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Potential of municipal solid waste generated in Bulgaria for energy production

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In order to achieve the goals of the circular economy, energy is seen as a key element, especially when it is extracted from clean and accessible renewable sources, such as various types of wastes. Incineration is one of the possible methods for wastes treatment, which is increasingly used to utilize their energy potential. In this regard, the current article presents calculations on the energy potential of municipal solid wastes (MSW) generated in Bulgaria, in order to determine their suitability to produce energy and satisfy the energy needs of the population. The results of the calculations determine the possibility of burning of municipal solid wastes in order to utilize their energy value.

The data from the calculations show that the solid waste generated by small settlements with inhabitants under 3 001 people have the highest energy value and their combustion can lead to energy savings for the needs of 218 828 households with an average monthly electricity consumption of about 350 kWh. However, due to the current technological, economic and environmental prerequisites in the country, it is recommended that the main efforts for building of combustion plants for waste incineration should be focused primarily on the recovery of the huge amount of waste generated by settlements with inhabitants over 50 000 people.

Keywords: municipal solid wastes (MSW); incineration/combustion; waste to energy; utilization of wastes; energy value

INTRODUCTION

MSW are generated from various sources of human activity. Miezah *et al.* [1] report that in developing countries, 55-80% of the MSW are generated from households, followed by commercial or market areas (10-30%). Lebersorger and Beigl [2] describe in detail the social and other factors on which the generated amounts of MSW depend – demographics, population density, age and education of the population, etc. Erasu *et al.* [3] also give a connection between the level of economic development of the respective country and the amount of generated household waste due to a change in consumer behavior and lifestyle of the people. According to Palanivel and Sulaiman [4], the characteristics and composition of MSW depend on the topography of the area, food habits and commercial status of the city, seasons, etc. Karak *et al.* [5] forecast the amount of solid waste generated and expect increasing of the total solid waste to 27 billion tonnes worldwide in 2050, compared to 13 billion tonnes in 1990.

According to data published by Kawai and Tasaki [6], the amount of MSW generated per capita for Bulgaria is 1.26 $kg.person^{-1}.day^{-1}$. This quantity is slightly below the average for the member states of the European Union (EU), where the values are in the range of 0.85–1.83 $kg.person^{-1}.day^{-1}$. The data of the Ministry of environment and waters of Bulgaria (MOEW) published in an official report [7] also show that the generation of household waste per capita per year in Bulgaria, compared to the EU-28 is below average and that the country has positive trends for this indicator. The same report finds that there are significant differences between the municipalities in the country in terms of the indicator of generated MSW per capita per year.

Currently, there is a general consensus in the world that much of the generated wastes, including MSW, can be applied as raw materials into a circular process, recovering their energetic and chemical content and avoiding the environmental and human-health issues related to the incorrect disposal. Many authors point out that the kind of wastes should be considered as such a potential material and energy resource [8-13] and that efforts are needed, both at institutional and state level, to increase the rate of their utilization [14, 15].

Incineration is one of the possible methods for treatment of household wastes, which is increasingly apllied to utilize their energy potential. The problem with wastes is that they usually contain 2 to 4 times less heat energy than conventional fuels. This is due to the heterogeneity in their composition, the presence of high moisture and ash substances, the differences in physicochemical properties and other reasons [1]. High humidity of wastes can lead to partial or complete impossibility of their use, from a technological point of view, and high ash content

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can lead to economic inexpedience. Both components reduce the proportion of the other useful components and lead to increases in heat loss, needed to evaporate moisture and to the removal of fuel particles mechanically entrained by the ash [16].

The aim of this article is to present the results of the calculations performed on the combustion air, flue gases composition and energy values from the incineration process of different groups of mixed solid wastes generated in Bulgaria and to assess their potential for energy production.

EXPERIMENTAL

Statistical and morphological data on the generated MSW and energy consumption in Bulgaria

According to official data of the MOEW [17], the total amount of MSW generated in Bulgaria in 2014 was 3 193 kt (17% of the total amount of generated non-hazardous waste in the country) and in comparison to 2008, there is a decrease in the generated quantities. In 2014, the generated household waste per capita was 442 kg.person^{-1}.year^{-1}, and the waste accumulation rate was close to the EU-28 average for 2013 (481 kg.person^{-1}.year^{-1}) and about 1/3 of the generated MSW were handed over for utilization. At the same time, the norm for recycling of MSW per person for 2014, for Bulgaria is 108 kg.person^{-1}.year^{-1} and is lower than the average European norm (EU-28) equal to 130 kg.person^{-1}.year^{-1}.

