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Cost Analysis of Waste-to-Energy Plant

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Preliminary note

In the paper the techno-economical analysis of the waste-to-energy plant that includes combined heat and power production is presented. The technology of waste combustion on the grate is chosen as the proven technology most often in use even today. Selection of this technology assumes application of all the most stringent environmental protection standards. The paper analyses two variants of flue gas cleaning systems.

Due to high requirements on environmental protection, the operating and maintenance costs of the facility are rather high while the calorific value of the municipal waste burned is relatively low (around 10 MJ/kg), which brings the waste-to-energy plant under consideration to the brink of economical viability for the given annual capacity of 100.000 tons of waste and the limiting gate fee value of 105 EUR per tone of waste, if solely direct cost-effectiveness is considered.

The parameters on which the cost-effectiveness of the waste-to-energy cogeneration plant depends range from purely technical, like plant capacity and the waste calorific value (including percentage of moisture and biodegradable matter) to entirely economical, such as loan conditions, costs of flue gas cleaning, costs of hazardous waste disposal, revenue from selling of electricity and heat, and the most important factor – charge levied upon a waste received at a waste-to-energy plant (the gate fee). High costs of ash and residue disposal could influence the total economic viability of the plant.

Analiza isplativosti energane na otpad

Prethodno priopćenje

U radu je predstavljena tehno-ekonomska analiza postrojenja za energetsku oporabu otpada koje uključuje i kogeneracijsku proizvodnju toplinske i električne energije. Odabrana je, danas još uvijek najzastupljenija, tehnologija izgaranja otpada na rešetki. Izbor te tehnologije podrazumijeva primjenu svih najstrožih standarda zaštite okoliša. U radu su analizirane dvije varijante sustava za čišćenje dimnih plinova.

Zbog visokih zahtjeva na zaštitu okoliša, troškovi pogona i održavanja postrojenja su visoki, te uz relativno nisku kalorijsku vrijednost komunalnog otpada koji se spaljuje (oko 10 MJ/kg) čine spalionicu otpada granično isplativom za odabrani kapacitet od 100.000 tona otpada godišnje i graničnu vrijednost naknade za zbrinjavanje otpada od 105 EUR/t otpada, ako se razmatra isključivo ekonomska računica.

Parametri o kojima ovisi isplativost kogeneracijskog postrojenja na otpad kreću se od čisto tehničkih poput kapaciteta spalionice i ogrjevne vrijednosti otpada (postotak vlage, odnosno biorazgradive tvari), do sasvim ekonomskih poput uvjeta kreditiranja, troškova čišćenja dimnih plinova, naknade za zbrinjavanje opasnog otpada, cijene koja se može postići prodajom električne i toplinske energije, te najvažnijeg parametra – ulazne cijene prihvata otpada (naknada za zbrinjavanje otpada). Visoki troškovi zbrinjavanja pepela i ostataka mogu utjecati na ukupnu ekonomsku isplativost postrojenja.

Keywords
Cogeneration by waste incineration
Municipal waste incinerator
Waste combustion on grate

Ključne riječi
Izgaranje otpada na rešetki
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1. Introduction

An adequate disposal of waste as well as its energy recovery is a necessity of a modern developed world. An increase in the standard of living causes growth of production of municipal solid waste. The landfills where such waste is disposed of without previous sorting, mechanical treatment or partial recycling, have long become since insufficient. Large quantities of waste which are being disposed of near major cities and settlements have a negative impact on human health and the quality of life in general.

Due to the EU directive [1], the quantity of biodegradable waste going to landfills should be decreased

Symbols/Oznake

B	- working hours, h/year - radni sati
H_d	- lower heating value, MJ/kg - donja ogrjevna moć
c	- efficiency coefficient of removal - koeficijent učinkovitosti uklanjanja
EF	- emission factor, kg/t - faktor emisije
q_{MSW}	- capacity, t/year - kapacitet
η	- steam generator efficiency, % - stupanj iskoristivosti kotla

Indices/Indeksi

e	- electricity - električna energija
th	- heat - toplinska energija
MSW	- municipal solid waste - kruti komunalni otpad

to 75 % (by weight) of totally produced biodegradable municipal waste in 1997 till the year 2012, 50 % till 2015 and 35 % till 2020, and it will not be possible to dispose of waste in landfills without prior treatment. One of the ways how that could be done is thermal treatment. The thermal treatment of waste reduces mass and volume of waste that is landfilled, saving valuable space on landfills. Also, the new EC Waste Framework Directive [2] specifies that such treatment should inevitably involve an energy recovery of waste, which would in turn decrease dependency of energy production from fossil fuels.

