A mathematical model for evaluating the economic indicators of waste treatment with energy recovery

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Abstract:

Assessing the sustainability of a certain waste management scenario with energy recovery requires the selection of sustainable indicators (environmental, economic and social) and their evaluation. Developing evaluation criteria and methods that reliably measure sustainability is a prerequisite for selecting the best waste treatment scenario with energy recovery and identifying non-sustainable scenarios. In the previously published paper, as the first step in assessing the sustainability of waste treatment with energy recovery, an established algorithm for assessing sustainability was presented. This algorithm provides the calculation of economic indicators by using a mathematical model.

In most cases, in sustainability assessment of a waste treatment scenario with energy recovery the used economic indicators are: investment costs, operating and maintenance costs, fuel costs, energy costs and revenues. Unfortunately, cost estimation is relatively crude in solid waste management, without enough available data. The published cost data are often fragmented or reflecting specific unique cases with limited information regarding costs breakdown, specific local conditions, operating practices, system performance, etc. Cost planning for waste management has been discussed in various forms (user charges, economic analysis and economies of scale). Some have focused primarily on quantitative approaches such as optimization techniques, statistical methods and cost-benefit analyses.

In this paper the focus is on the development of a new mathematical model for calculating the economic indicators (investment costs, operating and maintenance costs and revenues) of waste treatment scenarios with energy recovery depending on the composition and quantity of waste. 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 applied to calculate the indicator for the waste management scenarios with energy recovery: incineration and anaerobic digestion, and further verified in the case study of the city of Niš. The obtained results for the city of Niš, concerning investment and operating costs, are at the lower limit value of costs in the EU due to lower land prices, the construction costs, salary levels, etc. The higher price of electricity generated by waste treatment, due to government subsidies, leads to the total revenues being higher than the EU average.

Keywords:

Mathematical model, waste-to-energy, sustainability, economic indicators, costs.

1. Introduction

Measuring sustainability of energy systems is a major issue as well as a driving force of the discussion on sustainable development [1]. Developing evaluation criteria and methods that reliably measure sustainability is a prerequisite for selecting the best alternative, identifying non-sustainable waste treatment scenario with energy recovery, informing design-makers of the integrated performances of the alternatives and monitoring impacts on the social environment.

The criteria used to evaluate the waste treatment scenario with energy recovery in the literature are mainly divided into four aspects: technical, economic, environmental and social criteria. When adopting the economic criteria, they are usually associated with certain costs of waste treatment. Unfortunately, cost estimation is relatively crude in solid waste management. In order to provide a more accurate determination of waste treatment costs, several methods have been used: unit cost method, benchmarking and cost functions [2]. In the unit cost method each activity is disaggregated into separate items such as salaries, consumables, fuel costs or maintenance costs, and the required quantity of each item is noted. Multiplying this with the cost per item or unit cost, the total cost of each item is calculated and the overall cost of the service is then calculated by summing the total costs incurred by each item [3]. Benchmarking is a quick way to make a reasonable cost assessment by using actual cost data from a similar organization due to the lack of data in the considered country [4] or from the literature [5]. The cost function is used to describe more broadly the relationship of cost to variables. The cost functions method relates the cost of solid waste management to production factors or to variables such as amount of processed waste [6] or population density [7].

In this paper a mathematical model is developed with the aim of calculating the economic sustainable indicators (investment costs, operating and maintenance costs and revenues) of waste treatment scenarios with energy recovery. All of the above indicators are calculated depending on the composition and quantity of waste. The model is based on the analysis of the structure of investment and operating costs and revenues for each waste treatment and supported by the data available in the field and in the literature. The model is applied to calculate the indicator for the waste management scenarios with energy recovery: incineration and anaerobic digestion, and further verified in the case study of the city of Niš.

