled by the stochastic differential Eq. 2. Especially for the heat production revenues $F_{\mathrm{th}}(t)$, it was assumed that an attractive pricing strategy has been adopted (equal to 75% of the 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 policy assumption.

The annual integrals of Eq. 6 are given in nominal prices, but they are further converted to present values (PV), using the stochastically evolving interest rates modeled by a mean reverting derivative of the SDE described in Eq. 2. 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 Eq. 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 Eq. 1, whilst (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($NPV_{i,v}$)].

4 Setup of the Numerical Algorithm

4.1 Input Data of the Model

The historical data of actual loads and electricity system marginal prices (SMP) were acquired by the Hellenic Transmission System Operator [16]. 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 Statistical Service [10]. CO_2 allowance prices were retrieved by Point Carbon [31] whilst heating oil prices were acquired by the Greek Ministry of Development [13].

The net calorific value of the non-recyclable portion of the MSW used for energy conversion is assumed to be 10 GJ/tMSW or 2.8 MW_{th}/tMSW [32], which is assumed to remain constant over time. The complete set of techno-economical inputs is presented in the following Table 1. The data correspond to 1.300.000 t 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 Gohlke [12], Hesseling [15], Murphy and McKeogh [26]. The investment and operational costs (either running or fixed costs) were retrieved by the study of Tsilemou and Panagiotakopoulos [38].

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. This rationale is analytically formulated in Eq. 8, which provides the emission saving factors of Table 1:

$$Ef = -e \cdot Ef_e - h \cdot Ef_h + Ef_p - Ef_{lf} \tag{8}$$

where, e and h denote the electricity and thermal production per fuel unit respectively, whilst 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.

Table 1 Model inputs for electricity and CHP production

WtE process of MSW	Power generation capacity (MW_{el})	Investment costs (for 2009) (€/tMSW/a)	Efficiency El. only or El.//Th. (%)	CO_2 emissions ($tnCO_2$/tMSW)	Fixed costs (€/kW/a)	Running costs (€/tMSW)	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		
Anaerobic digestion (electricity only)	95	125	22	−1.69	1.2	40	0.05
Anaerobic digestion (CHP)	60		13//19	−1.74	2.1		

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

The source for the Ef_e, Ef_h values was the study of Rentizelas et al. [33]. *e*, *h* and Ef_p values were acquired by processing the numerical data reported in Gohlke [12], Hesseling [15], Moller et al. [25], Murphy and McKeogh [26] and Papageorgiou et al. [29]. Finally, the Ef_{lf} data have been retrieved by Tuhkanen et al. [40].

4.2 Stochastic Analysis

The simulation of the stochastic variables resulted to the MSW and oil prices evolution shown in Fig. 1 as well as to the CO_2 allowance and electricity price forecasts shown in Fig. 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 whilst on the other hand the evolutions of oil and electricity prices are mean-reverting, despite their GBM modeling. This behavior is in line with past relevant studies [2]. The results of the CO_2 allowance price representation are based on recent data and therefore, not enough experience has been gathered concerning its behavior within this newly born market. Also, it has to be noted that the future projections shown in Figs. 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 modeled evolution paths.

Concerning the evolution path of MSW gate-fees, a starting point is required. This is based on its current (2009) value, derived from a holistic reverse-logistics algorithm [36] which in turn utilizes activity based costing methods. The entire supply chain is taken into account, including collection, transportation, warehousing, handling and treatment activities. The resulting range was approximated between 21 and 24 Euros/tMSW, which is close to gate-fee calculations retrieved from the literature [26, 29]. 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 Eq. 2. 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 [26] and Tsilemou and Panagiotakopoulos [38]. Due to the uncertainty of the logistical—activity based—calculation of gate-fee, a sensitivity analysis is conducted in order to investigate the sensitivity of the model in this crucial parameter. The lower and upper price bounds, shown in the MSW graph (Fig. 1-up) indicate the limits of the above mentioned analysis.