The technology for thermal treatment of waste, which is most often used, is the incineration of unsorted waste on the grate, so called mass-burn. Sometimes, it is necessary to add fuel to such waste in order to increase its heating value, which will result in better efficiency of combustion. Often, natural gas, but also coal and wooden biomass are used as additional fuels, particularly if waste is not previously dried.

The technology of waste combustion on the grate is a mature technology that has been used already for hundred of years. The primary role of waste incineration is reduction of mass (up to 75 %) and volume of waste (up to 90 %) [3] but also destruction of dangerous organic compounds and pathogens.

There is a long tradition of waste incineration on the grate in Europe and extensive experience has been collected in more than four hundred operational incinerators processing 52 Mt/year of municipal solid waste (MSW) in 2003, which was around 20 % of the total quantity of MSW [4].

Methods of flue gas cleaning have experienced a strong development in the last decades. That provided for further existence of this technology in the time of ever stringent requirements on emissions in to the atmosphere and impacts on the environment.

2. Techno-economical analysis

Since there are no facilities for thermal treatment of municipal solid waste in the Republic of Croatia, the techno-economical analysis was conducted for a potential waste-to-energy (WtE) plant that would incorporate simultaneous production of heat and electricity. The choice of technology of incineration on a grate assumes application of all the most stringent environmental protection standards. The paper analyses two variants of flue gas cleaning systems.

2.1. Case study

Capacity

The technology of combustion on a grate is favourable for treatment of larger quantities of waste i.e. above 100.000 t/year. By increasing the capacity of the plant the cost of incineration per ton of MSW is falling while the energy efficiency of the treatment is growing. For the purpose of a sensitivity analysis of potential waste-to-energy plant in the conditions of Croatia, the referent capacity of 100.000 t/year was selected.

MSW Heating Value

Chemical and physical properties of the waste that is sent to the thermal treatment facility determine adequate technology and the level of energy efficiency. These characteristics are influenced by a number of local factors, such as: contracts with waste providers, methods of waste separation and pretreatment inside or outside the facility and market conditions.

The heating value of MSW is influenced by national systems for separate collection of waste whereby the share of particular combustible compounds in total municipal waste could be lowered by prior separation of recyclables, such as polymers. Furthermore, although the MSW calorific value considerably varies depending on the season as well as the geographical location (the area in which the waste is collected), for the purpose of this analysis the lower heating value of 10 MJ/kg of MSW was chosen.

Combustion system

Although all three major technologies of waste combustion on a grate (Von Roll, Martin, Keppel-Seghers) are very similar, the Von Roll system incorporates a cooling system that allows use of waste heat taken from the grate. This heat is used for heating flue gases before the process of selective catalytic reduction or it can be used for preheating the combustion air, and therefore the Von Roll technology was selected in this work (Figure 1).

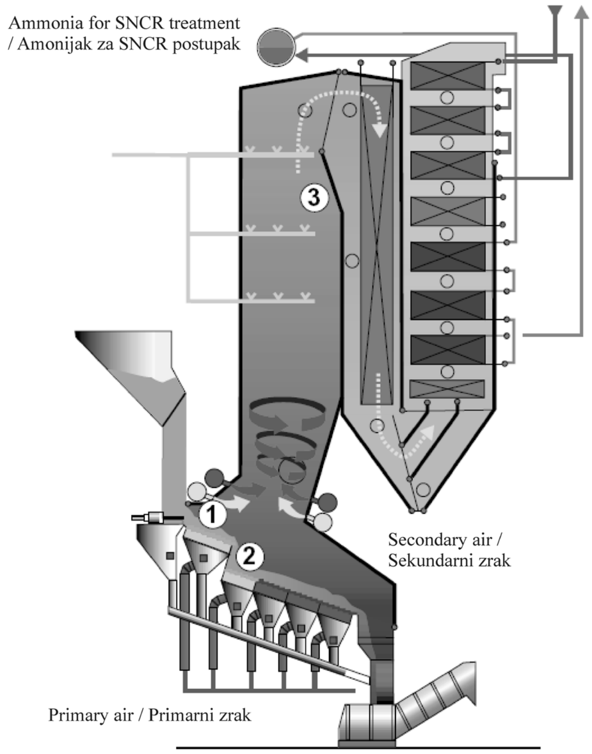

Figure 1. Von Roll waste combustion system [5]
Slika 1. Von Roll sustav za izgaranje otpada [5]

The Von Roll technology consists of the following components:

- A system for controlled and continuous input of waste to the grate,
- Reciprocating grate.
- Centre-flow secondary combustion chamber,
- High efficient heat recovery system,
- Steam generator,

The waste is fed into the hopper after which it is controllably added to the grate. The grate system comprises individual modules i.e. stationary and moving rows inclined at an angle of 18°. The modules transport the waste through the combustion chamber. The grate is divided into four zones of which each represents a particular combustion phase: drying, ignition, burning and complete combustion. The combustion process is controlled by regulation of each grate's zone, i.e. it is possible to control the rate of movement in each particular zone. Furthermore, each of the grate modules has an individually controlled air supply, permitting optimal control of the combustion process over the grate as a whole.