In a subsequent Report on the state and protection of the environment for 2017 [18], it is noted that “from 2009 to 2013 there is a decreasing trend and for the period from 2013 to 2017 the quantities of generated MSW remain relatively constant” (see Fig. 1). It is also noted that "for the reporting year 2017 the national target of 40% for recycling of the household waste, set in the legislation, has not been reached", and the generated MSW for 2017 are 3 080 kt. The norm for recycling of MSW for 2017, for Bulgaria is 117 kg.person^{-1}.year^{-1}, compared to the average for European countries (EU-28) equal to 144 kg.person^{-1}.year^{-1} [18]. Comparing with the data from 2014, it is seen that this indicator has made some progress in the degree of recycling, but is still below the EU average value.

Table 1 shows the distribution of energy consumption in the country for the period 2013-2017 by sectors, by data from the MOEW published in the National report on the state and protection of the environment for 2017 [18].

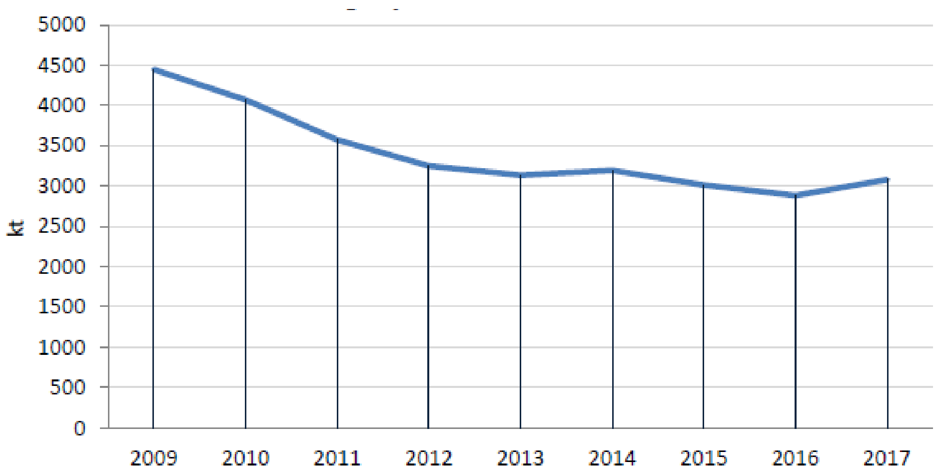

Figure 1. Quantities of generated MSW (kt) in Bulgaria during the period 2009-2017 [18]

Table 1. Total energy consumption by economic sectors, ktoe [18]

Sector	Year				
	2013	2014	2015	2016	2017
Industry	2 586	2 620	2 713	2 642	2 721
Transport	2 620	2 917	3 212	3 267	3 325
Household	2 241	2 165	2 193	2 252	2 319
Agriculture	194	190	186	185	173
Services	1 030	992	1 086	1 172	1 200
Total energy consumption	8 671	8 884	9 390	9 518	9 738

The report notes that in 2017, compared to the previous year, the most significant growth was observed in industry and households – 2.9%, followed by services and transport – 1.8%, and also a long-term downward trend in agricultural consumption – 7.0%.

The table shows that in this period, the total energy consumption in the country increased by about 12% and reached 9 738.0 ktoe. Official data also show that the share of energy produced from renewable sources is increasing, reaching 2 041.0 ktoe in 2017, compared to 2010 (1 396.6 ktoe). There is also an increase in the total consumption of electricity from renewable sources for 2017, reaching a value of 648.8 ktoe, compared to 2016 with a value of 633.3 ktoe. The contribution of the various sources is also noted: 57.2% from hydroelectric power plants, 18.9% from wind power plants, 18.6% from photovoltaics and 5.3% from biomass power plants [18].

The National action plan for renewable energy [19] notes that the country has significant forest resources and developed agriculture – sources of both solid biomass and raw materials for the production of biogas and liquid fuels from biomass, which could be used for energy production. According to this plan, by 2020 a mandatory national target of 16% share of the energy from renewable sources in gross total consumption of electricity has been set, which goal was achieved and reported in 2013, in the Second national report for progress of Bulgaria for the promotion and use of energy from renewable sources [20].

