MATHEMATICAL MODEL FOR EVALUATION OF COST-EFFECTIVENESS OF WASTE TREATMENT TECHNIQUE WITH ENERGY RECOVERY

by

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A cost-effectiveness of a specific waste treatment technique is very important factor when making the decision to invest in a waste treatment facility. Waste treatment can bring economic benefit through the value of product: recycled materials, the compost, the generated electricity, or heat. However, the expected economic benefits depend on many factors: the investment costs and operating costs of the waste treatment facility, revenues, the market price of the product obtained by waste treatment etc. The investment and operating costs and the revenue also depend on the amount of treated waste. This paper presents a mathematical model for evaluation of cost-effectiveness in the waste treatment technique with energy recovery depending on the amount of waste, i. e. evaluation the minimum amount of waste to be treated for a cost-effective waste treatment technique with energy recovery. To develop the mathematical model, a socio-economic analysis was used. The model is applied to calculate the lower limit of cost-effectiveness in the waste treatment techniques with energy recovery: incineration and anaerobic digestion, in the city of Nis, Serbia, as a case study. The obtained results show that the amount of waste currently generated in the city of Nis is not sufficient for the cost-effective incineration treatment, but with the currently available amount of waste, anaerobic digestion is the waste treatment that can be operated without losses in the city of Nis.

Key words: *waste treatment technique with energy recovery, cost-effectiveness, socio-economic analysis, costs, revenues*

Introduction

Many criteria should be taken into consideration in the selection of waste treatment technique. Since the criterion of economic return on investment is one of the most important for the investors, but also for the local authority, it is necessary to correctly predict all costs (investment and operating) that are related to specific waste treatment, and also to assess revenues. However, there are a number of factors that affect the cost-effectiveness of waste treatment. One of them is the amount of waste that generated on the considered territory. Adequate budgeting, cost accounting, financial monitoring, and financial evaluation are essential

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to the effective management of solid waste systems. In many cities, however, officials responsible for municipal solid waste management do not have accurate information concerning the real costs of operations [1]. In order to provide a more accurate determination of the waste treatment costs, in the literature can be found several methods: unit cost method, benchmarking, and cost functions [2].

Different research has been done in order to determine waste treatment costs and revenues and different method has been used. To provide comparative assessment of alternative management solutions for municipal solid waste the unit cost method was used [3]. Other authors also used the unit cost method to do the techno-economic assessment of recycling practices of municipal solid waste in Cyprus [4]. In order to do the technical, economic, and environmental analysis of biogas utilisation Marphy *et al.* [5] used the unit cost method. To develop the model for evaluation of cost effectiveness of recycling other authors also used the unit cost method [6]. Benchmarking method was used for environmental and economic analysis of waste disposal options for traditional markets in Indonesia [7]. Cost function method was also quite often used in literature. To provide techno-economic data and information useful for the development of strategic waste management plans, some authors used cost function method [8]. Other authors developed and presented cost function of solid waste treatment and disposal facilities relevant to European states [9]. In order to do the social cost-benefit analysis of waste-to-energy in the UK, Jamasb and Nepal [10] also used cost function method. The same method was used in economic comparison of composting and anaerobic digestion of biodegradable municipal waste [11]. Estimating cost functions is suggested as an improved cost planning method in developing countries [12]. Cost functions are also used in comparative techno-economic analysis of waste and biomass powered combined heat and power district heating plant [13].

In this paper, the mathematical model for evaluation of cost-effectiveness of waste treatment techniques with energy recovery is presented. The model was developed to assess the profitability of waste treatment and to find the minimum amount of waste to be treated for a cost-effective waste treatment technique with energy recovery. The model is based on the analysis of the structure of investment and operating costs for each waste treatment and supported by the data available in the field and in the literature. The model is flexible since it contains variables that depend on the specific economic conditions in the territory. The developed model is verified in the case study the city of Nis. Two scenarios of waste management with energy recovery were selected and examined. The cost data that do not exist in Serbia, due to the underdeveloped system of waste management, are taken from the EU and countries in the region.

Materials and method

Technology description

Waste incineration

Solid waste incineration is a highly complex technology, which involves large investments and high operating costs. Several types of incineration technologies are available today: mass burn, rotary kilns, and fluidized bed incineration [14]. However, an incinerator with energy recovery will comprise the following key elements: waste reception and handling, combustion chamber, energy recovery plant, emissions clean-up for combustion gases and bottom ash handling, and air pollution control residue handling.