The heat recovery system consists of a primary and secondary circle. Water under pressure in the primary circle cools the grate carrying away heat, which is transferred to the secondary circle in the heat exchanger. That waste heat could be used for preheating the combustion air or it could be used for the purpose of a district heating. This system helps to achieve a higher thermal efficiency of the process and also increases the life span of the grate.

The secondary combustion chamber is located above the main combustion zone of the grate. A number of nozzles located on the walls of the secondary chamber form the swirling flow of flue gases thus ensuring a uniform composition and temperature of the mixture, enhancing burnout of the unburned particles in gases and decreasing the consumption of ammonia in the Selective Non-Catalytic Reduction (SNCR) process of NO_X reduction.

The steam generator produces steam that is used for heat and electricity production. The flue gases pass through several stages of cleaning. There are several possible variants of the flue gas cleaning systems, according to the composition and capacity of waste that is burned. With the chosen technology it is possible to apply the wet, semi-dry and dry cleaning treatments as well as the Selective Catalytic Reduction (SCR) and the SNCR processes.

The basic input data are summarized in Table 1.

Table 1. Input data
Tablica 1. Ulazni podaci

Parameter / Parametar	Simbol / Oznaka	Value / Vrijednost	Unit / Mj. jedinica
Capacity / Kapacitet	q_{MSW}	100.000	t/year
Working hours / Radni sati	B	7.500	h/year
Lower heating value / Donja ogrjevna moć	H_d	10	MJ/kg
Steam generator efficiency / Stupanj iskoristivnosti kotla	η	80	%

Energy balance

Heat produced by combustion of waste is used for generation of steam. The steam flows to the condensation turbine that includes a high-pressure and a low-pressure stage between which a controlled steam extraction is located. The parameters of the live steam at the inlet of the high-pressure turbine stage are 400 °C and 50 bar while the parameters of controlled steam extraction are 198 °C and 15 bar. In this case study, it was assumed that heat is being sold to the nearby industry where it could be used e.g. for heating of process water or for agricultural businesses (e.g. drying, heating of the greenhouses, etc.). The overall calculated efficiency is around 50.8 %.

A certain amount of steam and electricity is spent in the facility itself. The specific consumption of electric energy is 0.1 MWh_e/t_{MSW} and heat 0.05 MWh_{th}/t_{MSW}, but the final balance is positive (Table 2). The net produced electric power is 6.23 MW_e while the thermal power is 10 MW_{th}. The produced electricity is fed into the national electric grid for which it should be possible to obtain special incentives (through the Croatian feed-in tariff system [6]) when electricity is produced from a renewable energy source (only biodegradable part of waste) or in the cogeneration regime.

Table 2. Energy balance of the WtE plant

Tablica 2. Energetska bilanca energane na otpad

Energy balance / Energetska bilanca	MWh/year
Production / Proizvodnja	
Electricity / Električna energija	46.710
Heat / Toplinska energija	75.000
Consumption / Potrošnja	
Electricity / Električna energija	10.000
Heat / Toplinska energija	5.000
Energy output / Izlaz energije	
Electricity / Električna energija	36.710
Heat / Toplinska energija	70.000

2.2. Initial costs

Investment costs could substantially vary with respect to several influential factors: design of the WtE plant, its size (capacity), existence of the local infrastructure as well as the possibility for selling of energy.

It is necessary to construct road infrastructure, weighing area and waste reception storage. Estimated costs of 4.6 million EUR include costs of construction of the access roads and the foundations for the waste storage. The combustion chamber-steam generator system includes:

- A system for waste feeding into the chamber,
- Combustion air supply,
- Combustion chamber with the grate,
- Ash and slag removal and storage,
- Flue gas channels providing heat for the feed-water heaters,
- Steam generator with a feed-water supply and steam output.

The combustion system with the steam generator, without the costs of construction and the costs of regulation and control equipment, for the WtE plant with the capacity of 100.000 t/year, was estimated to 19.5 million EUR.

The water and steam system consists of the following components:

- Water treatment facility,
- Air cooled condenser,
- Condensation turbine with controlled steam extraction,
- Controlled steam extraction with steam parameters 198 °C and 15 bar.

The costs of this system vary according to the ratio of production of hot water for heating and electricity. The cost of the water/steam system of around 8 million EUR was estimated in the case of analysed cogeneration plant.

