INFLUENCE OF LEGISLATIVE CONDITIONED CHANGES IN WASTE MANAGEMENT ON ECONOMIC VIABILITY OF MSW-FUELLED DISTRICT HEATING SYSTEM – CASE STUDY

by

Tihomir TOMIĆ[a*], Boris ĆOSIĆ[b], and Daniel Rolph SCHNEIDER[a]

[a] Department of Energy, Power Engineering and Environment, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia
[b] Adria Section of the Combustion Institute, Zagreb, Croatia

Original scientific paper
DOI: 10.2298/TSCI160212114T

District heating systems represents one of the ways by which the European Union is trying to reach set goals in energy efficiency and security field. These systems allow the use of different energy sources including local energy sources such as waste and biomass. This paper provides economic viability assessment of using these fuels in the district heating system. Economic evaluation is based on regression analysis from data of existing plants and on the locally dependent data. Some of parameters that are dependent of local parameters are price and available fuel quantity, therefore these values are separately modelled; biomass as a function of location of the plant while municipal waste as a function of location and the time changes in waste quantity and composition which depend of socio-economic trends and legislation. This methodology is applied on the case of district heating plants in the City of Zagreb where internal rates of return are calculated for four considered scenarios. Results indicate that waste powered plant can improve its profitability by co-combusting other local wastes while economic viability is achieved by introduction of region wide waste management system. Reducing plant capacity, based on prognosis of waste generation, showed that these plants can be competitive with biomass plants.

Key words: *district heating systems, municipal solid waste, waste prognosis, waste to energy, economic viability, biomass, waste water treatment, AD sludge*

Introduction

District heating systems (DHS) are increasingly discussed in the context of the further development of the EU energy system (ES) and represent one of the ways in which the EU is trying to reach set goals of reducing primary energy consumption, reducing pollution and increasing diversification of energy sources, which is emphasized in Article 14 of the Energy Efficiency Directive (2012/27/EU). In recent studies DHS are identified as an important factor in creating sustainable ES. Heat Roadmap Europe [1, 2] shows that expansion of DHS can reduce energy costs through greater use of local resources and reduce energy import. The concept of the 4th generation of district heating (DH) and its role in future ES is defined in [3]. DH enables the use of various technologies and renewable resources [4]. The design of 100% renewable ES relies on the expansion of DHS and corresponding technologies [5]. The role of DH in future ES is emphasized in [6]. In these conditions DHS can be

* Corresponding author; e-mail: tihomir.tomic@fsb.hr

expanded to cover over 50% of heat consumption [7]. The Swedish example [8] shows that DHS, to be considered as low-carbon systems, must be converted to utilize renewable energy sources. This path includes the usage of local energy sources. Introducing biomass fuelled DHS can help in emission reductions [9], but its extensive usage in ES can cause its shortage and competition for biomass between different sectors. European biomass potential is low and unevenly distributed when compared to energy demand [10]. In these conditions local governments have to decide which resource will be used to satisfy energy needs. One way to decrease demand for biomass and other fuels is the usage of municipal solid waste (MSW) as a fuel in DHS [11]. The use of waste to energy (WtE) technologies in DHS can also lead to increased penetration of DH. The path towards meeting EU waste management (WM) goals includes WtE technologies and also leads to emission reductions [12]. One of the deciding factors for local government in making this decision is economic viability of investment which gained on importance after the economic downturn. In [13] it is shown that combined heat and power (CHP) in conjunction with DH is economically preferable than individual means of heating and reduces consumption of primary energy, while primary energy sources can be replaced with energy derived from waste. Multicriterial evaluation of different energy sources for DHS is applied on the case of the city Vancouver [14], but WtE plants were not considered. It is concluded that the best energy source is different for different stakeholders. In [15] a LCA analysis of waste, biomass and natural gas fuelled DHS is given, but a comparison of economy indicators is not presented. The cost analysis of WtE plant has been conducted in [16], but no comparison with alternative energy production options is given. In these papers the quantity of waste is considered constant or is just extrapolated from historical data. Moreover, changes in waste composition and its lower heating value (LHV) are not considered. Forecasting MSW plays an important role in waste management system (WMS) planning [17]. Co-combustion of local biomass and wastes in existing plants can also help in meeting EU goals [18].

Due to the delay in meeting EU goals, resolving the problem of waste disposal in Croatia has gained in importance. This problem is especially pronounced in the City of Zagreb because of a sheer amount of waste that needs to be properly disposed of after landfill ban in 2018. Such circumstances urge the city government to consider the possibility of constructing a WtE plant and usage of residual waste (RW) as a fuel in DHS. In the same time the progress in separate collection of recyclable wastes reduces the amount of RW for energy recovery and raises the question of profitability of this investment in comparison with the use of other local energy source such as biomass, especially if Zagreb is the sole investor. This raises the question which fuel is more suitable for use in DHS, especially since both fuels fit in the context of the European energy policy. Due to the recession the main issue became profitability, which defines the research question: Investment in which DHS plant is more profitable, biomass or RW powered, in the time of shift in WM legislation?

A comparative techno-economic analysis of waste and biomass powered CHP DH plant is presented in this paper on the case of the City of Zagreb. Biomass is defined by its price, spatial distribution and transport costs and MSW by its amounts, composition and LHV, which are forecasted on the basis of socio-economic and legislative changes. In order to offset the effect of observed decrease in the quantity of mixed waste on plant operation three other scenarios are introduced, first of which considers reduction on plants capacity, the second considers co-combustion of anaerobic digestion (AD) sludge from the local wastewater treatment (WWT) plant, while and the third expands the scope of analysis to the entire region and considers importing waste from other counties. In joint, regionwide, WMS planning, spatial differences in waste generation have to be taken into account, as well as the impact of an introduction of waste transport system (WTS). The required techno-economic data for considered technologies are obtained by the means of regression analysis performed on gathered data for the existing plants.

Methods

Required input parameters for techno-economic analysis of biomass and RW powered cogeneration power plants, at a specific location, are shown in fig. 1.