Mass burning technologies are applied for large-scale incineration of mixed or source-separated municipal and industrial waste. It is technically robust and able to accommodate large variations in waste composition and heating value. The main advantages are that it is a well proven technology that can accommodate large variations in waste composition and in heating values and can be built in very large units (up to 50 t/h). The main disadvantage is relatively high investment and maintenance costs: the investment costs range considerably from 560-1030 € per ton, while the operating costs range from 28-67 € per ton [15]. The main advantages of the rotary kiln are similar, except that the maintenance is slightly higher and the energy efficiency slightly lower and may not exceed 80%. A main disadvantage of the fluidized bed incinerator is the usually very demanding pre-treatment. The capital and maintenance costs are relatively low.

The standard approach for the recovery of energy from the incineration of MSW is to utilize the combustion heat through a boiler to generate steam. An energy recovery plant is commonly referred to as a combined heat and power (CHP) Plant. An incinerator exclusively producing heat can have a thermal generating efficiency of around 80-90%; this heat may be used to raise steam for electrical generation at approximately 17-30% gross efficiency. Net electrical efficiencies are often cited up to ~27% for incinerators recovering electricity only [16]. Electricity can easily be supplied into the national grid and therefore sold and distributed. In contrast, heat will need to be used locally near the incinerator. The heat will therefore be dependent on identifying and establishing a local need.

Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process producing biogas through the biodegradation of organic material in the absence of oxygen with anaerobic microorganisms. More widespread uses of anaerobic digestion include: co-digestion of organic fraction of municipal solid waste (OFMSW), digestion of sludge from wastewater treatment plants, manure, and industrial wastewater with high content of organic matter [17]. The systems for anaerobic digestion can be divided technologically according to four characteristics of the digestion process: dry/wet digestion; thermophilic/mesophilic digestion; one-stage/two-stage digestion, and one-phase/two-phase digestion. The digestion temperature is 20-40 ºC for mesophilic or 50-65 ºC for thermophilic digestion [18]. The thermophilic process is more difficult to operate and the need for heating and insulation adds an extra cost to the treatment. Mesophilic digestion is the most common. The anaerobic digestion plant consists of several major technological elements: reception of waste, pre-treatment, digestion, gas handling, and management of digest from digestion and odor control.

Biogas released during anaerobic digestion (comprising of methane, 55-60%, and CO_2, 30-45%) can be used directly as a fuel for power generation, and has an energy content of 20-25 MJ/m^3. Typically around 100-350 m^3 per ton of biogas can be produced [17]. Compost can also be obtained from aerobically cured bio-solid. As by-product one ton of OFMSW produces 0.415 ton of compost [11]. Biogas and fiber and liquor can be used and none of this is landfilled.

The capital costs for dry AD plant capacity of 5,000-100,000 tons per year, range considerably from 200-1,000 € per ton, while the operating costs range from 40-15 € per ton [15]. If biogas is utilized in CHP, typically the electricity is produced at 30-35% efficiency and the thermal energy is produced at 40-50% efficiency [16].

System boundaries

For the needs of the present study the following considerations were taken in account.

- Model was developed to calculate the minimum amount of waste to be profitable waste management from the point of view of the municipality.
- The amount of waste was forecasted over the lifetime of the waste treatment facilities. The forecast for the amount of solid waste (x) for the year (n) was calculated according to eq. (1) [19]:

$$x = PP(1+GR_{\mathrm{pp}})^n w_{\mathrm{c}}(1+GR_{\mathrm{KF}})^n \tag{1}$$

where x is the forecasted amount of waste (facility capacity), PP – the present population, GR_{pp} – the growth rate of population, w_{c} – the actual key figure (the amount of waste per capita), GR_{KF} – the growth rate of key figure, and n – the facility lifetime.