The total cost of components of the WtE plant, without the cost of flue gas cleaning system (which are analysed separately), including costs of design, construction, electro-mechanical installations and other investment costs, is given in Table 3.

2.3. The investment costs of the flue gas cleaning system

Cleaning of flue gases represents an important part of the overall waste combustion process. Selection of the technology for the flue gas treatment depends on the flue gas composition, emission limit values, local conditions (water supply, waste water treatment, etc.) and estimation of operating and investment costs. Two variants of flue gas cleaning were analyzed.

Variant 1

In the first variant the flue gas cleaning system that includes the following components was examined:

- Selective non-catalytic reduction system,
- Bag filter,
- Semi-dry flue gas treatment system.

Table 3. The structure of initial costs of the WtE plant (excluding the cost of the flue gas cleaning system)

Tablica 3. Struktura početnih troškova energane na otpad (bez sustava za pročišćavanje dimnih plinova)

Type of cost / Vrsta troška	Cost (EUR) / Trošak (EUR)
Infrastructure and waste storage / Infrastruktura i spremnik otpada	4.600.000
Combustion system and steam generator / Sustav za izgaranje i kotao	19.500.000
Water and steam system / Sustav vode i pare	8.000.000
Design / Projektiranje	2.000.000
Construction / Izgradnja	7.000.000
Electro-mechanical installations / Elektro-mehaničke instalacije	5.000.000
Other investment costs / Drugi investicijski troškovi	6.000.000
Total / Ukupno	**52.100.000**

In this system (Figure 2), flue gases first enter the wet scrubber where the acid compounds are removed by water spraying. Before entrance into the bag filter, active coke and calcium hydroxide in the form of finely milled powder are injected into the flue gas channel, in order to remove sulphur oxides, HCl, HF and mercury. Reactions take place in the flue gas channel but also in the layer of precipitation residue on the bag filter. The results are calcium salts which are filtered in the bag filter. The wet scrubber and bag filter residues are collected for further disposal since they are classified as hazardous waste.

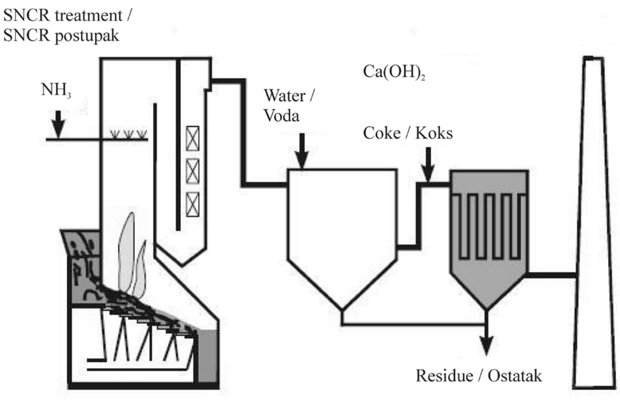

Figure 2. Variant 1 of the flue gas cleaning system

Slika 2. Varijanta 1 sustava za pročišćavanje dimnih plinova

The estimated initial costs of the overall system for the first variant are as follows [3]:

Table 4. Investment cost for variant 1

Tablica 4. Investicijski trošak za varijantu 1

System component / Dio sustava	Cost (EUR) / Trošak (EUR)
Semi-dry treatment / Polusuhi postupak	1.200.000
Bag filter / Vrećasti filter	2.200.000
SNCR process / SNCR postupak	800.000
Total / Ukupno	**4.200.000**

Variant 2

The system in the second variant consists of:

- A wet flue gas treatment system,
- Electrostatic precipitator,
- Selective catalytic reduction system.

Such a system (Figure 3) represents a wet flue gas treatment. The flue gases leaving the steam generator enter the electrostatic precipitator where they are cleaned. Then the flue gases enter the first wet scrubber where acid compounds (HCl and HF) and mercury are removed, after which, in the second wet scrubber with an addition of sodium hydroxide, sulphur oxides are removed. Finally, the SCR treatment follows to reduce the level of NO_X.

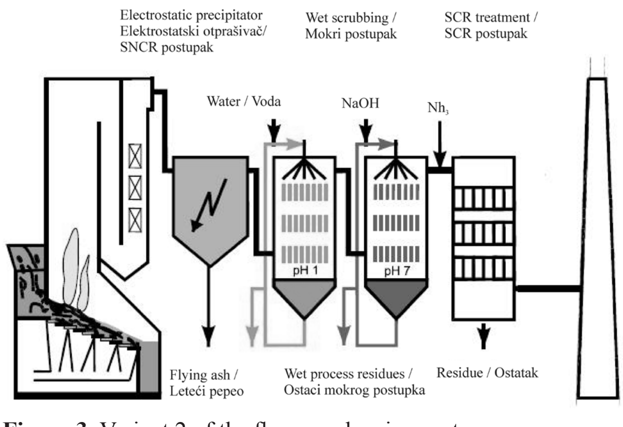

Figure 3. Variant 2 of the flue gas cleaning system

Slika 3. Varijanta 2 sustava za pročišćavanje dimnih plinova

The overall system costs for the second variant are given in Table 5 [3].