2. Technology description

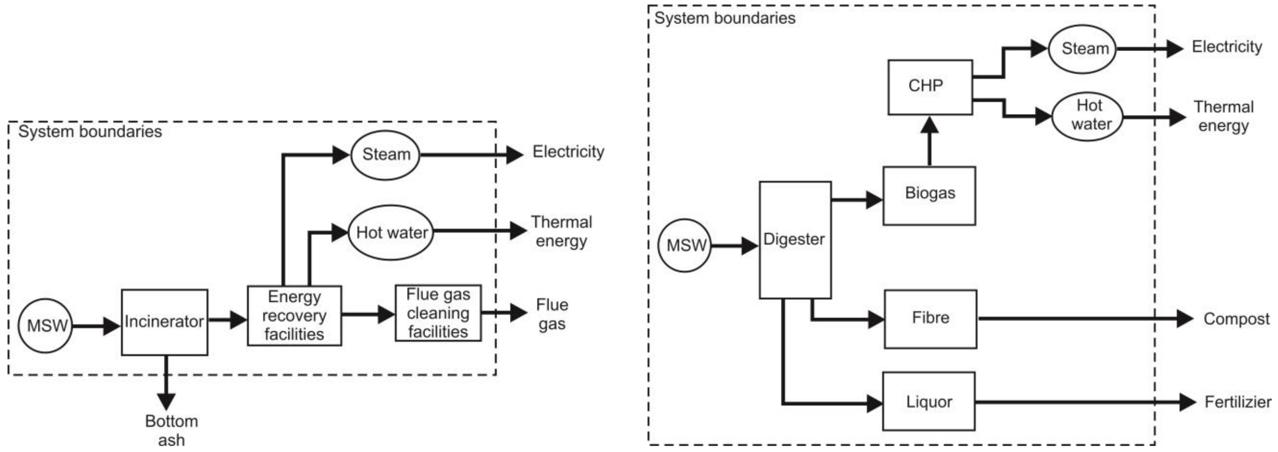
This description is done in order to assess the main technologies applicable to energy recovery from municipal solid waste (MSW) and to research factual information relating to their use and costs.

2.1. 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: the most widely used is mass burning (with a movable grate), rotary kilns and fluidized bed incineration [8]. 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. The main advantages of the moving grate 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 the investment and maintenance costs which are relatively high [8]. The investment costs range considerably from 560-1030 €/t, while the operating costs range from 28-67 €/t [9]. The main advantages of the rotary kiln are similar to the moving grate incineration system, except that the maintenance is slightly higher and the CHP efficiency slightly lower and may not exceed 80 %. The investment cost and particularly the maintenance cost are, however, relatively high. A main disadvantage of the fluidized bed for waste incineration 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 and this is the most efficient option for utilizing recovered energy from waste. 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 [10]. 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.



(a) *(b)*

Fig. 1. Incineration (a) and anaerobic digestion (b) process and system boundaries.

Figure 1 presents the incineration and anaerobic process on the basis of which a model to calculate economic indicators as well as the system boundaries will be developed.

Typically the residual component of MSW (non-recyclable, non-organic) in the incineration process produces electricity at an efficiency of about 20% and thermal energy at an efficiency of about 55% [9].

2.2. 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) from different sources; digestion of sludge from wastewater treatment plants; manure; industrial wastewater with high content of organic matter [11]. 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 division into dry or wet processes is a question of the moisture content in the biological reactor. The choice of moisture content in the process takes its starting point from the moisture content in the waste. The digestion temperature is 20-40 ºC for mesophilic digestion or 50-65 ºC for thermophilic digestion [12]. 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; management of digest from digestion and odour control.

Biogas released during anaerobic digestion (comprising largely of methane, 55-60%, and carbon dioxide, 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/t of biogas can be produced [13]. Compost can also be obtained from aerobically cured bio-solid. As by-product 1 t of OFMSW produces 0.415 t of compost [14]. Parasitic loads (the energy required in the AD process that is not contributing to the net electric yield) are relatively high at around 20-40% [13]. In AD the OFMSW volume is reduced by around 70%, therefore, assuming a 50% organic fraction, the total waste volume is reduced by around 35% [15], but all products (biogas) and by-products (fibre and liquor) from anaerobic digestion can be used and none of these are landfilled.

The capital costs for dry anaerobic composting plant (DRANCO process) capacity of 5,000-100,000 t/y, range considerably from 200-1000 €/t, while the operating costs range from 40-15 €/t [9]. If biogas is utilised in CHP, typically the electricity is produced at 30-35% efficiency and the thermal energy is produced at 40-50% efficiency [9].