The previously cited National action plan [19] for 2020 provides an estimate of the amount of primary energy derived from 550 kt of the biodegradable part of municipal solid waste and landfill gas, amounting to 110 ktoe, and predicts that the amount of electricity produced from biomass will reach 865 GWh. Also it is noted that, despite the available international estimates of the rich potential of biomass for electricity production in the country, the opinion of Bulgarian experts is that biomass can be directed to electricity generation only through plants for combined production of heat and power. Directing it to condensing plants is considered unprofitable from every point of view: environmental, economic and technological. Also, in that plan is noted that biomass is the renewable source with the greatest potential in Bulgaria and at the same time with a variety of applications – as a raw material for the production of briquettes, pellets and other solid fuels, such as fuel for cogeneration and direct combustion for heating and producing hot water for the population. Unfortunately, that plan mainly examines the possibilities for application of plant biomass in households and small installations, which, however, do not allow for the combustion of large quantities of municipal solid waste and energy production from them.

The data from the National waste management program 2014-2020 [7] mention that over 50% of the municipal waste is biodegradable and according to the size of the settlements the morphology is different and includes garden and green waste, food waste, paper, cardboard and other biodegradable wastes. At the same time that waste goes to different landfills, due to which it is not possible to introduce an average morphological composition for the country. Precisely for these and a number of other reasons, it is necessary to focus efforts on their utilization through their processing for energy production near the places of their generation and disposition.

Parameters of MSW, in view of their use for energy production

Before being subjected to incineration, the MSW must undergo a pre-sorting stage in which the biodegradable garden and non-combustible components and the hazardous and inert materials, contained in them to be removed. According to the Methodology for determining the morphological composition of municipal waste [21] the data for the formed different combustible fractions at certain types of generators, in kg.person^{-1}.year^{-1} are shown in Table 2.

Table 2. Formed different fractions of wastes at certain types of generators

Waste fraction, %	Size of the settlement, by number of inhabitants				
	less than 3001	3 001 – 25 000	25 001 – 50 000	50 001 – 150 000	over 150 000
Kitchen/food	15.60	23.20	28.00	30.60	28.90
Paper and cardboard	10.10	14.00	15.00	17.60	20.80
Textile	2.00	3.70	2.90	2.90	2.80
Wood	2.90	2.00	2.90	2.10	2.00
Rubber and leather	2.00	1.80	2.00	2.00	1.80
Plastic	10.30	10.10	12.80	15.40	11.30

For the purpose of calculating energy production during the combustion process, the "work mass" of the waste fraction is taken into account, which includes the individual content of the elements carbon (C^w), hydrogen (H^w), oxygen (O^w), nitrogen (N^w), sulfur (S^w), ash (A^w) and moisture (humidity) (W^w). The sum of all of them must be equal to 100% [22, 23], according to the equation:

$$C^w + H^w + O^w + N^w + S^w + A^w + W^w = 100\ \% \qquad (1)$$

Also, when calculating the energy potential of wastes, it is necessary to use thermal properties data, which for some "pure" fractions of the waste have long been known in the literature [22] – see Table 3.

In order to determine the possibility of energy production from the wastes, it is necessary to know their composition in relation to the above-mentioned elements with a calorific value by incineration. Practical determination through analysis by each element of each batch of waste, in this case is an expensive, laborious and slow process. That can be avoided by applying alternative calculation procedures based on the morphological composition, which can give a sufficiently accurate composition of the waste intended for incineration. Thus, e.g. using equations (2) and (3) proposed by Totev [22], the content of each element in the mixed MSW can be calculated based on its morphological composition and the total contribution for each element based on its individual content in each fraction of the mixed waste.

$$X_E = a_E * \frac{Y_E}{100} [\%] \qquad (2)$$

$$X_{total} = X_{E1} + X_{E2} + ... + X_{En} \qquad (3)$$

where: X_E – individual content of the specific element in the mixed waste, contained in the respective fraction of the morphological composition, %; Y_E – content of the specific element in the respective waste fraction, %; a_E – content of the respective fraction in the total amount of waste, %; X_{total} – total work mass of the respective element in the mixed waste, %; X_{E1} to X_{En} – individual contents of the element in each fraction of the waste, %.