It can be assumed that the investment cost of the remaining part of the plant is equal in both variants (Table 3), so the total investment cost of the WtE facility amounts to 56.3 million EUR for variant 1 and 59.8 million EUR for variant 2.

Table 5. Investment cost for variant 2

Tablica 5. Investicijski trošak za varijantu 2

System component / Dio sustava	Cost (EUR) / Trošak (EUR)
SCR process / SCR postupak	1.500.000
Electrostatic precipitator / Elektrostatski otprašivač	1.200.000
Wet scrubbing treatment / Sustav mokrog postupka	5.000.000
Total / Ukupno	**7.700.000**

2.4. Operating and maintenance costs

The costs of operation depend on the chosen variant of the flue gas cleaning system, since different technologies use various amounts of reagents and consequentially generate different quantities of waste material (ash, various residues from the flue gas cleaning process) that is necessary to be disposed of. Annual emission fees for CO_2, SO_X and NO_X enter the operating costs, which are being paid to the Environmental Protection and Energy Efficiency Fund of Republic of Croatia [7-8]. The CO_2 emission fee is equal in both cases, variant 1 and 2, while the SO_X and NO_X emission fees are calculated for each variant separately.

Maintenance cost

The maintenance costs of the combustion system and the steam generator are proportional to the waste flow. By increasing waste flow, the consumption of electricity, needed for the operation of feed-water pumps and fans supplying primary and secondary combustion air, increases, and at the same time, the cost of ash disposal grows. The annual maintenance cost is estimated at 3 % of the total investment cost.

Cost of emission fees

The emission fee for CO_2 is determined based on the annual quantity of carbon dioxide per ton of waste, which is calculated from the stoichiometric equations according to the waste composition as given in Table 6.

The amount of CO_2 from one ton of waste is 1062 kg_{CO2}/t_{MSW}. Then the annual emission is 106.200 t_{CO2}. Although all produced CO_2 directly enters the atmosphere contributing the green-house effect, only the share that comes from to the part of waste of fossil origin is taken, into calculation of the CO_2 emission fee according to the regulation [8]. Since waste is a heterogeneous mixture of wastes, the average CO_2 originating from the non-biodegradable part of waste is found to be in the range 33-50 % [9]. For further analysis the average value of 41.5 % was taken. In that case the CO_2 emission fee of 10.082 EUR/year is calculated.

Table 6. Chemical composition of MSW

Tablica 6. Kemijski sastav komunalnog otpada

Substance / Tvar	Mass ratio / Maseni udio, %
Water / Voda	20
Ash / Pepeo	25
Carbon / Ugljik	29
Hydrogen / Vodik	3
Nitrogen / Dušik	0.9
Oxygen / Kisik	18
Sulphur / Sumpor	0.3
Fluorine / Fluor	0.02
Clorine / Klor	0.5
Other / Ostalo	3.28
Total / Ukupno	**100**

One ton of waste contains approximately 3 kg of sulphur. From the stoichiometric calculation a mass of 6 kg of SO_2 per one ton of waste follows. At the annual level, taking into consideration the efficiency of SO_X removal by the semi-dry flue gas treatment of $c = 0.95$, this quantity amounts to 30 ton of SO_2 in variant 1. The emission fee for SO_2 is then 684 EUR/year. Generation of SO_2 in variant 2 is the same as in variant 1 but the efficiency of SO_X removal is different. Variant 2 applies the wet scrubbing process which is more efficient than the semi-dry process. The efficiency coefficient is $c = 0.98$ so the annual emission of sulphur dioxide is 12 t_{SO2}. From that the SO_2 emission fee (for variant 2) of 273 EUR/year follows.

NO_X emission is calculated using emission factors. The emission factor for waste depends on the type of waste and the method of treatment. The NO_X emission factor for waste combustion is $EF = 1.8$ kg of NO_X per ton of waste [10]. For a level of NO_X reduction in variant 1 (SNCR) the efficiency coefficient of $c = 0.45$ was taken. The NO_X emission fee of 2794 EUR/year follows. Emission of nitrogen oxides in variant 2 is differentiated only by the coefficient of efficiency of NO_X removal. In variant 2 the SCR method is used for NO_X removal, which is more efficient than the SNCR process. The efficiency coefficient is $c = 0.8$ so the annual emission fee for nitrogen oxides is 1016 EUR/year.