2. Economic indicators for waste treatment with energy recovery

In the conducted literature review, the most commonly used economic criteria for the sustainability assessment are: investment cost, operation and maintenance cost, revenues, net cost per ton, fuel cost, electricity cost, net present value payback period, service life, etc. In order to choose a solid waste management system in Finland, using a multi-criteria decision analysis some authors used net cost per ton as economic criteria [16]. For the selection among renewable energy alternatives in Turkey, a fuzzy multi criteria decision-making methodology is suggested, while implementation cost, economic value and availability of funds are used as economic criteria [17]. For trigeneration systems selection and evaluation the following economic criteria are used: investment cost, investment recovery period, total annual cost and net present value [18]. Energy costs, investment costs and efficiency are used for multi-criteria sustainability assessment with various options of the energy power system of Bosnia and Herzegovina [19]. In order to perform technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process, capital cost, operational and maintenance cost, fuel cost and external cost are used [20]. To evaluate options for energy recovery from municipal solid waste in India using the hierarchical analytical network process (HANP) other authors used capital cost, generation cost and operating and maintenance cost [11]. To assess a sustainable waste management model, investment cost, operational cost and revenue are used as economic indicators [21].

Investment costs comprise all costs relating to: land acquisition, the purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, construction work, drilling and other incidental construction work. Investment costs are the most used economic criteria to evaluate energy systems. Operation and maintenance costs consist of two parts: fixed and variable costs. Operation and maintenance costs are other most used economic criteria. Revenues comprise all revenues obtained from selling the products of waste treatment (gate fee, produced electricity and heat, compost and other fertilizer). Fuel costs refer to the funds spent for the provision of raw material necessary for energy supply system operation. Fuel costs are excluded from operation costs when fuel costs and operation and maintenance costs are both selected for evaluation. Electricity costs, which are the product costs of a power plant, are observed as a criterion to evaluate its economic performance from the viewpoint of consumers. Net present value (NPV) is defined as the total present value of a time series of cash flows. NPV is often used to assess its feasibility of an energy project by investor. Payback period of an energy project refers to the period of time required for the return on an investment to “repay” the sum of the original investment. Shorter payback periods are obviously preferable to longer payback periods to investors. A longer service life is preferable to investors and it is employed to select the best scheme from energy system alternatives.

3. Mathematical model

3.1. Model parameterization and assumptions

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

- The input variables for the model development of all considered waste treatment is the amount of waste and waste composition. The chemical composition of waste fractions is taken from the literature.
- The amount of waste was forecasted over the lifetime of the waste treatment facilities. A waste generation forecast requires a combination of data normally used for town planning purposes

along with specific waste generation data. The forecast for the amount of solid waste (x) for the year (n) was calculated according to Equation 1 [22].

$$x = PP * (1 + GR_{pp})^n * w_c * (1 + GR_{KF})^n \quad (1)$$

where: x – 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, n – the facility lifetime.

- It is assumed that the waste composition does not change during facility lifetime.
- The low heating value (H_{low} (kJ/kg)) of waste is calculated from the elemental composition (C, H, O, N, S) using an empirical formula (Equation 2), which provides a reasonably accurate approximation for usual waste mixtures [23].

$$H_{low} = 348 * C\% + 949 * H\% + 105 * S\% + 63 * N\% - 108 * O\% - 24.5 * H_2O\% \quad (2)$$

- Composition of biogas generated in anaerobic digestion is calculated from the elemental composition (C, H, O, N, S) using a Buswell Equation:

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \quad (3)$$

- Energy yield from biogas is calculated taking into account that the low heating value of methane is 36 MJ/m^3 i.e. 10 kWh/m^3 and assuming that 80% of organic fraction of waste is broken down.
- 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.

3.2. Mathematical Model

The economic aspects of waste treatment with energy recovery vary greatly between regions and countries, not only due to technical aspects but also depending on waste treatment policies.

3.2.1. Investment costs

The investment costs include project and permits costs, land acquisition costs, costs of site development, construction cost and facility costs (Equation 4).

$$IC(x) = P(x) + LA(x) + SD(x) + CC(x) + FC(x) \quad (4)$$

where: P(x) – the project and permits costs, LA(x) – the land acquisition costs, SD(x) – the costs of site development, CC(x) – the construction costs, FC(x) – the facility costs.

Project and permits costs (Equation 5) depend of facility capacity, but also on legislation, technology, etc.

$$P(x) = BA(x) * P_p \quad (5)$$

Land acquisition costs depend of land-take area (LT(x) – the land area required for the building footprint and the entire site (including supporting site infrastructure). A land-take area depends on the necessary infrastructure, technology and plant capacity, and land price (P_i) (Equation 6).

$$LA(x) = LT(x) * P_l \quad (6)$$

Table 1 provides an overview of land-take and building area for the incinerator facility with the moving grate technology and an anaerobic digestion facility.