Here, calculations were performed for the composition of mixed MSW according to [22], which was recalculated in working mass – see Table 4.

Table 3. Thermal properties of some fractions of wastes, in work mass [22]

Type of “pure” waste	Combustible element						
	S^w, %	O^w, %	W^w, %	A^w, %	C^w, %	H^w, %	N^w, %
Papper/cardboard	0.18	39.80	10.24	5.38	38.95	5.23	0.22
Textile	0.12	28.30	10.00	2.20	49.28	5.94	4.16
Wood	0.04	33.80	20.00	0.80	40.46	4.78	0.12
Rubber	1.98	0	1.20	9.88	76.69	11.25	0
Plastic and other particles	0.05	17.62	4.00	60.00	15.93	2.35	0.05

Table 4. Thermal properties, based on the morphological composition of municipal solid waste in Bulgaria, depending on the settlements of generation

MSW generated by settlements with a population of:	Combustible element						
	S^w, %	O^w, %	W^w, %	A^w, %	C^w, %	H^w, %	N^w, %
less than 3001	0.21	20.12	31.43	17.91	26.17	3.56	0.60
3 001 – 25 000	0.19	19.95	35.27	14.83	25.53	3.48	0.75
25 001 – 50 000	0.19	19.3	36.31	15.75	24.43	3.34	0.68
50 001 – 150 000	0.18	19.41	35.66	16.76	24.04	3.30	0.65
over 150 000	0.19	20.79	35.62	13.98	25.30	3.46	0.66

Calculation of the combustion process and the energy value of the MSW

In order to ensure the comparability of the results obtained, calculations were carried out per kilogram of the waste mass, subject to the following prerequisites:

- the combustion reactions involved in the actual combusting process are:

$C + O_2 = CO_2$; $2 H_2 + O_2 = 2 H_2O$ (vapor); $S + O_2 = SO_2$

- dry atmospheric air in proportion k (k = $\%N_2/\%O_2 = 3.76$), is used;

- stoichiometric calculations are converted to normal conditions (P = 1 at, t = 0 ^{0}C, V = 22.4 m^3);

- a calculation of theoretical (stoichiometric) combustion, before calculating the actual combustion, must be done. Some of the used equations are described in [23];

- the air flow rate value (α) for calculating actual combustion is assumed to be the maximum possible [23] – α = 1.7;

- the absolute humidity value is assumed to be 12 [23] – $g_{H_2O} = 12\left[g.water/m^3 dry.air\right]$

In the process of calculating the actual combustion, it is necessary to calculate the parameters: amount of oxygen; quantity of dry and humid air; excess air. The equations used are described in detail below.

- amount of oxygen required:

$$V_{O_2} = 0{,}01*(1{,}867*C^w + 5{,}6*H^w + 0{,}7*S^w - 0{,}7*O^w), \frac{m^3 O_2}{kg.fuel} \quad (4.1)$$

- required amount of dry air (DA):

$$L_\alpha^{DA} = \alpha * L_0^{DA} - L_0^{DA} = (\alpha - 1) * L_0^{DA}\left[m^3 DA/kg.fuel\right] \quad (4.2)$$

where L_0^{DA} is the required DA for the theoretical combustion.

- required amount of wet air (WA):

$$L_\alpha^{WA} = (1 + 0{,}001244*g_{H_2O}) * \alpha * L_0^{DA}\left[m^3 WA/kg.fuel\right] \quad (4.3)$$

- excess air required (EA):

$$L' = L_\alpha^{WA} - L_0^{WA}\left[m^3 EA/kg.fuel\right] \quad (4.4)$$

where L_0^{WA} is the required WA for the *theoretical combustion.

The products of actual combustion are: carbon dioxide (CO_2), water vapor (H_2O_v), sulfur dioxide (SO_2), nitrogen (N_2), oxygen from combustion products (O_2) and total flue gas (wet smoke (WS)). The equations used to calculate them are given below:

- CO_2: $$V_{CO_2}^\alpha = 0{,}01*1{,}867C^w, \frac{m^3 CO_2}{kg.fuel} \quad (5.1)$$

- H_2Ov:

$$V_{H_2O}^\alpha = V_{H_2O} + 0{,}001244*g_{H_2O}*(\alpha - 1)*L_0^{DA}, \frac{m^3.H_2O}{kg.fuel} \quad (5.2)$$

where V_{H2O} is the quantity of water vapour calculated in theoretical combustion.