Labour cost

It was assumed that the WtE plant will work 24 hours a day in three shifts, seven days a week. Required personnel for the plant operation, along with their annual gross salaries, are given in Table 7.

Table 7. Personnel and annual salaries

Tablica 7. Osoblje i godišnje plaće

Personnel / Osoblje	Number (1shift) / Broj (1 smjena)	Annual gross salary (EUR) / Bruto godišnja plaća (EUR)
Worker / Radnik	15	201.600
Engineers / Inženjer	5	84.000
Maintanance / Održavanje	3	50.400
Manager / Upravitelj	1	33.600
Total / Ukupno	**24**	**369.600**

The total annual labour cost (for three shifts daily) is 1.108.800 EUR.

Compensation cost

Compensation to local community and house owners living in the vicinity of a potential WtE plant due to decreased property values was estimated to be 2.46 EUR/t_{MSW}. This cost depends on the population density of WtE plant surroundings.

Total operating and maintenance (O&M) costs

A comparison of O&M costs of the facility with variants 1 and 2 is given in Table 8.

From Table 8 it could be observed that a large share of costs represents the costs of disposal of the thermal treatment residues, especially disposal of residue from the bag filter (variant 1), which is classified as hazardous waste. High costs of ash and residues disposal could influence the total economic viability of the WtE plant.

The maintenance costs of the flue gas cleaning system in variant 2 are higher than in variant 1, but due to more advanced technology the required amount of reagent is lower as well as the quantity of produced hazardous waste, whose disposal is quite costly. Finally, the annual operating costs for the second variant are lower than those for variant 1.

2.5. WtE plant revenues

Revenue from a waste disposal

The most important revenue of the waste thermal treatment plant is revenue from the waste disposal fee, so called gate fee. The gate fee depends on market conditions, operating costs, amount of energy that could be sold and the price of competitive methods of waste disposal. Examples from the EU countries show that the gate fee could substantially vary. Based on the sensitivity analysis (Figure 4) and European praxis, a relatively high gate fee of 120 EUR per ton of waste was chosen. The

Table 8. Comparison of O&M costs for different flue gas cleaning systems

Tablica 8. Usporedba pogonskih troškova za različite sustave čišćenja dimnih plinova

Type of cost / Vrsta troška	Variant 1 / Varijanta 1, EUR/year	Variant 2 / Varijanta 2, EUR/year
System maintanance (3 % of investment costs) / Održavanje sustava (3 % investicijskih troškova)	1.685.000	1.794.000
Natural gas / Prirodni plin	85.000	85.000
Process water / Procesna voda	12.000	12.000
Active coke / Aktivni koks	30.000	-
Reagent for SNCR (NH_3) / Reagens za SNCR (NH_3)	80.000	-
Reagent for SCR (NH_3) / Reagens za SCR (NH_3)	-	40.000
Reagent for semi-dry treatment ($Ca(OH)_2$) / Reagens za polusuhi postupak ($Ca(OH)_2$)	70.000	-
Reagent for wet treatment (NaOH) / Reagens za mokri postupak (NaOH)	-	35.000
Bottom ash disposal / Odlaganje pepela s dna	1.380.000	1.380.000
Flying ash from the steam generator / Leteći pepeo iz kotla	138.000	138.000
Flying ash from the electrostatic precipitator / Leteći pepeo iz elektrostatskog otprašivača	-	193.200
Bag filter residue / Ostatak iz vrećastog filtera	1.575.000	-
Solidified flying ash / Zgusnuti leteći pepeo	-	253.000
Wet treatment residues (heavy metals hydroxides) / Ostaci mokrog postupka (hidroksidi teških metala)	-	56.000
Emission fees / Naknada za emisije	13.560	11.371
Compensation / Naknada vlasnicima nekretnina u blizini postrojenja	246.000	246.000
Labour / Osoblje	1.108.800	1.108.800
Total / Ukupno	**6.427.360**	**5.352.371**

revenue from waste disposal is shown in Table 9. Such gate fee should ensure profitability in both variants (1 and 2).

Table 9. Revenue from waste disposal

Tablica 9. Prihod od zbrinjavanja otpada

Revenue / Prihod	Gate fee / Iznos, EUR/t	Total, EUR/year / Ukupno, EUR/god.
Waste disposal / Preuzimanje otpada	120	12.000.000

Revenue from selling electricity and heat

Selling electric energy into the distribution network ensures a stable buyer of electricity, while the heat is being sold, e.g. to neighbouring textile, paper or agricultural industry. The heat energy from the analysed WtE plant is the high-value heat (198 °C) that could achieve a higher price. This price could not be exactly determined since it is a matter of contract between the producer and the buyer. In this analysis the following selling prices of electric and heat energy were taken, as shown in Table 10.