Table 1. Land-take and building area for sitting incinerator and anaerobic digestion facility [24,25,26,27,28,29]

Incineration			Anaerobic digestion		
Facility capacity x(t/y)	Land-take LT (ha)	Buildings Area BA (m^2)	Facility capacity x(t/y)	Land-take LT (ha)	Buildings Area BA (m^2)
90,000	1.7	5,850	40,000	0.6	2,420
150,000	3.2	15,750	164,000		5,420
210,000	3.7	9,435	38,000	1.5	
240,000	6.6	8,468	5,000		2,500
250,000	2-5	7,200	300,000		35,000
250,000	4	6,600	60,000	1.8	
292,000	1.6				

From the presented data it can be concluded that LT(x) for an incinerator is typically between 1.25 – 2.00 ha per 100.000 t of waste (Equation 7a) and for an anaerobic digestion facility is typically between 1.50 – 3.00 ha per 100,000 t of waste (Equation 7b)

$$LT(x) = \begin{cases} 1.25 \div 2.00 * \dfrac{x}{100{,}000} & (7a) \\ 1.50 \div 3.00 * \dfrac{x}{100{,}000} & (7b) \end{cases}$$

Also, from the data presented in Table 1 for building area (BA(x)) for an incinerator facility, it can be concluded that the building area of 2,640 – 6,500 m^2 per 100.000 t of waste is required for the incinerator facility (Equation 8a) and the building area of 2,400 – 11,000 m^2 per 100.000 t of waste is required for the anaerobic digestion facility (Equation 8b).

$$BA(x) = \begin{cases} 2{,}640 \div 6{,}500 * \dfrac{x}{100{,}000} & (8a) \\ 2{,}400 \div 11{,}000 * \dfrac{x}{100{,}000} & (8b) \end{cases}$$

Site development costs (SD(x)) include costs of excavation, levelling, access roads, link to technological networks. Generally, site development costs also depend on the land-take area and price of civil works per square meter (Equation 9).

$$SD(x) = LT(x) * P_{sd} \tag{9}$$

Construction costs (civil works on building construction) (CC(x)) depend on the building area (BA) which houses facilities and price of construction work per square meter (P_c) (Equation 10).

$$CC(x) = BA(x) * P_c \tag{10}$$

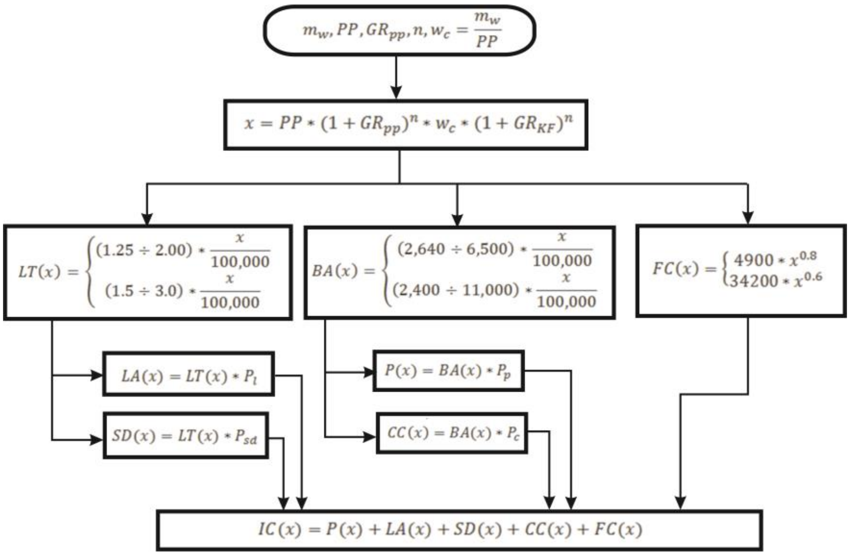


Fig. 2. Block diagram of a mathematical model for evaluating the investment costs.