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	Emission savings due to fossil thermal plant displacement	CO_2 emissions of the process	Landfill emissions
(Symbol) Unit	(e) MWh_{el}/tMSW	(h) MWh_{th}/tMSW	(Ef_e) tCO_2/MWh_{el}	(Ef_h) tCO_2/MWh_{th}	(Ef_p) tCO_2/tMSW	(Ef_{lf}) tCO_2/tMSW
Incineration (Electricity only)	0.8	0	0.876	0	0.28	1.6
Incineration (CHP)	0.6	1.2		0.27	0.28	
Gasification (Electricity only)	0.53	0		0	0.28	
Gasification (CHP)	0.33	0.7		0.27	0.28	
Landfill biogas (Electricity only)	0.2	0		0	0.35	
Landfill biogas (CHP)	0.2	0.3		0.27	0.35	
Anaerobic digestion (Electricity only)	0.5	0		0	0.31	
Anaerobic digestion (CHP)	0.35	0.5		0.27	0.31	

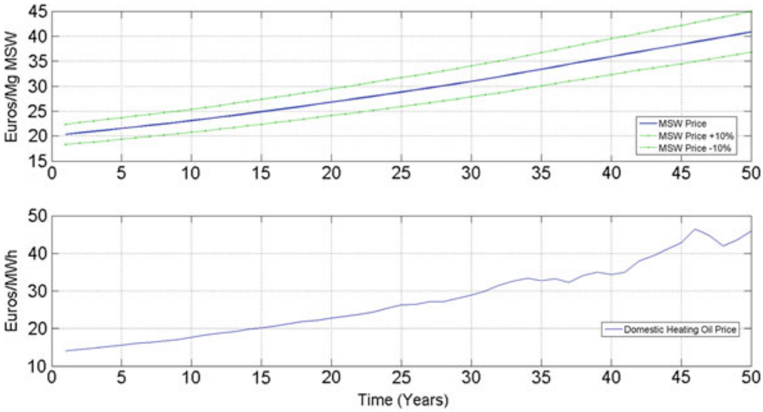

Fig. 1 Forecasting of MSW (*up*), and heating oil (*down*) prices

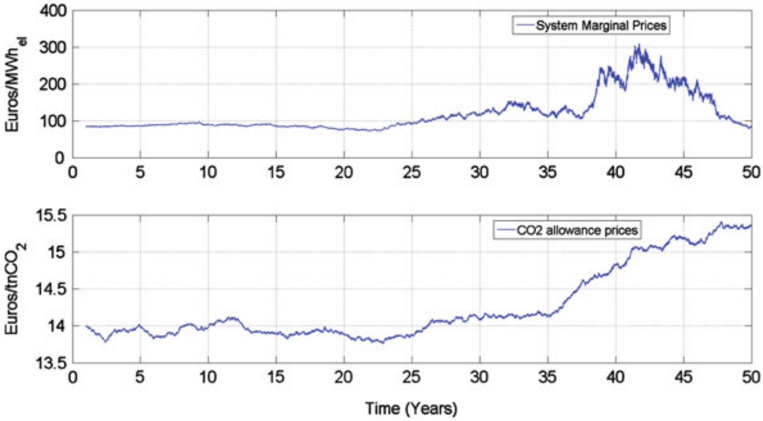

Fig. 2 Forecasting of electricity (*up*) and CO_2 allowance (*down*) prices

5 Model Results

The NPV comparison of the investigated technologies for the scenario of electricity production is presented in Fig. 3 while the corresponding NPV comparison for the CHP scenario is shown in Fig. 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 does not seem to be able to compete with the other options. In the case of electricity production, the incineration technology also proves to be the most interesting WtE option due to