Technology data are obtained by an regression analysis carried out over existing plants data. The regression analysis is used to draw a conclusion from a number of random variables (y_i) that depend on the independent variable (x). The conclusions are adopted on the basis of a series of dual data sets (x_1, y_1), … (x_n, y_n) on the basis of which it is possible to determine the nature of the dependency of random variables (y_i) on the independent variable (x). These dependencies can have linear character, as it is the case with investment costs, or can have other characters, such as exponential, logarithmic and power, as with other data sets. Regression parameters are determined by the means of the least squares method which estimates the value of regression parameters by minimizing the sum of the squared deviations of theoretical values from the experimental values. In the objective function of the least squares method, eq. (1), S represents the sum of squares, and the deviations r_i are given by eq. (2) where y_i represents a variable of data set while $f(x_i, \beta)$ represents y_i value of model function (fitted curve) for the value of independent variable x_i. The character of the function is determined by the function that causes the smallest deviation from a real data:

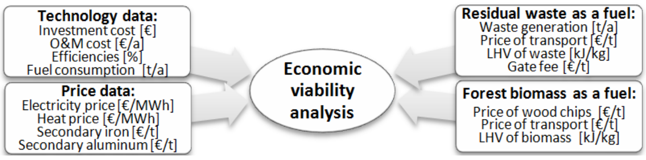

Figure 1. Required input parameters

$$S = \min \sum_{i=1}^{n} r_i^2 \tag{1}$$

$$r_i = y_i - f(x_i, \beta) \text{ for } i = 1, 2, 3, ..., n \tag{2}$$

Investment cost and efficiency model functions for biomass plants (fig. 2) are calculated from the data for existing biomass fuelled DH plants which are taken from many different sources [19-33]. The investment cost curve for WtE plants [34-53] is calculated in the same way (fig. 3).η

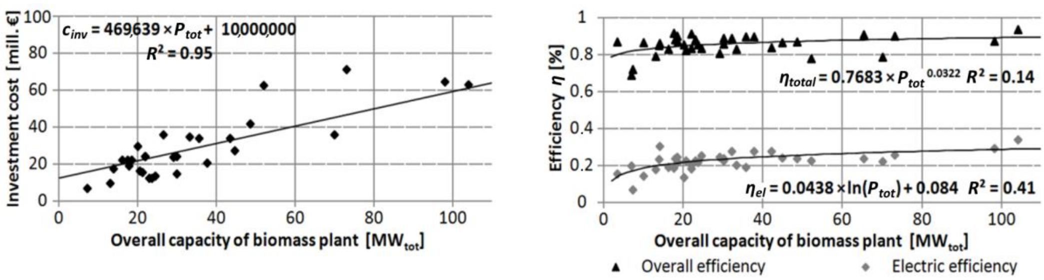

Figure 2. Techno-economic data for biomass plant

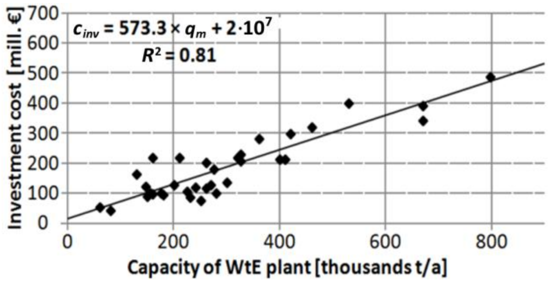

Figure 3. WtE plants investment data

Efficiency functions of WtE plants are calculated from ISWA report data [54]. The same methodology is used to determine investment and operation and maintenance (O&M) costs of waste transfer stations (TS), by using TS data [55] (tab. 1). All financial data are recalculated to the money value in 2015.

Yearly fixed O&M costs are assessed at 4% of investment cost for a WtE [56] and 2.2% for a biomass plant [57] while variable O&M costs are estimated at 19.1 €/t of waste for the WtE [56] and 0.14 €/MWh of fuel for biomass plant [57]. Personnel costs are estimated on the basis of the number of workers needed for the operation of considered plants [57, 58] and the gross average monthly salary.

Table 1. Regression analysis results for WtE plants

Plant	Parameter	Function	R^2	Eq.
WtE	Overall efficiency – η_{total} [%]	$\eta_{total} = 32.799 \times r^{-2E-06q_m}$	0.36	(3)
	Electric efficiency – η_{el} [%]	$\eta_{el} = 2.4133 \times \ln(q_m) - 17,664$	0.19	(4)
TS	Investment cost – c_{inv} [€/t]	$c_{inv} = 0.4715 \times q_m^{0.674}$	0.97	(5)

r – electricity to heat ratio, [–]
q_m – capacity, [t/a]

Analysed fuel data are: amounts, heating values and prices. Financial viability of the biomass plant depends on a continuous supply of biomass at the lowest price. In addition to the biomass price on forest road, transportation costs make a large part of its final price. Biomass price is calculated by using the existing model [59], where biomass price is calculated as a sum of its price in the forestries and its transport costs from each forestry office. It follows that the price of biomass at the site is greatly dependent on the plant size and location while its LHV depends on the average moisture content.

While biomass LHV and available quantity can be considered constant, properties and availability of MSW are dependent upon local parameters and temporal changes. Nowadays, disposal of MSW represents one of the major unsolved issues for many countries. Due to low contamination, separately collected MSW is easier to recycle and, when the WM hierarchy concept introduced by the Waste Framework Directive is taken into account, material recovery is the only both logical and feasible way of its treatment. On the other hand, material recovery of RW is a more complicated process and therefore its energy recovery is one of the widely used treatment methods. Waste quantity and its composition are the most important parameters when incineration technologies are considered. The composition and LHV of waste are linked through chemical composition of its components by Mendeliev equation, eq. (6):

$$\mathrm{LHV_{wet}} = 4.187\left[81C + 300H - 26(O - S) - 6(9H + W)\right]\left[\mathrm{kJkg^{-1}}\right] \tag{6}$$

Changes in waste amount and composition are forecasted using the IWM-LCA Prognostic model [60]. This model reduces the error of prediction by considering a wide range of socio-economic parameters such as life expectancy, household size, labour employed in agriculture, age distribution and population number as well as the gross domestic product per capita and waste legislation goals. Impact of these parameters on the waste production is discussed in [61] and [62]. Forecasted waste amounts and their compositions are used to calculate LHV of RW in the considered period, eq. (6). To offset changes in generation of RW, incineration of WWT AD sludge and establishment of network of TS are proposed.

AD sludge from WWT plant is residue which needs to be properly disposed of. One of the ways to do this is its co-combustion in WtE plant. Even due its low LHV, relatively large quantities of it that are produced in the city WWT plant make it a suitable candidate for substitution of decreasing waste quantities. LHV of sludge is taken from the Ecoinvent database [63], while produced quantities of sludge in the next 14 years are extrapolated on the basis of forecasted population.