Table 10. Revenue from selling electricity and heat

Tablica 10. Prihod od prodaje električne i toplinske energije

Energy / Energija	Selling price of energy / Prodajna cijene energije, EUR/kWh	Energy sold, MWh/year / Prodana energija, MWh/god.	Revenues, EUR/year / Prihodi, EUR/god.
Electricity / Električna energija	0.048	36.710	1.762.080
Heat / Toplinska energija	0.024	70.000	1.680.000
Total revenues from selling energy / Ukupni prihodi od prodane energije			**3.442.080**

If it were possible to achieve higher selling prices of heat and electricity (what was analysed for the price of heat, in Figure 5), the gate fee could be proportionally lower keeping the same revenue.

Revenue from selling separated metals

If the ash remaining after the waste thermal treatment is to be used in building industry, it will be necessary to remove metals (i.e. iron and aluminium) from it. Furthermore, these metals can be sold if market conditions allow i.e. if the costs of separation and storage could be covered. The examined facility could annually separate around 2400 tons of Fe and 400 tons of Al from 30.000 tons of ash produced annually (300 kg of ash per 1 ton of waste burned). The revenues from selling separated metals are given in Table 11. It should be noted that investment in the metal separation system as well as its continuous operation, bear certain costs which are in this paper, assumed to be equal to the realized revenue for the sake of simpler analysis.

Table 11. Revenue from selling separated metals

Tablica 11. Prihod od prodaje izdvojenih metala

Material / Materijal	Quantity, t/year / Količina, t/god.	Selling price / Prodajna cijena, EUR / t	Revenue, EUR/year / Prihod, EUR/god.
Fe	2.400	40	96.000
Al	400	550	220.000
Total / Ukupno			**316.000**

Input data

Input data needed for the economic analysis are summarized in Table 12.

Table 12. Data for the economic analysis

Tablica 12. Podaci za ekonomsku analizu

Basic data/ Osnovni podaci		
Capacity / Kapacitet	100.000	t/year
Electric power / Električna snaga	6.23	MW
Thermal power / Toplinska snaga	10	MW
Electricity consumption / Potrošnja električne energije	1.33	MW
Heat consumption / Potrošnja toplinske energije	0.67	MW
Working hours / Godišnji broj radnih sati	7500	h/year
Lifetime/ Eksploatacijski vijek	25	year
Interest rate (loan) / Kamata (kredit)	6 %	
Inflation/ Inflacija	3 %	
Real interest/ Realna kamata	3 %	
Loan repayment period/ Vrijeme otplate kredita	15	year
Income tax/ Porez na dobit	20 %	
Selling price of electricity/ Prodajna cijena električne energije	0.048	EUR/kWh
Increase of price of electricity/ Povećanje cijene el. energije	0.3 %	1/year
Selling price of heat/ Prodajna cijena topline	0.024	EUR/kWh
Gate fee/ Naknada za preuzimanje otpada	120	EUR/t

Although both discussed variants of the flue gas cleaning systems, and especially variant 2, could fully satisfy current emission limit values, the second variant, albeit initially more expensive, has a lower influence on the environment over the lifetime of the facility and at the same time lower O&M costs. Thus, the net present value of variant 2 after 25 years is higher than variant 1. The internal rate of return for the first variant is 13 % and for the second 14 %.

Taking into account given parameters that determine revenues and costs, it could be seen that the WtE plant based on the technology of the combustion on the grate becomes marginally viable (with the annual capacity of 100.000 tones of waste) for the values of gate fee above 105 EUR/t, if the costs of loan repayment are included (Figure 4). The cost-effectiveness (and the rate of return) depends on loan conditions, so in the case of different model of financing (e.g. public-private partnership) in which a county or city could participate, probably more favourable terms could be agreed what would in turn result in lower gate fees.

2.6. Sensitivity analysis

Applying a sensitivity analysis to the variations of parameters it is possible to anticipate certain problems that could occur during a period of exploitation of WtE plant. Figure 4 shows the sensitivity analysis for the net profit as a function of the gate fee. It could be seen that the facility starts to operate with the profit only when the gate fee surpasses 105 EUR/t_{MSW} in variant 1 and 110 EUR/t_{MSW} in variant 2.