- SO_2: $$V_{SO_2}^\alpha = 0{,}01*0{,}7S^w, \frac{m^3 SO_2}{kg.fuel} \quad (5.3)$$

- N_2: $$V_{N_2}^\alpha = V_{O_2} + \alpha * k * V_{O_2}, \frac{m^3 N_2}{kg.fuel} \quad (5.4)$$

- Excess O_2:

$$V_{O_2}^{'} = (\alpha - 1)*V_{O_2}, \frac{m^3 excessO_2}{kg.fuel} \quad (5.5)$$

- WS:

$$V_\alpha^{WS} = V_{CO_2} + V_{H_2O}^\alpha + V_{SO_2} + V_{N_2}^\alpha + V_{O_2}^{'}, \frac{m^3 WS}{kg.fuel} \quad (5.6)$$

On the basis of the calculated quantities for the combustion products (according to equations 5.1-5.6), the composition of the flue gas is determined by calculating the percentages of the individual components (X). Each component of the flue gas is a ratio of its volume (V_X) to the total amount of flue gas (V_α^{WS}), expressed as a percentage and calculated by the following equation:

$$\%X = \frac{V_X}{V_\alpha^{WS}}*100 \quad (6)$$

The sum of the individual values of each component of the flue gas must be equal to 100%.

In the present study, for the calculation of the heat of combustion (heating value) the equation (7) proposed by M. Ioelovich [24] was used. He proposed that equation as the most promising approach to improve the calculation of combustion heat, for application in the calculation of the energy of solid fuels based on natural materials, such as peat, lignite, firewood and other plant-based wastes.

q (MJ/kg) = 0.344*C + H + 0.105*S – 0.110*O – 0.015*N (7) where: C, H, S, O and N are the percentages of the corresponding elements in the burned material.

According to Ioelovich, that equation provides a decrease in the deviation of the calculated from the experimental results to 1-2%, and the obtained results are more accurate than those obtained in the calculation with the well-known Mendeleev equation.

Based on the values obtained for the combustion heat of the material, given that 1 kWh is equal to 3.6 MJ, it is easy to calculate the energy value that it will generate upon complete combustion of 1 kg and 1 ton of combustible material, respectively. The calculation of the saved energy for households is made on the basis of an assumption for average monthly electricity consumption for a family of four in Bulgaria, equal to 350 kWh, and assuming that the combustion rate it reaches is 1/10 of the generated total annual amount of municipal solid waste in the country.

RESULTS AND DISCUSSION

The results from the calculations done for the parameters of the combustion process of the various municipal wastes are given in Table 5, and for the combustion products and the composition of the expected generated flue gases – in Tables 6 and 7.

Table 5. Results of calculations for the amounts of oxygen, wet and dry air, and excess air required for combustion

MSW for combustion, generated by settlements with a population of**:**	Parameter calculated according to equation			
	(4.1)	(4.2)	(4.3)	(4.4)
less than 3001	0.55	4.51	1.83	1.86
3 001 – 25 000	0.53	4.38	1.78	1.80
25 001 – 50 000	0.51	4.18	1.70	1.72
50 001 – 150 000	0.50	4.10	1.66	1.69
over 150 000	0.52	4.29	1.74	1.77

Table 6. Results of calculations for combustion products (units of measurement are according to calculation formulas)

MSW for combustion, generated by settlements with a population of:	Parameter calculated according to equation					
	(5.1)	(5.2)	(5.3)	(5.4)	(5.5)	(5.6)
less than 3001	0.49	0.86	0.0015	4.05	0.38	5.79
3 001 – 25 000	0.48	0.89	0.0013	3.94	0.37	5.69
25 001 – 50 000	0.46	0.89	0.0013	3.77	0.36	5.47
50 001 – 150 000	0.45	0.87	0.0013	3.69	0.35	5.36
over 150 000	0.47	0.89	0.0013	3.86	0.36	5.59