Not to change collection costs for municipalities, a proposal from the Waste Management Plan of Zagreb County [64] is adopted and potential locations of TS are restricted to existing landfills locations. TS are waste collection points from where compressed waste is transported to the WtE plant, thus there is no waste treatment in TS and waste composition on the gate of WtE plant is unaltered. In the county in which the WtE plant is located RW is directly transported by collection vehicles and no TS are planned. This solution implies the inclusion of investment and O&M costs of WTS which are calculated from predicted waste quantity data. Annual waste disposal data for each landfill are used to define the share of particular landfill in the overall county waste disposal which is then used in conjunction with prognosis to determine yearly waste quantity which is collected on that landfill and which can be transported to the WtE plant. Because of the lack of data, an assumption is introduced that the composition of the collected waste on each landfill in the same county is equal to the predicted composition of RW in that county in the observed year. Coordinates of the landfills/TS in north-west and central Croatia and the planned incinerator plant are used in conjunction with the prognostic model and the Google^{TM} API embedded in Visual Basic^{TM} environment to determine which TS needs to be built, amounts of waste that need to be transported from each TS and to estimate the cost of transport. Minimisation of the transport cost is done by determining the shortest overall road distance needed to be crossed to satisfy incinerator consumption and positioning TS accordingly. Other data obtained this way are:

- investment cost for TS, using eq. (5),
- O&M cost of TS (assessed using literature data to 11.5% of investment cost [65]),
- quantity of waste transported from each TS,
- composition and LHV of waste transported to incinerator (by combining data of waste composition and quantity of transported waste from each TS/county),
- travel time,
- the required number of trucks and drivers, and
- cost of fuel.

Case study

The amount of MSW collected in Zagreb in 2012 was 295,293 tonnes out of which 232,587 tonnes is RW [66]. This waste, after the closure of the landfill Prudinec in 2018, needed to be properly treated and disposed. Planned technology for the final disposal of RW in Zagreb is incineration [67], so this paper is based on that type of plant which is considered as an integral part of DHS. Since the total installed capacity of Zagreb DHS is 1,420 $MW_{th,}$ and energy demand never falls below the thermal power of considered plants, there are no constraints on the demand side for driving either of these plants as base DH plant. Also, considered plant is waste/biomass fuelled and has dispatch priority, so its energy production is only determined by fuel supply. The size of the WtE plant is determined by the projected maximum quantity of waste that needs to be treated. Since Croatia is EU member, boundary conditions for projections are determined by the EU Directives 99/31/EC and 2008/98/EC for the period to 2020 (an increase of recycling/reuse of MSW to 50% and reduction of disposal of biodegradable part of municipal waste by 65% compared to 1997), and by EU's proposed circular economy package for the period to 2030 (an increase of recycling/reuse of MSW to 70% and reduction of food waste generation by 30%). Projected data (tab. 2) show that the total amount of MSW is growing, while the quantity of RW decreases rapidly by 2020 and then slowly increases by 2030.

Table 2. Projection of waste amount and LHV of waste in Zagreb

Year	2012	2020	2030
MSW [t/a]	295,292.81	353,000.00	432,350.00
RW [t/a]	232,587.16	108,300.00	115,000.00
LHV of RW [$MJkg^{-1}$]	11.07	12.54	11.74

This decrease in RW quantity is a result of the rapid fulfilment of EU conditions in an ideal case, if the targets would be reached, which by 2020 override the increase in the overall MSW generation due to growth in population and living standards while after 2020, due to a slower pace of rise of quantity of primary separated waste, the situation is reversed. The forecasted composition of RW in Zagreb and the chemical compositions for monitored waste fractions (wet basis), used for calculation of LHV, are shown in tab. 3. Projections show that LHV of RW changes over time as a result of changes in its composition. The LHV of the RW increases in the first period due to a larger reduction in the bio-waste share which has a lower LHV compared to other burnable components, while in the second period a reducing amount of recyclable components with higher LHV has a greater impact and overall LHV decreases.

In continental Croatia the average moisture content of fresh wood chips is 50% which results in LHV of 2.2 kWh/kg. To get greater efficiency, the collected biomass is naturally dried, in open piles, to acceptable moisture levels – in this case 30% of moisture (LHV of 3.4 kWh/kg) [57].

Gathered efficiency data, which are used in regression analysis, for biomass plants are gross values while those for WtE plant are net. Net values for biomass plant are obtained by reduction of electricity production by 8% which corresponds to the internal electrical consumption of such plants.

Table 3. RW composition in Zagreb and chemical composition of its components

Waste component	Mass fraction [%]			Element analysis on wet basis – mass fraction[2]						
	2012[1]	2020	2030	%W	%C	%H	%O	%N	%S	%Ash
Paper and cardboard	27.1	18.5	24.3	23.00	33.11	5.39	33.88	0.15	0.02	4.45
Glass	3.6	5.0	3.8	2.00	0.49	0.10	0.39	0.10	0.00	96.92
Metals	1.1	1.5	1.0	3.00	4.37	0.58	4.17	0.10	0.00	87.79
Plastics & composites	26.4	35.3	27.1	20.00	48.00	8.00	18.24	0.00	0.00	5.76
Bio waste	26.5	12.0	8.0	75.00	11.68	2.00	9.72	0.53	0.03	1.04
Garden waste	5.1	2.3	3.1	65.00	16.73	2.10	13.30	1.19	0.11	1.58
Other materials	10.2	25.3	30.2	20.50	20.91	2.39	12.78	0.40	0.10	42.93

[1] Taken from reference [67]
[2] Taken from reference [68]

A WtE plant charges a service of waste disposal and this is the primary income for such plant. Waste disposal fees (gate fees) in WtE plants in EU countries, range from 46 €/t to 174 €/t [69]. For the gate fee initial value the mean value of 110 €/t is taken. As for the biomass powered plant, it generates revenue only from the sale of energy. The heat price is calculated on the basis of the local distributor price list [70] while the electricity price is determined by the Tariff system for electricity from renewable energy sources and cogeneration [71]. The contract on the purchase of electricity is valid for 14 years, therefore calculations are done for the same time period. The WtE plant achieves income from the sale of secondary metals which are separated from the produced ash. The yield of secondary metals per year is calculated from the projected waste composition data and ratio of aluminium and iron [16] while their prices, which are dependent on global market, are taken from licensed exchange data distributor [72].

WtE plants, to maintain the correct process parameters, need auxiliary fuel in the form of oil or gas fuels. Based on ISWA data [19], this additional energy is accounted in input energy of WtE plant as 0.91% of the energy from RW. Power plants are treated as a part of the DHS and therefore the amount of heat generated during the full load is in all cases equal. Following this assumption, and the fact that the WtE plant needs to process all generated waste, a referent heat generation for the plants is defined by the WtE plant heat production at maximum load. The resulting heat power is used for modelling other considered plants.

Economic viability analysis in the scenarios is given by the internal rate of return (IRR) which represents the discount rate that equates the net present value of investment with zero. Financing method is not modelled and investment costs are only amortized to reduce taxes. Corporate income tax rate is 20%, which is in accordance with the Croatian legislation. For the assessment of profitability of investment a discount rate of 9% is assumed.