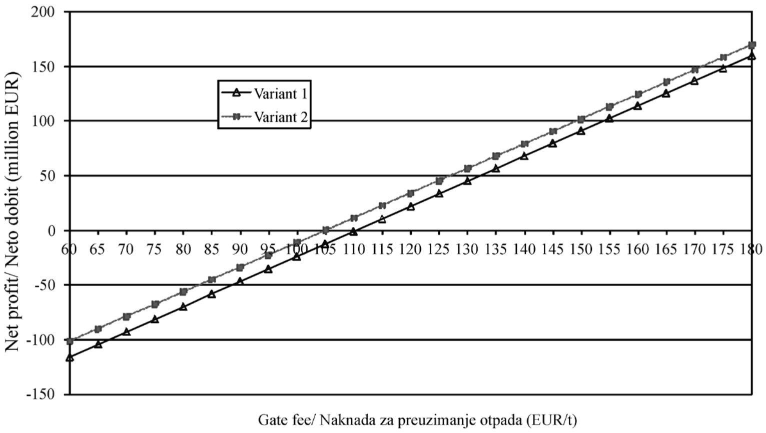

Figure 4. Sensitivity analysis (Gate fee)

Slika 4. Analiza osjetljivosti (naknada za preuzimanje otpada)

The dependency of the net profit on the selling price of heat is weaker than on the gate fee since the revenue from selling heat makes up a smaller part of the total profit. That analysis is shown in Figure 5.

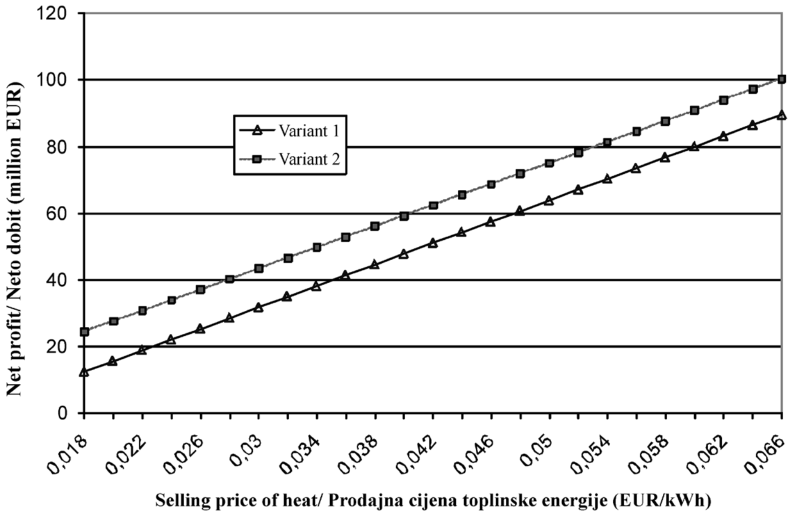

Figure 5. Sensitivity analysis (Selling price of heat)

Slika 5. Analiza osjetljivosti (prodajna cijena toplinske energije)

3. Conclusion

Installations for the thermal treatment of waste offer today acceptable solutions for waste disposal with the precondition of application of all the most stringent environmental protection standards. The technology of waste combustion on the grate is currently the most widespread technology for waste thermal treatment and it has been used for quite a long time. Methods of flue gas cleaning have experienced strong development in the last decades, which provided for further existence of this technology in the time of ever stringent requirements on emissions to the environment.

Both examined variants of the flue gas cleaning systems, and especially variant 2, could fully satisfy current emission limit values. The second variant, although initially more expensive, has a lower influence on the environment over the lifetime of the plant and at the same time lower operating and maintenance costs, so after 25 years its net present value is higher than those of variant 1.

The parameters on which the cost-effectiveness of the waste-to-energy cogeneration plant depends range from purely technical like the plant capacity and the waste calorific value (including percentage of moisture and biodegradable matter) to entirely economical such as loan conditions, costs of flue gas cleaning, costs of hazardous waste disposal, income from selling of electricity and heat, and the most important factor – a charge levied upon a waste received at a waste-to-energy plant (the gate fee). High costs of ash and residues disposal could influence the total economic viability of the WtE plant.

Due to high requirements on environmental protection, the operating and maintenance costs of the facility are rather high while the calorific value of the municipal waste burned is relatively low (around 10 MJ/kg), which brings the waste-to-energy under in consideration to the limit of economical viability for the given annual capacity of 100.000 tons of waste and the limiting gate fee value of 105 EUR per tone of waste, if solely direct cost-effectiveness is considered.

Furthermore, a more detailed economic analysis showed that the cost-effectiveness of the facility significantly depends on loan conditions. These conditions could be crucial in investment decision process. The model of public-private partnership could be one of the possible solutions, since the loan terms are more favourable when counties or cities are involved, whereby, in such model, their share would represent public part of ownership.

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