Facility costs (technical installations and machinery) (FC(x)) also depend on the facility capacity and the authors suggest that for the calculation of facility costs one should use the empirical equations from reference [6] obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of investment facility costs. Facility costs (€) for an incinerator facility with energy recovery with the capacity range 20,000 – 600,000 t/y is given in Equation 11a and for an anaerobic digestion facility with the capacity range 2,500 – 100,000 t/y is given in Equation 11b:

$$FC(x) = \begin{cases} 4900 * x^{0.8} & (11a) \\ 34200 * x^{0.6} & (11b) \end{cases}$$

3.2.2. Operating costs

Operating costs include fixed operating costs (independent of waste quantity) and variable operating costs (dependent of waste quantity) as shown in Equation 12.

$$OC(x) = OC_{fix} + OC_{var}(x) \tag{12}$$

where: OC_{fix} – the fixed operational costs, $OC_{var}(x)$ – the variable operating costs

The fixed 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. In the literature we can find various information about the number of employees for an incinerator to work [29, 30]. The general conclusion is that for 10,000 t of waste 1-3 employees are needed for incineration and 4-6 for anaerobic digestion. Maintenance costs of buildings and equipment in the literature are usually expressed in terms of percentage of investment costs [22, 31]. Maintenance costs of buildings amounted to 1 % of investment costs and maintenance costs of equipment amounted to 4 % of investment costs. Variable operating costs ($OC_{var}(x)$) consist of costs of chemicals for the flue gas cleaning system, electricity, water and handling of waste water and residue disposal.

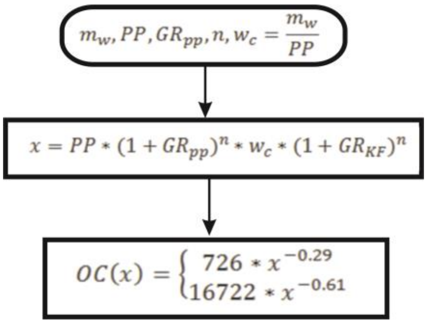


Fig. 3. Block diagram of a mathematical model for evaluating the operating costs.

Due to the influence of different elements in the structure of operating costs, the authors suggest that for the calculation of operating costs one should use the empirical equations from reference [6], obtained by statistical processing of data relevant to European states which provides a reasonably accurate approximation of operating costs. Operating costs (€/t) for an incinerator facility with energy recovery with the capacity range 20,000 – 600,000 t/y is given in Equation 13a and for an anaerobic digestion facility with the capacity range 2,500 – 100,000 t/y is given in Equation 13b.

$$OC(x) = \begin{cases} 726 * x^{-0.29} & (13a) \\ 16722 * x^{-0.61} & (13b) \end{cases}$$

3.2.3. Revenues

Revenues consist of revenue from the gate fee (R_{gf}), produced electricity (R_{ee}) and heat (R_{he}) and compost as by-product in anaerobic digestion (R_c) and depend on the capacity and efficiency of the plant and waste composition, represented in Equation 14.

$$R(x) = R_{gf} + R_{ee} + R_{he} + R_c \tag{14}$$

The gate fee (R_{gf}) vary greatly between regions and countries and is in the range of 18 €/t of waste in Spain to 460 €/t in Germany for incineration and in the range of 40 €/t of waste in France to 120 €/t in United Kingdom for anaerobic digestion [32].

$$R_{gf} = GF * m_w \tag{15}$$

Revenues obtained by selling produced electricity (R_{ee}) in waste incineration depend of waste composition i.e. lower heating value of waste H_{low} (Equation 2), efficiency of energy recovery systems, selling rate of produced energy (α_e) (electricity can easily be supplied into the national grid and sold, and the selling rate in most cases is 100%), and price of produced electricity (P_e (€/kWh)).

$$R_{ee} = H_{low} * \eta_e * \alpha_e * P_e * m_w \tag{16}$$

Revenues obtained by selling produced heat (R_{he}) in waste incineration depend on waste composition i.e. lower heating value of waste H_{low} (Equation 2), efficiency of heat recovery systems (η_h), selling rate of produced heat (β_h) (heat will need to be used locally and will depend on a local need, and the selling rate in most cases is less than 100%), and price of produced heat (€/kWh).