Scenarios

Three scenarios are discussed. The first scenario considers the profitability of WtE plant powered by the RW from the Zagreb alone, thus its yearly number of working hours varies according to the amount of generated RW. The impact of its capacity reduction to the levels that, according to the projections, still do not violate local and European legislation is also analysed. In the second scenario a more local waste is used to compensate some of the changes in the RW generation and that is AD sludge from Zagreb WWT plant. Since a WtE plant is planed next to WWT plant, transport costs are not modelled. For LHV of this sludge is taken a value of 2.42 MJ/kg [63], and available quantities range from 52,400 tonnes in first [73] to 54,038 tonnes in the fourteenth year. The third scenario is defined by fuel supply which enables the constant work of WtE plant. Required RW amount is provided by import from neighbouring counties. This extends the scope of analysis on the whole north-west and central Croatia. The counties' RW quantities prognosis results are shown on fig. 4.

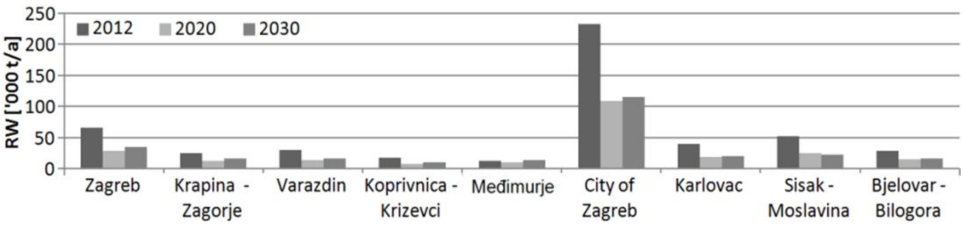

Figure 4. Projection of RW quantities by counties

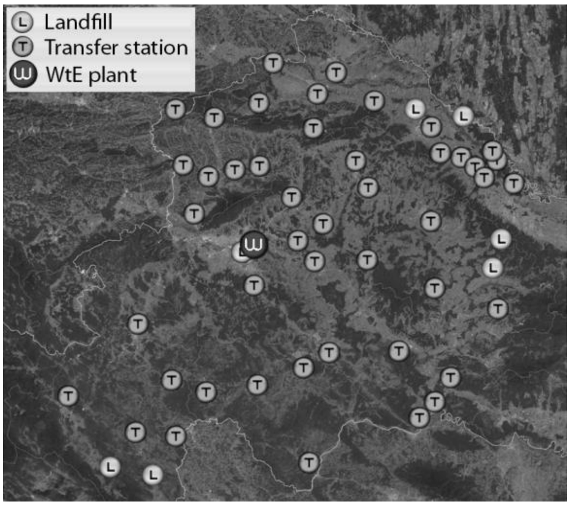

Figure 5. Locations of plants

Extension of the boundaries seeks inclusion of WTS, which consists of TS and transport trucks, into analysis. To calculate the needed data series for entire region Visual Basic™ is used. Input data consist of coordinates of all landfills and WtE plant (fig. 5), counties' RW quantities prognosis results, Google™ API data (road distances and trucks travel time between each landfill and incinerator plant) and other techno-economic data (tab. 4). TS amortisation period is 15 years. Locations of all landfills are presented on fig. 5 and marked with letters L, which represents landfill without TS (no waste is transported), and T, which represents landfill with TS. Calculated transport data are shown in tab. 5.

Table 4. Input data

	Value	Reference
Truck capacity [t]	24.00	–
Average truck consumption [l/100 km]	30.00	[74]
Price of fuel [€/l]	1.04	–
Annual gross salary [€]	12,459	[75]
Time for loading/unloading [min]	30.00	–

In all scenarios a biomass DH plant is an alternative plant used for comparison of profitability of WtE plant. To ensure a safety of supply of biomass, its supply is provided from a greater number of forestries whose total capacity exceeds the requirements. This enables an assumption of constant operation of a biomass powered plant of 7,500 hours per year in all scenarios.

Table 5. Calculated transport data

Year	1	3	5	7	9	11	13	14
Number of transfers [–]	0	1,295	2,589	3,884	5,179	5,123	5,067	5,039
On road time [h/a]	0	1,589	3,729	6,607	10,990	10,624	10,314	10,112
Cost of drivers ['000 €/a]	0	12.46	37.38	49.84	74.75	74.75	74.75	74.75
Cost of fuel ['000 €/a]	0	22.72	64.43	134.09	234.28	225.97	218.30	214.76

Results and discussion

Techno-economic data for reference plants at full load (7,500 working hours) are calculated according to previously defined methods (tab. 6). All plants are designed to meet the same heat consumption of DHS. The size of WtE plant is defined to address the problem of waste in the City of Zagreb in the years 2012 and 2019, while the biomass plant is modelled as an alternative solution with the same net thermal capacity. All scenarios in this paper are derived on basis of the reference plants. Amortization periods per type of investment are shown in tab. 7.

Table 6. Calculated techno-economic data of reference plants at full load

	WtE plant		Biomass plant
	Scenarios: 1, 2, 3	Scenarios: 1.1	
Capacity [t/a]	233,000.00	124,000.00	145,790.00
LHV of fuel [$kWhkg^{-1}$]	3.08	3.08	3.4
Heat capacity of furnace [MW_t]	96.43	51.32	47.21
Heat capacity [MW_t]	29.29	29.29	29.29
Electric capacity [MW_e]	11.73	5.46	10.66
Fuel energy [MWh/a]	723,197.93	384,877.87	354,061.43
Net heat production [MWh/a]	219,668.54	219,668.54	219,668.54
Net electric production [MWh/a]	87,951.55	40,948.20	79,928.60
Production of secondary iron/alu. [t/a]	5,520.0/920.0	2,296.0/496.0	–
Price of secondary iron/alu. [t/a]	217.4 €/t / 1,362.0 €/t	217.4 €/t / 1,362.0 €/t	–
Gate fee/biomass price [€/t]	110.00	110.00	41.23
Electricity price [€/kWh][2]	0.0553	0.0736	0.0736
Heat price [€/kWh][3]	0.0281	0.0281	0.0281
Investment [€]	153,578,900.00	91,089,200.00	29,195,551.80
Fixed O&M costs [€/a]	6,143,156.00	3,643,568.00	642,302.14
Variable O&M costs [€/a]	4,417,658.24	2.351.028,42	49,568.60
Personnel cost [€/a]	1,456,919.06	830,287.21	189,473.68
Fuel cost [€/a]	−25,630,000.00	−13,640,000.00	6,010,921.78

[1] Taken from reference [72]
[2] Taken from reference [71]
[3] Taken from reference [70]

Table 7. Amortization periods per type of investment

Type of cost	Investment costs			Amortization [years]
	WtE – larger[1]	WtE – smaller[1]	Biomass[2]	
Infrastructure	12,547,396	7,441,988	1,926,906	20
Combustion and water/steam system	75,023,293	4,449,7074	11,853,394	15
Flue gas treatment	11,456,986	6,795,254	1,547,365	15
– Semi-dry flue gas treatment	3,271,231	1,940,200		
– Bag filter	6,004,935	3,561,588		
– SNCR system	2,180,820	1,293,466		
Design	5,452,051	3,233,667	1,372,191	5
Construction	19,089,857	11,322,387	7,444,865	20
Electro-mechanical inst.	13,637,806	8,088,721	2,160,471	15
Other investment costs	16,371,511	9,710,109	2,890,360	15

[1] Taken from reference [16]
[2] Taken from reference [57]

Scenario 1. Incineration of RW from the City of Zagreb

In this scenario, WtE plant has 7,487 working hours in the first and only 3,594 in the last year (tab. 8). This drop below 50% of the plant capacity results in the IRR of 3.89% which is well below the defined discount rate. Without an introduction of new waste streams, a reduction of the plant capacity is required.