- It is assumed that the waste composition does not change during facility lifetime.
- The low heating value, H_{low}, of waste is calculated from the elemental composition (C, H, O, N, S) using an empirical formula, eq. (2) [20]:

$$H_{\mathrm{low}} = 348\mathrm{C}\% + 949\mathrm{H}\% + 105\mathrm{S}\% + 63\mathrm{N}\% - 108\mathrm{O}\% - 24.5\mathrm{H_2O}\% \tag{2}$$

- Composition of biogas generated in AD is calculated from the elemental composition (C, H, O, N, S) using a Buswell equation [21]:

$$\mathrm{C}_c\mathrm{H}_h\mathrm{O}_o\mathrm{N}_n\mathrm{S}_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)\mathrm{H_2O} \rightarrow$$
$$\frac{1}{8}(4c - h + 2o + 3n + 2s)\mathrm{CO_2} + \frac{1}{8}(4c + h - 2o - 3n - 2s)\mathrm{CH_4} + n\mathrm{NH_3} + s\mathrm{H_2S} \tag{3}$$

- Energy yield from biogas is calculated taking into account that H_{low} of methane is 36 MJ/m^3, and assuming that 80% of organic fraction of waste is broken down.
- It was assumed that the cost of waste collection and transportation are the same for all scenarios, and is not taken into consideration. Replacement cost is not specifically taken into account.
- The facility lifetime varies depending on the type of waste treatment (20-40 years). In order to facilitate the comparison, the same lifetime of 20 years was adopted for all the facilities.
- It has been taken that there is equality between the revenues and income, as well as costs and outflows.
- The Economic Commission of the EU, for the programming period 2007-2013, prescribed a discount rate for beneficiaries of EU funds of 3.5% for other.

Mathematical model for cost-effectiveness evaluation

To develop the mathematical model for evaluation of cost-effectiveness of waste treatment technique with energy recovery, a socio-economic analysis was used. Unlike the financial analysis that evaluates the feasibility of the project from the perspective of investors, the socio-economic analysis is more complex since it identifies the benefits and costs that are not directly associated with the project and considers the wider socio-economic aspect of the project (greenhouse gasses, GHG, savings for the waste treatment alternatives, job creation, *etc.*).

The analysis of the breakpoints or the lower break-even point analysis is an integral part of the analysis of project profitability and is associated with a risk analysis to achieve positive business results. The lower break-even point or minimum amount of waste, W_{min}, for cost-effective waste treatment technique with energy recovery, calculated on the basis of equality of the net present value (NPV) of costs, NPV_{cost}, and the net present value of revenues, NPV_{revenue}, and the initial conditions of the net present value of benefits, NPV_{benefit}, is equal to zero, as shown in eq. (4):

$$NPV_{\text{benefit}} = NPV_{\text{revenue}} - NPV_{\text{cost}} = 0 \tag{4}$$

The NPV criterion shows the net present value of cash flow financing and it is part of the socio-economic analysis and benefit accounting prices and the social discount rate.

The segment net present value related to the costs, NPV_{cost}, consists of investment and operating costs, as shown in eq. (5):

$$NPV_{\text{cost}} = I_o + \sum_{t=1}^{20} \frac{OC_t}{(1+i)^t} \tag{5}$$

where I_o is the investment costs, OC_t – the operating costs in the t-th year, i – the social discount rate, and t – the project life time.

Investment costs (land acquisition, site preparation, building construction, purchase of facility, and equipment) depend on the facility capacity. For the purchase costs of facility and equipment the authors suggest that for the calculation of investment costs one should use the empirical equations from reference [9] obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of investment facility costs. Investment costs for an incinerator facility with energy recovery with the capacity range 20,000-600,000 tons per year is given in eq. (6a), and for an anaerobic digestion facility with the capacity range 2,500-100,000 tons per year is given in eq. (6b):

$$I_o = \begin{cases} \text{(a)}\ \ 4900x^{0.8} \\ \text{(b)}\ \ 34200x^{0.6} \end{cases} \tag{6a,b}$$

The operating costs, $OC(x)$ consist of fix operating costs and variable operating costs, as shown in eq. (7). The fix operating costs, OC_{fix}, depend on the number of employees, the percentage of skilled and unskilled workers and engineers, and the local salary level and maintenance costs of buildings and equipment. For 10,000 tons of waste, 1-3 employees are needed for incineration and 4-6 for anaerobic digestion [22]. Maintenance costs of buildings amounted to 1% of investment costs and maintenance costs of equipment amounted to 4% of investment costs [15, 19]. Variable operating costs, $OC_{\text{var}}(x)$ consist of costs of chemicals for flue gas cleaning system, electricity, water, and handling of waste water and residue disposal.

$$OC(x) = OC_{\text{fix}} + OC_{\text{var}}(x) \tag{7}$$

The authors suggest that for the calculation of variable operating costs one should use the empirical equations, eqs. (8a) and (8b), presented in tab. 1, obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of variable operating costs.