$$R_{he} = H_{low} * \eta_h * \beta_h * P_h * m_w \tag{17}$$

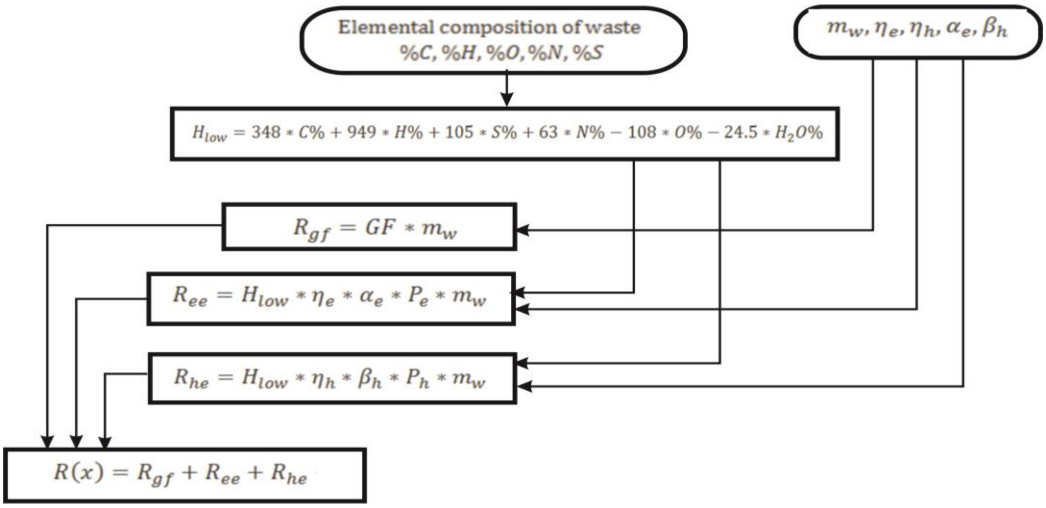


Fig. 4. Block diagram of a mathematical model for evaluating the revenues from waste incineration.

Fig. 5 presents a block diagram of a mathematical model for evaluating the revenues from anaerobic digestion of waste.