Table 8. The impact of changes in the amount of RW and its LHV on WtE plant

Year	1	3	5	7	9	11	13	14
Waste treated ['000 t/a]	232.6	201.5	170.4	139.4	108.3	109.6	111.0	111.7
Working hours [h/a]	7,487	6,487	5,486	4,486	3,486	3,529	3,572	3,594
LHV [MJkg^{-1}]	11.07	11.44	11.80	12.17	12.53	12.35	12.17	12.08
Gate fee income [mill. €/a]	25.58	22.17	18.75	15.33	11.91	12.06	12.21	12.28
Electr. income [mill. €/a]	4.853	4.343	3.791	3.195	2.557	2.552	2.545	2.541
Heat income [mill. €/a]	6.158	5.511	4.810	4.055	3.245	3.238	3.229	3.225
Sec. mat. income ['000 €/a]	974.6	916.8	836.7	734.2	609.5	573.5	536.5	517.6
Total O&M costs [mill. €/a]	12.01	11.23	10.44	9.66	8.87	8.91	8.94	8.96

Scenario 1.1. Reducing the size of WtE plant

As the city landfill needs to be closed by the end of 2018, WtE plant capacity can be reduced to the capacity of 124,000 t/a, which is enough to process all RW in 2019. In this scenario, there is no major change in the number of working hours (tab. 9) which results in the IRR of 13%.

Table 9. The impact of changes in the amount of RW on smaller capacity plant

Year	1	3	5	7	9	11	13	14
Waste treated ['000 t/a]	124.0	124.0	124.0	124.0	108.3	109.6	111.0	111.7
Working hours [h/a]	7,500	7,500	7,500	7,500	6,550	6,631	6,713	6,753
Gate fee income [mill. €/a]	13.64	13.64	13.64	13.64	11.913	12.06	12.21	12.28
Electr. income [mill. €/a]	3.022	3.121	3.221	3.320	2.987	2.980	2.972	2.968
Heat income [mill. €/a]	6.158	6.361	6.564	6.766	6.087	6.073	6.057	6.049
Sec. mat. income ['000 €/a]	519.6	564.1	608.7	653.3	609.5	573.5	536.5	517.6
Total O&M costs [mill. €/a]	6.82	6.82	6.82	6.82	6.42	6.46	6.49	6.51

The sensitivity analysis of investment profitability, depending on the change in fuel prices and the selling price of heat, was performed (fig. 6).

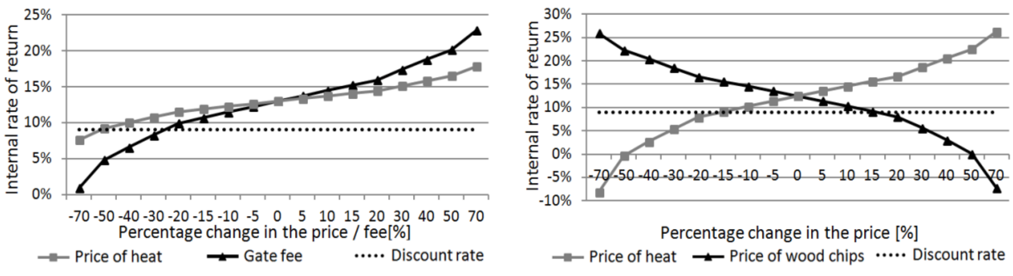

Figure 6. Sensitivity analysis of investment in WtE and biomass plant

It can be seen that the plant remains cost effective even if the gate fee is reduced to 81.95 €/t, or heat price to 0.0132 €/kWh. Better economic results are achieved due to lower investment and O&M costs, a higher overall number of working hours and higher overall efficiency which by Tariff system for electricity production from renewable energy sources and cogeneration [71] results in a higher electricity purchase price (tab. 6). This plant shows an overall better economic sustainability than a biomass plant, which has IRR of 12,46%, and is less sensitive to changes of fuel and heat price (fig. 6).

Scenario 2. Co-combustion of local WWT AD sludge and RW

Co-combustion of WWT AD sludge and RW results in the increase of overall number of operating hours of WtE plant, compared to Scenario 1, which has a positive impact on plant's economy (tab. 10). Because of low LHV of AD sludge, LHV of combusted fuel is lower, but an overall increase in fuel quantity leads to higher income from energy production and gate fees. At the same time, only variable costs are increased which results in IRR of 8.50%, when gate fees for the sludge and RW are on the same level.

Table 10. The impact of co-combustion of WWT AD sludge on WtE plant

Year	1	3	5	7	9	11	13	14
Waste treated ['000 t/a]	232.6	201.5	170.4	139.4	108.3	109.6	111.0	111.7
AD sludge treated ['000 t/a]	0.00	31.07	53.05	53.38	53.70	53.77	53.84	53.87
Working hours [h/a]	7,487	7,487	7,194	6,204	5,215	5,260	5,305	5,328
LHV [MJkg^{-1}]	11.07	10.23	9.57	9.47	9.18	9.08	8.98	8.94
AD sludge gate fee [mill. €/a]	0.00	3.42	5.84	5.87	5.91	5.92	5.92	5.93
RW gate fee [mill. €/a]	25.59	22.17	18.75	15.33	11.91	12.06	12.21	12.28
Electr. income [mill. €/a]	4.853	4.849	4.654	4.064	3.431	3.427	3.421	3.418
Heat income [mill. €/a]	6.158	6.153	5.905	5.156	4.354	4.348	4.341	4.337
Sec. mat. income ['000 €/a]	974.6	916.8	836.7	734.2	609.5	573.5	536.5	517.6
Total O&M costs [mill. €/a]	12.01	12.01	11.78	11.01	10.23	10.27	10.3	10.32

By keeping a constant gate fee for RW and changing gate fee for sludge and vice-versa, by keeping it constant for AD sludge and changing it for RW, sensitivity analysis is conducted (fig. 7). In this analysis also impact of heat price changes is shown.