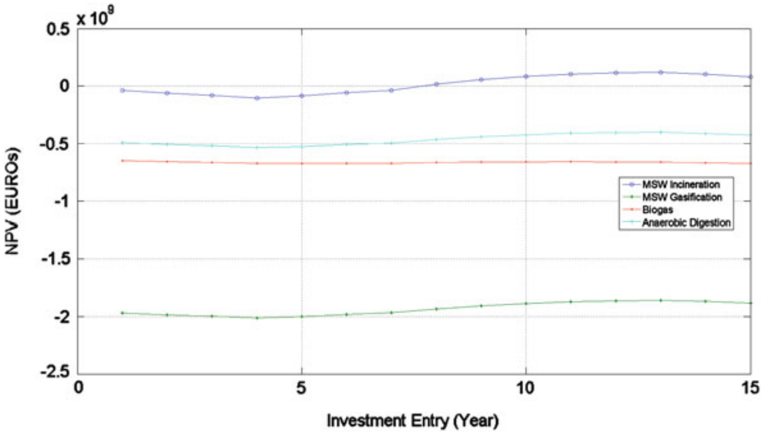

Fig. 3 NPVs for electricity production

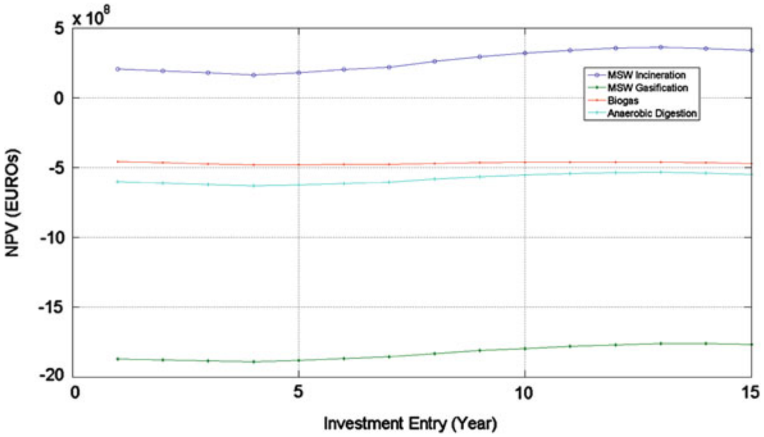

Fig. 4 NPV for CHP production

its higher electrical efficiency and lower investment costs and emission rates. On the other hand the gasification technology comprises of negative NPVs over time and therefore will probably fail to gain a considerable market share in the next years. Landfill biogas exploitation (pipeline gas supply) does not seem to be able to follow the energy market trends, despite its low running and capital costs.

The resulting NPVs are also negative in both scenarios of energy production—either power or CHP 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. The anticipated yields of anaerobic digestion and landfill biogas exploitation through pipelines, are quite similar. The low efficiencies of power and heat production render anaerobic digestion a non profitable WtE option. Negative NPVs (close to the NPVs of landfill gas exploitation) characterize this technology too. Moreover, the heat production efficiency is very low thus resulting to slightly lower NPVs compared to those of solely power production. This result characterizes anaerobic digestion whilst the economic performance of the remaining technologies may be significantly improved by considering CHP production. District heating networks based on MSW fuel, may 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 (Fig. 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 in 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 Figs. 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 Fig. 5 the financial break-down of a WtE project is presented. These results have been obtained for: (1) the optimal investment entry time, (2) the optimal technology selection (MSW incineration and CHP production) and (3) by assuming a 33-year period of operational life-time. 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 (€/MWh_{th}) shown in Figs. 1 and 2.