Table 1. Cost function of variable operating costs

Waste treatment	Cost function of variable operating costs (€t^{-1})	Amount of waste (t)	Equation
Incineration	$OC_{\text{var}}(x) = 84.23\ x^{-0.168}$	$18{,}700 \leq x \leq 250{,}000$	(8a)
Anaerobic digestion	$OC_{\text{var}}(x) = 427.10\ x^{-0.356}$	$14{,}000 \leq x \leq 61{,}000$	(8b)

The net present value of the related revenues is shown in eq. (9):

$$NPV_{\text{revenue}} = \sum_{t=1}^{20} \frac{R_{\text{p}t}}{(1+i)^t} + \sum_{t=1}^{20} \frac{R_{\text{CO}_2 t}}{(1+i)^t} + \sum_{t=1}^{20} \frac{R_{\text{fee}\,t}}{(1+i)^t} \tag{9}$$

where $R_{\text{p}t}$ is the revenue from sales of waste treatment product (electric and thermal energy, compost) in the t-th year, $R_{\text{CO}_2 t}$ – the revenue from GHG emission saving in the t-th year, and $R_{\text{fee}\,t}$ – the revenue from gate fee in the t-th year.

Revenues achieved from sales of energy (electricity and heat) depend on the price of energy, low calorific value of waste in incineration, or energy value of biogas in anaerobic digestion, and efficiency (electric and thermal). Revenues obtained from selling compost, R_c, depend on the amount of compost obtained from 1 ton of waste, A_c, and price of compost, P_c [€ per ton], and is shown in eq. (10a) for incineration, and (10b) for anaerobic digestion:

$$R_\text{p} = \begin{cases} \text{(a)}\ \ (P_\text{e} H_{\text{low}} \eta_\text{e} + P_\text{t} H_{\text{low}} \eta_\text{t}) W_{\min} \\ \text{(b)}\ \ (P_\text{e} E_\text{b} \eta_\text{e} + P_\text{t} E_\text{b} \eta_\text{t} + A_\text{c} P_\text{c}) W_{\min} \end{cases} \tag{10a,b}$$

where P_e is the price of the generated electric energy, P_t – the price of the generated thermal energy, H_{low} – the low calorific value of waste, E_b – the energy yield from biogas, η_e – the electrical efficiency, η_t – the thermal efficiency, A_c – the amount of compost per ton of waste, and P_c – the compost price.

Revenues generated from reductions in CO_2 emissions are given in eq. (11):

$$R_{\text{CO}_2} = P_{\text{ct}} \text{CO}_{2\text{Equ}} W_{\min} \tag{11}$$

where P_{ct} is the carbon trading price, $\text{CO}_{2\text{Equ}}$ – the amount of CO_2 that is saved per ton of treated waste.

Revenues achieved by the gate fee are shown in eq. (12):

$$R_{\text{fee}} = GF\ W_{\min} \tag{12}$$

where GF is the gate fee.

Mathematical model for evaluation of cost-effectiveness of waste treatment technique with energy recovery is presented in fig. 1.

Assuming that the revenues are annually constant for a given payback period, the minimum amount of waste annually ($W_{\min}$) for the cost-effective waste treatment technique with energy recovery is calculated by replacing eqs. (5)-(12) in eq. (4), as shown in eq. (13a) for incineration, and in eq. (13b) for anaerobic digestion:

$$W_{\min} = \begin{cases} \dfrac{I_o + \displaystyle\sum_{t=1}^{20} \frac{OM_\text{t}}{(1+i)^t}}{(P_\text{e} H_{\text{low}} \eta_\text{e} + P_\text{t} H_{\text{low}} \eta_\text{t} + P_{\text{ct}} \text{CO}_{2\text{Equ}} + GF) = \displaystyle\sum_{t=1}^{20} \frac{1}{(1+i)^t}} & \text{(13a)} \\[3ex] \dfrac{I_o + \displaystyle\sum_{t=1}^{20} \frac{OM_\text{t}}{(1+i)^t}}{(A_\text{c} P_\text{c} + P_\text{e} E_\text{b} \eta_\text{e} + P_\text{t} E_\text{b} \eta_\text{t} + P_{\text{ct}} \text{CO}_{2\text{Equ}} + GF) \displaystyle\sum_{t=1}^{20} \frac{1}{(1+i)^t}} & \text{(13b)} \end{cases}$$