For the initial gate fee of 110 €/t, this investment is not cost-effective. The overall relatively low sensitivity to changes of gate fees stems from working with two different fuels, while lower sensitivity to changes in the gate fee for the AD sludge, in comparison to RW, is a result of its lower LHV.

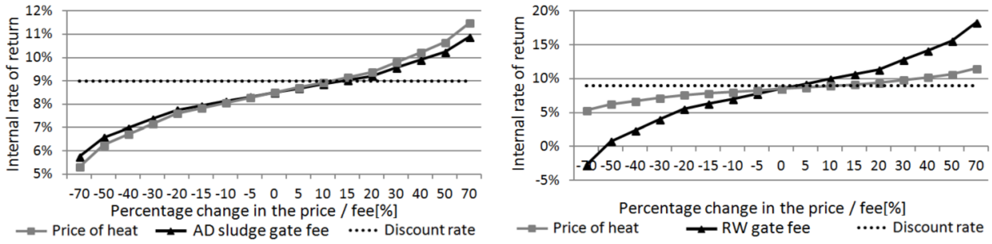

Figure 7. Sensitivity analysis for co-combustion of AD sludge in WtE plant

Scenario 3. Import of RW from the region

In this scenario the WtE plant has a constant load (tab. 11). The amount of treated waste and income from gate fee as well as variable expenses are constant due to waste import. Also, two new O&M expenditures are introduced: TS costs and transport costs. Transport costs vary over the years as quantity of transported waste changes. LHV of fuel is dependent on LHV and amount of waste transported from each county. Energy income also varies because of this. The IRR for this system consisting of WtE plant, TS and WTS amounts to 10.89%, which makes the investment profitable.

Table 11. The impact of import of waste on WtE plant

Year	1	3	5	7	9	11	13	14
Waste treated ['000 t/a]	232.6	232.6	232.6	232.6	232.6	232.6	232.6	232.6
Working hours [h/a]	7,487	7,487	7,487	7,487	7,487	7,487	7,487	7,487
LHV [MJkg^{-1}]	11.07	10.88	10.77	10.71	10.51	10.39	10.30	10.23
Gate fee income [mill. €/a]	25.58	25.58	25.58	25.58	25.58	25.58	25.58	25.58
Electr. income [mill. €/a]	4.853	4.770	4.720	4.696	4.607	4.554	4.515	4.486
Heat income [mill. €/a]	6.158	6.052	5.989	5.959	5.846	5.778	5.729	5.692
Sec. mat. income ['000 €/a]	975	1.497	1.934	2.561	3.059	2.858	2.673	2.562
Total O&M costs [mill. €/a]	12.01	12.01	12.01	12.01	12.01	12.01	12.01	12.01
TS costs ['000 €/a]	528.6	528.6	528.6	528.6	528.6	528.6	528.6	528.6
Transport cost ['000 €/a]	0.0	35.2	101.8	183.9	309.0	300.7	293.1	289.5

A sensitivity analysis of investment's profitability, depending on the change of gate fee and the selling price of heat, is shown in fig. 8. It can be seen that a change of gate fee has a much greater impact on the investment's profitability than changes of the heat price. This is due to high financial compensation and the quantity of treated waste. Thus, by reducing gate fee under 98.04 €/t, or heat price under 0.0149 €/kWh, the WtE plant becomes unprofitable.

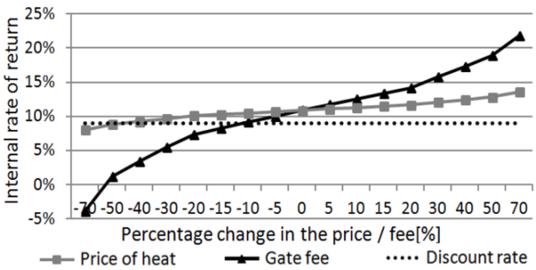

Figure 8. Sensitivity analysis of WMS

Compared to the biomass plant, the WtE plant is less profitable, but profitability of an investment in biomass plant is more sensitive to market changes. The biomass plant's profitability comes into question by increasing biomass price over 47.72 €/t, or by reducing the heat price under 0.0238 €/kWh. The WtE plant reaches profitability of the biomass plant with the gate fee over 131.93 €/t.

Conclusions

The EU has identified CHP and DH as a path to mitigate problems in the energy sector. In this path local energy sources play an important role, two of which are analysed in this paper – waste and biomass. Waste is identified as a possible energy source for the City of Zagreb, and waste fired CHP DH plant is a part of the national WM plan. While this plan has got a foothold in national legislation and correlates with European energy goals, and is at the same time on the track with plans for future ES development, there are still many debates, mainly about the size of WtE plant, which originate from mutual non-compliance of county's WM plans. In these debates incinerators of capacities up to 300,000 t/a have been mentioned. Such independent planning of a complex system, such as a WMS, can prove to be economically unsustainable. Therefore, in this paper the profitability of the construction and operation of a large WtE plant in the case of separate, when it processes only waste from Zagreb, and joint WM planning, when it imports RW from surrounding counties, is analyzed. In the case of separate WM planning, building of a smaller plant is also considered. A comparison of the profitability of such investments with the profitability of biomass CHP DH plants also puts the justification of such investments to the test from the energy point of view. The emphasis is placed on tracking local changes, at the level of each county, in the amount and composition of MSW caused by changes in EU legislation and socio-economic movements over time.

Also, in the case of biomass, its spatial distribution and characteristics need to be taken into account as well.

From the results of the first scenario it can be concluded that, at the present time, investment in a large WtE plant is an economically unsustainable solution on the level of one municipality alone. The main reason for this is the reaching of EU WM goals which result in rapid implementation of primary separation of recyclable waste components and thus decreasing the amount of RW. In these circumstances building a smaller WtE plant in conjunction with rapid implementation of separate collection of waste can be a way to go. In this scenario, a timely implementation of new WMS is of crucial importance because every delay leads to new expenses. In the second scenario the compensation of this decrease is done by co-combustion of other locally available fuel in WtE plant – WWT AD sludge. In this way the overall number of working hours of the plant is increased which puts this plant just under the point of profitability. In the last scenario a scope is expanded and all north-west and central Croatia are considered as a waste generator that can fuel WtE plant trough network of TS and WTS. Results show that by ensuring a high number of working hours of this kind of facility, as well the whole system, can be economically feasible. This can be done by taking the projected waste quantities and building plant of suitable size into account by cooperation of counties and creation of joint WM plan which offsets changes in waste quantity and composition or by finding other local waste streams that could be used as a plant fuel.