It is reminded that stochastic modeling might not be considered to represent the real future evolution of the corresponding stochastic variables. It rather reflects their

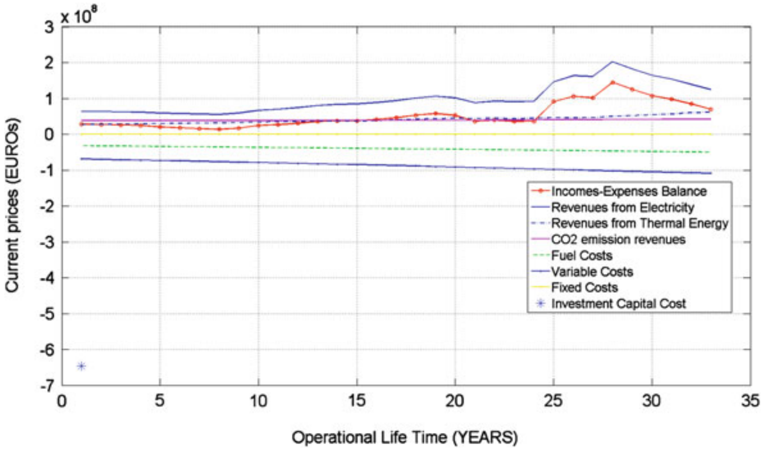

Fig. 5 Financial break-down for the project's operational life time for optimal investment entry

past behavior by sampling the induced uncertainties through appropriate probability distributions, determined by recent history. This inherent limitation of stochastic modeling should definitely be accounted during any decision making process.

6 Sensitivity Analysis

The model has been analyzed in respect of its sensitivity in the MSW price variations. More specifically, the optimal NPV, the optimal investment entry time as well as the payback period are calculated for various MSW projection paths in the range (−10, +10%) compared to the original MSW price path. The results are shown in the following Fig. 6.

Concerning the anticipated yields (NPV) the model is sensitive enough but—on the contrary—the optimal investment entry and the payback periods are slightly influenced by MSW price variations. The investment entry is clearly insensitive as the imposed quantitative variations of MSW price modify homogeneously its projection profile over time. The payback periods are slightly reduced as the MSW price reduces, thus indicating a weak sensitivity which in turn may be explained by the small proportion of MSW logistical costs as compared to the other expense streams.

7 Conclusions

An investigation of four different WtE options has been conducted in respect of their long-term economical efficiency. MSW incineration, gasification, landfill biogas exploitation and anaerobic digestion have been compared, either by solely

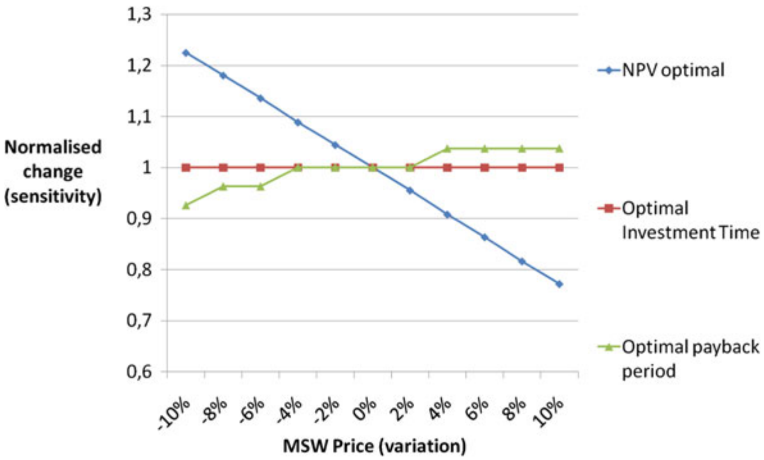

Fig. 6 Sensitivity of the model in the MSW price

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 modeling 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 Euros/tMSW. The conclusions from the analysis may be summarized as follows:

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 under the assumptions made. 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-either with pipeline systems or by using anaerobic digesters- fails to prove its efficiency as long as they present negative financial yields over time. Nonetheless, the environmental benefits of biogas exploitation render it a crucial requirement for any existing landfill. It should be reminded though, 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 network 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 favor 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 model presented is sensitive in the variations of MSW price, provided that the sensitivity criterion relies on the anticipated NPVs over time. The payback period and the optimal investment entry times present either a slight or zero sensitivity respectively, thus indicating a weak dependence on MSW price variations.

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: thermal depolymerisation, 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.

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