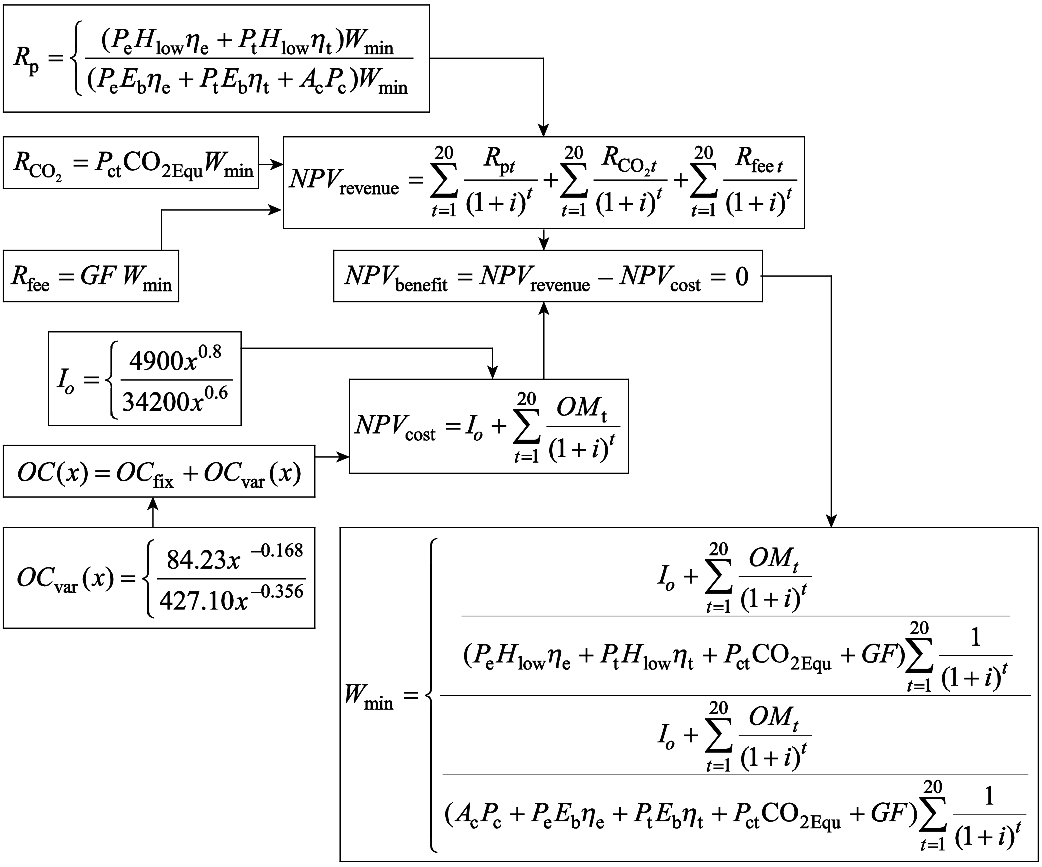

Figure 1. Mathematical model for evaluation of cost-effectiveness of waste treatment technique with energy recovery

Experimental research

Study area

To calculate the minimum amount of waste for cost-effective waste treatment technique with energy recovery with the socio-economic aspects, the city of Nis is chosen as a case study. The city area covers 596.71 km^2. In the city of Nis, according to the census of 2011, lived 260,237 inhabitants [23]. In most cities in Serbia, the waste is disposed of in open dumps or unsanitary landfills endangering the environment and human health. In Serbia there are only seven sanitary landfills. The situation is similar in the city of Nis. At present, the city has a dysfunctional unsanitary landfill and waste management comes down to the collection and disposal of waste in the landfill. Amount of waste that was generated in the city of Nis is 72,100 tons per year [24]. In the city there are several private companies involved in the recycling of waste (mainly metals, paper, plastics and e-waste). There are several locations with containers for the collection of recyclable materials (plastics, glass, aluminum cans, paper). The waste is collected and transported once a week. Waste collection is charged by the surface of the housing unit. Table 2 presents the composition and quantity of waste generated annually in the city of Nis [24].