Based on calculations, it is possible to give an answer to the research question. Investments in both plants can be cost-effective, but competitiveness of WtE plant with biomass plant can be achieved only if process of planning of WMS is properly done and detail prognosis of waste generation is a part of it. Also, timely and proper implementation of adopted plans is crucial for economic viability of this kind of investments. Even though biomass plant has proved to be more cost effective in the majority of the scenarios, building a WtE plant can help in solving the RW disposal problem which would otherwise need to be tackled in another way. This is even more emphasized when co-combustion of other types of wastes is taken into account, like AD sludge or other local wastes. So, in order to give an unambiguous answer to this question, the bigger picture has to be looked upon, where a multicriteria analysis, which includes integration of other possible waste streams, of both energy and waste systems, must be conducted.

Acknowledgment

This work has been financially supported by the Croatian Science Foundation under grant No. DR-5-2014 (Career development of young researchers), European Union’s seventh Programme (FP7/2007-2013) project S2Biom (grant agreement no: 608622) and by the European Union’s Intelligent Energy Europe project STRATEGO (grant agreement EE/13/650). This support is gratefully acknowledged.

References

[1] Connolly, D., *et al*., Heat Roadmap Europe 1, Aalborg University, Aalborg, Denmark, 2012
[2] Connolly, D., *et al*., Heat Roadmap Europe 2, Aalborg University, Aalborg, Denmark, 2013
[3] Lund, H., *et al*., 4th Generation District Heating (4GDH) Integrating Smart Thermal Grids Into Future Sustainable Energy Systems, *Energy*, *68* (2014), Apr., pp. 1-11
[4] Connolly, D., *et al*., Heat Roadmap Europe: Combining District Heating With Heat Savings to Decarbonise the EU Energy System, *Energy Policy*, *65* (2014), Feb., pp. 475-489
[5] Mathiesen, B. V., *et al*., 100% Renewable Energy Systems, Climate Mitigation and Economic Growth, *Applied Energy*, *88* (2011), 2, pp. 488-501

[6] Lund, H., *et al*., The Role of District Heating in Future Renewable Energy Systems, *Energy*, *35* (2010), 3, pp. 1381-1390
[7] Munster, M., *et al*., The Role of District Heating in the Future Danish Energy System, *Energy*, *48* (2012), 1, pp. 47-55
[8] Di Lucia, L., Ericsson, K., Low-carbon District Heating in Sweden – Examining a Successful Energy Transition, *Energy Research & Social Science*, *4* (2014), Dec., pp. 10-20
[9] Gebremedhin, A., Introducing District Heating in a Norwegian Town – Potential for Reduced Local and Global Emissions, *Applied Energy*, *95* (2012), July, pp. 300-304
[10] Ericsson, K., Nilsson, L. J., Assessment of the Potential Biomass Supply in Europe Using a Resource-focused Approach, *Biomass & Bioenergy*, *30* (2006), 1, pp. 1-15
[11] Sahlin, J., *et al*., Effects of Planned Expansion of Waste Incineration in the Swedish District Heating Systems, *Resources Conservation and Recycling*, *41* (2004), 4, pp. 279-292
[12] Anić Vučinić, A., *et al*., Greenhouse Gases Reduction Through Waste Management in Croatia, *Thermal Science*, *14* (2010), 3, pp. 681-691
[13] Lončar, D., Ridjan, I., Medium Term Development Prospects of Cogeneration District Heating Systems in Transition Country – Croatian Case, *Energy*, *48* (2012), 1, pp. 32-39
[14] Ghafghazi, S., *et al*., A Multicriteria Approach to Evaluate District Heating System Options, *Applied Energy*, *87* (2010), 4, pp. 1134-1140
[15] Eriksson, O., *et al*., Life Cycle Assessment of Fuels for District Heating: A Comparison of Waste Incineration, Biomass and Natural Gas Combustion, *Energy Policy*, *35* (2007), 2, pp. 1346-1362
[16] Schneider, D. R., *et al*., Cost Analysis of WtE Plant, *Strojarstvo*, *52* (2010), 3, pp. 369-378
[17] Cho, H. S., *et al*., Effect of Quantity and Composition of Waste on the Prediction of Annual Methane Potential from Landfills, *Bioresource Technology*, *109* (2012), Apr., pp. 86-92
[18] Radovanić, P. M., *et al*., Opportunities of Solid Renewable Fuels for (Co-)Combustion with Coal in Power Plants in Serbia, *Thermal Science*, *18* (2014), 2, pp. 631-644
[19] Kirjavainen, M., *et al*., Small-scale Biomass CHP Technologies: Situation in Finland, Denmark and Sweden, Report 12, OPET, Espoo, Finland, 2004
[20] ***, Centre for Biomass Technology, www.videncenter.dk/Groenne%20trae%20haefte/ Groen_Engelsk/Kap_09.pdf
[21] ***, EVONIK Industries, www.duh.de/uploads/media/5_Blass_281107_01.pdf
[22] ***, AEBIOM, www.aebiom.org/IMG/pdf/Seeger.pdf
[23] Obernberge, I., Techno-economic Evaluation of Selected Decentralised CHP Applications Based on Biomass Combustion in IEA Partner Counties, Final Report, BIOS, Graz, Austria, 2004
[24] ***, PromoBio, www.promobio.eu/tiedostot/tiedotteet/Fact%20sheet_admont_be2020_final1.pdf
[25] Shustrova, T., *et al*., Biomass Combined Heat and Power in the United Kingdom, M. Sc. thesis, Technische Hochschule Nurnberg, Nuremberg, Germany, 2013
[26] ***, Power Plants Around the World, www.industcards.com/ppworld.htm
[27] Lacher, E., *et al*., Sustainable Exploitation of Biomass, 4Biomass Project: WP3 Report, Austrian Energy Agency, Vienna, Austria, 2009
[28] ***, AEBIOM, www.biomasseverband.at/veranstaltungen/tagungen-und-vortraege/cross-border-bioenergy-workshop/chp-workshop/?eID=dam_frontend_push&docID=102
[29] ***, Energiateollisuus, The Role of CHP, http://energia.fi/sites/default/files/chp_esite2010_engl.pdf
[30] ***, International District Energy Association, www.districtenergy.org/assets/CDEA/Case-Studies/StPaulDistrict-Energy6-27-07.pdf
[31] White, J. H., Weiman, S., *St. Paul Biomass Cogeneration Power Plant*, Tenn., USA, 2005
[32] Aittola, J. P., New Exploratory Technologies 2010, Heat – Electricity Plants in Finland, http://next.utu.fi/2010/presentations/Aittola-CHP_power_in_Finland.pdf
[33] ***, Jyvaskyla Energy, www.jyvaskylanenergia.fi/filebank/801-JE_Social_Responsibility_Report_2013_ENG.pdf
[34] Wood, S., *et al*., Review of State-of-the-art Waste-to-energy Technologies, Stage Two Report – Case studies, WSP, London, UK, 2013
[35] ***, A2A Group, www.a2a.eu/gruppo/export/sites/default/a2a/en/plants_networks/ waste_to_energy/documenti/folder_brescia.pdf
[36] ***, Friotherm, A. G., www.friotherm.com/webautor-data/41/sysave006_uk.pdf
[37] ***, Epem S. A., Database of Waste Management Technologies, www.epem.gr/waste-c-control/database/html/costdata-00.htm#Incineration