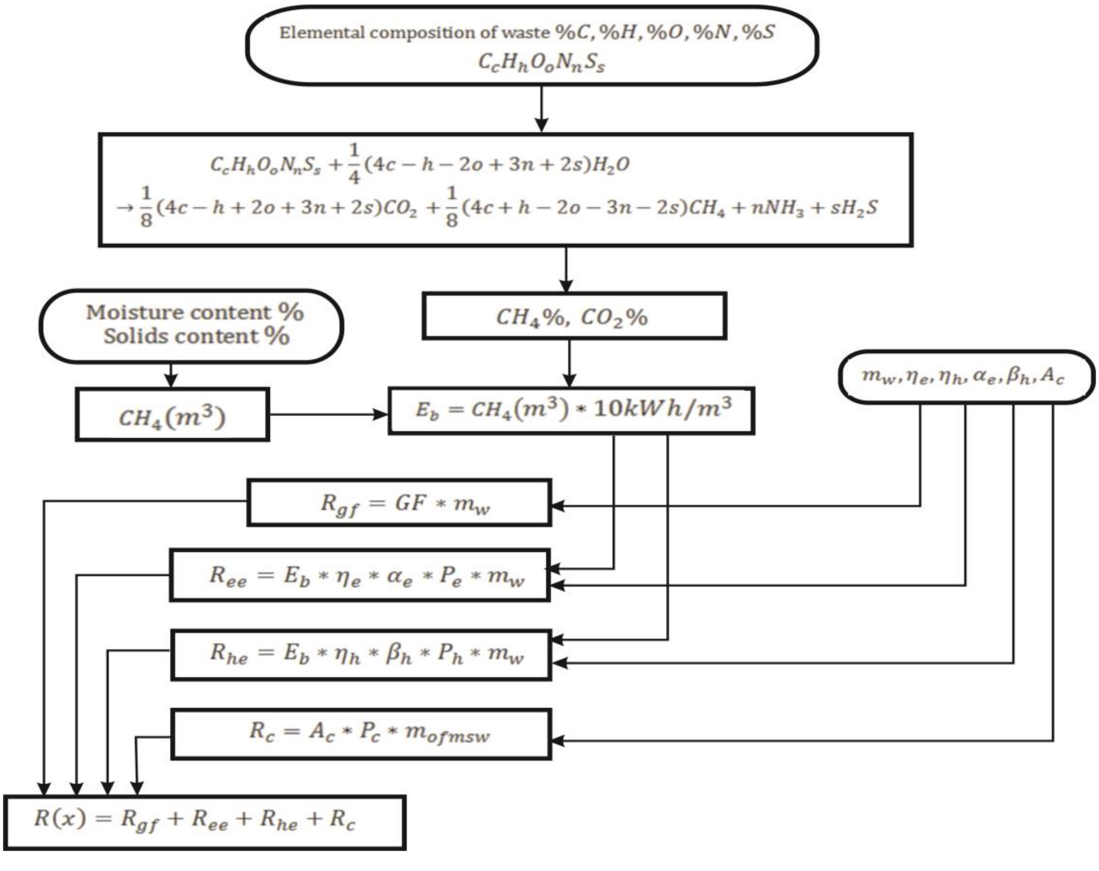


Fig. 5. Block diagram of a mathematical model for evaluating the revenues from anaerobic digestion of waste.

Revenues obtained by selling produced electricity (R_{ee}) in anaerobic digestion depend on waste composition (amount and composition of generated biogas and energy yield) i.e. energy value of biogas (E_b), efficiency of energy recovery systems (η_e), selling rate of produced energy (α_e) and price of produced electricity (P_e (€/kWh)).

$$R_{ee} = E_b * \eta_e * \alpha_e * P_e * m_w \quad (18)$$

Revenues obtained by selling produced heat (R_{he}) in anaerobic digestion depend on waste composition (amount and composition of generated biogas and energy yield) i.e. energy value if biogas (E_b), efficiency of heat recovery systems (η_h), selling rate of produced heat (β_h) and price of produced heat (P_h(€/kWh)).

$$R_{he} = E_b * \eta_h * \beta_h * P_h * m_w \quad (19)$$

Revenues obtained from selling compost (R_c) depend on the amount of compost obtained from 1 t of waste (A_c), and price of compost (P_c(€/t)).

$$R_c = A_c * P_c * m_{ofmsw} \quad (20)$$

4. Results and discussion

To verify the developed mathematical model for evaluating economic indicators, the city of Niš was chosen as a case study. Table 2 shows the composition and quantity of generated waste [32].

Table 2. The composition of municipal solid waste in the city of Niš (2014) [32] and chemical composition of waste fraction (dry basis) [33].

Fraction	Percentage (%)	Production (t/year)	C (% dw)	H (% dw)	O (% dw)	N (% dw)	S (% dw)
Food waste	13.79	9,011.49	48.0	6.4	37.6	2.6	0.4
Paper	7.26	4,744.26	43.5	6.0	44.0	0.3	0.2
Cardboard	4.24	2,770.76	44.0	5.9	44.6	0.3	0.2
Diapers	3.50	2,287.18	35.5	5.67	44.0	<0.1	-
Plastics	21.83	14,265.47	60.0	7.2	22.8	-	-
Textiles	2.63	1,718.65	55.0	6.6	31.2	4.6	0.15
Rubber	5.25	3,430.77	78.0	10.0	-	2.0	-
Leather	0.61	398.62	60.0	8.0	11.6	10.0	0.4
Yard waste	13.55	8,854.65	47.8	6.0	38.0	3.4	0.3
Glass	5.39	3,522.26	0.5	0.1	0.4	<0.1	-
Metals	1.62	1,058.64	4.5	0.6	4.3	<0.1	-
Dirt, ash, etc.	20.33	13,285.25	26.3	3.0	2.0	0.5	0.2
Total	100.00	65,348.00					

The input data was taken as follows: the quantity of waste generated was 65,348 t, waste composition as shown in table 2, the population of the city of Niš according to the last census from 2011 amounted to 260,237.00, population growth was -2.2, facility lifetime was 20 years. Based on these data the capacity of the plant was calculated as 171,320 t.

The price of land in the City of Niš ranged between 1,000–3,000 €/ha, site development costs were 20 €/m^2, the project and permits costs (utility costs) were 40 €/m^2 and construction costs were 450 €/m^2. Data for w_c–actual key figures (the amount of waste per capita) was calculated on the basis of the quantity of waste generated and the number of inhabitants per day, amounting to 0.76. The gate fee was 20 €/t, and preferential prices for energy from waste were adopted as 8.5 c€/kWh for power plants and 12 c€/kWh for biogas power plants. Energy efficiency for incineration and anaerobic digestion was taken as 27% and 30%, respectively, and thermal efficiency as 55% and 45%, respectively. The selling rate of produced energy was adopted as 1 and the selling rate of produced heat was adopted as 0.55.