Table 2. The composition of municipal waste and chemical composition of waste fraction (dry basis) [24, 25]

Fraction	Percentage [%]	Production [tons per year]	C [%]	H [%]	O [%]	N [%]	S [%]
Food waste	33.7	24,298	48.0	6.4	37.6	2.6	0.4
Yard waste	10.4	7,494	47.8	6.0	38.0	3.4	0.3
Paper	15.3	11,031	43.5	6.0	44.0	0.3	0.2
Plastics	17.7	12,762	60.0	7.2	22.8	–	–
Glass	5.1	3,677	0.5	0.1	0.4	< 0.1	–
Metals	1.9	1,370	4.5	0.6	4.3	< 0.1	–
Other	15.9	11,464	26.3	3.0	2.0	0.5	0.2
Total	100.0	72,100					

This paper considers two scenarios: incineration and anaerobic digestion. Scenarios are developed on the basis of the composition of municipal waste, Waste Management Plan of Nis [24], and strategic documents in Serbia [26].

Scenario 1: Except glass and metal (5,047 t), the rest of the waste (67,053 t) is sent to the incineration facility with cogeneration plant to produce electricity and heat. Energy efficiency in an electricity production is 27%, and 55% for heat production.

Scenario 2: Amount of 17,809 t of recyclable waste (glass, metal and plastic) is recycled and the organic waste (42,823 t) is sent to the anaerobic digestion facility with cogeneration plant to produce electricity and heat. Energy efficiency in an electricity production is 30%, and 45% for heat production. The rest of the waste is landfilled.

Using the previously described methodology, the minimum amount of waste treatment: incineration and anaerobic digestion was calculated, while the costs and revenues of the other treatment in scenarios are not taken into account.

Reference data

The analysis of the investment cost is based on the following data: the land take area for Scenario 1 is 40,000 m^2, the buildings for equipment, manipulative space and warehouses are 15,000 m^2. The land take area for anaerobic digestion is 10,000 m^2, the buildings for equipment, manipulative space, warehouses are 5.000 m^2.

The analysis of the operating cost is based on the following data: Labor costs are calculated based on the number of workers required for the performance of waste treatment, with an average salary in Serbia. Energy costs for the plant and fuel for the equipment are calculated based on data on the consumption of facility and equipment and the current prices of electricity and fuel on the territory of Serbia.

Preferential prices for energy from waste were adopted as 8.57 c€ per kWh for power plants and 15.66-12.31 c€ per kWh for biogas power plants [27], while the revenue generated from electricity and heat production is calculated on the basis of the incinerator efficiency given in the description of the scenario. The low heating value of waste was calculated as 11,833 kJ/kg. The calculated composition of biogas was 57.42% CH_4, 42.58% CO_2, and 3.13% NH_3. Then the amount of methane per ton of waste was calculated as 290 m^3 per ton, and at the end of the energy yield from biogas was calculated as 2,905.35 kWh per ton. The average amount of compost obtained from 1 t of organic fraction of municipal solid waste (OFMSW) was 0.415 t [11].

The amount of CO_{2Equ} that is saved per ton of waste treatment is taken from the literature [28]. The carbon trading price on the world market amounts to 6 € per ton [29], based on which the savings that are reflected in the reduction of CO_2 emissions are calculated. The adopted gate fee is the one currently valid in the city of Nis [24].

Results and discussion

Table 3 shows the total investment and operating costs and revenues for developed scenarios.

Table 3. Socio-economic analysis of developed scenarios

Scenario	Scenario 1	Scenario 2
Investment costs		
Land acquisition costs [€]	80,000	20,000
Site preparation costs [€]	800,000	200,000
Buildings construction costs [€]	6,000,000	2,900,000
Facility costs [€]	38,000,000	8,600,000
Operating costs		
Building maintenance costs [€ per year]	240,000	29,000
Equipment maintenance costs [€ per year]	405,000	344,000
Labour costs [€ per year]	384,000	240,000
Variable operating costs [€ per year]	915,020	612,600
Revenues		
Electricity produced [€ per kWh]	74.40	18.00
Thermal energy produced [€ per kWh]	35.00	9.45
Gate fee [€ per ton]	26.00	20.80
Compost [€ per ton]	–	30.00
CO_2 emission saving [€ per ton]	6.15	16.40

Using the previously described model for calculating the minimum amount of cost--effective waste management scenario, eqs. (4)-(13a,b), and based on the data listed in tab. 3 as well as adopted discount rate and project life time, the net present value of total costs and revenues, and the minimum amount of waste are calculated and presented in tab. 4.