[38] Granatstein, D. I., Technoeconomic Assessment of Fluidized Bed Combustors as Municipal Solid Waste Incinerators: A Summary of Six Case Studies, IEA Task 23, CETC, Nepean, Canada, 2000
[39] ***, UK Government, www.gov.uk/government/uploads/system/uploads/attachment_data/ file/230869 /Annex_B_-_pfi_projects_in_procurement_march_2013.xlsx
[40] ***, UK Government, www.gov.uk/government/uploads/system/uploads/attachment_data/ file/221036 /pb13889-incineration-municipal-waste.pdf
[41] ***, ARUP, Bradford and Calderdale Residual Waste Management Project, www.arup.com/Projects/ Bradford_and_Calderdale_Residual_Waste_Management_Project.aspx
[42] ***, Green Investment Bank, www.greeninvestmentbank.com/news-and-insight/2013/green-investment -bank-announces-investment-in-new-waste-to-energy-project/
[43] ***, Waste Management World, www.waste-management-world.com/articles/2014/11/320-000-tpa-recycling-biogas-and-waste-to-energy-plant-secures-finance-in-yorkshire.html
[44] Kalogirou, E., MVB (MSW & Biomass) Waste to Energy Plants and the AVG Hazardous WTE Plant in Hamburg, Germany, WtERT Technical Report, Columbia University, NY, USA, 2010
[45] Kalogirou, E., Oslo Norway WtE Plant, WtERT Technical Report, Earth Engineering Center, Columbia University, NY, USA, 2011
[46] ***, State of Green, https://stateofgreen.com/en/profiles/ramboll/solutions/waste-to-energy-chp-ege-in-oslo-norway
[47] ***, Vantann Energia, www.vantaanenergia.fi/en/waste-to-energy-gives-a-new-life-for-rubbish/
[48] ***, eew, www.eew-energyfromwaste.com/en/our-sites/breisgau.html
[49] ***, eew, www.eew-energyfromwaste.com/fileadmin/content/Materialbestellung/Knapsack _Standortflyer.pdf
[50] Kalogirou, E., Report of Participation at Meeting of MatER, Synergia, Torino, Italy, 2013
[51] ***, SACE, www.eib.org/epec/resources/presentations/sace-guarantees-psf-may2011.pdf
[52] ***, HZ INOVA, www.hz-inova.com/cms/wp-content/uploads/2014/11/hzi_ref_lausanne-en.pdf
[53] ***, EPEM, www.epem.gr/waste-c-control/database/html/costdata-00.htm
[54] ***, International Solid Waste Association, www.iswa.org/index.php?eID=tx_iswaknowledgebase_ download&documentUid=3119
[55] de Gioannis, G., *et al*., Effects of Separate Collection Efficiency on the Cost of the MSW Management System-a Case Study, *Proceedings*, Biomass and WtE Symposium, Venice, Italy, 2006, pp. 1-10
[56] ***, Eunomia Research & Consulting, http://ec.europa.eu/environment/waste/studies/pdf/ euwastemanagement_annexes.pdf
[57] Lončar, D., *et al*., Support for Developers – Best Practices for Wood Biomass Cogeneration (in Croatian), Final Report, Center for Technology Transfer – CTT, Zagreb, Croatia, 2009
[58] ***, European Commission, http://eippcb.jrc.ec.europa.eu/reference/BREF/wi_bref_0806.pdf
[59] Ćosić, B., *et al*., Location Optimization for Biomass Trigeneration System with Pit Thermal Energy Storage: the Case of the City of Petrinja, *Proceedings* (Ban, M., *et al*.), 10th SDEWES Conference, Dubrovnik, Croatia, 2015, pp. 1-21
[60] Boer, E., *et al*., Waste Management Planning and Optimisation, Verlag, Stuttgart, Germany, 2005
[61] Sircar, R., *et al*., Holistic Forecast of Municipal Waste (in German), *Muell und Abfall*, (2003), 01, pp. 7-11
[62] Dennison, G. J., *et al*., A Socio-economic Based Survey of Household Waste Characteristics in the City of Dublin, Ireland, *Resources, Conservation and Recycling*, *17* (1996), 3, pp. 245-257
[63] ***, Ecoinvent Centre, Ecoinvent Database v3.2., www.ecoinvent.org/
[64] ***, Waste Management Plan of Zagreb County, www.zagrebacka-zupanija.hr/media/filer_public/70/31 /7031202c-530f-49b2-8326-c7b68f43f2d3/plan_gospodarenja_otpadom.pdf
[65] ***, A Goldsmith Resources, www.bcgov.net/archives/county-government/public-works/solid-waste-and-recycling/2014-costprojects-wastedisposal.pdf
[66] ***, AZO – Environmental Protection Agency, www.azo.hr/lgs.axd?t=16&id=5082
[67] Mužinić, M., *et al*., Waste Management Plan for the City of Zagreb for the Period to 2015 (in Croatian), Project Report, IPZ Uniprojekt, Zagreb, Croatia, 2014
[68] Magrinho, A., Semiao, V., Estimation of Residual MSW Heating Value as a Function of Waste Component Recycling, *Waste Management*, *28* (2008), 12, pp. 2675-2683
[69] Watkins, E., *et al*., Use of Economic Instruments and Waste Management Performances, Final Report Bio Intelligence Service, Paris, France, 2012
[70] ***, HEP-Toplinarstvo, http://www.hep.hr/toplinarstvo/en/customers/price.aspx

[71] ***, Tariff System for Electricity Production from Renewable Energy Sources and Cogeneration (in Croatian), Official Gazette of the Republic of Croatia, 133, 2013
[72] ***, Argus Media, Metal Prices, www.metalprices.com
[73] Tedeschi, S., *et al*., Final Treatment of Wastewater Sludge in the City of Zagreb (in Croatian), *Građevinar*, *64* (2012), 2, pp. 133-139
[74] ***, Ifeu Institute, http://transport-namas.org/wp-content/uploads/2014/04/IFEU-2011-HDV-emissions-in-Germany.pdf
[75] ***, Croatian Pension Insurance, www.mirovinsko.hr/default.aspx?ID=76

Paper submitted: February 12, 2016
Paper revised: April 21, 2016
Paper accepted: April 25, 2016