The low heating value of waste was calculated as 11,832.62 kJ/kg. For the calculation of energy yield from biogas, the proceedings were conducted in several steps: biogas composition was calculated on the basis of a Buswell equation, where the formula for an organic part of municipal solid waste was used as $C_{32}H_{54}O_{16}N$. 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/t, and at the end of the energy yield from biogas was calculated as 2,905.35 kWh/t. The average amount of compost obtained from 1 t of OFMSW was 0.415 t [14].

Based on the amount and composition of waste given in Table 2 and the input data, as well as using equations 1–20 and following the steps in the mathematical model for calculating the investment costs (Fig. 2), operating costs (Fig. 3) and revenue from waste incineration (Fig. 4) and anaerobic digestion (Fig. 5), the calculated economic indicators are shown in Table 3, where: i(€/t) – the investment costs per ton of waste, r(€/t) – the revenues per ton of waste.

Table 3.Calculated economic indicators.

Cost structure	Incineration	Anaerobic digestion	Cost structure	Incineration	Anaerobic digestion
Investment costs (€)			Operating costs (€)		
LT (ha)	3.00	4.70	OP (€/t)	22.04	10.73
LA (€)	8,994.33	14,133.94	Revenues (€)		
SD (€)	5,996.22	9,422.63	Rgf (€)	1,306,960.00	815,673.60
BA (m^2)	7,829.35	11,478.48	Ree (€)	4,929,391.43	4,265,663.97
P (€)	313,173.94	459,139.04	Rhe (€)	4,134,674.73	2,349,498.85
CC (€)	3,523,206.85	5,165,314.20	Rc (€)	-	507,756.82
FC (€)	75,377,828.56	47,240,203.83	R (€)	10,371,026.17	7,938,593.23
I (€)	79,229,199.90	52,888,213.65	r (€/t)	158.70	121.48
i (€/t)	462.46	308.71			

Table 3 presents investment and operating costs and revenues calculated by applying the mathematical model for the case study of the city of Niš. From the obtained results it can be concluded that investment costs, as well as operating costs and revenues, are much higher for incineration. But the investment costs for incineration of 462.46 €/t are lower than the costs in the EU, which range from 560-1030 €/t, due to the lower price of land, constructing costs, salary levels, etc. The same conclusion can be applied to anaerobic digestion, where investment costs are 308.71 €/t, while the EU average is 200-1000 €/t [9]. This also applies to the operational costs: for incineration they amounted to 22.04 €/t in contrast to the EU where they range from 28-67 €/t, while for anaerobic digestion they amounted to 10.73 €/t, while in the EU they range from 15-40 €/t. The calculated total revenues are at the upper limit of EU average (ranging from 60–250 €/t for incineration and 56–126 €/t for anaerobic digestion [31]) due to the higher state subsidies, i.e. higher prices of electricity produced by waste treatment. In Serbia the electricity price obtained from incineration is 8.50 c€/kWh, and 12 c€/kWh for anaerobic digestion, while the EU electricity prices range from 2.0–4.0 c€/kWh.

5. Conclusion

The newly developed mathematical model for evaluating economic indicators of waste treatment scenarios with energy recovery (investment costs, operating costs, and revenues) is presented in the paper. The model is based on the analysis of the structure of investment and operating costs, as well as revenues for each waste treatment with energy recovery. All of the above indicators are calculated depending on the composition and quantity of waste. For each indicator an algorithm that predicts several steps for its calculation is presented. The model, when calculating the revenues, requires the following input data related to the technical characteristics of the system: energy and thermal efficiency of the plant. The developed model is sufficiently general to be applicable to any case study, because it contains local elements (price of land, construction cost, design and permit prices, price of the produced electricity and heat, gate fee, the price of compost).

The obtained results for the city of Niš, for investment costs of 462.46 €/t for incineration and 308.71 €/t for anaerobic digestion and operating costs of 22,04 €/t for incineration and 10,73 €/t for anaerobic digestion, are at the lower limit of costs in the EU due to lower land prices, the construction costs, salary levels, etc. Due to government subsidies, the higher price of electricity generated by waste treatment affects the total revenues of 158.70 €/t for incineration and 121.48 €/t for anaerobic digestion, which are at the upper limit of the EU average.

The results obtained by this model can be used for assessing the sustainability of certain waste treatments with energy recovery.

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