Table 4. Results of the analysis

Net present value / Minimum amount of waste	Scenario 1	Scenario 2
NPV_{cost} [€]	52,908,500	16,232,435
$NPV_{revenue}$ [€ per ton]	610	292
W_{min} [ton]	86,715	55,541

In Scenario 1 the available amount of waste for incineration is 67,053 t, while the minimum amount of waste for cost-effective incineration is 86,715 t. This also points to the insufficient amount of waste and the need for supplying the waste from the municipalities in the region. Given the size of the investment, which amounts to 45,380,000.00 €, this makes sense. If the gate fee was increased to 70 € per ton of waste, the amount of waste currently generated would be sufficient for a cost-effective incineration.

In Scenario 2 the available amount of waste for biogas production by anaerobic digestion is 42,823 t, and the calculated minimum amount of waste for the cost-effective anaerobic digestion is 55,541 t. This shows that the city of Nis does not generate enough waste for anaerobic treatment.

Conclusions

The cost-effectiveness of a waste treatment technique is one of important factors when making the decision to invest in a waste treatment facility. Waste treatment can bring economic benefit through the value of product: recycled materials, the compost, the generated electricity or heat. To assess the cost-effectiveness of a waste treatment technique, it is necessary to correctly predict all costs (investment and operating) that are related to specific waste treatment, and assess revenues. But, the investment and operating costs and the revenue depend on the amount of treated waste.

In this paper, the mathematical model for evaluation of cost-effectiveness of waste treatment technique with energy recovery was developed using the socio – economic analysis. The model is flexible since it contains variables that depend on the specific economic conditions in the certain territory. Using the presented model, can be easily identified waste treatment which can be applied, according to the amount of waste, its composition on a certain territory and cost-effectiveness.

The model is verified in the case study the city of Nis. According to the obtained results it can be concluded that the amount of waste currently generated in the city of Nis is not sufficient for the cost-effectiveness of incineration. With the currently available amount of waste in the city of Nis, anaerobic digestion is the waste treatment that can be operated without losses at the moment. The amount of waste that can be used for biogas production by anaerobic digestion is 42,823 t, and the calculated minimal amount is 55,541 t, and that means there is not enough waste for anaerobic treatment in the city of Nis.

Nomenclature

A_c	– amount of compost per ton of waste, [ton per ton]
$\mathrm{CO}_{2\mathrm{Equ}}$	– amount of CO_2 that is saved per ton of treated waste, [kg per ton]
E_b	– energy value of biogas, [kWh per ton]
GF	– gate fee, [€ per ton]
GR_KF	– growth rate of key figure, [–]
GR_pp	– growth rate of population, [–]
H_low	– low calorific value of waste, [kJkg^{-1}]
I_o	– investmens costs, [€]
i	– social discount rate, [%]
NPV_cost	– net present value of costs, [€]
NPV_revenue	– net present value of revenues, [€]
NPV_benefit	– net present value of benefits, [€]
n	– facility lifetime, [years]
OC_t	– operating costs in the t-th year, [€ per ton]
OC_fix	– fix operating costs, [€ per ton]
$OC_\mathrm{var}(x)$	– variable operating costs, [€ per ton]
P_c	– price of compost, [€ per ton]
P_ct	– carbon trading price, [€ per ton]
P_e	– price of the generated electric energy, [c€ per kWh]
PP	– present population, [–]
P_t	– price of the generated thermal energy, [c€ per kWh]
R_{CO_2t}	– revenues from GHG emission saving in the t-th year, [€]
$R_{\mathrm{fee}t}$	– revenues from gate fee in the t-th year, [€]

$R_{\mathrm{p}\,t}$ – revenues from sales of waste treatment product in the t-th year, [€]
t – project life time, [years]
w_c – actual key figure (the amount of waste per capita), [kg per cap per day]
W_min – minimum amount of waste, [ton]
x – forecasted amount of waste (facility capacity), [tons per year]

Greek symbols

η_e – electrical efficiency, [%]
η_t – thermal efficiency, [%]

Subscripts

e – electric
t – thermal
min – minimum

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