Table 7. Results of flue gas composition calculations, in %

MSW for combustion, generated by settlements with a population of:	CO_2	H_2O_v	SO_2	N_2	O_2
less than 3001	8.45	14.79	0.025	70.09	6.64
3 001 – 25 000	8.38	15.71	0.023	69.32	6.56
25 001 – 50 000	8.34	16.23	0.024	68.88	6.52
50 001 – 150 000	8.37	16.29	0.024	68.79	6.51
over 150 000	8.45	15.99	0.024	69.01	6.53

Table 8. Results for heating values, electricity and economized electricity

MSW for combustion, generated by settlements with a population of**:**	Heating value, MJ/kg	Electricity, kWh/ton	Electricity*, GW/year	Economized electricity from conventional sources for household, count/year
less than 3001	10.36	2878.4	919.1	218 828
3 001 – 25 000	10.08	2799.0	893.7	212 793
25 001 – 50 000	9.63	2675.2	854.2	203 378
50 001 – 150 000	9.44	2633.3	837.6	199 432
over 150 000	9.89	2746.2	876.9	208 777

* At combusting of 1/10 of the annual amount of generated MSW

The initial composition of the mixed MSW (see Table 4) shows insignificant differences in the fractional composition. This logically assumes that no significant difference should be expected in the results obtained from the calculations for the required amounts of oxygen, wet and dry air and excess air for the combustion process, and for the composition of the flue gases and the amount of combustion products. The results presented in Tables 5-7 confirm this expectation. For example, the difference between the minimum and maximum required quantities of excess air for the combustion process is insignificant, 1.69 (for MSW from settlements with inhabitants between 50 001 and 150 000) and 1.86 (for MSW from settlements with less than 3 001 inhabitants), respectively The results for the type of combustion products and their quantities also do not differ significantly. The differences in the percentage distribution of the generated gases are significant, albeit to a minimal extent, only in terms of the distribution between the fractions of generated water vapor and nitrogen. Significant differences are expected in terms of the economic effect of saving transport costs for transporting waste to regulated landfills and saving energy from conventional sources, in case they are incinerated as close as possible to the place of their generation.

The calculations for the energy value, the amount of produced energy and the possible amount of saved energy produced from conventional fuels, given in Table 8, are performed without taking into account the heat losses of the heat generator due to incomplete combustion of the fuel due to chemical or mechanical reasons. These calculations give a satisfactory idea of the potential of the different groups of MSW generated in the country, in view of their use for energy production.

Again, as with the parameters of the combustion process, insignificant differences are observed between the values obtained for the heating value and the electricity obtained from the combustion of a ton of waste, as the average values for both indicators are 9.88 MJ/kg and 2 746.4 kWh/t, respectively. It is interesting to note that the calculated values show that the MSW generated by small settlements with inhabitants under 3 001 people, display the highest energy value and their combustion can lead to energy savings for the needs of 218 828 households. However, the problems at the incineration of that waste are related to technological capabilities for their collection and landfilling, ensuring of continuous operation of the combustion plants and the high cost of building and maintaining the necessary infrastructure related to their possible incineration on site and realization of the produced electricity, which is often unaffordable for small municipalities. On the other hand, the largest amounts of generated waste – from settlements with inhabitants over 150 000 people, have an energy value as maximum close to the average and the generated electricity and the energy saved for households are closest to the average compared to the different types of MSW. For that reason, it is recommended that the initial efforts to build combustion plants for waste combustion in the country should be focused mainly on the recovery of these amounts of waste in order to achieve the fastest and most significant effect, both in terms of environmental protection and achieving higher economic efficiency.

CONCLUSIONS

The results obtained from the calculations for the required amounts of oxygen, wet and dry air and excess air for the combustion process and for the composition of the flue gases and the amount of combustion products of MSW generated by settlements with different populations based on the initial morphological composition, do not logically show a significant difference.

The calculations of the energy value, the amount of produced energy and the possible amount of saved energy produced from conventional sources for households, give a satisfactory idea of the potential of the different groups of municipal solid waste generated in the country and prove their possible application for energy production.

The highest energy value can be produced by the solid wastes generated by small settlements with inhabitants under 3 001 people –10.36 MJ/kg. Their combustion can lead to savings in electricity produced from conventional fuels for 218 828 households with an average monthly electricity consumption of 350 kWh.

Based on the various technological, economic and environmental prerequisites, at present it is recommended that the main efforts to build combustion plants for waste combustion in the country should be aimed primarily at recovering the huge amount of waste generated by settlements with inhabitants over 50 000 people.

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